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Organic carbon content under different types of land use and soil in peninsular Spain

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Abstract The stock and distribution of soil organic C in peninsular Spain were calculated using soil profile descriptions available in the Spanish soil literature. Two soil databases have been compiled, containing data from 2,851 horizons and 1,030 profiles. The soil organic C concentration (SOCC; mass of soil organic C per unit area) has been calculated for each profile, using in most cases a relationship between bulk density (BD) and C content derived from horizon data. The databases have been combined in a geographical information system with a digitized land use map and a soil map to obtain the stocks of soil C under different types of land use and soil, as well as a map of SOCC. The total soil C stock is 3.7 Pg (mean SOCC is 7.59 kg C m^{-2}), with an estimated error of 36% due to errors in horizon C content, BD and stoniness. The variability of SOCC is great within land use and soil type data [mean coefficient of variation (100 SD /mean) is about 70% in both cases]. SOCCs are highest in meadows (improved grazinglands) and bushland, and lowest in cultivated areas. Conifer and broadleaved woodlands and pastures show an intermediate range of SOCC. Mean SOCCs under different types of land use differ significantly in many cases, and correlate very well ($r=0.94$) with the average mean annual precipitation.

Keywords Carbon cycle · Land uses · Peninsular Spain · Soil organic carbon · Soil units

Introduction

Soil organic C is the biggest of C reservoirs in the so-called "fast C cycle", which is composed of C in soils, biota, surface ocean waters and the atmosphere (IPCC 1990). Soil is the final destination of the vast majority of photosynthetic C fixed in terrestrial ecosystems (a small part of it goes to the sea). Eventually, all of this C, except for a tiny fraction, will return to the atmosphere, but turnover rates are slow, and these cause the formation of a big C reservoir in soils. Soil organic C plays an essential role in soil physical and chemical characteristics, and therefore in soil fertility.

The amount of organic C contained in the world's soils is about 1,600 Pg C (to 1 m depth) (Eswaran et al. 1993) according to the most recent estimate; this compares very well with those of several other authors (Schlesinger 1977, 1984; Post et al. 1982; Bouwman 1990). These data are based either on vegetation types or on soil types, or also on C-cycle models (Meentemeyer et al. 1981; Esser 1991). Agreement is worse when comparing estimated C stocks in ecosystems, which may be due to differences in ecosystem classification and areas.

The short-term dynamic character of the C cycle has become clearer recently, not only because of the "visible" accumulation of C in the atmosphere, but also because of consideration of biospheric C reservoirs. Organic C in biota and soils is very sensitive to human action and, whereas biotic C is spectacularly changed through land clearance, soil C changes are less apparent, but of no less consequence. It is well known that transforming a forest into cropland or grassland implies generally a considerable loss of soil C (Bouwman 1990), and the massive land use changes which have occurred in the two last centuries have caused the release of a relatively large quantity of CO_2 to the atmosphere. On the other hand, more recent functioning of vegetation as a biospheric sink (Kauppi and Tomppo 1993; Ciais et al. 1995; Keeling et al. 1996), along with the long residence time of soil C at high latitudes, means that some soils currently act as C sinks (Kirschbaum 1996). The future role of soils in the global C cycle may be as a C source or sink, depending on land use changes, land management and environmental changes (Schlesinger 1995).

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Soil organic matter accumulation is the result of many intricate processes, but may be expressed simply as the summation (integral) over time of the difference between the rate of litter production and root exudation and the rate of litter and root exudate decomposition. Environmental changes which affect these two rates differently will lead to a change in the amount of stored soil C, but, unfortunately, even considering only the effects of an environmental factor (temperature) on soil organic matter balance, there is disagreement as to whether soil will become a source or sink of C as temperatures increase due to global warming (Jenkinson et al. 1991; Kirschbaum 1993).

Many empirical relationships have been proposed between soil C and environmental factors, mainly climate. The relationship is neither simple nor unique: C accumulation in different areas depends differently on different variables (Porta et al. 1994; Oyonarte et al. 1994; Homann et al. 1995). At a planetary scale, organic matter accumulation is favoured by high precipitation and/or low temperatures, as well as edaphic factors such as poor drainage (Oades 1988). In any case, studies on global soil C dynamics, and soil C behaviour, under changing environmental conditions need to evaluate the stock and distribution of soil organic C. A direct application of those studies lies in assessing the C budget of a territory (Adger and Brown 1994).

Evaluations of soil organic C in the world are based on assigning a C density (C mass per surface unit) to each one of the ecosystem or soil classes considered, using data from soil profiles within these categories. It has been found (Kern 1994) that the ecosystem approach is convenient at a global scale, but not so at more detailed scales, where geomorphological (aspect, slope) and edaphic factors (deficient drainage) become dominant; a soil classification is preferred at such scales.

Soil C concentrations show large spatial variability, even in a particular ecosystem or soil group. Human modification of ecosystems or soils can profoundly affect soil C reservoirs. In land areas where original ecosystems are profoundly transformed, there seems to be no special reason to use ecosystem classification as a basis on which to estimate soil C pools: the best classification must be that which gives the smallest coefficients of variation (CVs) of soil C concentrations, and a land use classification may be more appropriate. This is applicable in the case of peninsular Spain, where original ecosystems have been changed everywhere: about two-fifths of the territory is used as cropland (rainfed or irrigated), a fifth is forest (defined as tree-covered surface with a mean cover of 20% or greater), and the rest is a degraded woodland in the form of bushland or grassland, pastures and water reservoirs and urban areas. The results of using this type of land use classification may then be compared to the results of using a different classification (as a soil map).

Materials and methods

In this study, a geographical information system (GIS) has been elaborated to calculate the soil organic C concentration (SOCC) under the different land uses as defined in the Spanish land use map (Ministry of Agriculture 1988) and by FAO soil units (FAO-UNESCO 1974), for peninsular Spain. A map of SOCC was then drawn based on the land use map. The elements of the GIS are: (1) two soil databases, compiled from literature data of soil profiles, (2) a land use map, and (3) an incomplete FAO soil units' map. GIS work was carried out using a workstation (Digital), with ARC/INFO 7.1 software under UNIX.

Soil databases

Spanish soil literature from about 1960 to 1995 was searched for data on soil profiles. For each Spanish province, an adequate number of profiles was searched for; in many cases where soil profiles were part of provincial or regional soil studies, soil profiles are representative of the soil types in the province. In other cases, available profiles were taken from more local studies and are not representative of the whole territory. Chosen profiles have variable depth, but they are usually more than 1 m in depth, unless the soil is shallow, which is frequent. Data for two small provinces (from a total of 47) in the north of Spain were not found.

In each province, an horizon database was compiled, with each record being a soil horizon; fields are: horizon number, profile number to which each horizon belongs, organic C percent (C%), horizon depth (*d*), bulk density (BD), sand percent (%sand), clay percent (%clay), textural class, gravel (defined as the volumetric fraction of particles with diameter between 2 mm and 2 cm), stoniness (fraction of particles with diameter >2 mm), altitude and province code; 2851 horizons, belonging to 1030 profiles, were recorded.

For each province, a profile database was then elaborated; records are the profiles in the province, and fields are profile number, number of horizons in the profile, UTM coordinates of the profile, a description of the location, land use, vegetation, soil type, slope, aspect and parent rock of the profile. SOCC were calculated for each profile (see below).

The majority of the 1030 recorded profiles were not given UTM coordinates in the original description; in most cases the description of the geographical location of the profile is given with reference to road distances. 1:50,000 maps of the Military Cartographers of Spain have been used to situate the profiles: local UTM coordinates (spherical lunes 29–31) were read from those maps and transformed with reference to spherical lune 30, to give continuity to the map. From the 1030 original profiles, 846 have been so converted and situated on the map (Fig. 1).

Besides the profile data mentioned above, it was considered necessary to know the mean annual temperature and precipitation for each soil profile. These parameters have been obtained for 833 out of the 846 profiles on the map, due to imperfect map adjustment for the coastline. Mean soil annual temperatures are read from a digitized map of mean soil annual temperatures in peninsular Spain (Hontoria 1995) obtained from data of 484 stations (soil temperature = atmospheric temperature + 1.5 °C); this map has been vectorized to make possible its use in the ARC/INFO software. Mean annual precipitation was calculated using an inverse square distance interpolation of data from the five closest pluviometric stations in the profile's catchment basin; a total of 4094 stations were considered (Saa 1991).

Land use map and soil map

This map (1:1,000,000) is the digitized version of the Spanish land use map (Ministry of Agriculture 1988), which represents land use in Spain in the period 1984–1985. The minimum surface rep-

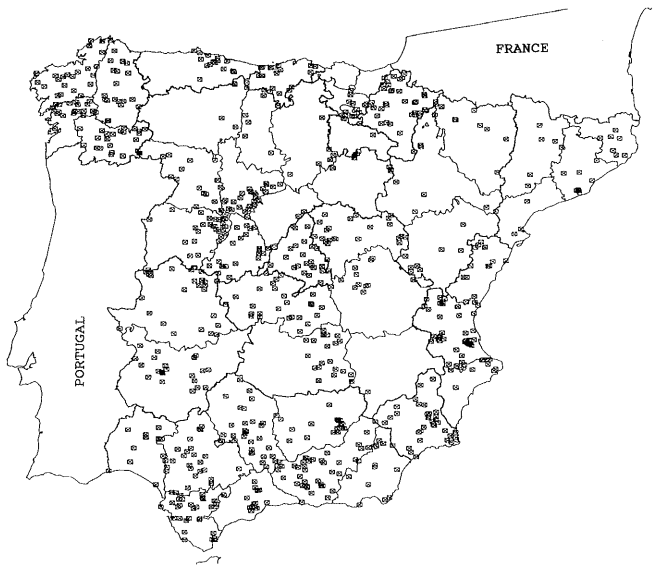

Fig. 1 Distribution of soil profiles in peninsular Spain. *Thin lines* indicate provincial limits, and *thick lines* are the limits of autonomous regions

resented (minimum surface of a cartographical unit) is 10 km^2. Land use is divided into 23 principal categories, three of them mixtures of type of land use. The number of polygons was 9,945, after the correction of some mistakes in polygon coding.

A Soil (FAO) map (1:1,000,000) is being made by Dr J. J. Ibáñez and co-workers in the Centro de Ciencias Medioambientales, and is going to be part of the European Communities' soil data base (version 3.1). The 2088 polygons of this map are classified in soil map units (SMU), which are made up of one or more soil typological units (STU), corresponding to the FAO-UNESCO soil units (FAO-UNESCO 1974; CEC 1985). There are 61 STUs, including rocky outcrops, combined in 83 SMUs. About a quarter of the territory is made up of polygons with SMU = 0 (which means no SMU has been assigned to them); this includes urban areas, polygons with an area of <25 km^2 and very heterogeneous polygons. Land use and soil maps have been transformed from their original Lambert projection to UTM coordinates with reference to spherical lune 30.

Results and discussion

SOCC can be computed by summing up the C content in all the horizons in a soil profile:

$$\mathrm{SOCC} = \sum_{1} \mathrm{BD}_i \times \%\mathrm{C}_i \times d_i \times (1-f_i) \times 0.1 \qquad (1)$$

where BD_i, $\%\mathrm{C}_i$, d_i and f_i are, respectively, bulk density (Mg m^{-3}), %C, horizon thickness (cm) and volumetric fraction of materials >2 mm diameter in horizon *i*.

In Spain, the area of soils with high %C (peatlands) is small, according to soil maps (about 0.16% of the total area), and organic soils are probably over-represented in the 1030-profile database, as 20 of these profiles have one or more horizons with >20% organic C. These 20 profiles have not been considered to avoid a probable overestimation of the stock of soil C, as they are not considered representative. Thus 1010 profiles remain in the profile database.

BD and stoniness estimation

The BD of only 242 soil horizons from the 2851 records have been measured, and it is therefore necessary to estimate BDs for the rest of the horizons. To this end, a simple relationship between BD and percent organic matter has been deduced from Adams (Adams 1973):

$$\mathrm{BD} = \frac{1}{a + b\%\mathrm{C}} \qquad (2)$$

where a and b are constants.

Many equations relating BD to %C (or percent organic matter) have been proposed, for soils in Spain and elsewhere, using simple linear relationships (Saini 1966; Barahona and Santos 1981) (which may be appropriate at low %C) to lineal logarithmic %C (Jeffrey 1970), or as in the case of Eq. 2 (Jeffrey 1970; Rawls 1983) or more complicated equations (Curtis and Post 1964; Manrique and Jones 1991). The best functional form for the relationship between BD and %C varies with the set of soil data. It seems clear that soils with similar characteristics may fit better in a simple BD/%C relationship; if BD and %C are obtained for these soils using the same analytical methods the fit will surely improve. These two statements do not apply to the present soil dataset.

The 242 BD data in the database are not well distributed in the territory; in particular, data of BD are lacking for the north of Spain. Therefore, a set of 192 soil horizons with BD data, from published data, has been selected to fit BD vs. %C; most of these horizons are not in the database of 2851 horizons. This former set covers better the spectrum of environmental conditions in Spain.

Table 1 shows the fits of this data set to four functions. The minimum SE of the estimates was calculated with the equation $\sqrt{y} = a + bx$, but the equation which fits the data of two parameters more closely (biggest r) is Eq. 2 (Fig. 2); the distribution of residuals is much more uniform across %C in this case than in the case of the $\sqrt{y}$ fit and, therefore, Eq. 2 has been selected to estimate BD.

In every case in Table 1, the scattering of experimental data points is great, particularly at low %C, in-

Table 1 Results of some fits of bulk density (BD) = f(%C)

Equation	a	b	SD	r
2[a]	0.622	0.098	0.23	0.82
6[b]	1.29	−0.50	0.25	0.77
7[c]	1.17	−0.018	0.15	0.66
8[d]	0.575	0.104	0.22	0.83
	(n = −0.0012)	(n = −0.0012)		

[a] [$y = 1/(a+bx)$] See Eq. 2 in text. y is BD, x is %C and p is horizon depth. a, b, and n are constants
[b] $y = a + b.\log x$
[c] $\sqrt{y} = a + bx$
[d] $\dfrac{1}{(a+bx)(1-np)}$

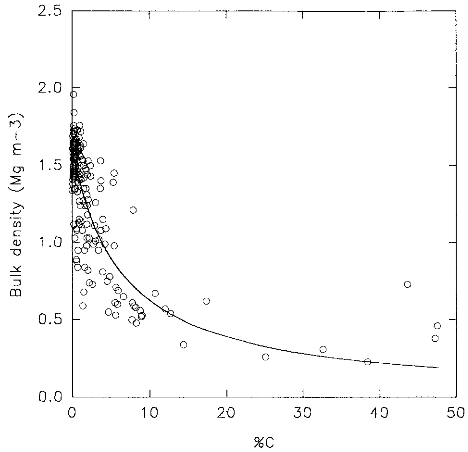

Fig. 2 Fit of bulk density vs. %C. *Circles* are the experimental values from 192 horizons, and the curve is given by Eq. 8

dicating that other factors are determinant in causing these variations of BD. An attempt has been made to incorporate two of these possible factors (d and horizon texture). Taking into account horizon depth (Eq. 8 in Table 1) does not improve the fit significantly. Soil texture seems an obvious influence on BD (Rawls 1983). The correlation of BD with %sand in the set of 192 data is positive ($r=0.213$, $P<0.01$), and that with %clay negative ($r=-0.226$, $P<0.01$), as expected. A multiple linear correlation of BD vs. %C, %sand and %clay (156 data points in total) gives $r=0.780$, whereas fitting BD to %C alone one obtains $r=0.750$ ($P<0.001$), which means that the correlation does not improve significantly with the introduction of %sand and %clay. A similar conclusion was reached in two other studies, one of them undertaken in Spain (Barahona and Santos 1981) and the other in the United States (Curtis and Post 1964). A relationship between texture and BD should, however, exist, but it may be more complex than the simple lineal correlations assumed in the works mentioned above. Another study, using data from about 12,000 soil pedons, found that BD was poorly related to %clay, %sand or percent silt (Manrique and Jones 1991).

Stoniness (fraction of particles with a diameter >2 mm) is given in only 186 profiles, corresponding, however, to a wide set of field conditions. It is assumed that this sample is representative of the whole population with respect to stoniness (f_i). Mean stoniness in those profiles is 0.243 ± 0.193; the frequency distribution of f_i decreases non-uniformly as stoniness increases, whereas the distribution of $\sqrt{f_i}$ is much more normal. In a profile description, sometimes only gravel is given, so f_i is probably bigger than the derived value, and the real SOCC smaller than the calculated SOCC.

Soil C concentrations have been corrected for stoniness (in the cases where f_i data are not available) by means of the expression: $BD_{corr}=(1-f_i)BD$, where f_i is the mean profile stoniness (0.243).

Distribution of soil C concentrations amongst different types of land use

By applying Eq. 1 to the soil horizons in the 1010-profile database, a set of 1010 C concentrations was obtained. The distribution of C concentrations is skewed towards low C concentrations (mean SOCC = 7.59 kg C m^{-2}, SD = 6.67 kg C m^{-2}). This mean SOCC value is intermediate between the values found by Schlesinger for temperate forest (11.8 kg C m^{-2}) and woodland and shrubland (6.9 kg C m^{-2}) (Schlesinger 1977), which are the categories where most of the original Spanish ecosystems may be included.

Applying a logarithmic transformation to SOCC, a Gaussian-like distribution is obtained (Fig. 3). The Kolmogorov test of normality reveals that the hypothesis of normality can be rejected at the 5% level, but not at the 1% level.

The 1010 profiles were classified according to land use (following the Spanish land use map legend) according to original profile descriptions. Eighty-five profiles were not classified because of a lack of information. The fraction of the 945 profiles which corresponds to each land use category was calculated and compared with the fraction of the total area which each type of land use occupies in the land use map of peninsular Spain. It is concluded that the classified profiles present a distribution of land uses very similar to that of the whole of peninsular Spain.

In Table 2, mean C densities and SDs of SOCC in the profiles belonging to each of 12 important (and more extensive) types of land use in peninsular Spain are represented, along with the same parameters for log(SOCC), and statistical errors of estimates of mean SOCC and SDs of SOCC (0.01% level). Land use appears as an important determining factor for the mean concentration of organic C in a soil. Land use history influences SOCC for each type of soil use, and may account for an important part of the variability in SOCC for each type of land use. In spite of this, and also of

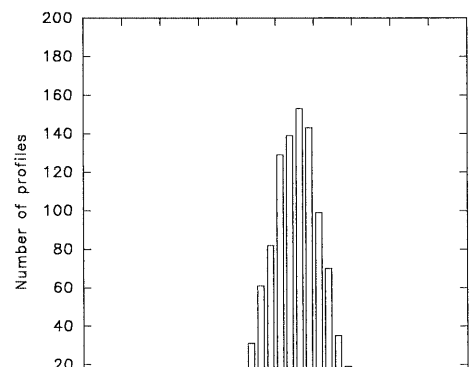

Fig. 3 Distribution of logarithm of soil organic C concentration (SOCC)

Table 2 Soil organic C concentrations (SOCCs) under the main types of land use in peninsular Spain. *M* Meadow, *Bu* bushland, *BF* broadleaved forest, *CF* coniferous forest, *P* pasture, *IF* irrigated farming, *DF* dryland farming, *O* olive grove, *V* vineyard

Land use	SOCC ± SD (Mg C ha^{-1})	SOCC ± SD[a]	CV[b]	No. of profiles	Error (SOCC) (%)[c]	Error (SD) (%)[d]
DF	50.8 ± 33.7	1.62 ± 0.29	66.3	206	3.2	13
Bu	113 ± 80	1.94 ± 0.34	70.8	146	3.7	15
BF	93.6 ± 58.2	1.89 ± 0.28	62.2	81	4.2	20
CF	75.8 ± 66.9	1.74 ± 0.37	89.2	73	6.4	22
P	73.2 ± 56.7	1.72 ± 0.42	77.5	61	8.1	24
IF	57.6 ± 36.3	1.68 ± 0.28	63.0	34	7.4	32
O	39.9 ± 28.3	1.49 ± 0.36	70.9	45	9.3	28
V	42.5 ± 28.9	1.53 ± 0.31	68.0	25	10.5	37
M	131 ± 122	1.99 ± 0.33	93.1	29	7.9	34
Bu-BF	74.0 ± 36.8	1.87 ± 0.23	53.9	28	6.0	35
Bu-CF	123 ± 162	1.93 ± 0.34	136	18	10.8	44
P-BF	59.0 ± 28.3	1.70 ± 0.28	49.3	20	9.6	42

[a] Mean ± SD of the log(SOCC) distribution
[b] Coefficient of variation (*CV*) of the original SOCC distribution (CV = 100 × SD/mean)
[c] Sampling error of mean SOCC (99% level): err(SCD) = 2.58.SD.100/mean.$\sqrt{n}$
[d] Sampling error of SD of SOCC (99% level): err(SD) = 2.58.100.$\sqrt{(0.5/m^{-1})}$ where *n* is the number of profiles

the sometimes subjective character of the classification of land use made using profile descriptions, there are clear differences in mean SOCCs between profiles of different types of land use. In Table 3, the results of a two-tailed *t*-test are given for the most important types of land use: dryland farming differs significantly with respect to mean SOCC from the other types of land use, except other croplands (irrigated and vineyards). Bushland differs from every type of land use in this respect in the table, except meadows. No significant differences are found among conifers and broadleaves and conifers and pastures. Soil C concentrations are highest in meadows (although the CV of SOCC in this case is also the highest), bushland and broadleaved areas, and lowest in cultivated areas. Conifer woodlands and pastures show an intermediate range of SOCC. The differences in C content between types of land use are of course due to differences in the balance between soil C inputs and outputs under the different types of land use. The causes of these differences may lie in land management (land cultivation or grazing), environmental factors (for example, mean precipitation and temperature can differ widely between types of land use), or more specific causes (grasslands and forests differ in C turnover rates due to differences in relative above- and below-ground productivity and litter quality).

Variability of SOCC is great within land use categories (weighted average of CV = 71.7%), but also within ecosystem, life-zone or soil classifications. Thus, in Post et al. (1982), with a Holdridge life-zone classification with 22 categories, the weighted average of CV = 72.7%. In Schlesinger, using an ecosystem classification with nine categories, the mean CV = 52.4% (Schlesinger 1977).

Work on the dependence of SOCC of the database profiles of several environmental parameters (Hontoria et al. 1999) reveals that mean annual precipitation is the parameter the most significantly (and positively) correlated with SOCC from the parameters studied.

Considering the large variation of SOCC and mean precipitation within a land use category, as well as errors in the estimates of mean soil C and precipitation, it is noteworthy that when the profiles are grouped into the 12 categories of land use, mean SOCC and the average of mean annual precipitation show a very good correlation ($r = 0.937$) (Fig. 4). In the present case, therefore, the significant differences in mean SOCC may be, in principle, attributed to the different average environmental conditions prevalent in the different types of land use. Grouping of profiles by land use seems thus to be a natural way of relating soil C and precipitation.

C stocks in land use categories

Using the mean soil C concentration of the 1010 profiles in the database and the area of peninsular Spain obtained from the corrected soil use map, the total stock of C in the soils of peninsular Spain can be estimated as: mean SOCC × area = 7.59 kg C m^{-2} × 49.46 × 10^6 ha = 3.75.10^{15} g C (3.75 Pg C). The amount of soil C

Table 3 Significance of differences in mean SOCCs for land use categories. Two-tailed *t*-values are represented. For abbreviations, see Table 2

	M	Bu	BF	CF	P	IF	DF	V	O
M		0.763	1.59	2.34*	2.43*	3.12**	3.52***	3.79***	3.95***
	Bu		2.10*	3.71***	4.05***	6.07***	8.86***	8.02***	8.71***
		BF		1.83	2.10*	4.00***	6.22***	5.89***	6.96***
			CF		0.169	1.73	2.96**	3.34**	3.95***
				P		1.63	2.94**	3.31**	3.97***
					IF		1.01	1.77	2.34*
						DF		1.38	2.26*
							V		0.363
								O	

*95% level, **99% level, ***99.9% level

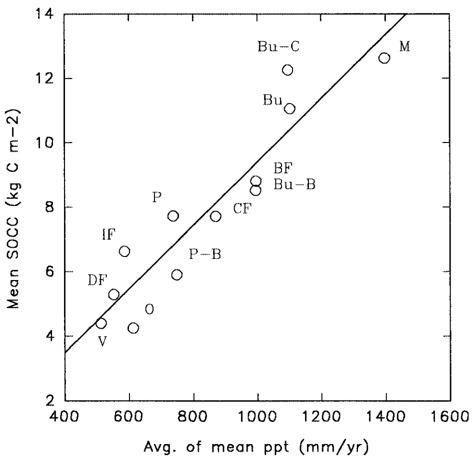

Fig. 4 Fit of mean SOCC under the main types of land use vs. the average mean annual precipitation. *M* Meadow, *Bu* bushland, *BF* broadleaved forest, *CF* coniferous forest, *P* pasture, *IF* irrigated farming, *DF* dryland farming, *O* olive grove, *V* vineyard, *Bu-B* Bushland with broadleaved trees, *Bu-C* bushland and coniferous trees, *P-B* pasture with broadleaved trees

in the areas corresponding to the different types of land use has been calculated in the same way, i.e. by computing the average SOCC of the 933 soil profiles which have been assigned a land use code according to land use, and multiplying it by the area of this type of land use, obtained from the land use map. There are 51 profiles whose assigned land use code is not represented in the land use map. These profiles have not been used in the calculations of the stock of C, so that a total of 882 profiles have been taken into account.

Conversely, about 13% of polygons in the soil use map have codes which do not correspond to any of the codes assigned to the profiles in the database. These polygons have been assigned mean SOCC of other types of land use in the following way: to greenhouses (code = 10) and sugarcane (code = 11), the mean SOCC of irrigated crops (code = 8) was assigned. Extensive cropland (code = 17) was assimilated into cropland (code = 16). Unproductive land (code = 22) was assigned a mean SOCC = 0. In the case of mixed land use, the assigned SOCC was the mean of the average SOCC of the two types of land use which are combined (for example, in areas with code = 1/2, which indicates a mixed conifer/broadleaved woodland, the SOCC assigned is the mean SOCC of both conifer and broadleaf woodland).

In Table 4, the results of these calculations are given for five broad types of land use, along with the surfaces occupied by them. Forest is the land use with more soil C in absolute terms; conifer forest dominates with respect to quantities of soil C, but it should be taken into account that most of the trees in "bushland + trees" are broadleaves, so that soil C corresponding to these two tree categories are similar. "Other uses" and "bushland" have large amounts of soil C, which make necessary the consideration, beside forests, of these types of land use when studying C balances in a territory (Adger and Brown 1994). Total C in peninsular Spain (adding the partial quantities) is 3.70 Pg C; the difference between this and the first calculation of soil C (without dividing the surface area by types of land use) is <2%.

Table 4 Soil C under the main land use categories in peninsular Spain. For abbreviations, see Table 2

		Surface (km^2)	Mean SOCC (kg C m^{-2})	Amount of C (Tg)
Forests	Conifers	63,010	7.50	473
	Broadleaves	23,991	9.36	225
	Mixed	18,934	12.1	229
Total forests		105,935	8.74	926
Bu		78,492	11.3	890
Cropland (DF)		121,740	5.08	618
Bu + trees		40.938	8.20	336
Other uses[a]		147,458	6.28	926

[a] IF, submerged land (under water reservoirs), P, M, O, V and others

Elaboration of the map of soil C concentrations

In order to appreciate the geographical distribution of SOCCs and its pattern it is useful to create a map of soil C concentrations. Using as a basis for this the digitized land use map and the SOCCs of the 819 soil profiles together with data of precipitation and temperature, a SOCC map was constructed (Fig. 5). To this end, each polygon in the land use map was assigned a C density in the following way:

1. If there are soil profile(s) in the polygon, polygon SOCC is the mean of the SOCC of the profile(s).

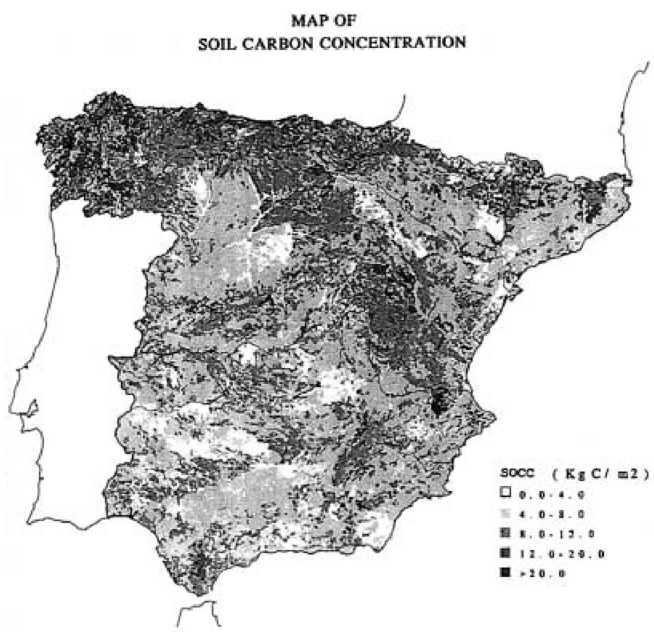

Fig. 5 SOCC map of peninsular Spain

2. If there are no soil profiles in the polygon, polygon SOCC is taken as the mean SOCC of the land use category to which the polygon belongs.

Soil C is very spatially variable at the scale of the map. This could have been easily anticipated, given the large spatial heterogeneity of climate, geology and land use in peninsular Spain, which determine inter alia the storage of organic matter in soils. Zones with a high C content coincide roughly with areas of high rainfall (Cantabric rim in the north of Spain, mountain ranges), whereas dry inland plateaus, the Ebro basin, the Mediterranean coast and the South (i.e. areas with low rainfall) show low soil C concentrations.

Calculation of soil C stocks by using a soil map

A FAO soil map of peninsular Spain (1:1,000,000) has been used to estimate the C reservoir in soils. The basic idea is to obtain the mean SOCC for each soil type and, using the areas occupied by each soil type, calculate the stocks of soil C corresponding to each soil type and the total amount of soil C. Unfortunately, the description of a soil type does not correspond to one single system; one can find three or more different soil classifications in the original profile descriptions: a Spanish classification based on the Kubiëna system (Kubiëna 1953), FAO-UNESCO classification, and other systems of soil taxonomy. Only 330 soil profiles from the 1010 profiles in the database are classified according to FAO-UNESCO. In order to expand this set, the profiles originally described according to the Spanish classification were re-classified according to the FAO-UNESCO system using a published table of correspondences (Monturiol and Guerra 1975) and comparing definitions of soil types. In this way, 291 additional profiles were assigned FAO-UNESCO soil names. The mean SOCC in the set of 621 (330+291) profiles is 8.08 kg C m^{-2} (SD=7.38 kg C m^{-2}). A *t*-test shows that there is no significant difference in mean SOCC between this set and the 1010-profile set ($t=1.35$).

The 621 soil profiles classified according to FAO-UNESCO taxonomy were grouped into 23 major soil groups (Table 5), and assigned the mean SOCC of the profiles which belong to each soil group. There are seven soil groups in the soil profile database (gleysols, leptosols, calcisols, alisols, solonetz, chernozem and podzoluvisols) which do not appear in the soil map attributes. Conversely, there are two FAO soil groups in the soil map which are not present in the soil profile database (histosols and andosols). To complete the list of assigned SOCC, the bibliography has been searched for histosols and andosol profiles. Five new andosol profiles and four histosol profiles, one of them new, have been chosen, and their SOCCs have been calculated.

Variation of SOCC within the 25 soil groups in Table 5 is considerable and of the same order of magnitude (CV=70.0%) as that within types of land use.

Table 5 Soil C in the main soil groups in peninsular Spain. SMU Soil map units

Soil group	Surface (km^2)	Mean SOCC (MgC ha^{-1})	C stock (Tg)
Alisols	–	57.8±20.2	–
Acrisols	9,872	101±76.5	99.5
Cambisols	157,500	71.4±57.8	1,120
Chernozem	–	233±81	–
Podzoluvisols	–	120±40	–
Rendzinas	14,010	68.8±47.1	96.3
Gleysols	–	174±130	–
Phaeozems	1,654	132±65	21.9
Lithosols	32,610	112±93	367
Fluvisols	22,380	75.8±58.9	170
Kastanozems	11.8	111±41	0.131
Luvisols	42,970	66.0±42.2	283
Leptosols	–	98.8±56.4	–
Histosols	803,2	888±325	71.3
Podzols	1,388	188±164	26.1
Arenosols	1,629	22.2±12.6	3.61
Regosols	37,060	48.7±35.6	181
Solonetz	–	22.0±6.7	–
Andosols	99.1	244±74	2.42
Rankers	14,970	131±105	196
Vertisols	5,522	68.9±37.8	38.0
Planosols	5,166	33.6±10.7	17.4
Xerosols	17,010	59.0±35.9	100
Calcisols	–	49.1±27.0	–
Solonchaks	6,832	76.3±49.0	52.1
Rock outcrops	15.9	0	0
SMU=0	116,750	91.6±87.0	1,070
SMU=–3	2,275		

SOCC and C stocks of soil groups with few profiles in the database must have large errors due to the small number of profiles considered when calculating SOCC, although this fact does not suggest a big error in the total C stock, as these soils occupy small surfaces (an exception is lithosols, with only three profiles but occupying about 7% of the surface of peninsular Spain).

Soil group surface areas for the whole of peninsular Spain are obtained by calculating for each map polygon the area of each soil type (there are 61 soil types, included in 18 soil groups) associated with the SMU to which the polygon belongs. This is possible as soil types associated with each SMU and fractions of SMU surfaces corresponding to each soil type are in the map attributes database. The next step is to add up all the soil type areas across all map polygons, and group the areas into 18 major soil groups. As 11.7×10^6 ha is not classified (about a quarter of the area of peninsular Spain), absolute surfaces and C stocks according to soil group should be somewhat greater than those in Table 5; the total amount of C is 3.93 Pg C.

The total stock of soil C in peninsular Spain can also be estimated from the area of land obtained from the soil map and the mean SOCC of the 621 FAO profiles, as 49.39×10^6 ha$\times$8.08 kg C m^{-2}=3.99 Pg C. This is about 1.5% more than the prior estimate, and 6.4% more than the highest estimate based on land use (3.75 Pg C).

Estimation of errors in SOCC and C stock calculations

To estimate the errors in SOCC and calculated C stock, one may determine:

1. Errors in factors which determine SOCC, i.e. BD, %C, d, and stoniness.
2. Sampling errors, due to the limited number of profiles taken in each land use category. Given the high variation in SOCC, typically 25 or more profiles are required to estimate mean SOCC with a $\leq 10\%$ error (Table 2), assuming that log(SOCC) has a normal distribution and random sample. Under these assumptions, soil organic C stock in the whole of peninsular Spain and also in the main land use categories can be estimated rather accurately, given the high number of profiles taken. More difficult to assess is the "scaling up" or generalization error, which occurs when the mean SOCC from a sample of profiles is attributed to the whole surface of a particular land use to calculate the amount of C in it.
3. Surface errors and the assignment of land use errors.

The first class of errors is perhaps the easiest to evaluate. Errors in the calculation of SOCC have been estimated from estimated errors in BD, %C and f_i and a simulation of the effect of these errors. First of all, 805 values of log %C were chosen at random from a normal distribution (mean $= -0.1186$, SD $= 0.5575$), whose parameters (mean, SD) are the parameters of the experimental distribution of log %C. From the random log %C values, the %C values were obtained. Then, BD was calculated using Eq. 2; 805 values of simulated stoniness were taken from random values of a normal distribution of $\sqrt{f_i}$, with mean $= 0.4469$ and SD $= 0.208$, which coincided with the experimental distribution of f_i. Depth was assumed to be 0.726 m, which is the mean soil depth in the profiles. A set of 805 simulated ("error free") SOCCs was calculated according to Eq. 1 using these simulated factors (mean SOCC $= 9.10$ kg C m^{-2}; SD $= 9.60$ kg C m^{-2}).

The relative error in the calculation of %C depends on the analytical method used and on the fraction of soil C. The weighted average of relative errors in %C for the main Spanish laboratories has been calculated from the data given by the Comisión de métodos analíticos del Instituto de Edafología (1973) (i.e. 7.8%). To determine soil organic C the Walkley-Black method was used (Walkley and Black 1934), which was the method used for the analysis of organic C for most of the database profiles. The relative error in BD is taken to be: SE/(mean BD) $= 0.229/1.28 = 0.18$ (18%). The relative error in stoniness was calculated in the same way, i.e.: $0.193/0.757 = 0.25$ (25%). These two last errors are large compared with assumed errors in other works (Homann et al. 1995), which is obviously due to the "calculated" nature of BD and f_i in the present case.

Simulated errors are introduced in %C, BD and f_i using these mean errors and Eqs. 3–5:

$$\%\mathrm{C(err)} = \%\mathrm{C} + 0.078 \cdot \%\mathrm{C}.a \tag{3}$$

$$\mathrm{BD(err)} = \mathrm{BD} + 0.229.a \tag{4}$$

$$\sqrt{f_i}\,(err) = \sqrt{f_i} + 0.208.a \tag{5}$$

where a is a random value taken from the normal distribution where mean $= 0$, SD $= 1$; 805 values ("with errors") of these three parameters are calculated, and, from them, 805 error-affected SOCCs are obtained using Eq. 1 (mean SOCC $= 8.03$ kg C m^{-2}; SD $= 10.2$ kg C m^{-2}). By comparing the simulated error-free and error-affected SOCCs, the relative error in SOCC may be estimated as 0.36 (36%).

In the present case, the experimental and estimated errors in the variables which determine SOCC seem to be the dominant unknown factors with respect to the total stock of soil C. The surface and generalization errors are not known, but, if we accept that a rough measure of them is given by the different results obtained with the land use and the soil type approaches, they must be approximately 8%.

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