Modeling Regional Effects of Climate Change on Soil Organic Carbon in Spain

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Abbreviations: DPM, decomposable plant material; HI, harvest index; NT, no-tillage; RPM, resistant plant material; SOC, soil organic carbon; SOM, soil organic matter.

Core Ideas

The model predicted a general increase in SOC stocks by 2100 in all climate scenarios

Irrigated crops showed the largest SOC stocks

Carbon inputs were the most important driver for SOC stocks

No-tillage and cover crops have at least doubled SOC sequestration rates

ABSTRACT

Soil organic C (SOC) stock assessments at the regional scale under climate change scenarios are of paramount importance in implementing soil management practices to mitigate climate change. In this study, we estimated the changes in SOC sequestration under climate change conditions in agricultural land in Spain using the RothC model at the regional level. Four Intergovernmental Panel on Climate Change (IPCC) climate change scenarios (CGCM2-A2, CGCM2-B2, ECHAM4-A2, and ECHAM4-B2) were used to simulate SOC changes during the 2010 to 2100 period across a total surface area of 2.33 . 10^4 km^2. Although RothC predicted a general increase in SOC stocks by 2100 under all climate change scenarios, these SOC sequestration rates were smaller than those under baseline conditions. Moreover, this SOC response differed among climate change scenarios, and in some situations, some losses of SOC occurred. The greatest losses of C stocks were found mainly in the ECHAM4 (highest temperature rise and precipitation drop) scenarios and for rainfed and certain woody crops (lower C inputs). Under climate change conditions, management practices including no-tillage for rainfed crops and vegetation cover for woody crops were predicted to double and quadruple C sequestration rates, reaching values of 0.47 and 0.35 Mg C ha^{-1} yr^{-1}, respectively.

INTRODUCTION

Agricultural activities significantly contribute to global emissions of the major greenhouse gases (CO_2, CH_4, and N_2O) (Paustian et al., 2004). Nevertheless, in the agricultural sector, there are several options to mitigate climate change effects by either reducing the sources of greenhouse gas emissions, enhancing their sinks (e.g., negative emissions via CO_2 sequestration), or reducing CO_2 emissions by substitution of biological products for fossil fuels or energy-intensive products (Smith et al., 2014). In the recent decades, special attention has been paid to soil organic C (SOC) sequestration and its role in mitigating climate change. Although estimates are subject to a large degree of uncertainty, optimistic studies (e.g., Hansen et al., 2013) suggest that global agricultural soils could sequester at least 10% of the current annual emissions of 8 to 10 Gt yr^{-1}. In particular, SOC mitigation potential for European croplands is estimated between 9 and 38 Mt CO_2 yr^{-1} by 2050 (Frank et al., 2015). Furthermore, increasing SOC is vital to the ecosystem functioning as a consequence of the positive effects on soil structure, water retention, and cation exchange capacity (van Keulen, 2001), thus contributing to enhanced soil quality and water availability (Johnston et al., 2009). Agricultural intensification has caused growth in the use of management practices that lead to decreasing SOC stocks (e.g., monoculturing, overtillage). The application of improved agricultural management practices that lead to both enhanced SOC sequestration and increased soil fertility is therefore required for climate change mitigation (Haddaway et al., 2015). Among these potential mitigating practices, conservation tillage (minimum tillage and no-tillage [NT]) has been recommended for semiarid areas of the Mediterranean basin (López-Garrido et al., 2014), since it (i) increases SOC stocks through developing macroaggregates (Panettieri et al., 2015), (ii) prevents soil disturbance and SOC decomposition (Peterson et al., 1998; Plaza-Bonilla et al., 2010), (iii) enhances water use efficiency (Lampurlanés et al., 2016), and consequently, (iv) may lead to higher yields than conventional tillage systems (De Vita et al., 2007; Morell et al., 2011). The application of organic amendments to agricultural soils and the use of cover crops are also regarded as effective ways of restoring soil C stocks. Experimental and modeling studies have successfully shown an increase in SOC after application of organic amendments such as pruning residues (Sofo et al., 2005) or compost (Mondini et al., 2012), and using cover crops for both woody (Pardo et al., 2017) and arable (Bleuler et al., 2017) cropping systems.

Supplying stakeholders and policymakers with scientifically robust information on soil management practices to restore and increase C stocks is paramount in developing appropriate strategies to mitigate climate change. In this sense, SOC models provide reliable and practical information, as they can estimate SOC potential and assess future trends (Mondini et al., 2012). Using dynamic SOC models at a regional scale, thus linking GIS with soil organic matter (SOM) models (Farina et al., 2017), enables us not only to consider the local parameters that control SOM dynamics (e.g., soil properties, climate, and land use), but also to analyze their spatial variability. In this context, the SOM model RothC (Coleman and Jenkinson, 1996) has been applied to numerous field studies worldwide under various types of agricultural management and agroclimatic regions (Jenkinson et al., 1999; Kaonga and Coleman., 2008; Liu et al., 2009). In Mediterranean Spain, process-based models (e.g., the Century model: Álvaro-Fuentes et al., 2012a) have already been used at the plot (Nieto et al., 2010; Álvaro-Fuentes et al., 2012b; Nieto and Castro, 2013) and regional (Álvaro-Fuentes et al., 2012a; Pardo et al., 2017) scales. Among these studies, Álvaro-Fuentes et al. (2012a) was been the first to investigate the effect of Spanish climate change conditions on SOC changes at the regional level, but they did not use the C model under a spatially explicit environment. Therefore, to our knowledge, there have not been many studies so far investigating SOC dynamics at the regional scale, linking GIS with SOC models and considering climate change conditions. Accordingly, the main general aim of this study was to evaluate the impact of climate change on SOC content at a regional level in Spain using the RothC simulation model. In this context and to make the assessment more relevant for decision making, we included spatial mapping and recommended soil management practices. Furthermore, different alternative management practices to increase SOC sequestration under climate change conditions were also simulated. We hypothesized that (i) climate change conditions would reduce SOC sequestration capacity, and (ii) alternative management practices could help to enhance soil C sequestration under climate change conditions.

MATERIALS AND METHODS

Study Area

Our study area (47,719 km^2) in northeastern Spain comprised the entire Aragon autonomous community. This is located at the center of the Ebro River depression, an enclosed basin situated between two high mountain ranges: the Pyrenees in the north and the Iberian mountains in the south. This location has an irregular orography and large climate heterogeneity. Annual precipitation in the central part of the region rarely reaches 400 mm, with mean air temperatures close to 14°C. In contrast, in the northern and southern areas (the Pyrenees and the Iberian mountains, respectively), annual precipitation reaches 1000 mm (Cuadrat, 1999; Peña et al., 2002).

In the Aragon region, agricultural land occupies 49% of the total surface. Field crops occupy almost 80% of the agricultural area, involving rainfed (74%) and irrigated (36%) land. The main crops in the rainfed areas are barley (*Hordeum vulgare* L., 65%) and wheat (*Triticum aestivum* L., 31%). As for irrigated crops, corn (*Zea mays* L., 47%) and barley (22%) are the most abundant crops, with smaller proportions of wheat and alfalfa (*Medicago sativa* L.). Woody crops in Aragon represent 30% of the sales of vegetative products of the study area, with almonds (*Prunus dulcis* L.), olives (*Olea europaea* L.), and grapes (*Vitis vinifera* L.) as the main crops (DGA, 2012).

Rain-fed crops are commonly managed under either cereal–fallow rotations or monocropping together with intensive tillage (56% of rainfed surface is intensively tilled). However, land managed under conservation tillage (i.e., NT) instead of intensive tillage has increased in recent years, representing 20% of land surface currently (DGA, 2012). Within irrigated crops, corn (47%), barley (22%), and wheat (17%) are commonly grown as part of a rotation (GEA, 2000). Surface irrigation and sprinkler irrigation systems are most widely used at similar rates (MAPAMA, 2013). Regarding tree crops, the most generalized practice is minimum soil tillage, representing 55% of woody crop surfaces (DGA, 2012).

The RothC Model

The RothC model (Coleman and Jenkinson, 1996) requires a small number of easily available input data and has been widely used to simulate the impact of agricultural land management on SOC changes (Coleman et al., 1997; Falloon and Smith, 2002; Johnston et al., 2009). As a summary, the RothC model divides the SOC into five fractions: four of them are active, and one is inert (i.e., inert organic matter). The active pools are decomposable plant material (DPM), resistant plant material (RPM), microbial biomass, and humified organic matter. The decomposition of each pool (except inert organic matter) is governed by first-order kinetics (yr^{-1}), characterized by its own turnover rate constant (10 for DPM, 0.3 for RPM, 0.66 for microbial biomass, and 0.02 for humified organic matter) and modified by factors related to air temperature, soil moisture, and vegetation cover, which are main input parameters to run the model. RothC does not include a plant growth module, and thus plant C inputs to soil have to be entered as exogenous inputs to the model. Incoming plant C is split between DPM and RPM, depending on the DPM/RPM ratio of the particular incoming plant material or organic residue. Both of them decompose to produce microbial biomass, humified organic matter, and evolved CO_2. For most agricultural crops and improved grasslands, a DPM/RPM ratio of 1.44 is used (i.e., 59% of the plant material is DPM and 41% is RPM; Jones et al., 2005).

The model uses a monthly time step to calculate total SOC and its different pools on a years-to-centuries timescale. The climate input parameters include monthly average air temperature, monthly precipitation, and monthly open-pan evaporation. Other input parameters are soil clay content, monthly C input from plant residues or exogenous organic matter (e.g., manure), and monthly information on soil cover, whether the soil is bare or covered by plants.

Input Datasets and Spatial Layer Linkages

The Aragon autonomous community covers 21 agricultural regions. Information on agricultural land uses was obtained from the Corine Land Cover. We distinguished five main classes of land cover: rainfed arable land, irrigated arable land, orchards, olive groves, and vineyards. The last three classes were compressed into a general class of woody crops. Soil data were obtained from a recent assessment at the national level (López Arias and Grau Corbí, 2005). In this assessment, among others, variables such as soil texture and SOC to the 30-cm soil depth were analyzed and spatially represented for the entire Spanish area (Rodríguez Martín et al., 2009). For our study, a total of 309 georeferenced points were selected (Supplemental Fig. S1). We set up an equal-interval classification (five intervals) and a mean value of each interval for SOC stocks and clay content properties layers (Supplemental Fig. S2) to overcome the large variability in both SOC stocks (25–151 Mg ha^{-1}) and clay content (14–30%) across the area studied.

Climate change data, corresponding to 50-km × 60-km grids, were produced by the Meteorological State Agency using a regionalization technique explained in Brunet et al. (2008). We simulated SOC changes for the period of 2010 to 2100 under four climate change scenarios and one baseline scenario. The latter consisted of historical average monthly temperature and precipitation data of more than one decade. The four climate change scenarios were obtained from two atmosphere-ocean global circulation models, ECHAM4 and CGCM2, forced by two Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios, A2 (medium-high emissions scenario) and B2 (medium-low emissions scenario) (Nakicenovic et al., 2000; more details can be found in the section "Climate Change Scenarios" below). Furthermore, potential evapotranspiration for each decade from 2010 to 2100 was estimated monthly using air temperature according to the Hargreaves method (Allen et al., 1998).

The overlay of climate grids on the spatial layers of agricultural land uses and clay content through ArcMap 10. 2. 2 (MaDGIC, 2014) resulted in 1337 individual polygons. Mean SOC stocks for initialization purposes were assigned to the spatial units through a query operated in Microsoft Access.

Model Running and Parametrization

Carbon inputs derived from plants and animal manure application were estimated. To explore the maximum potential for SOC sequestration in the study area, simulations were performed assuming that all plant residues were returned to the soil. Within rainfed and irrigated crops, annual average crop yield values for the 2003 to 2013 period were obtained from the Agricultural Statistical Yearbook of Aragon (DGA, 2012). Total aboveground biomass was estimated from crop yields using average harvest index (HI) values obtained from different studies performed in the study area (Daudén and Quilez, 2004; Daudén et al., 2004; Moret et al., 2007; Berenguer et al., 2009; Yagüe and Quilez, 2010a, 2010b; Álvaro-Fuentes et al., 2013; Erice et al., 2014; Plaza-Bonilla et al., 2014). After an extensive literature review of the study conditions, HI values were set to 0.42 and 0.38 for rainfed and irrigated crops, respectively. We assigned a HI of 0.50 to corn, assuming its different morphology compared with the other irrigated crops. Belowground plant residues were estimated from shoot/root ratio. Similarly to HI, a literature review was performed to obtain mean shoot/root values representative of the study area (Lohaus et al., 1998; Vamerali et al., 2003; Plaza-Bonilla et al., 2014). The final mean shoot/root values were fixed to 4.12, 7.66, and 2.21 for rainfed crops, irrigated crops, and corn, respectively. For both irrigated and rainfed crops, we assumed that 50% of C inputs occurred in the month of harvest and the remaining 50% in the three previous months.

For woody crops, pruning residues were also estimated using data obtained from studies performed in Spain or in similar Mediterranean conditions (Di Blasi et al., 1997; González et al., 2005; Nieto et al., 2010; Velazquez-Marti et al., 2011; Aguilera et al., 2015). The final pruning values considered were 1.52, 2.90, and 4.80 Mg ha^{-1} for olive groves, vineyards, and orchards, respectively. We assumed that 70% of the C inputs occurred in the pruning months and the remaining 30% during the four previous months. Carbon inputs from animal manure application were based on the studies of Sanz-Cobeña et al. (2014) and Pardo el al. (2017) and were calculated as follows: dry matter excretion rates (kg location^{-1} yr^{-1}) for livestock were first obtained from the National Inventory Report (MAPAMA, 2011) and then subsequently multiplied by the livestock population of each animal category for 2008 and for each agricultural region (MAPAMA, 2009). Outdoor grazing animals' excreta were assumed to reach mainly grasslands, which were not included in the present study. Consequently, to estimate manure flows applied to croplands, we deducted animal excretion during grazing from the total excreta by applying the grazing factor proposed by the Spanish National Inventory (UNFCCC, 2014). Finally, manure flows applied to cropland dry matter was converted to C by assuming 80% content of volatile solids and 55% of C content in volatile solids. (Adams et al., 1951). We assumed that C inputs of animal manure were applied only to arable land (irrigated and rainfed).

To run the model, monthly C inputs derived from plant residues and from animal manure application were assigned to each of the spatial units according to land use. The splitting ratios for DPM and RPM (DPM/RPM) were assigned differently for each agricultural system. We assumed 49% DPM, 49% RPM, and 2% humified organic matter for manure and 59% DPM and 41% RPM (DPM/RPM = 1.44) for both irrigated and rainfed crops based on Coleman and Jenkinson (1996). Regarding woody crops, and to refine the data, we considered a better resistance to degradation than cropping systems

(50% DPM and 50% RPM, DPM/RPM = 1), since woody crops contains higher lignin content.

Water inputs from irrigation were also taken into account and added to monthly precipitation in the weather file of the model and managed as baseline conditions. Average irrigation doses of the different crops applied in the baseline climatic scenario were obtained from Lecina et al. (2010), and rates were calculated considering the different cropping areas. For the climate change scenarios, we chose to keep the same irrigation patterns and rates as in the baseline climatic scenario. Although we acknowledge the robustness that an adjustment of the irrigation strategies could bring to climate change scenarios (Zhao et al., 2015), we decided to have a conservative assumption (i.e., unchanged irrigation) due to large uncertainties (Wada et al., 2013) associated with choosing a specific irrigation adjustment (Klove et al., 2014). Indeed, for this region (the Ebro region), there have been many studies that have shown large variation in the range (3–20%) of irrigation need predictions (Iglesias and Minguez, 1997; Jorge and Ferreres, 2001; Döll, 2002; Fischer et al., 2007; Rey et al., 2011; von Gunten et al., 2015).The large uncertainty in these estimates is not only due to climate models and scenarios used (García-Vera, 2013), but also to factors in relation with future human impacts on land use changes and demands (Pulido-Velazquez et al., 2015). For example, the future choice of crop types by farmers as a response to climatic change or social and economic factors (von

Gunten et al., 2015) is likely to play an important role in constraining future irrigation water demand (Wada et al., 2013).

RothC initialization requires C pools to be sized. For regional-scale simulation, C pool quantification is infeasible. As an alternative method, we used the pedotransfer functions established by Weihermüller et al. (2013), which have been shown to be helpful in initializing the reactive pools of the RothC model. These functions are based on easily available variables such as SOC stocks and clay content, which, for this study, were derived from Rodríguez Martín et al. (2016).

Since the regional simulation is computationally intensive and time consuming due to the combination of a large number of runs for each polygon and a large number of polygons, we developed a VBA (Visual Basic for Applications)-based program in Excel to simulate changes in SOC stocks simultaneously for the different polygons for the period of 2010 to 2100.

Climate Change Scenarios

Climate change projections suggest that Mediterranean Spain is likely to become one of the areas in Europe that will be more severely affected by climate change. Christensen et al. (2007), for example, showed that the highest climate change impact would affect the Mediterranean part of Spain, with a temperature raise of > 6°C. As a summary of the climate data used in this study, all climate change scenarios predict a decrease in precipitation and an increase in mean air temperature in the following order (Fig. 1, Supplemental Fig. S3): CGCM2-B2 < CGCM2-A2 < ECHAM4-B2 < ECHAM4-A2. Although there is an overall decrease in monthly precipitation of 10.6 and 9.5 mm under ECHAM4-A2 and ECHAM4-B2 scenarios and 3 and 4 mm under CGCM2-B2 and CGCM2-A2 scenarios, respectively, the average monthly temperature rises from 2°C under CGCM2-B2 to 7°C under ECHAM4-A2. Not only do climate change scenarios show lower annual precipitation, but they also indicate different annual precipitation distribution than the baseline scenario (Fig. 1). The climate models producing the largest changes in climate (ECHAM4-B2 and ECHAM4-A2) predict a significant decrease in precipitation during the typical precipitation season (spring and autumn) (Fig. 1). The decadal distribution pattern of annual precipitation is significantly modified among the climate change scenarios compared with the current climatic conditions (Supplemental Fig. S3). However, the annual and decadal temperature distribution are not modified by climate change (Fig. 1, Supplemental Fig. S3). Finally, when we compare the climate projections used in our study for the different Aragon climatic regions, we can observe that the Ebro depression in the central area of Aragon showed the highest temperatures under climate change conditions and the smallest average precipitation decrease compared with the other two mountainous areas (the Pyrenees mountains in the north and the Iberian mountains in the south, Supplemental Table S1).

Soil Management Scenarios

To enhance SOC stocks under climate change conditions during the simulation period of 2010 to 2100, we simulated alternative soil management scenarios, such as NT and vegetation cover for rainfed and woody crop systems, respectively. For NT practices, we considered two livestock future projections for livestock numbers and, thus, for animal manure. Then, we analyzed the effect of these practices (Supplemental Table S2) under the most extreme climate change scenario (ECHAM4-A2).

No-tillage has been shown to be an interesting strategy for rainfed systems of Aragon in terms of SOC increase (Álvaro-Fuentes et al., 2008). However, the NT effect of reducing organic matter decomposition rates cannot be directly simulated with the RothC model. Therefore, we indirectly considered NT practices by accounting the impacts of NT on plant residue data (Nemo et al., 2017). On the basis of experimental studies from the zone (Lampurlanés and Cantero-Martínez, 2006; Plaza-Bonilla et al., 2017), we made the assumption that plant C input at sowing was greater under NT (60%) than under deep or minimum tillage.

Since future projections for livestock production are subject to a large degree of uncertainty (Thornton, 2010; van Grinsven et al., 2015), we explored the potential range of livestock change by both an increase and a decrease in animal numbers (±20% animal production). Both scenarios are supposed to match potential demand-driven trends, the first by rising income and urbanization of the population, and the second if the population has a concern over eating animal products. A linear increase or decrease in animal numbers for the 2010 to 2030 period and a stable situation for the 2030 to 2100 period were assumed for this study.

The use of vegetation cover in olive groves could be an efficient strategy to increase SOC sequestration and reduce erosion impacts (Gómez-Muñoz et al., 2014). This strategy is especially relevant in the context of Mediterranean olive groves, as it has been confirmed by some studies already (e.g., Álvarez et al., 2007). Accordingly, for woody crops, we simulated soil management consisting of a natural vegetation cover and assumed a residue of dry biomass of 1570 kg ha^{-1} yr^{-1} based on Gómez-Muñoz et al. (2014) and monthly C inputs of 0.06 Mg ha^{-1} (assuming 45% C content in dry matter).

RESULTS AND DISCUSSION

Regional Soil Organic Carbon Changes under Climate Scenarios

Results showed an increase in total SOC stocks in Aragon for the 2010 to 2100 period under baseline and climate change conditions (Fig. 2). To explore the potential for SOC sequestration, simulations were performed under the assumption that all plant residues were returned to the soil. Therefore, the observed increase can be partly explained by the biomass returns and C input levels considered during the simulation period, mainly due to pruning in woody crop systems (Sofo et al., 2005), crop residues in both rainfed and irrigated systems (Powlson et al., 2011), and the climate change conditions in both mountainous zones. Comparing SOC content evolution among climate scenarios, the greatest enhancement in SOC content was observed in the baseline scenario (assuming no climate change conditions), with SOC values increasing from 49.5 (2010) to 75.2 Mg C ha^{-1} (2100). In comparison, in all the climate change scenarios, the potential for SOC sequestration decreased, with the lowest SOC increase found in the two ECHAM4 climate scenarios (A2 and B2, 68.5 and 68 Mg C ha^{-1}, respectively), (Fig. 2). For CGCM2-A2 and CGCM2-B2 scenarios, intermediate SOC values were observed at the end of the simulation period (2100), with 70.2 and 70.8 Mg C ha^{-1}, respectively (Fig. 2). The lowest SOC sequestration rates found in ECHAM4-A2 and ECHAM4-B2 scenarios (Fig. 2) were associated climatically with the greatest decline in precipitation rates and rise in temperature (Supplemental Table S3).

It is worth noting that ECHAM4-A2 showed slightly larger SOC contents than ECHAM4-B2, mainly in the last five decades of the simulation period (Fig. 2). In that period, average temperatures were consistently higher under the ECHAM4-A2 scenario than under ECHAM4-B2, whereas precipitation rates were slightly lower (Supplemental Fig. S3), thus suggesting the combined effect of both climatic variables on soil moisture deficit and consequently on SOC evolution. In line with our results, Smith et al. (2005) underlined the combined effects of climate change on SOC dynamics as a balance between temperature increase and soil moisture variation for the entire European agricultural surface.

The climate change conditions of the scenarios considered resulted in slight differences in SOC sequestration rates. The estimated decrease in potential SOC sequestration rates under climate change conditions could be mainly associated with the higher temperature predicted in the climate change scenarios (Supplemental Table S3), which could have triggered greater decomposition rates (Davidson and Janssens, 2006). Hence, the effect of average temperature increases of 6 to 7°C (Fig. 1a) in the whole Aragon region would be linked to the lowest SOC estimated under ECHAM4 scenarios. However, lower precipitation and reduced soil moisture can slow down SOC decomposition (Skopp et al., 1990), thus counteracting the higher temperature influence. These two combined effects would explain the slight differences in SOC evolution observed between ECHAM4 and CGCM2. In the CGCM2 scenarios, the average temperature rise was moderate (2–3°C), but the precipitation decrease was also moderate, which involves a smaller restriction on SOC decomposition rate due to soil moisture deficit. As a result, potential SOC sequestration rates simulated in the CGCM2 scenarios were just slightly higher than in the ECHAM4.

The spatial distribution of SOC levels in 2100 in the ECHAM4-A2 scenario showed lower SOC contents than those found under baseline conditions (Fig. 3). For example, in the humid zones (Pyrenees and Iberian zones, located in the north and south parts of Aragon, respectively), the model predicted a decrease of total surface with SOC contents >97 Mg C ha^{-1} in 2100 (Fig. 3). Similarly, in the central region of the study area, where the drier conditions prevailed (<400 mm precipitation), the area with SOC levels <57 Mg C ha^{-1} also increased (Fig. 3). These results provide an indication of the effects of warming on SOC dynamics.

Our results suggest that the decrease in soil moisture seems to constrain soil microbial activity, this effect being very clear in rainfed cropping systems. In fact, the RothC water balance results showed that, for about half of the year, microbial activity was reduced up to 90% compared with the rest of the year. Compared with another study applied in the same area (Álvaro-Fuentes et al., 2012a) and using a different model (Century), however, this moisture effect was the major factor controlling SOC dynamics. The difference between results from different models is likely explained by differences in two parameter values. The rate modifier for temperature parameter value is always higher in RothC than in the Century model, and the opposite is found for the rate modifier for moisture value (Falloon and Smith, 2002). The underlying uncertainty in the response of soil C to soil moisture is generally attributed to the associated uncertainty in the relationship between soil moisture and soil microbial processes (Falloon et al., 2011). This relationship is complex and depends on several processes, particularly oxygen diffusion and biochemical processes. In RothC, the soil moisture reduction depends on soil clay content, precipitation, and evaporation rate (Bauer et al., 2008), which underestimates the influence of other possible factors. A better understanding of the relationship between soil moisture and SOC decomposition is needed to reduce this uncertainty and improve our confidence in SOC changes under climate change predictions.

According to variability within climate change scenarios and considering the different agricultural systems modeled, irrigated crops showed the highest SOC increase at the end of the simulation period for all climate scenarios (Table 1). For all climate scenarios, rainfed crops showed smaller increases in C sequestration than irrigated crops (Table 1). This could be associated with the limited amount of harvest residue in rainfed conditions, especially after drought periods in semiarid Mediterranean areas (Navarrete et al., 2009), and with the higher water supply in irrigated crops, mainly by irrigation, as it increases SOC stocks through greater plant residue (Gillabel et al., 2007).

The smallest SOC increase was observed in the vineyard and olive grove cropping systems for all the climate scenarios. Indeed, olive groves showed SOC losses under all climate change scenarios, reaching −7.5 Mg ha^{-1} (Table 1) under the ECHAM4-A2 scenario. In Mediterranean areas, olive plantations are traditionally cultivated in nonirrigated soils with low fertility, with low planting densities and intensive tillage, making them more susceptible to SOC losses (Nieto et al., 2010).

The highest SOC stock can be explained by greater C input in irrigated crops than in rainfed and woody crops, and a lower temperature in the baseline scenario versus climate change conditions. It therefore seems likely that the model is sufficiently sensitive to the C input and temperature.

Climate change could alter C inputs, as changes in temperature, precipitation, and atmospheric CO_2 levels could affect net primary production (Falloon et al., 2007). The RothC model does not include changes in these C net primary production-related inputs (Meersmans et al., 2013), constraining the reliability of SOC stock changes estimations. In Mediterranean conditions, it is unlikely that crop yield or C inputs would increase under climate change conditions with higher temperature and lower water availability (Wan et al., 2011). Higher atmospheric CO_2 has the potential to increase crop yield as a result of enhanced crop photosynthesis (Högy et al., 2009; Álvaro-Fuentes et al., 2012a) and an increase in water use efficiency via lower stomatal conductance (Morgan et al., 2004). However, plant quality and quantity respond not only to concentrations of CO_2 but also to changes in temperature and precipitation patterns (driven by changes in the occurrence of extreme climatic events or changes in average conditions), and stressors such as ozone concentration or salinity. The extent to which these variables can affect crop yield will depend on complex interactions between these variables, nutrient availability, type of species (e.g., C_3 vs. C_4 species, herbaceous vs. woody species, etc.), and the indirect effect of climate change on forage pests and diseases. Moreover, although out of the scope of this study, some possible adaptation practices including improvement of crop varieties, implementation of technology change, and adjusting the harvest date could offset the declining trend of crop yields and hence of C inputs.

Soil Organic Carbon Changes under Management Scenarios

Considering the warmest climate change scenario (ECHAM4-A2), the two NT scenarios stored almost more than twofold the SOC stored in the control during the study period (Fig. 4). Both livestock scenarios showed similar levels of SOC sequestered, with

43 and 42.8 Mg C ha^{-1} for the increased and decreased livestock projections, respectively (Fig. 4). Hence, the decrease or increase in manure (20% until 2030) did not significantly affect the SOC content in agricultural soils of Aragon during the period of 2010 to 2100. This might be explained by the fact that the amount of animal manure assumed in our study region was much lower than the total C inputs from the plant residues.

Navarrete et al. (2009) found an annual average sequestration rate ranging between 0.4 and 0.5 Mg C ha^{-1} under Mediterranean conditions and NT soil management, which is similar to the values that we have observed in this study (0.47 Mg C ha^{-1}) over the simulated 90-yr period. The average annual sequestration rate achieved in our case study is included in the range values of the mentioned study, since in our case, we are assuming total incorporation of residues while considering the warming conditions of the ECHAM4-A2 climate change scenario. Similarly, referring to woody crop systems, vegetation cover under the ECHAM4-A2 climate change scenario quadrupled the SOC sequestration rate compared with the unchanged soil management (control) (Fig. 5).

According to these findings, both soil management practices of NT in rainfed and vegetation cover crops in woody crops are effective in enhancing SOC stocks in Mediterranean Spain under climate change conditions (Supplemental Fig S4).

Model Evaluation

We evaluated the model results against measured data only for the baseline SOC stock predictions, as the RothC model is not able to simulate crop yields. Considering that such SOC data are scarce at the scale of the studied region (Aragon scale), we used the data from Álvaro-Fuentes et al. (2009), which measured SOC sequestration rates in field experiments in Aragon. Under the baseline scenario, in rainfed systems, the RothC model simulated SOC sequestration rates of 21.4 Mg C ha^{-1} during a period of 90 yr, which is equivalent to 0.23 Mg C ha^{-1} yr^{-1} (Table 1). We observed a slight difference between mean simulated and measured values (0.23 and 0.18 Mg C ha^{-1} yr^{-1}, respectively). This is due to the fact that we are considering the maximum potential of the SOC sequestration assuming a total incorporation of C inputs, thus proving that RothC model results agree reasonably with the expected and measured ranges. However, future research efforts should be made using more and larger, reliable datasets (e.g., under more management practices and cropping systems) to increase our confidence in the RothC results under different management practices and cropping systems.

Climate change is expected to affect crops responses in many and complex ways (e.g., average yields, plant quality). For example, whereas water shortage has undoubtedly a negative effect on yield, this can be partly offset, as has been found in common crops like wheat (Challinor et al. et al., 2014; Ferrise et al., 2016), by photosynthetic stimulation and enhanced water use efficiency through stomatal closure as a result of enhanced CO_2 atmospheric concentration.

For the Iberian Peninsula, most studies that do not consider adaptation measures predict a reduction in crop rainfed dry matter yields for all climate change projections (e.g., 20%: Ciscar et al., 2014), being especially severe for the end of the 21st century (e.g., wheat: Hernandez-Barrera et al., 2017) due to increased drought duration and intensity.

Provided that attempting to robustly predict changes in crop yields (i) is out of the scope of this study, (ii) involves complex methodologies and uncertain assumptions (e.g., a limited set of available field data), and (iii) depends on other farmer decisions (e.g., technology improvements: Iglesias and Quiroga., 2007; changes in varieties, planting times, irrigation, and residue management: Challinor et al., 2014), we assumed that climate change did not affect crop yields and, subsequently, the amount of C plant residue inputs to the soil compared with the baseline scenario. In recognition of this limitation, for illustration purposes, we made a simple scenario test to see the SOC model response to changes in crop yields in representative rainfed cropping (wheat) systems in our study region. For this exercise, we used the range of potential yield change (±30%) found in the study of Iglesias et al. (2000) and explored the SOC changes as a result of steps of 10% change under CGCM climate change scenarios. Results from this test indicate that each

10% change in dry matter yields resulted in 5% change in SOC storage, compared with the control scenario (with no C input change) at the end of the simulation period (Supplemental Fig. S5). These results certainly confirm the importance that future studies attempt to focus on C input effects variations associated with uncertainty in dry matter yields in climate change scenarios.

Qualitative Analysis of Uncertainty

Uncertainty related to this work may be ascribed to the model applied, the initial size characterization of SOC fractions, and the nonavailability of some data at the temporal or spatial levels. Indeed, for most of the parameters (e.g., inputs of irrigation water, HI), modeling was performed according to the most common practices of the study area. Despite RothC performance shown in many studies (Coleman et al., 1997; Falloon and Smith, 2002; Falloon et al., 2006), we have to take into account some limitations of the model and of the procedure applied. The model uses a monthly time step to calculate total SOC, which may overlook some processes of SOC changes occurring at daily timescale. The proposed regional analysis is based on a spatial division of the agricultural Aragon territory into different geographical areas that share a set of specific parameters (e.g., climate, soil properties, and land use). The model runs each one of the spatial units independently so that possible interaction (e.g., water and soil erosion, horizontal flows) between neighboring polygons is ignored (Paustian et al., 1997). Regarding erosion, RothC does not consider the C lost by this phenomenon, which may become a limitation in certain areas where soil loss is more accentuated (Martínez-Mena et al., 2008). Changes in soil management and C input values throughout the study period were not considered, which brings another source of uncertainty. However, assuming constant soil management conditions during simulation period allows isolated analysis of the impact of climate change on SOC sequestration. Finally, regional climate change projections are subject to several sources of uncertainty associated with global general circulation models and regionalization techniques.

Conclusions

This study has shown significant variations in the SOC sequestration capacity among the different agricultural systems in a representative Spanish area under climate change conditions. Regarding the different agricultural systems tested, whereas irrigated crops resulted in largest SOC sequestration potential even under the most extreme scenario (ECHAM4), rainfed crops, vineyards, and olive groves showed the lowest potential. These differences are probably due to low productivity of certain rainfed agricultural systems that led to a reduction in harvest residue matter, suggesting that C inputs must be the greatest SOC driver.

According to comparisons among climate change scenarios, temperature increase and rainfall decrease will generally lead to a decline in SOC content. Indeed, ECHAM4 scenarios predicted the greatest impacts on SOC sequestration for the next 90 yr due to a high temperature increase.

No-tillage, in the case of rainfed crops, and vegetation cover, for olive groves and other woody crops, were the alternative management strategies to alleviate climate change effects and SOC loss. These changes in management enhanced the amount of SOC sequestered and were found to be effective strategies in reducing CO_2 emissions and increasing soil potential to sequester C under future climate change conditions.

Supplemental Material

Five supplemental figures and three supplemental tables are available online.

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Tables

Table 1. Changes in soil organic C content during the period of 2010 to 2100 for different agricultural systems and under five different climate scenarios (baseline, CGCM2-A2, CGCM2-B2, ECHAM4-A2, and ECHAM4-B2) in the 0- to 30-cm soil layer.

Agricultural classes†	**Baseline**	**CGCM2-A2**	**CGCM2-B2**	**ECHMA4-A2**	**ECHMA4-B2**
	Mg C ha^{-1}				
RC	21.4	16.7	17.6	17.1	16.7
IC	46.2	39.5	39.1	29.4	28.2
OR	20.5	16.3	17	16	16.1
OG	−4	−6.3	−6.1	−7.5	−7.4
V	5.3	3	3.3	4.7	5

† RC, rainfed crops; IC, irrigated crops; OR, orchard; OG, olive groves; V, vineyard.

Figures

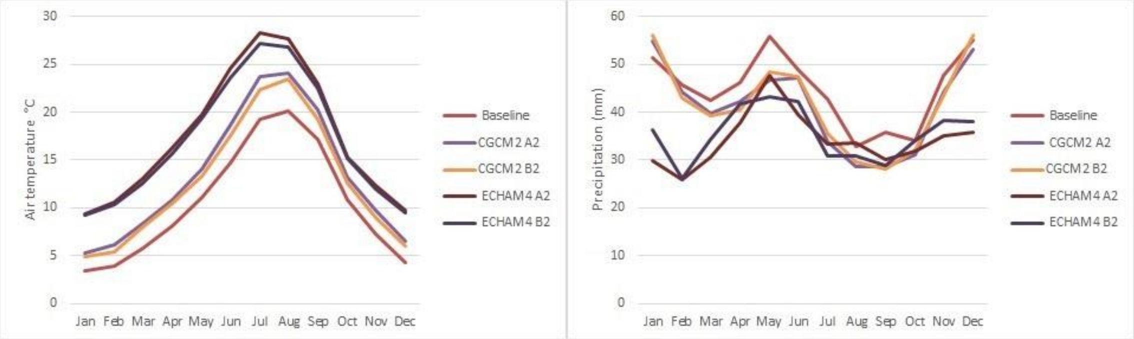

Fig. 1. Mean monthly air temperature and precipitation distribution for the different climate scenarios during the 2010-2100 period in the Aragon region.

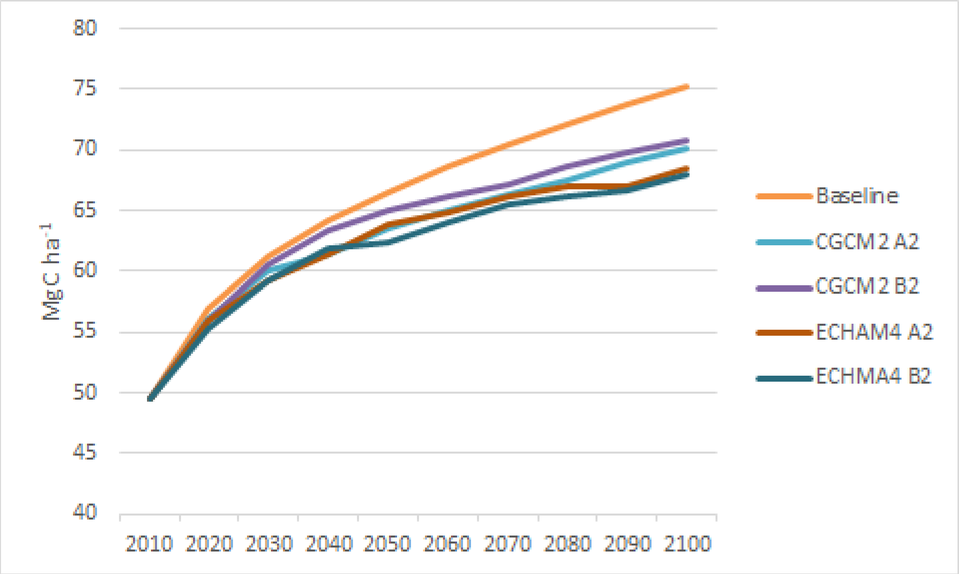

Fig. 2. Soil organic carbon (SOC) content evolution under the Baseline scenario and the four climate scenarios tested (CGCM2 A2, CGCM2 B2, ECHAM4 A2, ECHAM4 B2) during the 2010-2100 period at the 0-30 cm soil layer in the agricultural surface of the Aragon region.

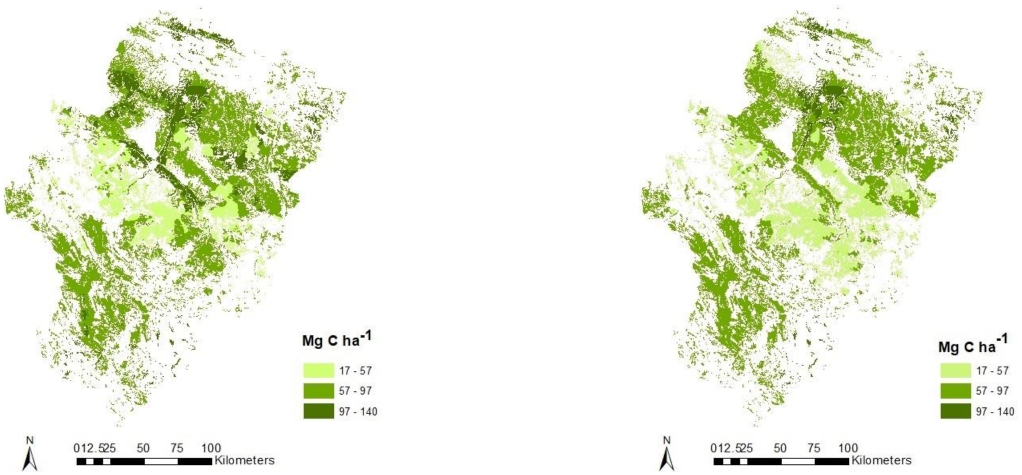

Fig. 3. Spatial distribution of soil organic (SOC) content in 2100 under the Baseline scenario (on the left) and the ECHAM4-A2 climate change scenario (on the right) at the 0-30 cm soil layer in the agricultural surface of the Aragon region.

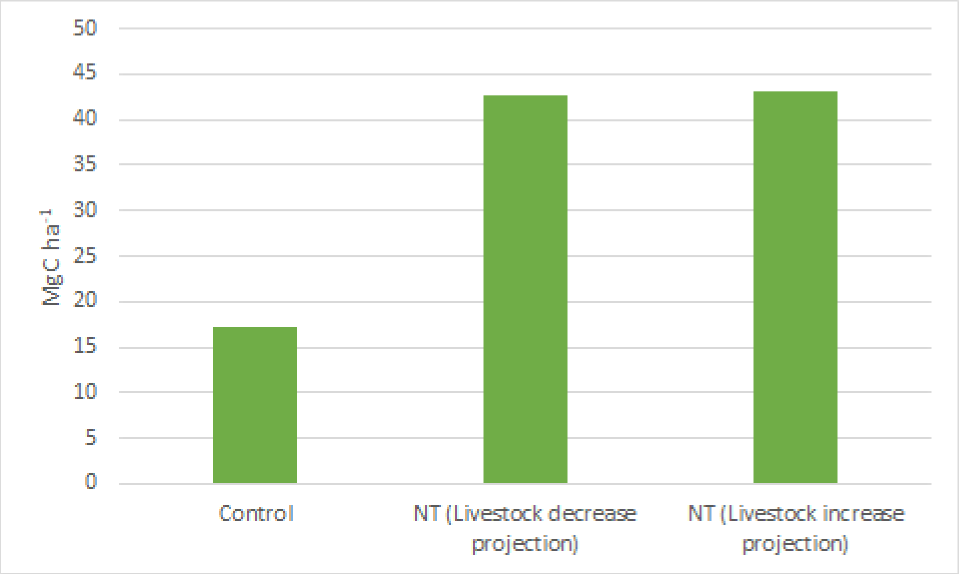

Fig. 4. Changes in soil organic carbon content for the 0-30 cm soil layer in the rain-fed crop (RC) system between the control scenario and the two no-tillage (NT) scenarios (livestock decrease and increase) under the ECHAM4 A2 climate change scenario during the 2010-2100 period.

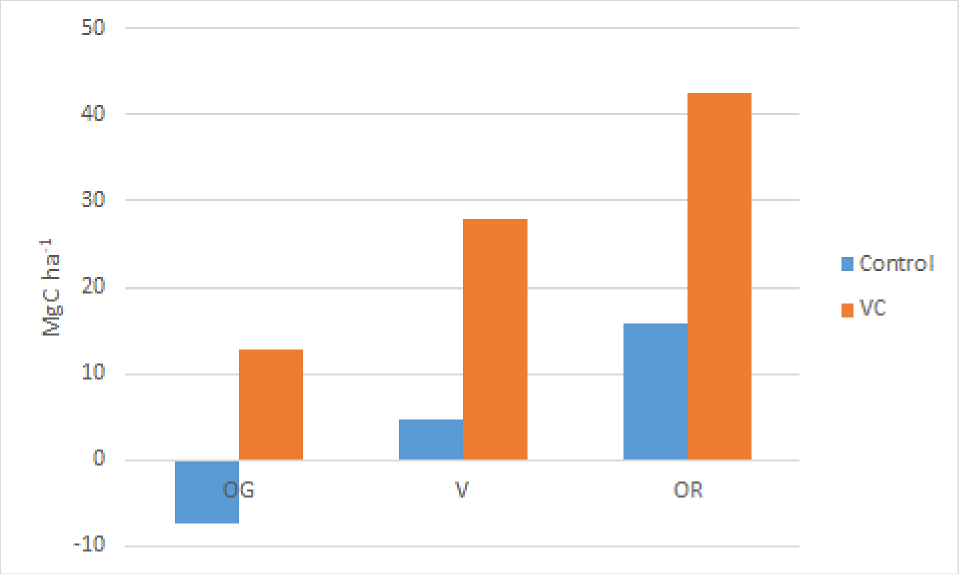

Fig.5. Changes in soil organic carbon (SOC) content for the 0-30 cm soil layer in the woody crop (WC) systems (orchards, OR; olive groves, OG; and vineyards, V) between the control scenario and the vegetation cover (VC) scenario under the ECHAM4 A2 climate change scenario during the 2010-2100 period.