The potential impact of agricultural management change on soil restoration of the cereal-growing regions of central spain

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Abstract

Practices that restore degraded agricultural soils are important for improving overall environmental quality. In order to implement best practices that maintain agricultural productivity and in the process restore soils and environmental quality, there needs to be better understanding of how soil management affects soil factors associated with and leading to soil degradation and desertification. This study presents new information about how agricultural land management changes affect soil restoration and SOC levels for cereal-growing regions of central Spain. The results show extensification of agricultural practices using long term pasture rotations (e.g. 5-year) may improve soil degradation via the restoration of SOC levels.

Keywords: soil restoration, crop rotation, soil organic carbon, semi-arid, Mediterranean, carbon sequestration.

1 Introduction

Cropland agriculture comprises a significant percentage of the world's arid and semi-arid regions. In these areas, the precipitation limitations, climate variability and anthropogenic factors can lead to soils being vulnerable to degradation and desertification. Soil degradation can be defined as the loss of productivity or utility resulting from natural or anthropogenic factors (Lal [16]; Lal et al. [20]) and generally results from a set of interconnected processes, each often categorized as being mainly a physical, chemical or biological soil process. The factors that affect the level of degradation in semi-arid cereal-cultivated central

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Spain, and other similar regions, include variations among soil properties, climate, topography and type and management of vegetation cover. Loss of soil structure, leading to crusting and erosion; reduced total exchange capacity (TEC), an important factor in soil fertility; and a reduction in the total carbon within the soil are common processes of degradation in semi-arid soils (Lal et al. [20]; Manlay et al. [23]). In central Spain, the cause of soil degradation has been related to agricultural land management (De Alba-Alonso [5]), and in a broader regional context, the agricultural policy and subsidy drivers behind management choices (Boellstorff and Benito [2]).

The level and type of soil degradation may vary significantly between land practice factors, and thus be potentially deterred by new policy that can mandate management changes. An added benefit in restoring degraded soil carbon levels is the possible role agricultural land managers may have in new carbon sequestration programs and policy (Olsson and Ardö [26]; Lal [19]). Estimates show restoration of degraded SOC levels worldwide can have a significant contribution in minimizing rates increase of atmospheric carbon dioxide levels in the next 2-5 decades (Lal [17, 18]). Currently operating carbon credit exchange programs exist in Canada and Australia, however the uncertainty presented by SOC measurement have not been acceptable for some policy-makers to implement programs in Europe (Macey [22]). Uncertainty in measurement of SOC is a significant concern for understanding the role of land management change in agricultural regions, which show a higher level of variation in estimations among all major land use types (Janssens et al. [13]; Smith [29]). However, even though there isn't widespread agreement on if carbon credit exchange programs should be used in the agricultural sector, improved agroenvironmental benefits brought about by restoration of SOC should be taken into consideration (Sauerbeck [28]; Lal [18]).

This applied study presents a methodology to determine the land management effect on soil degradation and restoration in semi-arid central Spain. The first part of the study uses direct observations of current soil properties under typical land management in the region to determine variation among them. The second part of the study uses these values to estimate soil restoration under different land management types. The results can be extrapolated to other areas with similar climate, physical and anthropogenic factors. The goal of the study is to determine if soil degradative factors vary significantly by physiographic position or land management. The second goal is to estimate soil restoration potential of different land management scenarios and suggest best management practices (BMPs) that also account for agricultural productivity.

2 Materials and methods

2.1 Study area

The Experimental Farm Station *La Higueruela* (40º3′N, 4º26′W), which was established in 1973 by the Spanish Center for Environmental Research, is located in the *Alberche* River watershed in the north central part of the Toledo province (Figure 1). The Station is situated within the *Arroyo Grande* catchment (43 km^2), a sub-tributary to the *Alberche* River, part of the larger Tagus River system. The climate averages 450 mm annually with cool, wet winters and hot, dry summers. Soils in the region are derived from arcosic sandstone and detritic carbonate deposits, and are characterized by sandy clay loam texture with overall low organic matter content, which is concentrated in the upper part of the A horizon (10 cm). The rolling topography ranges in elevations from 130 to 530 m. Seventy percent of the land area has slopes between four and ten per cent.

Soil erosion results from the combined effects of cultivation and high intensity storms. Cereal crops typically follow a winter rotation and are alternated with cycles of unseeded fallow and legumes (*Vicia sativa* L.) to augment soil moisture and nitrogen. Mouldboard ploughing, generally applied both post-harvest and during unseeded fallow periods, is used for weed control and breaking soil crust to improve water infiltration (De Alba-Alonso [4]; Boellstorff and Benito [2]). Mouldboard ploughing results in displacement of the cultivated layer (Fitzjohn et al. [7]; Van Oost et al. [30]). Tillage erosion and displacement due to water erosion have a net effect of lateral variation in soil properties. This variation is visible on the landscape as whitish areas on steep convex shoulder slopes, where topsoil has been removed and lighter subsoils exposed, and as dark areas on gentler sloping or concave positions, where topsoil is thicker or has accumulated by erosion (Figure 1, part c).

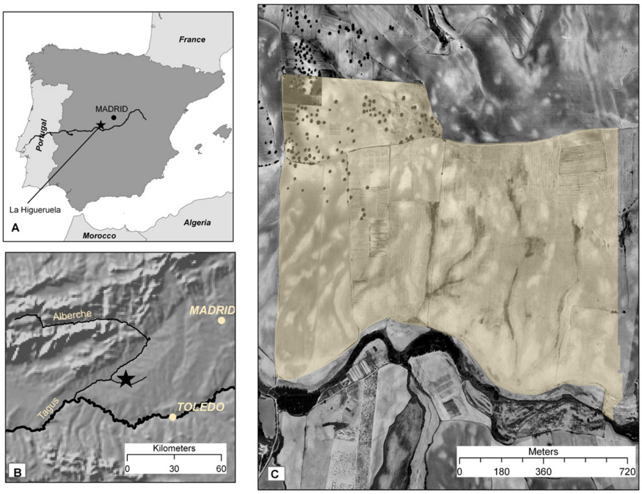

Figure 1: (a) and (b) Location of *La Higueruela* Experimental Station; (c) shaded area showing location of field areas sampled.

2.2 Sample data collection

To compare SOC and soil properties important in maintaining SOC levels, samples from the upper 10 cm of the Ap horizon were collected (June 2006) from fields managed by the Experimental Station. Sample sites in long-term cereal and pasture managed fields are representative of the broader *Alberche* River watershed. Within selected fields, samples were taken along predominant landscape positions. Three subsamples within a m^2 area were combined for a composite sample. A separate core sample was collected for measuring bulk density. Samples were air-dried and sieved through a 2mm screen. SOC values were measured using the wet oxidation method for measuring oxidisible carbon (Walkley and Black [31]) and TEC and mean weight diameter were also measured for each sample (Table 1).

Table 1: Average soil property values by management type and landscape position.

	SOC	TEC	MWD
MANAGEMENT			
Cereal (n=22)	0.59	25.41	38.48
Pasture (n=10)	0.99	34.26	37.53
LANDSCAPE POSITION			
Summit (n=11)	0.63	20.62	37.26
Shoulder/side slope (n=10)	0.64	27.85	37.18
Toe/foot slope (n=11)	0.65	27.97	37.98

SOC = Soil organic carbon (%), BD = bulk density in g/cm^3, TEC = total exchange capacity (ME/100g), MWD = mean weight diameter (μm). Shaded values are factors with significant difference.

2.3 Sample comparisons and SOC prediction

Sample analyses results were grouped by landscape position and by management type. Values differed significantly for SOC and TEC ($p<0.01$ and $p<0.1$ respectively) by management type, with higher values for pasture-managed than cereal-cultivated samples for both SOC and TEC (Table 1). The measure of soil aggregate stability (MWD) did not vary significantly between these two management types. The differences in the values for these factors were not significant when compared by landscape position.

Soil carbon cycling utility programs such as Roth-C, Century and SOCRATES are useful in determining spatial and temporal estimated rates of SOC level change under specific vegetation management, climatic, and soil factors scenarios. An advantage of soil carbon modelling is the ability to estimate carbon changes for individual SOC compartments, including plant matter, microbial biomass and soil humus (Figure 2). SOC pools decompose at different rates and thus have varying effects on potential soil restoration and soil carbon sequestration. The long-term soil carbon compartment of humus has shown to be significant for soil restoration (Drogovoz [6]; Manlay et al. [23]) and because of its long residence-time in the soil, CO_2 sequestration (Sauerbeck [28]).

The Soil Organic Carbon Reserves and Transformations in EcoSystems model (SOCRATES) (Grace [9]) estimates changes in the five main SOC compartments. Comparison between SOCRATES results and observed data from 18 long-term trials by Grace et al. [10] resulted in high agreement with field data (r^2=0.96) for a range of terrestrial ecosystems in Europe, North America and Australia. The model also produced more accurate results compared with Roth-C when compared with sampled field data from *La Higueruela* long-term cereal trial measurements for this study.

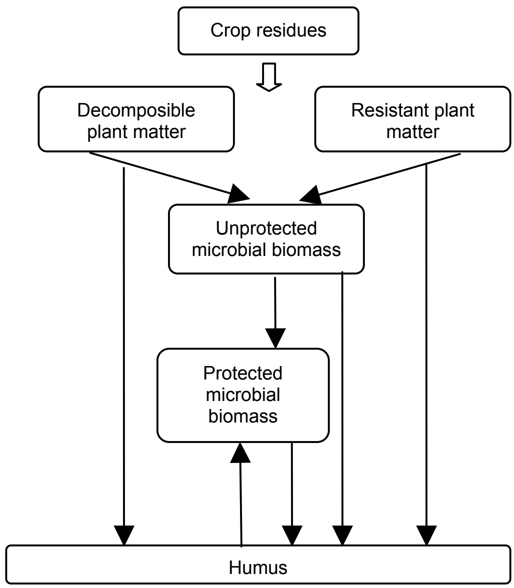

Figure 2: SOCRATES model SOC compartments and transfers. Reproduced with permission from Grace et al. [11].

The modelled carbon input is from plant matter estimated from a net primary calculation (Lieth [21]). The input is divided into decomposable and resistant plant matter (DPM and RPM) by a set ratio of 0.59 (DPM/RPM) tested for arable land (Jenkinson [14]; Grace et al. [11]). The plant matter in each compartment decomposes directly into humus and also contributes to the humus compartment via microbial biomass compartments. The rates of decomposition are determined by the soil properties and were calibrated using C_{14} incubation data (Amato and Ladd [1]; Ladd et al. [15]). These decomposition values are for optimum moisture conditions (25ºC) and are 0.84, 0.07, 0.055, 0.0009 weekly for decomposable organic matter, resistant organic matter, protected microbial biomass, and soil humus respectively. The decomposition rate for unprotected microbial biomass (0.95) is calculated on a daily time-step to simulate its rapid turnover. The amount of carbon (*Y*) that decomposes from each compartment during a weekly, or daily, time-step follows an exponential decay function:

$$Y = Y_0 (1 - e^{-abk}) \quad (1)$$

The function relates initial amount of carbon in a particular compartment, Y_0, to the factor for temperature (a), soil moisture (b), and the individual compartmental decomposition rate (k).

2.4 Land management SOC-change modelling

To compare land management effects on potential soil restoration, changes in SOC were modelled for typical agricultural land management in the *La Higueruela* region. Three hypothetical alternatives were designed for comparing the effects of conversion to permanent pasture, alternative rotations and extensification (Freibauer et al. [8]; Smith [29]). All scenarios were modelled for a 25-year period. This length of inventory period is recommended by the Intergovernmental Panel on Climate Change as part of the guidelines for national greenhouse gas inventories (IPCC [12]). A traditional scenario (T) represents typical cereal cultivated rotations of wheat (with residue retained), legume pasture, and unseeded fallow. Two hypothetical scenarios represent modifications to typical cereal rotation using longer periods of legume pasture, for five (P5) or ten years (P10), within five-year blocks of wheat-fallow rotation. The continuous pasture scenario (CP) models the potential effects of transitioning land to legume pasture for the entire modelled period.

The initiating values for monthly temperature and precipitation were monthly average values recorded at *La Higueruela* (1975–2006). These climate values remained constant for the 25-year modelling period. The average of cereal-cultivated fields in the study region SOC value of 0.59 per cent (Table 1) was used as an initiating value for the modelling process.

3 Results and discussion

The sample analyses and modelled results reflect typical low SOC values of the region, and are in agreement with values developed in similar large-scale Spanish national studies (Rodríguez-Murillo [27]; OECC and UCLM [25]). However, variation among the modelled results illustrates important impacts that land management may have on SOC in this region.

The total SOC per cent at the end of the 25 year period was greatest for continuous pasture, followed by the 10-year and then 5-year pastured scenarios (Figure 3). Traditional land management had the lowest percentage of SOC at the end of the modelling period, with only 0.07 T per ha yr^{-1} average, a total of 1.7 T ha^{-1} over the 25-year period. The long-term soil carbon component of soil humus shows less increase for pasture scenarios, as compared with total SOC. In extrapolating modelled results over the 43 km^2 watershed where the Station is located, the 5-year pasture rotation management (P5) could result in an estimated 40 metric tons SOC over traditional management in the next 25 years. According to total SOC or soil humus, transitioning cultivated land to pasture would be the best management practice (BMP) and could result in an increase of 200 metric tons of SOC. Making a broader estimate for the entire province of Toledo (1.5 million ha) would require taking into consideration variation in soil, climate and differences in the land management, however if all the variables were consistent with the smaller study area, a management transition to pasture could result in 12 million tons of over a 25-year time period.

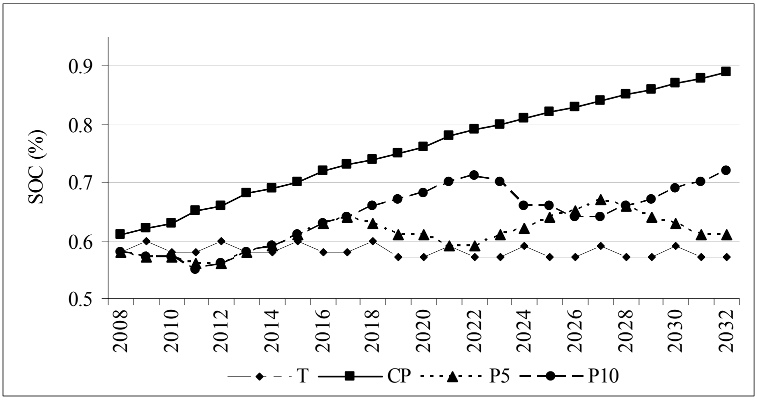

Figure 3: Modelled SOC values for the four scenarios. T=traditional, CP=continuous pasture, P5=cereal with 5-year pasture cycles, P10=cereal with 10-year pasture cycles.

Table 2: Modelled SOC and soil humus totals over 25 year period.

	T	CP	P5	P10
Total SOC				
T ha^{-1}	1.66	10.29	3.30	4.70
T ha^{-1} y	0.07	0.41	0.13	0.19
Soil humus				
T ha^{-1}	0.48	3.49	1.59	2.09
T ha^{-1} y	0.02	0.14	0.06	0.08

T=traditional, CP=continuous pasture, P5=cereal with 5-year pasture cycles, P10=cereal with 10-year pasture cycles.

4 Conclusion

Transitioning cultivated soils to continuous pasture would improve the soil quality of this region and could play a role in increased terrestrial carbon storage and lowered atmospheric rate increases in agreement with Spain's 2008–2012 carbon emissions reduction commitment. This increase in soil carbon may be significant for overall reduction of over 100 million metric tons CO_2 equivalent needed for Spain to meet national greenhouse gas national allocation plan commitments for 2008–2012 (CEC [3]; MPR [24]). If these management changes were implemented as a part of soil restoration policy or carbon emissions reduction policy, there would be a need to address how to maintain economic support for farmers normally dependent on production subsidies or income linked with production. Without current emissions trading in the EU, payment to farmers from other sectors wanting to offset their emissions wouldn't be an option. The current carbon trading program applied in the U.S. Great Plains region uses trade measurements based on a very conservative estimate of SOC increase and highlights soil restoration benefits that accompany the management changes. The low estimates are used as a means to account for uncertainties in SOC monitoring and concerns that errors could ultimately lead to increases in CO_2 emission levels. However, there the recognition that increased SOC can contribute to reductions in atmospheric CO_2 rate increases in the short term and that conservative estimations over a fixed time period are a main focus of the program. It's possible similar agricultural land management changes in the EU and other regions will make their way into emission reduction policy and plans in the future through carbon credit exchanges. The soil restoration benefits of these management shifts linked with increased SOC and soil humus would be an important consideration for improving the sustainability of semi-arid agroenvironments.

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