Relationships Between Soil Organic Carbon and Site Characteristics in Peninsular Spain

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ABSTRACT

The relationships between soil organic C (SOC) content and soil and site properties, including climate, land use, and other variables, are important for assessing the effects of future land use and climate changes on soil organic C stocks. Data were obtained for 766 soil profiles taken from published soil studies of sites throughout peninsular Spain. Relationships between SOC and mean annual precipitation, mean annual temperature, land use, soil moisture regime, altitude, texture, and slope gradient were statistically analyzed by simple correlation, stepwise multiple regression analysis, and error source estimation. The variables best correlated with SOC were mean annual precipitation and the length of dry summer season. Land use alone explained 33% of the SOC variability. Almost 50% of the SOC variability was explained by all the variables included in the study. Almost 30% of the SOC variability could be attributed to errors in the values assigned to climate variables, SOC measurements, and within-site SOC variability. If the relationships found between SOC and climate and land use hold in the future, a moderate degree of climate change (10% increase in temperature and 10% decrease in precipitation) could lead to a 15% loss of SOC from soils in the most unfavorable case. The magnitude of the effects of land use changes on SOC content, for example, from cropland to scrubland, may equal that of a climate change.

INTEREST IN DETERMINING SOC STOCKS on a global, continental, and regional scale has increased recently with progress in the knowledge about anthropogenic climate changes (Houghton et al., 1996). Future changes in climate, atmospheric CO₂ concentrations, and land use will decisively influence the fate of C stored in soils, thereby affecting the atmospheric CO₂ reservoir and the climate of the earth. Therefore, relationships between the stock of soil organic matter and climate, land use, and other site characteristics are important to formulate and evaluate process models (Burke et al., 1989) and to assess the effects of future land use and climate changes on soil organic matter (Post et al., 1996).

Climate and soil properties are key factors determining SOC content. Climate influences the SOC content through the production and decomposition processes of plant litter. In general, SOC increases with increasing precipitation and decreases with increasing temperature (Jenny, 1941; Kononova, 1966; Burke et al., 1989). The net temperature effect on SOC is generally smaller than the precipitation effect (Birch and Friend, 1956). The soil-water balance, which integrates climate data (ET) and pedological and topographical features, may be a

critical factor determining SOC content (Grigal and Ohmann, 1992). The precipitation distribution (Jones, 1973) and soil moisture regime may also be important factors.

Soil texture has been shown to influence SOC content through the role of clay in the protection of soil organic matter from decomposition (Anderson et al., 1981) and the role of clay and silt in water availability (Schimel and Parton, 1986) and, therefore, in plant productivity. Topographical factors, such as the slope aspect and slope gradient, affect ET and water infiltration, thereby modifying the soil moisture content and, consequently, net primary production, plant litter production, and decomposition (Birkeland, 1984). The relationship between SOC and altitude has also been investigated: Sánchez (1969) and Sims and Nielsen (1986) reported a positive correlation between altitude and SOC, probably due to the influence of elevation on precipitation.

Human modifications of the plant cover and soil through land use changes also produce considerable alterations, usually a loss of stocks of soil organic matter (Bouwman, 1990). Between 20 and 40% of SOC is lost after the cultivation of previously untilled soils and most of this loss occurs within the first few years (Davidson and Ackerman, 1993). Thus, both land use and the type of vegetation must be taken into account when relating SOC with environmental conditions.

The relationships found between SOC and soil and site variables are usually able to explain only a fraction of the SOC variability: 51% in range soils and 54% in cultivated soils (Burke et al., 1989); 65% in total C of upland forests (Grigal and Ohmann, 1992); and 50% over a depth of 0 to 100 cm in forested mineral soil (Homann et al., 1995). A large proportion of unexplained variations may be due to the effect of uncertainties or the exclusion of important site characteristics. Homann et al. (1995) found that half of the unexplained variations may be due to the combined effects of errors in variable measurement, natural within-site variability, and uncertainty of site characteristics.

Most previous studies were conducted in temperate and tropical regions, but not in areas with a Mediterranean climate like Spain. By virtue of its geographical position on the Atlantic Ocean and the Mediterranean Sea between Europe and Africa, its varying orography, soil properties, and land management history, peninsu-

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Abbreviations: CV, coefficient of variation; ET, evapotranspiration; PPT, mean annual precipitation; SMCS, soil moisture control section; SMRa, probability that the soil moisture control section is dry for more than half the cumulative days per year when the soil temperature at a depth of 50 cm is >5°C; SMRb, consecutive days SMCS is moist in some or all parts when the soil T_{50 cm} is >8°C; SMRe, cumulative days SMCS is dry in some or all parts; SMRd, consecutive days SMCS is dry in all parts in the summer; SMRe, consecutive days SMCS is moist in all parts in the winter; SOC, soil organic carbon; T, mean annual temperature.

Climate data for the pedons were estimated by using a geographical information system and placing pedon locations on a 1 km $\times$ 1 km grid of the corresponding climatic data layer. The annual temperature layer was obtained by converting 467 weather station temperatures (with data covering > 15 yr) into the equivalent sea level temperatures. To this end, the weather station temperatures were interpolated (with a 6-point search radius) by means of an algorithm of the inverse of the square of distance between stations. Then a linear regression equation was applied to estimate the temperature on the basis of the altitude data from a digital model of the 1 km $\times$ 1 km grid. The annual precipitation layer was obtained by means of an algorithm of the inverse of the square of their distances. The soil moisture regime was included by means of the calculation of five variables (Table 1) that corresponded to the conditions established for determining a non-tropical soil moisture regime (Soil Survey Staff, 1994). The soil moisture variables were calculated for 467 weather stations by means of a daily water balance model based on the Newhall model (Newhall, 1972). This model uses the Thornthwaite potential ET and takes into account a soil water holding capacity of 200 mm. The layers of the variables corresponding to the soil moisture regime were established by interpolating the results obtained for each station (Hontoria, 1995).

The data set is representative of the study area since the pedons were collected from 45 of the 47 administrative divisions in peninsular Spain. The mean annual temperature and mean annual precipitation of the data set were 13.3°C (SD = 2.8) and 796 mm (SD = 425), respectively, compared with 13°C (SD = 2.9) and 705 mm (SD = 349) for peninsular Spain as a whole. The proportions of the five land use categories in this study were similar ($\pm 5\%$) to the distribution of these land uses in peninsular Spain. The main soil units in Spain were well represented in the total of 766 profiles.

Statistical Analysis

Regressions were performed to find the best predictive equation using Statgraphics software (Statistical Graphics Corp., Englewood Cliffs, NJ). The relationship between SOC content and site characteristics was determined for both the surface horizon and the top 18 cm by stepwise backward regression. The confidence level was 99% and the criteria for entry-removal was $F = 4$. The categorical variable land use was divided into five classes: forest, scrub, pasture, herbaceous

Table 1. Soil moisture regime variables (adapted from Soil Survey Staff, 1994).

SMR†	Description
SMRa	Probability that the soil moisture control section (SMCS) is dry for more than half the cumulative days per year when the soil temperature at a depth of 50 cm is > 5°C.
SMRb	Number of consecutive days that the SMCS is moist in some or all parts when the soil temperature at a depth of 50 cm is > 8°C.
SMRc	Number of cumulative days that the SMCS is dry in some or all parts.
SMRd	Number of consecutive days that the SMCS is dry in all parts in the 4 mo following the summer solstice.
SMRe	Number of consecutive days that the SMCS is moist in all parts in the 4 mo following the winter solstice.

† Soil moisture regime.

lar Spain shows a high environmental variability. It is, therefore, an interesting area for the performance of an integrated analysis of the relationships between SOC and key driving variables. Such a local analysis is necessary to estimate the potential effects of a hypothetical climate change on the region. Furthermore, Spain has started a process of land use changes as a result of European Union policies orientated to reducing agricultural and increasing forested land. This study will help to improve the estimation of SOC storage in natural and cultivated ecosystems and potential changes in SOC content due to land use changes.

The objectives of this study were to establish (i) relationships between SOC and climate, land use, and other site characteristics in peninsular Spain by considering the effects of main variable SOC stocks of different hypothetical effects on Spanish SOC stocks of different scenarios of climate and land use changes.

MATERIALS AND METHODS

The study area was peninsular Spain (excluding the Canary and Balearic Islands), located between 36 and 43.8°N and between 9°W and 3°E. The total area is ca. 500 000 km², of which 40% is cultivated, 20% is forested, 20% is degraded woodland, and 20% is rangeland, pastures, and other land uses. The climate is mainly Mediterranean with cool, moist winters and hot, dry summers, although northern Spain has a cold-temperate maritime climate. Mean annual rainfall varies from 200 to 2800 mm with an average of 705 mm. The mean annual temperature varies from 1°C to 19°C and averages 13°C. The moisture regime is 75% xeric, 19% udic, and 6% arctic (Hontoria, 1995). The orography is very complex, with four main mountain chains in the E-W direction and one mountain chain in the N-S direction, two large fluvial depressions, and two plateaus.

Database Description

Pedon data were extracted from published soil studies that correspond to sites throughout peninsular Spain. The information was organized in two databases. One database contained horizon information on SOC, depth, bulk density, sand and clay content, textural class, and stoniness (particle fraction with a diameter > 2 mm). The second database contained pedon information: the number of horizons, local universal transverse mercator coordinates (Zone 30), altitude, land use, vegetation, soil type, slope gradient, slope aspect, and parent rock. The independent variables used in the study were not available for all the pedons. Position and land use was known for all 766 pedons but only 408 included complete information about position, land use, texture, altitude and slope gradient. In most cases organic C was determined by the standard Walkley-Black method (Walkley and Black, 1934). The SOC content because of horizon thickness, the SOC content was estimated for the top 18 cm. This value was chosen so that comparisons could be made across soils including cultivated soils with an 18-cm plow layer (Soil Survey Staff, 1994). Correlation results were similar for the surface horizon and the top 18 cm. The similarity between the surface horizon with a mean thickness of 20 cm and the 18-cm limit may be the reason for this finding. Thus, the distinction between the surface horizon and the top 18 cm was not relevant and the

fitting regression equation of SOC vs. PPT and T obtained from the experimental data. In this way, SOC was totally explained ($R^2 = 1$) by climate variables (PPT, T, with their squares and cross products). Errors were introduced in the variables SOC_{pc}, PPT, and T to obtain three new variables (SOC_{pc}, PPT, T) using the expression

$$(\text{Variable with error}) = (\text{Variable}) + (\text{Variable}) \times (\text{Error}) \times (a)$$

where (a) was a random value generated from the normal unity distribution (mean = 0, SD = 1) by the random number generation routine of the Stargraphics package. The new SOC_{pc} variable was regressed against the PPT, and T, error variables using the same form of the above regression equation and thus obtaining a new R^2 . The calculation process of error variables and subsequent regression was repeated 10 times and the mean R^2 was calculated. The mean R^2 was compared with the perfectly correlated $R^2 = 1$ to study the percentage of the SOC variability explained by the combined errors in SOC, PPT, and T.

Hypothetical Climate Change Effects on Soil Carbon Stocks in Peninsular Spain

In order to predict the effect of hypothetical changes in the independent climate variables on the SOC content, the empirical relationship between SOC and the climate was used, assuming that the regression would hold in the event of a climate change. The effects of temperature and precipitation changes on SOC were estimated for each land use simply by changing the values of these two variables by a given amount in the regression equation and recalculating the new SOC values. The mean PPT and mean T obtained from the data set were used as reference values and modified for each scenario. These calculations mainly provide an illustration of the potential magnitude of the changes in soil organic matter storage with moderate changes in mean annual temperatures and precipitation. Changes in mean annual temperatures and precipitation of $\pm 10\%$ are possible scenarios in peninsular Spain over the next 50 yr (Comisión Nacional del Clima, 1995). Four climate change scenarios were included for the whole study area: (i) T constant, PPT 10% down; (ii) PPT constant, T 10% up; (iii) T 10% up, PPT 10% down; and (iv) T 10% up, PPT 10% down. Although changes in the climate may differ significantly from one area to another inside Spain, more spatially detailed calculations of the potential SOC changes were not justified in view of the uncertainties of the climate change scenarios (Comisión Nacional del Clima, 1995).

RESULTS AND DISCUSSION

The SOC content variability in peninsular Spain was very high in all the categories; total data, noncultivated sites, and cultivated sites (Table 2). On average, noncultivated sites had a higher SOC than cultivated sites. The highest values corresponded to scrubland in noncultivated sites (mean = 5.8%, SD = 4.0). Woody crops (fruit trees, olive groves, and vineyard) had the lowest SOC content. There were statistically significant differences among the five main land use categories at the confidence level of 95% (P value = 0.0 in the Kruskal-Wallis test), except between herbaceous and woody crops. The results indicate that cultivation decreases soil organic matter levels, as has been noted by many au-

Estimation of Error Influence

crops, and woody crops (Table 2); and it was included in the regression using the classical approach of the "dummy" variable (five dummy variables coded 0 for absence and 1 for presence). The regressions were performed separately for the whole sample and for the subsamples of cultivated (373) and noncultivated pedons (393). The independent variables were mean annual precipitation, mean annual air temperature, conditions of the soil moisture regime (SMRA, SMRB, SMRC, SMRD, and SMRE [Table 1]), types of land use, altitude, silt and clay content, and slope gradient. The sets of independent variables used in the regression were (i) all the independent variables and (ii) PPT, T, and types of land use. The squares of precipitation and their cross products ($T \times PPT \times T$, $PPT \times PPT$) were included in both sets. Pairs of variables highly correlated ($r > 0.7$) with each other (PPT with SMRC or SMRD, and SMRD with SMRC) were excluded in the same regression. Other site variables, such as the slope aspect, also seem to be related to the SOC content (Birkeland, 1984), but the lack of sufficient data in the pedon descriptions prevented any attempt to include these factors in the study.

Table 2. Surface horizon soil organic C for the main types of land uses.

	n	Mean	SD
All pedons	766	2.9	3.0
Noncultivated pedons	393	4.4	3.4
Cultivated pedons	373	1.3	1.3
Main land uses:			
Forest†	188	3.9	3.0
Scrubland	124	5.8	4.0
Pasture‡	111	3.3	2.6
Woody crops§	110	1.0	0.8
Herbaceous crops	233	1.2	1.0
† Forest: coniferous, broadleaves, scrub, broadleaves +			
‡ Pasture: pasture, pasture + broadleaves, grassland, scrub.			
§ Woody crops: rainfed fruit trees, vineyards, and olive groves.			
Herbaceous crops: rainfed or irrigated herbaceous crops with or without isolated trees.			

Table 3. Correlation coefficients between soil organic C and variables for surface horizon data.

	Cultivated†	Noncultivated‡
PPT§	0.45***	0.43***
TI¶	-0.29***	-0.10*
SMR#	-0.34***	-0.13***
SMRb††	-0.20***	-0.19***
SMRc‡‡	-0.47***	-0.38***
SMRd§§	-0.53***	-0.40***
SMRe	0.16***	0.15**
Altitude	0.18***	0.08
Clay content	0.02	0.06
Silt content	0.06	0.02
Slope gradient	0.20***	0.20***
n	373	373
r	0.45***	0.43***
n	366	366
r	-0.27***	-0.10*
n	373	373
r	-0.18***	-0.37***
n	373	373
r	-0.55***	-0.40***
n	366	366
r	0.03	0.17**
n	293	293
r	0.09	0.21***
n	361	361
r	0.28***	0.28***
n	170	170

† Noncultivated: forest, scrubland, pasture.

‡ Cultivated: herbaceous crops, woody crops, cultivated grassland.

§ PPT, mean annual precipitation.

* **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

¶ TI, mean annual temperature.

SMR, probability that the soil moisture control section (SMCS) is dry for more than half the cumulative days per year when the soil temperature at a depth of 50 cm is > 5°C.

†† SMRb, consecutive days SMCS is moist in some or all parts when the soil T (50 cm) is > 8°C.

‡‡ SMRc, consecutive days SMCS is dry in some or all parts.

§§ SMRd, consecutive days SMCS is dry in all parts in the summer.

|| SMRe, consecutive days SMCS is moist in all parts in the winter.

Correlation Results

There was a significant relationship between the surface horizon SOC and some of the site variables (Table 3). Mean annual precipitation, SMRd (consecutive days

that the SMCS is dry in all parts in the summer), and SMRe (cumulative days that the SMCS is dry in some

or all parts) were the variables most closely correlated with SOC.

The increase in the SOC content with precipitation agrees with the results of previous studies. However,

the *r* value for the whole sample was smaller than the values reported by other authors; e.g., *r* = 0.85 obtained in Portugal (Martins et al., 1995), or *r* = 0.9 in New Zealand (Tate, 1992). A reason for the lower correlation found in this study may be the larger error in PPT estimations due to the complex orography of peninsular Spain as well as the variability and interdependence with other factors, such as land use, which influences the SOC content. The correlation between SOC and temperature was negative and lower than that between SOC and precipitation. The *r* value is also lower than the *r* values reported in other studies; e.g., Tate (1992) found *r* = -0.66 in a soil climosequence in New Zealand. The SOC content showed a significant correlation with all the variables of the soil moisture regime. The *r* value with SMRd was only slightly lower than with precipitation, but in inverse relation (*r* = -0.53). Therefore, not only is the mean annual precipitation (PPT) related to the SOC content, but the precipitation regime in relation with the temperature regime or, to be more exact, the lack of precipitation accompanied by high temperatures (the summer season in the Mediterranean climate), also seems to be an important factor. The length of the summer season quantified by SMRd seems to be more important for scrubland and herbaceous uses.

No significant correlation was found between SOC content (silt content, clay content, and clay + silt content), which is not in agreement with previous studies. As reported by Kadeba (1977), the effect of texture on the C content varies depending on the parent material. In the area of this study the high heterogeneity of parent materials may obscure the influence of texture on SOC.

The correlation of SOC with altitude was low, but significant for the whole sample. This contrasts with *r* = 0.7 reported by Sims and Nielsen (1986). Altitude has an influence on temperature and sometimes on precipitation. For the sample studied, the correlation between altitude and temperature was significant at 99.9% (*r* = -0.70), but no correlation was found between precipitation and altitude. In Spain, Saa (1991) showed that precipitation at 4094 weather stations was not related to altitude because of the complex orography of peninsular Spain. This correlation was significant in some basins only.

Soil organic C of the whole sample showed a positive correlation with the slope gradient. Such a result is surprising, as a negative correlation would be expected from the negative effects of potential erosion on the SOC content. This correlation may be explained by the slope influence on land use: steeper slopes are mainly devoted to forest, scrubland, grassland. This statement is supported by the positive correlation found between slope and forest or slope and scrubland and the negative correlation between slope and herbaceous crops or slope and woody crops.

In general, the correlation values between SOC and climate and site characteristics were lower in the subsamples of noncultivated and cultivated sites than in the whole sample. This may be explained by the lower CV and the narrower range in the SOC content or in some independent variables (PPT, SMRd, and SMRe) within the subsamples. For cultivated sites, the correlation with SMRd was slightly higher than in the set as a whole. In Mediterranean areas it seems that the length of the dry summer season is a relevant factor for the SOC content in cultivated land. The silt content had a significant correlation with SOC in cultivated sites, while this factor was not correlated with SOC in the other cases (Table 3). The positive *r* value of SOC with the slope gradient was even higher for cultivated pedons than for all pedons, due to the use of steeper slopes for cultivated grassland. This use has a high SOC content that is possibly related to the type of vegetation, higher PPT, and more conservative management practices. In contrast, flatter areas are usually devoted to herbaceous or woody crops because of tillage requirements.

Regression Results

Stepwise regression of SOC vs. climate and site characteristics for all pedons is given in Table 4. The best equation managed to explain 47% of the SOC variability.

It's pedons.

† Set I: climate and soil moisture variables (with PPT, excluding SMRC and SMRD), land use, altitude, silt content and slope gradient.

†† SMRE, consecutive days SMCS in moist in all parts in the winter. - Variables not entered in the stepwise regression.

TABLE 0. Stepwise regression of surface horizon soil organic C with climate data and land use for cultivated pedons.

§ T, mean annual temperature.
‡ PPT, mean annual precipitation.
§§ Climate variables (PPT, T) and land use.

s legitimate to speak of a true cause-effect relationship between land use, PPT, and T as "independent" vari-

vegetative cover is a factor influencing the SOC content (Grigal and Ohmann, 1992).

history on the SOC content in order to improve the SOC models.

Estimation of the Error Influence

and I used to estimate the influence of random errors on the regression coefficient was

$$-0.241 \cdot 10^{-3} \times \text{PPT} \times \text{T} \quad (R^2 = 37\%)$$

1). The SOC^{pc} values (SOC^{pc}) from climate variables ($R^2 = 2.86$) was similar to the mean

with climate data and land use for noncultivated pedons.

SE	No. cases	% of total
0.28	2.91	39.3

‡ PPT, mean annual precipitation.
§ T, mean annual temperature.

Scenario	T constant, PPT 10% down	PPT constant, T 10% up	T 10% up, PPT 10% up	T 10% up, PPT 10% down
Forest	-7.8%	-5.6%	+0.8%	-12.9%
Scrubland	-5.5%	-4.0%	+0.6%	-9.1%
Pasture	-9.0%	-6.5%	+0.9%	-14.8%

Scenario	T constant, PPT 10% down	PPT constant, T 10% up	T 10% up, PPT 10% up	T 10% up, PPT 10% down
Forest	-7.8%	-5.6%	+0.8%	-12.9%
Scrubland	-5.5%	-4.0%	+0.6%	-9.1%
Pasture	-9.0%	-6.5%	+0.9%	-14.8%

Errors in the study of Homann et al. (1995) explained $\leq 38\%$ of volumetric SOC variability, the researchers having used a nonlinear relationship between SOC and the dependent variables. The inclusion of errors in bulk density (6%) and rock volume (5%) in their sensitivity analysis may explain their results in comparison with the present case.

Hypothetical Effects of Climate and Land Use Changes on Soil Organic Carbon Stocks

In order to predict the order of magnitude of potential effects on the SOC content for four different climate change scenarios, the regression equation of SOC vs. climate variables and land use (Table 4, set ii, $R^2 = 45\%$) was applied with the assumption that this regression would hold in the event of a climate change. This last assumption may be questionable as the basic processes of plant litter production and decomposition that underlie the SOC-climate relationship may change as a result of increased temperature and CO_2 concentration. In addition, the obtained regression may correspond to a particular state of soil C accumulation, not necessarily to a steady state. Even if the climate were not to change significantly in the future, the soil C stock would continue to evolve toward equilibrium and, therefore, the SOC-climate relationship may change. Hypothetical effects of climate changes on SOC are given in Table 7. As expected, SOC would diminish with decreasing precipitation and increasing tempera-

Land use and climate have been identified as the main factors influencing the SOC level in peninsular Spain, with other site variables, including the slope gradient, altitude, and texture, playing only minor roles. The variables best correlated with SOC were PPT, SMRD (num-

ture, while the isolated effect of the precipitation change on SOC would be higher than that of the temperature change. A decrease in SOC due to the expected temperature increase in precipitation or compounded by a decrease in precipitation. Within noncultivated uses, pasture seems to be most sensitive to climate changes because of its lower SOC average, while scrubland is the least sensitive.

It must be borne in mind that the above potential effects of climate change on SOC may be of limited value because less than half of the SOC variability (45%) was explained by PPT, T, and land use. In spite of that, some insight may be gained of the relative effects of temperature, precipitation, and land use on soil C stocks for a given change in climate.

On the other hand, the magnitude of the effect of a land use change on the SOC content may equal that of a climate change. For example, between 1960 and 1985 the area of rainfed cropland in Spain decreased by almost 15% and the scrubland area increased by almost 30% (MAPA 1988), which, according to the mean SOC values (Table 2) by the weighted land use proportions, gives a potential increment in the SOC content of $\approx 10\%$. In this calculation, it is assumed that after a certain number of years, the average SOC content would tend to be the average SOC of the new land use (Table 2). In the case of a change from forest or scrubland to cropland use, the SOC content would probably evolve to an average of $\approx 1\%$ if current soil management practices remain unaltered. These practices seem to be more relevant with regard to the SOC content than the climate for the rainfed cropland use under xeric conditions; for example, 34% of the SOC variation in scrubland was explained by the climate, while this percentage decreases to 17% for rainfed cropland and to 9% for woody crops. In the case of changing from cropland to scrubland use, this assumption may certainly be questionable since the climate variables SMRD, SMRC, T, and PPT, in this order, play major roles in the final SOC content, and a spatial study would be necessary to evaluate the total SOC increment, depending on the specific conditions in each area. It must further be taken into account that soil resilience after cultivation is not the same in all the soils, and in some cases the damage may even be irreversible. However, most of the current scrubland areas were cultivated areas abandoned at different times, with different soil resilience capacities. It can be assumed that the current average of the scrubland SOC content is representative of this scenario of land use change. Therefore, a calculation should be made to obtain at least an order of magnitude of the effect of land use change on the SOC content in peninsular Spain.

ber of consecutive days with the soil control section dry in the summer), and SMRC (number of cumulative days with the soil control section totally or partially dry). The correlation between SOC and SMRD highlights the importance of the length of the dry summer season in Mediterranean regions, and this should be researched further. The relation of SOC with land use, management practices, land use history, degree of erosion, or the relation between slope and land also need further research.

In the regression analysis, only 47% of the SOC variability was explained by land use, climate variables, of the soil moisture regime, altitude, and the slope gradient. The climate variables (PPT, T) and land use by themselves explained 45% of the SOC variation. It is remarkable that site variables such as the soil moisture regime, texture, altitude, and the slope gradient did not contribute to explaining more than an additional 2% of the SOC variability. The relatively low percentage of the SOC variability that can be explained may be partially attributed to the effect of random errors in SOC and climate variables. Such errors explained 29% of the total SOC variability in a simulation. Interactions among factors in an integrated study across complex gradients may also be considered a justification of the low amount of SOC variability explained. The relationship between land use and slope gradient is an example of these interactions. In addition, the remaining SOC variability could be attributed to other factors not included in this study, such as greater variable uncertainty, microclimate, topography, slope aspect, vegetation degree of erosion, management practices, and land use history. It is desirable that this information, together with soil bulk density and stoniness data, be adequately represented in future soil databases.

SOC stocks in Spain are sensitive to slight changes in temperature and precipitation variables, with considerable potential losses of soil C in the event of higher temperatures (10%) or lower precipitation (10%). The magnitude of the effects of land use changes (for example, from cropland to scrubland) on the SOC content may equal that of climate changes. Field studies about land use changes and management practices involved in the change, mainly from cropland to forest or to scrubland and vice versa, are necessary for an improved evaluation of the impacts on soil organic matter stocks, particularly as this evaluation is involved in the current European Union policy promoting cropland removal and reforestation.

ACKNOWLEDGMENTS

Dr. Miguel Quemada's helpful comments on this manuscript are gratefully acknowledged.

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Soil Surface Carbon Dioxide Fluxes Induced by Spring, Summer, and Fall Moldboard Plowing in a Sandy Loam

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ABSTRACT

Soil tillage is believed to influence soil organic matter decomposition. We hypothesized that the short-term impacts of tillage on soil surface CO_2 emissions would vary following spring, summer, and fall moldboard plowing of a sandy loam (loamy, mixed, frigid Umbic Dystrochrept). At all dates, plowing increased CO_2 emissions by 7 to 20 $\mu\text{mol m}^{-2} \text{s}^{-1}$ during the first hours following tillage due to degassing of soil CO_2 . The effects of tillage following this initial burst varied with date of plowing. Fall incorporation of fresh maize residues increased CO_2 losses by 173 kg C ha $^{-1}$ during a period of 4 d compared with a non-tilled control, until halted by a sudden drop of 6°C in soil temperature with the onset of winter. In contrast, the cumulative CO_2 fluxes following spring plowing of fall-applied residues were 186 kg C ha $^{-1}$ lower than on a non-tilled control. This effect of spring plowing on CO_2 fluxes lasted for 2 wk, during which soil temperatures in the plow layer were below 10°C. Summer plowing increased CO_2 emissions by as much as 2 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for a period of 65 d, resulting in cumulative soil C losses of 685 kg C ha $^{-1}$ compared with the undisturbed control. Variations in tillage-induced CO_2 emissions between dates were attributed to differences in soil microclimatic conditions following plowing events. The study of the impact of tillage on soil organic matter decomposition should consider the time of year when the soil is tilled.

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Increases in soil surface emissions of CO_2 have been observed in the hours or days following tillage operations (Reicosky and Lindstrom, 1993). These short-term tillage-induced losses of soil C can vary from <10 kg C ha $^{-1}$ (Ellert and Janzen, 1999) to as much as 1992 kg C ha $^{-1}$ (Reicosky and Lindstrom, 1993) (Table 1). Similarly, long-term studies have yielded conflicting observations on the effects of reduced tillage on soil C. While conservation tillage has been proposed as a means for increasing soil C sequestration (Kern and Johnson, 1993; Paustian et al., 1997), other long-term comparative studies have not shown consistent effects of conservation tillage on soil C compared with conventional tillage (Powlson and Jenkinson, 1981; Douglas et al., 1986; Haynes and Knight, 1989; Balesdent et al., 1990; Lal et al., 1990; Angers et al., 1997).

Moldboard plowing can affect soil surface CO_2 emissions by two main mechanisms. First, CO_2 can be lost

by passive degassing when the plow opens the soil and decreases soil resistance to gas transfer (Reicosky and Lindstrom, 1993). Passive degassing continues until a new equilibrium is reached between the soil CO_2 production rate and the rate at which CO_2 is transferred to the soil surface. Second, plowing can influence CO_2 emissions by modifying decomposition rates of crop residues and native soil organic matter (SOM). Burial usually stimulates decomposition by increasing the contact between crop residues and the soil matrix and the associated biota, nutrients, and water (Douglas et al., 1980; Holland and Coleman, 1987; Hendrix et al., 1988; Shomberg et al., 1994). Also, microclimatic conditions in the plow layer are usually different from those near the surface of a non-tilled soil (Gupta et al., 1983), and the activity of the decomposers may change when the residues are incorporated. In addition, mechanical soil disturbance by plowing breaks macroaggregates and exposes previously protected SOM to decomposers (Beare et al., 1994).

The objective of this study was to quantify the short-term impacts of tillage on soil C oxidative losses by monitoring the soil surface CO_2 fluxes following moldboard plowing. We hypothesized that the short-term impacts of tillage on soil surface CO_2 emissions would vary following spring, summer, and fall moldboard plowing.

MATERIALS AND METHODS

The study was carried out from October 1996 to October 1997 at the Chapais Experimental Farm, Lévis, Québec, in a 0.4-ha field with 5% slope facing NW. The soil was a St-Pacôme sandy loam (loamy, mixed, frigid Umbic Dystrochrept) with 0.70 g sand, 0.11 g silt, and 0.19 g clay g $^{-1}$ soil. The average C and N contents were 19.9 $\pm$ 2.0 g kg $^{-1}$ and 1.78 $\pm$ 0.19 g kg $^{-1}$, respectively. The average bulk density of the undisturbed soil was 1.31 $\pm$ 0.09 g cm $^{-3}$. Barley (*Hordeum vulgare* L.) was grown from 1993 to 1995 under conventional tillage practices followed by maize (*Zea mays* L.) in 1996. On 4 Oct. 1996, the crop was chopped and 15 Mg dry matter ha $^{-1}$ left on the soil surface. Different sections of the same field were moldboard plowed to a 0.20-m depth at 0700 h (EST) on 25 Oct. 1996, 9 May 1997, and 23 July 1997. The moldboard plow consisted of two 36-cm-wide plows. Following tillage, the soil had a granular structure with very few clods. No

Abbreviations: SOM, soil organic matter.

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