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Soil organic carbon in northern Spain (Galicia, Asturias, Cantabria and País Vasco)

Carbono orgánico en los suelos del norte de España (Galicia, Asturias, Cantabria y País Vasco)
Carbono orgânico nos solos do norte de Espanha (Galiza, Astúrias, Cantabria e País Basco)

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ABSTRACT

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The soil organic carbon content was analyzed in more than 7,000 soil samples under different land uses, climates and lithologies from northern Spain (Galicia, Asturias, Cantábria y País Vasco). GIS maps (1:50 000) were made of the % SOC and SOC stocks. The % SOC varies according to land use (higher in forest and scrub soils and lower in agricultural soils) and climate, and there is a highly significant correlation between SOC content and mean annual precipitation. There are significant differences between the soils of Galicia/Western Asturias (GA_w) and those of the rest of the study area (Central and Eastern Asturias, Cantabria and País Vasco) ($A_{ce}CV$), although these are neighbouring regions. In forest and/or scrub soils with a *udic* soil moisture regime, in GA_w, the SOC is usually > 7% and the average stocks 260 t ha^{-1} (0-30 cm), and >340 t ha^{-1} (0-50 cm) in soils with thick organic matter rich horizons (> 40 cm); these values greatly exceed the average contents observed in forest soils from temperate zones. Under similar conditions of vegetation and climate in soils of $A_{ce}CV$ the SOC average is 3% and the mean stocks 90-100 t ha^{-1} (0-30 cm). The *andic* character of acid forest soils in GA_w and the formation of C-Al,Fe complexes are pointed out as the SOC stabilization mechanism, in contrast to the neutral and calcareous soils that predominate in $A_{ce}CV$, where the main species of OC are easily biodegradable.

RESUMEN

Se analiza el contenido de carbono orgánico (CO) en más de 7.000 muestras de suelos del norte de España (Galicia, Asturias, Cantábria y País Vasco) bajo diferentes tipos de ocupación, condiciones climáticas y litología, y se elaboran mapas SIG (1:50 000) del porcentaje y stock de carbono en los suelos. El porcentaje de CO varía de acuerdo al uso del suelo (mayor en suelos forestales y con matorral, y menor en suelos de cultivo) y al clima, reconociéndose una correlación altamente significativa entre el porcentaje de CO y la precipitación media anual. En cualquier caso, aún tratándose de regiones próximas, se establecen diferencias importantes entre los suelos de Galicia-oeste de Asturias (G/A_o) y los del resto del área de estudio (Asturias central y oriental, Cantabria y País Vasco) ($A_{ce}CV$). En suelos forestales y/o con matorral y régimen de humedad údico, en G/A_o, el porcentaje de CO es habitualmente > 7% y el stock medio 260 tC ha^{-1} (0-30 cm) y puede ser > 340 tC ha^{-1} (0-50 cm), teniendo en cuenta la abundancia de suelos con rasgos cumúlicos y horizontes humíferos con > 40 cm de espesor; los valores obtenidos superan ampliamente los contenidos medios señalados por diferentes autores para suelos forestales de áreas templadas. En similares condiciones de vegetación y clima, el contenido medio de CO en suelos de ($A_{ce}CV$) es de 3% y el stock medio 90-100 tC ha^{-1} (0-30 cm). El carácter ándico de los suelos forestales ácidos de G/Ao, y la formación de complejos C-Al,Fe se señala como mecanismo de estabilización del CO, en contraste con los suelos neutros y calcáreos que predominan en $A_{ce}CV$, en los que la especie principal es el CO fácilmente biodegradable.

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RESUMO

Analisou-se o teor de carbono orgânico en mais de 7.000 amostras de solo do norte de Espanha (Galiza, Astúrias, Cantábria e País Basco), sob diferentes usos, condições climáticas e litologias, e procedeu-se ao mapeamento SIG (1:50 000) da percentagem e stock de carbono nos solos. A percentagem de CO varia de acordo com o uso do solo (maior em solos de floresta e mata e menor em solos agrícolas) e condições climáticas, observando-se uma correlação altamente significativa entre a percentagem de CO e a precipitação média anual. Em qualquer caso, mesmo para regiões vizinhas, registam-se diferenças significativas entre os solos da Galiza-oeste e das Astúrias (G/A_o) e o resto da área em estudo (Astúrias central e oriental, Cantabria e País Basco) ($A_{ce}CV$). Em solos de floresta e/ou de mata e regime de humidade údico, em G/A_o, a percentagem de CO é geralmente > 7% e o stock médio 260 t C ha^{-1} (0-30 cm), e > 340 t C ha^{-1} (0-50 cm) em solos com espessos horizontes ricos em matéria orgânica (> 40 cm); estes valores excedem largamente os teores médios observados em solos florestais de zonas temperadas. Em condições semelhantes de vegetação e clima, em solos de $A_{ce}CV$, o teor médio de CO é de 3% e o stock médio de 90-100 t C ha^{-1} (0-30 cm). O carácter andico dos solos florestais ácidos da Galiza, e a formação do complexos C-Al,Fe são apontados como o mecanismo de estabilização do CO, em contraste com os solos neutros e calcários prevalecentes em $A_{ce}CV$, onde a espécie predominante é o CO facilmente biodegradável.

KEY WORDS
Digital map of SOC, soil-C stocks

PALABRAS CLAVE
Mapa digital de COS, stocks de C-suelo

PALAVRAS-CHAVE
Mapa digital de COS, stocks de C-solo

1. Introduction

From the United Nations Framework Convention on Climate Change (1994), the Kyoto Protocol 1997-2005 (United Nations 1998) has established targets for reductions in emissions of greenhouse gases (GHG), with mandatory compliance for industrialized countries. Policy measures include the possibility of using carbon sinks (plant biomass and soil), taking into account the net fixation/emissions due to certain activities (Land use, Land Use Change and Forestry) as outlined in articles 3.3 and 3.4 of the Protocol. The assessment of biomass as a sink generated additional rights in some EU member states of between 1% and 4% above the emission targets, for the period 2008-2012. Soil was not considered in these calculations because of the lack of sufficient data for modelling the net fixation on a temporal scale for each geographical region and land use, despite the abundance of information about the importance of soil as a carbon sink. The global C content of soils throughout the world is estimated to be close to 1,600 Pg C (0-100 cm) (Batjes 1992; Eswaran et al. 1993; Sombroek et al. 1993), which is twice the amount estimated to exist in vegetation biomass (Lal et al. 1995; IPCC 2000; Saugier et al. 2001).

Taking into account data reported by different authors (Bohn 1982; Post et al. 1982; Eswaran et al. 1993), the United States Department of Agriculture constructed maps of the organic C content of the world's soils (scale 1: 100,000,000) (USDA 2000). The maps show the zonal nature of the distribution, with values > 800 tC ha^{-1} (0-100 cm depth) in peatland areas of *frigid* and *cryic* environments, and of < 20 tC ha^{-1} in *aridic* environments. In Europe, the European Soil Bureau has made several maps (scale 1:1,000,000) by applying a calculation model to the available data included in the "European Soil Database" and harmonized in accordance with the international classification scheme (FAO-UNESCO-ISRIC 1990) and the CORINE report on land cover and land use (Rusco et al. 2001; Jones et al. 2003, 2004). The maps show the % SOC (0-30 cm depth), but not the SOC stocks (tC ha^{-1}) because there are insufficient data available for bulk density. In their final recommendations, the authors indicated the main deficiencies and urged Member States to validate the information provided or, where appropriate, to apply sampling programmes and analysis aimed at amplifying the database and thus to improve the model fit (Jones et al. 2004). Subsequently, Hiederer et al. (2011) performed an estimation of Global SOC and the Harmonized World Soil Database. In their conclusions they recognized that the various sources of spatial data for estimating global SOC stocks need further proccesing or data amendments in order to provide coherent and comparable results, and indicated again the scarcity of some necessary parameters for calculation (bulk density, coarse fragments and soil depth).

The objective of this study is to create a semi-detailed map (1:50,000) of the organic carbon content of the soils of some regions in northern Spain (Galicia, Asturias, Cantabria and the País Vasco), amplifying the existing information on geo-referenced samples in environments with different climate, land cover, soil type, lithological substrate, etc.

2. Material and Methods

The study area includes the territories of the autonomous communities of Galicia (29 574 km²), Asturias (10 604 km²), Cantabria (5 321 km²) and the País Vasco (7 234 km²) in northern Spain. Overall, the soil temperature regime in the whole territory is *mesic* and the soil moisture regime is *udic*, with an average annual rainfall between 800 and > 2000 mm; in some inland areas of Orense (Galicia) and south of Álava (País Vasco), the soil moisture regime is *xeric*. The lithology is varied. In Galicia and western Asturias there is a predominance of acid rocks (granite, quartz schists and shales) and a lower proportion of basic (gabbros and amphibolites) and ultramafic rocks (serpentinites); the soils are mainly classified as *haplic* and *andic Umbrisols* on acid rocks, *umbric Andosols* on basic rocks and *haplic Phaeozems* on serpentinites (IUSS-WRB 2014). In the Cantabrian coast the lithology is mainly calcareous sedimentary materials (marl, limestone, sandstone and other) and soils are classified as *calcaric Phaeozems* (*haplic Umbrisols* when decalcified), or *calcaric* (or *eutric*) *Cambisols* if not satisfied the requirements for *umbric* or *mollic* epipedon (IUSS-WRB 2014).

In total, 7 140 soil samples were collected under different types of land use (forests, shrubs, crops, meadows, pastures, marshes, dunes, peats, etc.), 3 752 in Galicia and 3 388 in Asturias, Cantabria and the País Vasco (hereafter ACV). Most of the samples (4 505) correspond to the surface layer with higher organic matter content (A horizon: 0-10/15 cm or 0-30 cm, as the case) and the remaining (2 635) to the underlying layer (AB, B or C horizons), up to a depth of 50 cm. Air-dried soil samples (< 2 mm) were analyzed for total carbon content (LECO-TruSpec CHN analyzer), total inorganic carbon (carbonate-C) (by Bernard calcimeter method), total N (LECO), pH-H_2O (1:2.5) and pH-KCl; furthermore, the dry bulk density was determined (by using cylindrical cores of 5 x 5 cm) as well as the volume of coarse fragments (> 2 mm). The organic C content (% OC) was determined by difference between total C and inorganic C. Soil organic carbon stocks (OCS) (tC ha^{-1}) were computed separately for both layers from OC content, coarse fragments content, layer thickness and bulk density, as:

$$OCS_L = \% OC \times BD \times [1- (VG/100)] \times LT$$

where, OCS_L: total amount of soil organic carbon to given depth (tC ha^{-1}); OC: soil organic carbon content for given depth; BD: dry bulk density (g cm^{-3}); VG: volume of gravels; LT: thickness of soil layer (cm).

The OCS stocks thus computed for the two layers were then combined to estimate the OCS stocks for 0-30 and 0-50 cm. Where the soil depth was less than 30 (or 50) cm, stocks were computed to that depth. The analytical results were analyzed by ANOVA, taking into account land use, soil type, lithology, climate, altitude and proximity to the sea.

Moreover, the following thematic maps (GIS) were constructed: (A) Land use maps, using information from CORINE Land Cover and PNOA (National Institute of Geography) and the Forest Map of Spain (Ministry of Agriculture); the Information System of Land Occupation of Spain (SIOSE-2009) (Xunta de Galicia) was used for the territory of Galicia. The combined information was standardized and adapted to the study objectives, and the following units were finally considered for cartography: 1. Marine and coastal environments, differentiating beaches and dunes, coastal salt marshes, estuaries and cliffs; 2. Rocky outcrops; 3. Peatlands; 4. Shrublands; 5. Forests (natural or reforested); 6. Grasslands and pastures; 7. Cropland of cereals or vegetables; 8. Vineyards; 9. Urban areas and infrastructures, including quarries and mines; 10. Water surfaces. (B) Soil depth maps (by field descriptions and photointerpretation), considering the following units: < 10, 10-20, 20-30, 30-40, 40-60, 60-100 and > 100 cm thick.

Finally, maps of the soil organic carbon content (% OC) and COS (tC ha^{-1}) for 0-30 and 0-50 cm soil thickness) were elaborated at 1:50,000 scale. Treatment and georeferenced analysis of the data was implemented with the GIS software tools (ArcGis Desktop 9.3).

3. Results

3.1. Organic carbon contents of Galician soils

The OC content of Galician soils varies widely, from < 0.2% in beaches and coastal dunes, to > 35% in areas with peat, both of which are scarcely represented. The cartographic distribution is strongly dependent on the type of land use. More than 65% of the territory was found to be covered by shrubs and/or trees (mainly reforested areas with understory of shrub); crops and pasture occupy 27% of the land, and the remaining 10% has very diverse coverage (urban, infrastructures, rock, marshes, etc.) (**Figure 1**). On a local scale, considering the main types of land use, the % OC of the soil followed the order: vineyards<cereal and vegetable crops<grassland<forest≤shrub (**Figure 2**). This is a common sequence in different parts of the world and is related to the different amounts and/or recalcitrance of organic debris; it should be noted that the management of agricultural soils in Galicia often involves the application of organic amendments. Overall, for the whole region, the mean values obtained follow this sequence according to land use, although a wide variation of the values indicating the influence of other factors are observed (**Table 1**).

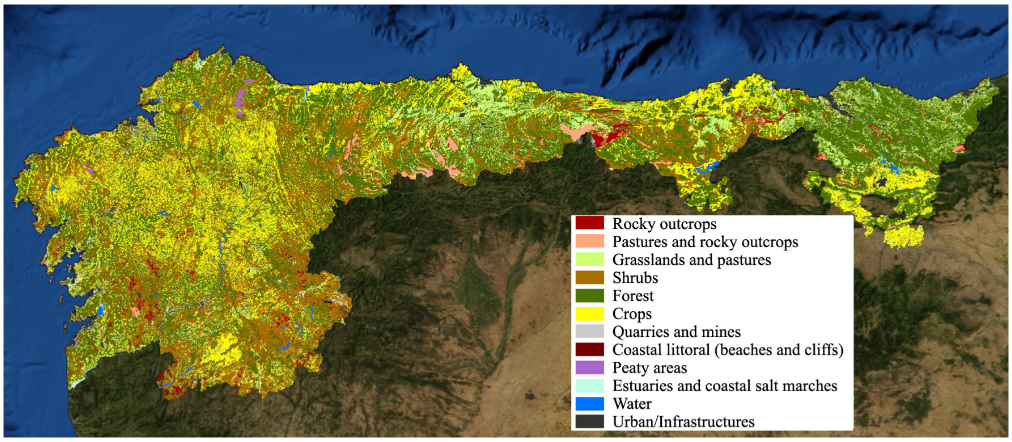

Figure 1. Map of land use in northern Spain (made at scale 1:50 000, Calvo de Anta et al. 2013).

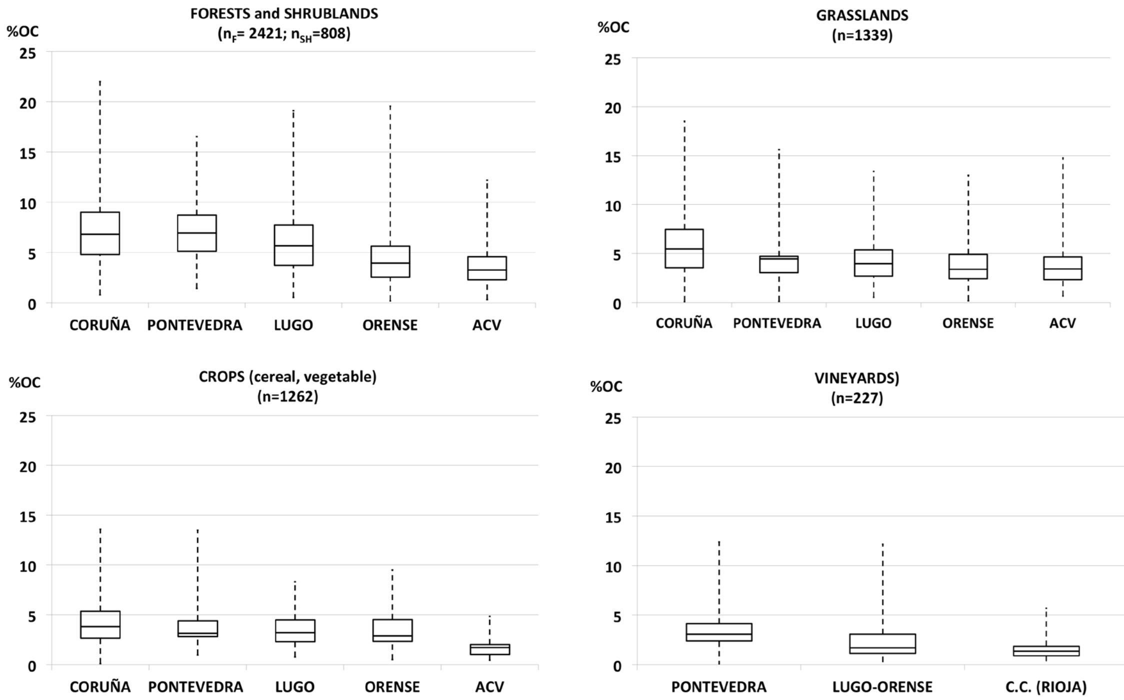

Figure 2. Variation in the soil organic carbon content in different land use types (0-30 cm depth) (ACV: Asturias, Cantabria and País Vasco).

On reducing the scale, the climate factors become more important, more specifically the hydric regime since the temperature regime is relatively homogeneous throughout the territory. The data obtained for 1,384 surface horizons of forest and/or shrubland soils (F-SH), in areas with different rates of annual mean precipitation, revealed a highly significant correlation ($p < 0.01$), described by the following equation:

$$\% OC_{F\text{-}SH} = 0.005\ P - 0.27 \pm 1.74\ (R= 0.75)$$

where, $OC_{F\text{-}SH}$ is the soil organic carbon (0-30 cm) and P is the annual mean precipitation (mm) (Figure 3a). The equation describes a similar trend to that observed in forest soils developed from granites in Portugal (Madeira et al. 2004), although the OC contents are greater in Galicia (0.6% higher) (Figure 3c).

The cartographic variability, depending on the weighting of the different factors (land use, climate, altitude, etc.), is illustrated in Figure 4. Ignoring the aforementioned extreme values, the most common interval of variation ranged between 3-4% OC, for cropped soil close to the coast at an elevation <100 m and in inland areas of Lugo and Orense, and 8-10% in shrubland and/or forest areas at an elevation of > 400 m, in the provinces of La Coruña and Pontevedra. In global terms, 63% of the surface of Galicia has > 6% of OC (6-10%), which coincides with the presence of forest soils (F-SH) in the wettest areas (> 1200 mm of annual rainfall).

Soil organic carbon stocks (tC ha^{-1}) were determined considering the % OC and the bulk density of the material. The BD is also related to the % OC, resulting a highly significant negative correlation between these two parameters (Figure 5); the BD was not correlated with texture (values ≥ 1.5 g cm^{-3} were recorded both in soils derived from marls, with > 40% clay, and in coastal dunes containing 100% sand). As result, the BD of the soils varied according to an inverse sequence to % OC, lower in the F-SH soils and higher in cropped soils, and increased from the surface to subsurface horizons (Table 1).

Table 1. Organic Carbon (OC), nitrogen, bulk density (BD) and pH in soils in different land use (median and range) (Sh: shrublands; F: forests; G: grasslands; C: cereal/vegetable crops; V: vineyards; GR: soils on granitic rocks; S: schists; SL: slates; Q: sandstones and quartzites; B: basic rocks; UB: ultrabasic rocks; LM: limestones and marls) (c,e: Central and Eastern)

			GALICIA		
	Sh	**F**	**G**	**C**	**V**
Soil layer (cm)			% OC		
0-30/40	6.03 0.4-22 n=658	5.67 0.6-20 n=901	4.54 0.2-21 n=605	3.6 0.1-16 n=428	2.26 0.4-6 n=107
30/40-50	1.21 0.1-5 n=220	0.98 0.1-8 n=301	0.67 0.1-5 n=220	1.15 0.2-4 n=150	1.10 0.1-3 n=50
			% N		
0-30/40	0.33 <0.01-5.8 n=658	0.29 <0.01-1.5 n=901	0.33 <0.01-3.0 n=605	0.29 <0.01-1.6 n=428	0.17 <0.01-1.9 n=107
			BD (g cm^{-3})		
0-30/40	0.95 0.6-1.3 n=336	0.91 0.5-1.4 n=491	1.06 0.7-1.4 n=271	1.08 0.6-1.5 n=104	1.08 0.9-1.5 n=33
30/40-50	1.18 1.0-1.6 n=117	1.15 0.7-1.7 n=103	1.11 0.8-1.2 n=117	1.29 0.7-1.6 n=130	1.29 0.8-1.6 n=33
			pH_{H2O}(F-Sh)		
	GR	**S**	**SL/Q**	**B**	**UB**
0-30/40	4.8 3.6-5.5 n=658	4.9 4.2-6.8 n=901	4.4 3.3-5.4 n=605	5.1 4.0-6.5 n=428	5.9 4.4-6.7 n=107
30/40-50	4.9 3.8-5.9 n=220	5.0 3.3-6.8 n=301	4.7 3.7-6.6 n=220	5.0 3.2-6.8 n=150	6.5 4.7-6.8 n=50
			ASTURIAS$_{(c,e)}$, CANTABRIA, P.VASCO		
	Sh	**F**	**G**	**C**	**V**
			% OC		
0-10/15	4.76	3.59	4.12	1.85	1.20
10/15-30	1.85	2.11	1.49	1.85	1.20
0-30	2.82 0.5-16 n=150	2.60 0.20-23 n=1520	2.81 0.5-15 n=734	1.85 0.2-16 n=834	1.20 0.2-10 120
			% N		
0-30	0.25 <0.01-1.6 n=150	0.17 <0.01-1.3 n=1520	0.39 <0.01-3.8 n=734	0.2 0.03-1.9 n=834	0.15 0.03-1.0 n=120
			BD (g cm^{-3})		
0-10/15	1.04	0.95	1.03	1.29	1.38
10/15-30	1.05	1.07	1.13	1.29	1.38
0-30	1.05 0.7-1.6 n=84	1.07 0.5-1.6 n=1410	0.89 0.7-1.5 n=619	1.29 0.4-1.6 n=282	1.38 0.5-1.6 n=66
			pH_{H2O}(F&Sh)		
		LM	SL	Q	
0-30		6.94 5.5-8.7 n=1501	4.54 3.5-5.6 n=648	4.25 3.3-5.3 n=209	

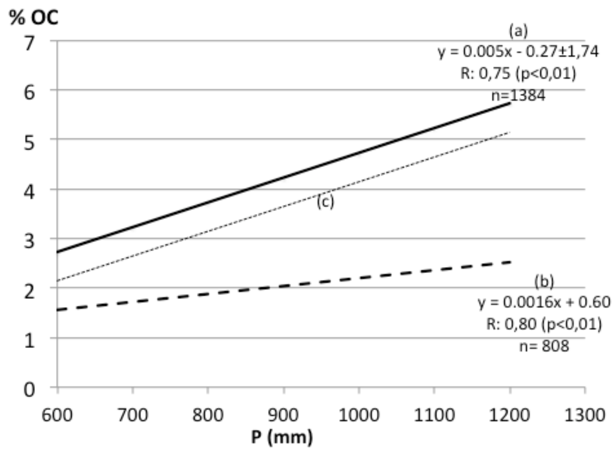

Figure 3. Representation of % OC vs. annual mean precipitation in forest and shrubland soils (0-30 cm depth): (**a**) Galicia and western Asturias; (**b**) central and eastern Asturias, Cantabria and the País Vasco; (**c**) forest soils of Portugal (Madeira et al. 2004).

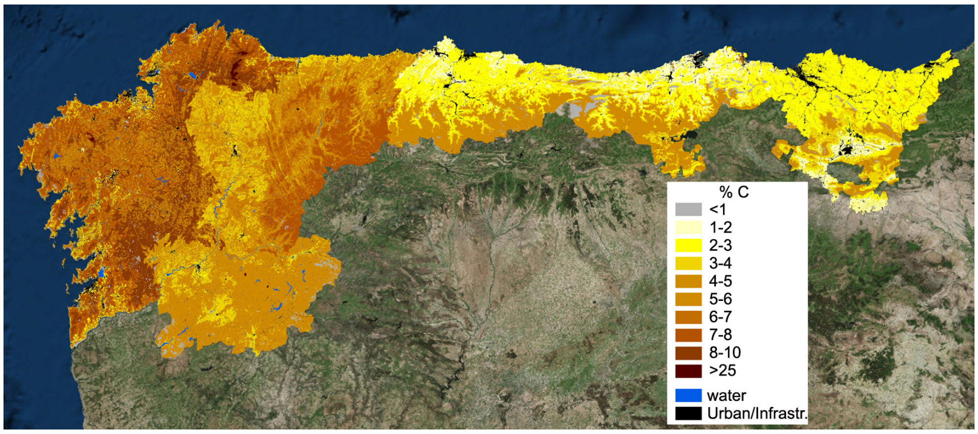

Figure 4. Map of soil organic carbon content in northern Spain (Galicia, Asturias, Cantabria and País Vasco) (topsoil: 0-30 cm) (made at scale 1:50 000, Calvo de Anta et al. 2013).

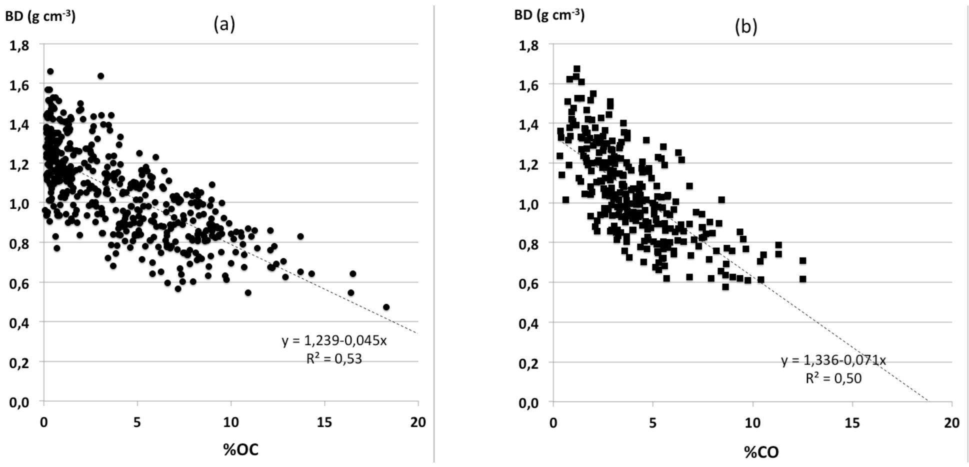

Figure 5. Relationship between organic carbon content (OC) and bulk density (BD): (**a**) soils of Galicia; (**b**) soils of Asturias, Cantabria and the País Vasco (including topsoil and subsoil).

The mean OC stocks (OCS) in the upper layer of the Galician soils ranged between 90 tC ha^{-1} (0-30 cm), in cropped soils in the coastal area and inland areas of the provinces of Orense and Lugo (*xeric* conditions), and 260 tC ha^{-1}, in forest soils with shrub understory at an elevation of > 400 m in the provinces of La Coruña and Pontevedra (**Table 2** and **Figure 6**). Sandy areas, *leptic* soils and areas with part of the surface sealed contain < 20 tC ha^{-1}. In topsoil (0-30 cm), the peat soils contain less OCS than well-drained forest soils at the same latitudes, due to the low BD of the organic materials (approximately 0.2 g cm^{-3}). In general, the OCS in Galician soils is higher than that observed in nearby areas of Europe, in temperate-humid environments. As reference, in forest soils of France, the mean values ranged between 70 and 80 tC ha^{-1} (0-30 cm), with maximum values of 100 tC ha^{-1} in alpine zones (Arrouays and Deslay 2001), and in forest soils of humid zones in northern Portugal, the mean stocks are 215 tC ha^{-1} (Madeira et al. 2004).

The geographical distribution of the OCS in Galician soils is shown in **Figure 7**. In summary, in 92.5% of the territory, the OCS surpassed 100 tC ha^{-1} and was distributed as follows: 29.3% in the range 100-160 tC ha^{-1}; 34.9% in the range 160-200 tC ha^{-1}; 18.4 % in the range 200-240 tC ha^{-1}; and 10% in the range 240-280 tC ha^{-1}. OCS < 100 tC ha^{-1} are found in only 1.5 % of the territory (< 20 tC ha^{-1} in 0.7% and 20-100 tC ha^{-1} in 0.9%). Sealed (or without soil) surfaces such as urban areas, roads, infrastructures, water surfaces, etc., occupy the remaining 6% of the territory (see **Figure 6**).

Taking into account the data obtained for topsoil and subsoil layers, the total OCS was estimated for the upper 50 cm of the soil; a profile-type comprising a humiferous horizon of 30 cm thick and the underlying layer (20 cm) was considered (A_{30} B, C_{20}). The mean values obtained range between 125-130 and 270-280 tC ha^{-1} (0-50 cm) (**Table 2**), within the range indicated above, for agricultural soils of coastal and/or *xeric* areas and for forest soils (F-SH) in the wettest zones, respectively. In mountain peatland, the mean stocks are ≥ 350 tC ha^{-1} (0-50 cm).

The actual OCS is even higher if one considers the frecuent occurrence of soils with *cumulic* characteristics in F-SH areas with slopes > 13%. In the mid-lower slopes, the humiferous horizons usually reach a thickness of more than 40 cm (and even 60 cm), i.e. *umbric-pachic* characteristics (IUSS-WRB 2014), with evidence of several K cycles from different phases of biostasy-rhexistasy that have occurred during the Quaternary. Considering type-profiles with humiferous horizons of thickness 40 cm (A_{40} B, C_{10}), the OCS in the upper 50 cm of the soil may surpass 340 tC ha^{-1} (**Table 2**) in large forest (F-SH) hillsides with > 1200 mm of annual precipitation. Analysis of this type of soil shows a slight variation in the % OC with depth (age) of the material, even at > 100 cm depth, indicating the existence of organic matter stabilization processes. Radiocarbon dating analysis (by accelerator mass spectrometry: AMS) of the deep layers of some representative profiles supported this hypothesis, with the result that most of the samples analyzed date from more than 1000 +/- 30 years BP (before present-1950), reaching 6150 +/- 30 years BP in the bottom of the thickest *umbric-pachic* profile analyzed, at 165-170 cm (Calvo de Anta et al. 2014). These are similar to the dates pointed by other researchers for the same type of soil (Martínez Cortizas, pers comm). According to this, the high organic matter content in Galician soils does not seem to depend only on current vegetation or climate, but also on stabilization processes that take place over long periods of time. Densimetric and physico-chemical analysis of carbon speciation performed on a selection of forest soils have shown the dominance of the C-Al forms in the soil dense fraction (that represents > 50% of the total OC in the 0-20 cm top layer, and > 90% in the 20-40 cm underlying layer) (Calvo de Anta et al. 2014), i.e. it reveals the importance of the formation of organo-aluminium complexes in the stabilization of organic matter, what has been previously noted (García-Rodeja et al. 1987; Calvo de Anta and Álvarez Rodriguez 1992; Macías and Calvo de Anta 1992; Macías et al. 2004; Verde 2009). The results obtained demonstrate the significant role of forest soils in Galicia as carbon sinks, particularly in the wettest zones in the provinces of La Coruña and Pontevedra where there is a predominance of *andic (pachic) Umbrisols*. The mean values differ substantially from those indicated for temperate forest soils (150 tC ha^{-1}, 0-100 cm) and are similar to or higher than those reported for forest soils in boreal regions (250 tC ha^{-1}, 0-100 cm) (Lal et al. 1995; Saugier et al. 2001; Robert and Saugier 2004).

Table 2. Estimates of soil organic carbon stocks in northern Spain. Mean values for different soil depth, according to land use and altitude (m.a.) (nomenclature as in Table 1) (P: peat; H: horizon; P-t: Profile-type)

		CORUÑA, LUGO (n), ASTURIAS(w)				PONTEVEDRA			
		P-t (cm):A30 (B,C)20		*A40 (B,C)10*		*A30 (B,C)20*		*A40 (B,C)10*	
	m.a.	*0-30*	*0-50*	*0-40*	*0-50*	*0-30*	*0-50*	*0-40*	*0-50*
		tC ha^{-1}				tC ha^{-1}			
Sh	*<100*	133	156	177	189	131	154	175	186
	100-400	219	242	292	304	214	236	285	296
	>400	257	279	342	353	247	269	329	340
F	*<100*	162	182	216	226	150	171	200	210
	100-400	190	211	253	264	179	199	238	248
	>400	205	225	273	283	184	204	245	255
G	*<100*	114	154	153	173	111	151	148	168
	100-400	191	231	254	274	175	215	233	253
	>400	239	278	318	338	223	263	297	317
C	*<100*	89	125	118	136	87	124	117	135
	>100	145	181	193	211	122	158	163	181
V		-	-	-	-	100	141	133	154
P(H)		210	350	280	350	-	-	-	-

		Inner LUGO				ORENSE			
		P-t (cm):A30 (B,C)20		*A30 (B,C)20*		*A30 (B,C)20*		*A40 (B,C)10*	
		0-30	*0-50*	*0-40*	*0-50*	*0-30*	*0-50*	*0-40*	*0-50*
Sh	*<400*	128	151	171	182	103	125	137	148
	400-600	144	166	192	203	103	125	137	148
	600-800	185	208	247	258	111	134	148	159
	>800	191	214	255	266	146	168	194	205
F	*<400*	124	144	165	175	97	117	129	139
	400-600	141	162	189	199	97	117	129	139
	600-800	169	190	225	236	103	123	137	147
	>800	202	223	270	280	111	132	148	158
G	*<400*	111	151	148	168	102	142	137	157
	400-600	121	161	161	181	102	142	137	157
	600-800	151	191	201	221	110	150	147	167
	>800	162	202	216	236	128	168	171	191
C	*<600*	95	131	127	145	92	134	123	144
	600-800	97	133	129	147	94	136	126	146
	>800	97	133	129	147	103	145	138	158
V		-	-	-	-	55	96	73	94
P(H)		210	350	280	350	210	350	280	350

		ASTURIAS (c,e), CANTABRIA, P.VASCO	
		P-t (cm):A10 (BA)20	
		0-10	*0-30*
Sh	*<600*	48	86
	600-800	55	99
	>800	66	118
F	*<600*	32	74
	600-800	36	85
	>800	44	203
G	*<600*	39	60
	>600	57	102
C	*<600*	23	68
	>600	24	72
V		17	50
P(H)		-	210

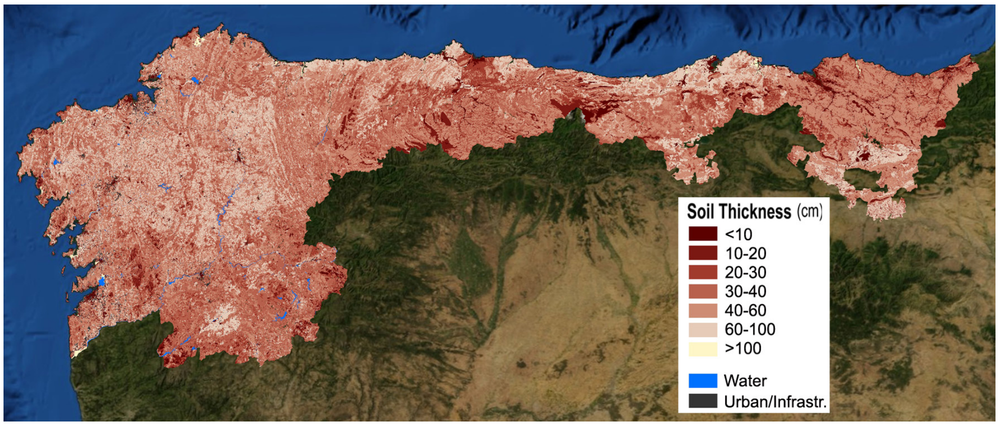

Figure 6. Map of soil thickness (made at scale 1:50 000, Calvo de Anta et al. 2013).

3.2. Organic carbon in the soils of Asturias, Cantabria and the País Vasco

Overall, the predominant type of land use in Asturias, Cantabria and the País Vasco is forest cover (62%), which is higher in Asturias (67%) and Cantabria (68%) than in the País Vasco (52%); grasslands and pasture together occupy 17% of the territory, and a mosaic of grasslands and crops, 16% (**Figure 1**). The climatic parameters are also similar to those in Galicia (*mesic/udic* regime in general; *mesic/xeric* in some zones). On a local scale, the % OC follows a similar pattern to that indicated for Galicia, vine crops<cereal crops<grasslands, forest, shrubland, with very little difference between the latter three (**Figure 2**). However, the OC content in soils of central and eastern Asturias, Cantabria and the País Vasco (A_{ce}CV) is much lower than that observed in areas of Galicia with similar climate (in western Asturias soils are similar to those of northern Lugo and Coruña). Differences are even seen in field observations, in which shallow soils developed on calcareous material, with a thin brown coloured A horizon (10/15 cm), followed by BA, B or C horizons with lower organic matter contents, are generally recognised.

The geographical distribution of OC of the soils varies, for each type of land use, in a north-south climate gradient, as a function of the distance from the sea and/or the elevation. The lowest OC contents are generally observed in the vineyard soils and in cereal-crop soils at elevations < 600 m (on average 1-2% OC, 0-30 cm), and the highest in shrubland areas at elevations > 1000 m (on average 6% OC). Rainfall was again the main factor accounting for the variation, and % OC was positively and highly significantly correlated with annual precipitation ($p < 0.01$) (was not correlated with temperature). The data obtained for 808 samples of forest soils (F-SH) (0-30 cm) were fitted to the following equation:

$$\% \ OC_{F\text{-}SH} = 0.0016 \ P - 0.60 \pm 1.74 \ (R= 0.80)$$ (**Figure 3b**),

where, $OC_{F\text{-}SH}$ is the OC in forest and/or shrubland soils and P is the annual mean precipitation. According to this, for a similar land use and precipitation, the % OC in the A_{ce}CV soils is 1.8 to 2.3 times lower than those observed in Galicia, for 600 and 1300 mm of precipitation, respectively.

The final map of the OC content of the ACV soils is shown in **Figure 4**. Overall, there is a predominance of soils with 2-3 % OC (0-30 cm), corresponding to zones with F-SH and grasslands at elevations < 800 m. At higher elevations, soils with 3-5% OC predominate and are only surpassed in high mountain areas, in which some patches of peat are seen.

The bulk density of the ACV soils fluctuates between 0.6 and 1.7 g cm^{-3}, is lower in forest and shrubland soils than in agricultural soils, and is significantly correlated with the organic matter content (Table 1 and Figure 5). Finally, the carbon stocks were calculated for each soil separately and for the combined ACV soils (Table 2), in which the upper 0-10/15 cm layer and the entire 0-30 cm layer were differentiated. Except for the western area of Asturias, in which the OC contents are similar to those in the north of Lugo and La Coruña, for the rest of ACV, the mean OCS varies between 50 tC ha^{-1} (0-30 cm) in vineyards (mainly Rioja Alavesa) and 100-120 tC ha^{-1} (0-30 cm) in grasslands and forests at elevations > 800 m (>150 tC ha^{-1} in high mountain shrubs). The final map of the OCS is shown in Figure 7.

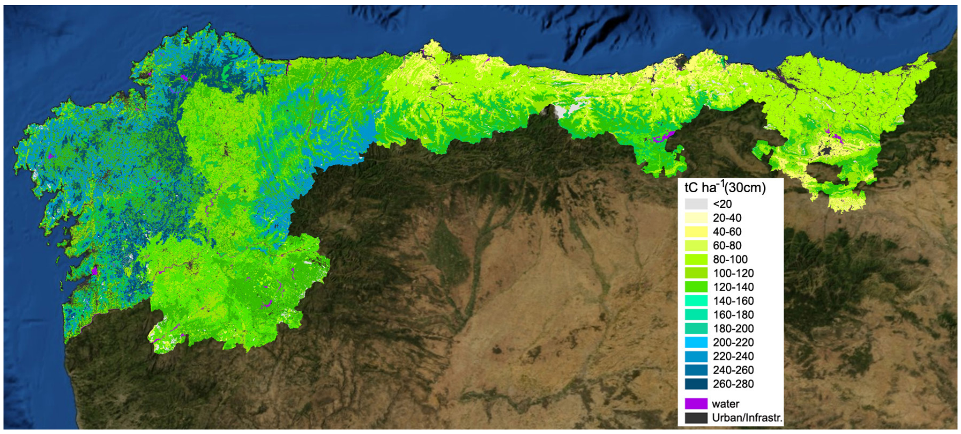

Figure 7. Map of soil organic carbon stocks in northern Spain (Galicia, Asturias, Cantabria and País Vasco) (topsoil: 0-30 cm) (made at scale 1:50 000, Calvo de Anta et al. 2013).

4. Discussion and Conclusions

Analysis of more than 7,000 samples of soil from different regions in northern Spain (Galicia, Asturias, Cantabria and the País Vasco), under similar climate conditions and types of land cover, reveal important differences in the organic carbon contents of the soils. Thus, although forests and shrublands predominate across all regions (> 60% of the area) and the prevailing climate regime is *udic/mesic* throughout most of the area, the OC content of the soils is much higher in Galicia, in both relative and absolute terms, than in the other regions. In Galicia, the thickness of the humiferous horizon of forest soils (F-SH) is often more than 30 cm (sometimes > 40 cm) and the % OC is > 7% (up to 10%), except in some xeric areas in the province of Orense. In the other three regions (central and eastern Asturias, Cantabria and the País Vasco) (western Asturias is similar to the north of Lugo and Coruña) the soils have a thin humiferous horizon (10/15 cm) with a mean OC content of 3-6%, which decreases to 1-3% in the underlying layer; as a result, the mean OC content in the 0-30 cm layer varies between 2-3% and 3-5% depending on the elevation or precipitation. The predictive models for % OC versus annual mean precipitation show differences in OC contents that are between 1.8 and 2.3% higher in Galicia (in areas with 600 and 1300 mm of precipitation, respectively). The mean OC stocks in F-SH soils under a *udic* soil moisture regime in Galicia are 260 tC ha^{-1} (0-30 cm) and may reach up to > 340 tC ha^{-1} (0-50 cm) considering the abundance of soils with cumulic characteristics and humiferous horizons of thickness > 40 cm. These values greatly surpass the mean values reported for temperate forest soils. The mean of OCS ranges between 70 and 120 tC ha^{-1} (0-30 cm) across central and eastern Asturias, Cantabria and the País Vasco, at elevations respectively below and above 800 m, and is only higher in high mountain shrubland soils (> 150 tC ha^{-1}); the value did not increase significantly when the OC stocks in the 0-50 cm layer were calculated.

The observed differences may be related to the lithological substrate and the soil properties. The forest soils of Galicia have acid (pH < 5.0) humiferous horizons that often show *andic* properties both in soils on acidic rocks (mainly granites) and especially in soils on basic rocks. The variable charge of these soils and the high content of free aluminium, which is reactive at these pH values, favors the formation of C-Al complexes, the dominant carbon species in these soils (Calvo de Anta et al. 2014). In Asturias (central and eastern), Cantabria and the País Vasco, there is a predominance of soils developed on calcareous materials (limestone, sandstone, marls) more or less decalcified (soil pH 5.5-8.7) as well as on slates, sandstones and quartzites, and all these soils contain very low levels of reactive Al. The carbon speciation analysis showed the absence of C-Al complexed forms, and biodegradable forms (easily oxidizable carbon) were the most common, both in the light fraction and the dense fraction of the soil (Calvo de Anta et al. 2014), thus explaining the lower stability of the organic matter in these soils and therefore the lower OC content.

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