Climate change effects on organic carbon storage in agricultural soils of northeastern Spain

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Abstract

The interactive effects of climate change and atmospheric CO_2 rise could have potential effects on both soil organic carbon (SOC) storage and the capability of certain management practices to sequester atmospheric carbon (C) in soils. In this study, we present the first regional estimation of SOC stock changes under climate change in Spanish agroecosystems. The Century model was applied over a 80-yr period (i.e., from 2007 to 2087) to an agricultural area of 40,498 km^2 located in northeast Spain under five different climate scenarios. The model predicted an increase in SOC storage in the 0-30 cm soil depth in all the climate change scenarios tested (i.e., ECHAM4-A2, ECHAM4-B2, CGCM2-A2 and CGCM2-B2). Among climate change scenarios, SOC stock changes ranged from 0.15 to 0.32 Tg C yr^{-1}. The Century model also predicted differences in SOC sequestration among agricultural classes. At the end of the simulation period, the greatest SOC stocks were found in the rainfed arable land under monoculture and no-tillage (MC-NT) class and in the grape-olive (GO) class with average stocks greater than 80 Mg C ha^{-1}. On the contrary, both the alfalfa (AF) and the cereal-fallow (CF) classes showed the lowest SOC stocks with predicted values lower than 60 Mg C ha^{-1}. Under climate change conditions, Spanish agricultural soils could act as potential atmospheric C sinks. Nevertheless, both the magnitude of the change in climate and the adoption of beneficial management practices could be critical in maximizing SOC sequestration.

1. Introduction

Agricultural soils play a major role in climate change mitigation (Robertson et al., 2000). Changes in management and/or land use increase or decrease the stocks of SOC. In agroecosystems the amount of SOC stored within the soil profile is a result of the balance between C gains, mainly from crop residues, and C losses from the decomposition of soil organic matter (SOM) by microorganisms. Among management practices, the intensification of cropping systems through the suppression of long fallowing has permitted the increase of significant amounts of crop residues returned to soils (Sherrod et al., 2003; Álvaro-Fuentes et al., 2008). Similarly, the conversion from dryland to irrigated agriculture involves an increase in crop productivity and in greater C inputs (Denef et al., 2008). Furthermore, the reduction in tillage intensity has been recognized as a viable option to increase SOC stocks through decreasing SOC decomposition (Peterson et al., 1998; Plaza-Bonilla et al., 2010).

Nevertheless, the effects of agricultural management on SOC dynamics could potentially be affected by climate change due to increases in the anthropogenic CO_2 emissions. In the Mediterranean region, the atmosphere-ocean general circulation models (AOGCM) predicted a significant increase in air temperatures and lower precipitations (Gibelin and Déqué, 2003), with temperature increases higher than 6 ºC in summer in the Iberian Peninsula (Christensen et al., 2007). Since climate is one of the main driving factors in SOC turnover (Paul, 1984), changes in soil temperature and moisture due to climate change might impact SOC stocks and changes. Increases in soil temperature have been associated with higher decomposition rates (Kirschbaum, 1995; Davidson and Janssens, 2006), but experimental data showed that decreases in soil moisture slow down microbial activity and thus SOC decomposition (Linn and Doran, 1984; Skopp et al., 1990). Moreover, despite the effects of climate on microbial activity, the increase in atmospheric CO_2 has been associated with changes in net primary productivity (NPP) and changes in the C:N ratio of the plant material produced. Experimental data suggested that plant physiological changes due to elevated CO_2 lead to NPP increases (Ainsworth and Long, 2005). Consequently, the interactive effects of climate change and the increase in atmospheric CO_2 could have potential effects on both SOC storage and the capability of certain management practices to sequester atmospheric C in soils. The interactive effects of climate change, atmospheric CO_2 rise and management have been investigated at both plot scale (Paustian et al., 1996; Lugato and Berti, 2008; Álvaro-Fuentes and Paustian, 2011) and regional/national scale (Smith et al., 2005, 2007; Falloon et al., 2007). The use of process based SOM models linked to spatial data through geographical information systems (GIS) permits the integration of the spatial variability of the parameters that control SOM dynamics. In four different regions worldwide (i.e., Brazil, Jordan, India and Kenya), Falloon et al. (2007), using the Global Environmental Facility Soil Organic Carbon (GEFSOC) (Milne et al., 2007), simulated SOC changes under climate change. They observed differences in the response of soil and vegetation C storage to climate change among the different regions studied. Similarly, Smith et al. (2005), simulating climate change effects on SOC storage for overall European croplands and grasslands, observed different regional patterns among European areas due to differences in climate conditions across Europe.

The complex orography of Spain, which results in a large range of local climates (Guereña et al., 2001), together with the large agricultural heterogeneity in terms of agricultural classes and management, could have a noteworthy impact on the effects of climate change on SOC turnover in Spanish agroecosystems. To date, no regional assessment of the potential role of SOC storage under climate change has been reported for Spanish agricultural soils. For this reason, in this study we present the first regional estimation of SOC stock changes under climate change conditions made in Spanish agroecosystems. For this purpose, we chose a representative area of 40498 km^2 located in northeast Spain, on which we simulated SOC stock changes under different climate change conditions with the Century model.

2. Materials and methods

2.1. Study area

The study area covers the total agricultural land of four autonomous communities (i.e., Aragón, Cataluña, La Rioja and Navarra) located in northeast Spain (Fig. 1), with a total modelled surface of 40,498 km^2 (Table 1). The area is bounded in the north by the Pyrenees Mountains, in the south by the Iberian Mountains and in the east by the Mediterranean Sea. The area is characterized by an irregular orography resulting in different climatic conditions across the area. Accordingly, annual precipitation and mean annual air temperature range from 300 mm and 14.0 ºC in the middle part of the studied area up to 2000 mm and 3.3 ºC in the mountain ranges, respectively. Soils are mainly Aridisols, Inceptisols and Entisols with loamy soil textures (i.e., loam, clay loam and silty clay loam).

We chose this region due to the large number of different agricultural classes and management practices performed by farmers in the area (Table 1). Almost 80% of the agricultural land is occupied by rainfed agriculture. Within rainfed conditions, small grains are the most important cropping systems occupying almost the 70% of the total agricultural surface. Over the last half century, long fallowing together with intensive tillage (i.e., mouldboard ploughing) has been broadly used in the study area.

However, although during the last decades these systems have shifted to more intensive cropping systems (i.e., cereal monocultures) together with reductions in tillage intensity (i.e., reduced tillage and no-tillage systems), a significant proportion of the region is still managed under long fallowing and mouldboard ploughing. Conservation tillage systems started being adopted in the late 1980s. However, the general expansion of conservation tillage in the area took place in the mid-late 1990s (Cantero-Martínez, personal communication). Currently, the proportion of area managed with conservation tillage systems is close to 25 percent of the total dryland farming area with a similar proportion of land surface occupied with either reduced tillage or no-tillage (Aragon Conservation Agriculture Association, personal communication). Besides cereals, primarily wheat and barley, the other two major rainfed Mediterranean crops are olive trees and vineyards (Table 1). In the study region, irrigated agriculture is divided between field crops (e.g., corn, alfalfa and wheat) and orchards (e.g., apples, peaches and pears). Although the proportion of land under irrigation is only about 20%, these irrigated cropping systems have a noteworthy value due to their economical benefit for farmers.

2.2. The modelling system

We used the Century general ecosystem model (Parton et al., 1988) within the GEFSOC modelling system (Easter et al., 2007; Milne et al., 2007), which allows simulating both SOC stocks and SOC stocks changes at a regional scale. The GEFSOC system links the Century model to a GIS system allowing regional scale SOC assessments. The Century model was previously parameterized and validated for Mediterranean conditions based on long-term experiments located within the study area (Álvaro-Fuentes et al., 2009). Furthermore, although the Century model was originally parameterized to simulate SOC dynamics in the 0-20 cm depth, in that previous study (Álvaro-Fuentes et al., 2009), the model was modified to simulate SOC dynamics in the 0-30 cm soil depth according to the procedure proposed by Metherell et al. (1993).

Our study simulated SOC changes during the 2007-2087 period under different climate change conditions. To meet this objective, predicted SOC stocks for the year 2007 should be as closer as possible to the current measurable SOC contents in the region. To establish a reliable initial SOC stock value, we initialized SOC pools based on historical land use and management conditions with a similar approach as Álvaro-Fuentes et al. (2011) for the same study area. In this preceding study, SOC stocks and changes for the 1977-2007 period were successfully simulated in the same surface area of northeast Spain (Álvaro-Fuentes et al., 2011). Briefly, for the initialization of the most recalcitrant SOM pool (passive pool), an equilibrium period was simulated for 7000 years with a tree-grass system with a 40-year fire return interval. The slow SOM pool was initialized simulating the last 270 years according to historical data obtained from both the Agricultural Statistics Yearbooks published since the 1980s by the Spanish Ministry for Environment and Rural and Marine Affairs (MARM, Madrid, Spain, www.marm.es), and the Statistical Yearbook of Spain, which have been published yearly since 1858 by the National Statistics Institute (INE, Madrid, Spain, www.ine.es). Current land use was obtained from the Corine Land Cover 2000 (CLC2000) map. The original land use classes in CLC2000 were reclassified into eight new classes, which allowed us to adapt the CLC2000 land use classes to the classes described in the 2007 Agricultural Statistics Yearbook (MARM, 2007) according to the major crops and management systems in the area (Table 1). Soil data was obtained from the European Soils Database (ESDB) (Van Liederkerke et al.,

2006) and the new SOTER database and associated SOTER GIS coverage created for our region by Álvaro-Fuentes et al. (2011) were used.

We used the Spanish climate database produced by the Meteorological State Agency (Spanish Ministry for Environment and Rural and Marine Affairs). This database comprised not only current and past climate data but also climate change predictions in a 50 x 60 km resolution.

As mentioned above, predicted initial SOC stocks for agricultural soils in 2007 were obtained following the initialization approach used in Álvaro-Fuentes et al. (2011). The only difference was the climate database used. In this previous study, they used a raster layer with 200 m spatial resolution obtained from the Digital Climatic Atlas of the Iberian Peninsula (Ninyerola et al., 2005). However, since this database does not have climate change predictions, it was not useful for the aim of this study.

Our predicted values were similar to those found in the Álvaro-Fuentes et al. (2011) study (i.e., 245 vs. 244 Tg C, respectively). Thus, despite the lower resolution of the climate database used in this study, the regional scale accuracy of the prediction of the SOC stock at the beginning of the simulation period was not reduced.

2.3. Climate change scenarios and CO_2 increase simulation

The SOC change during the 2007-2087 period was simulated under one baseline scenario and four climate change scenarios. The baseline scenario consisted of the average of monthly precipitation and mean monthly maximum and minimum air temperature during the period 1961-1990 for each 50 x 60 km grid. The four climate change scenarios were obtained from two AOGCMs (i.e., ECHAM4 and CGCM2) forced by two IPCC emissions scenarios (SRES: A2 and B2) (Nakicenovic et al. 2000). The A2 and B2 scenarios were equivalent to atmospheric CO_2 concentrations of 856 and 621 ppmv, respectively, in the year 2100. We assumed a linear CO_2 concentration increase over time. The climate data was produced by the Meteorological State Agency (Spanish Ministry for Environment and Rural and Marine Affairs) using a regionalization technique explained in Brunet et al (2008) to better adjust the climate change scenarios to the conditions of the modelled area. For the overall study area, all four climate change scenarios predicted a decrease in the precipitation and an increase in the mean air temperatures (i.e., maximum and minimum), in the following order compared to the baseline scenario: CGCM2-B2 < CGCM2-A2 < ECHAM4-B2 < ECHAM4-A2 (Table 2). Climate change scenarios not only showed lower annual precipitation but also different precipitation distribution compared to the baseline scenario (Fig. 2). The two climate models producing the greatest changes in climate (i.e., ECHAM4-B2 and ECHAM4-A2) predicted a significant decrease in precipitation during the fall period when the typical precipitation peak occurs (Fig. 2).

The Century model is able to simulate the impacts of increased atmospheric CO_2 on plant processes. Century considers the following effects on crop growth as a result of an increase in atmospheric CO_2: (1) higher photosynthesis rates; (2) increased water use efficiency due to reduced stomatal conductance; (3) decrease in plant N concentration; and (4) increase in C allocation to roots (Metherell et al., 1993; Paustian et al., 1996).

In our simulations, land use and management practices did not vary over the 2007-2087 period. Although we understand that these factors are going to change over time, for the purposes of this study (i.e., assessing the response of agricultural soils to climate change) it was considered most appropriate to keep management and land use constant over the simulation period.

3. Results

As commented previously, the Century model was applied in an Spanish agricultural area of 40,498 km^2, with the next main cropping systems: alfalfa (AF); cereal-fallow (CF); grape-olive (GO); irrigated arable land (IR); rainfed arable land under monoculture and conventional tillage (MC-CT); rainfed arable land under monoculture and no-tillage (MC-NT); rainfed arable land under monoculture and reduced tillage (MC-RT); and orchards (OR).

At the end of the simulation period (i.e., 2087), the total SOC stock predicted for the overall modelled surface ranged from 245 to 270 Tg C for the 0-30 cm soil depth (Fig. 3). Among climate change scenarios, the predicted total SOC stock varied in the following order: CGCM2-A2 > CGCM2-B2 > ECHAM4-A2 > ECHAM4-B2 > Baseline (Fig. 3). Since the initial SOC stock (i.e., 2007) was the same for all five climate scenarios, the total SOC stock change during the 2007-2087 period followed the same pattern. Thus, the model predicted the greatest SOC stock change in the CGCM2-A2 scenario, with 0.32 Tg C yr^{-1} and the lowest SOC stock change in the baseline scenario with almost no change (Table 3). Simulations for the CGCM2-B2, ECHAM4-A2 and ECHAM4-B2 scenarios provided intermediate SOC stock changes, i.e., 0.32, 0.23 and 0.21 Tg C yr^{-1}, respectively (Table 3).

Among agricultural classes, SOC stocks at the end of the simulation period were equal or greater than 70 Mg C ha^{-1} at four classes (i.e., MC-NT, GO, MC-RT and OR) and lower than 60 Mg C ha^{-1} at three classes (i.e., MC-CT, CF and AF) (Table 4). In 2087, the MC-NT was the only agricultural class with SOC stocks greater than 90 Mg C ha^{-1}.

Over the 80-yr simulation period, the only agricultural classes with SOC gains in all five climate change scenarios were the GO and MC-NT classes (Table 4). The greatest SOC change was predicted in the MC-NT class, with SOC increases ranging from 12% and 35% among the different climate scenarios (Table 4). The greatest SOC increase was predicted with the ECHAM4-A2 scenario and the lowest SOC increase with the Baseline scenario. In the GO class, SOC increased between 1% and 22% with the lowest SOC increase predicted was under the Baseline scenario and the greatest under the CGCM2-A2 scenario (Table 4). In contrast, the rest of the agricultural classes (i.e., MC-CT, MC-RT, CF, OR, IR, AF) showed SOC losses in at least one climate scenario (Table 4). The AF class was the only class with SOC losses in all climate change scenarios. The greatest SOC losses were predicted in the both ECHAM4 scenarios (i.e., ECHAM4-A2 and ECHAM4-B2). For the CF class, the model predicted SOC losses in all climate scenarios except in the CGCM2-A2 scenario in which no SOC change was predicted (Table 4). For the OR class, the only two scenarios with SOC losses were the ECHAM4 scenarios (i.e., ECHAM4-A2 and ECHAM4-B2). Furthermore, the IR, MC-CT and MC-RT classes only showed SOC losses under the Baseline scenario (Table 4).

The Century model predicted increases in C inputs in all climate scenarios except for the Baseline scenario in which no changes in C inputs were observed (Fig. 4). The greatest increase in C inputs over the 2007-2087 period was predicted in the CGCM2 scenarios (i.e., CGCM2-A2 and CGCM2-B2) and particularly in the CGCM2-A2 scenario with a gain in C inputs of 44% (Fig. 4). The model predicted higher C inputs in the ECHAM4-A2 scenario compared to the ECHAM4-B2 scenario over the first 60-yr simulation. However, in the last 10-yr period (i.e., 2077-2087), the model predicted a decrease in C inputs for the ECHAM4-A2 scenario resulting in similar C inputs between both ECHAM4 scenarios at the end of the simulation period (Fig. 4).

4. Discussion

In agricultural soils of northeast Spain, the Century model predicted an increase in SOC storage under climate change conditions. In our study, the baseline scenario (i.e., with neither CO_2 increase nor climate change) showed a steady SOC evolution over the 2007-2087 period. It can be assumed that under the baseline scenario, SOC achieved equilibrium conditions since both climate and agricultural management kept invariable during the simulation span (i.e., 80 years). In general, it is assumed that most SOC accumulation occurs during the first 20 years following a change in management and after this initial period SOC levels reach an equilibrium level (West and Six, 2007). In central Spain, Hernanz et al. (2009), studying tillage effects on SOC change over a 20-yr period, observed that SOC levels remained steady after 11 years.

Over the 80 years simulated in this study, the Century model predicted net increases in the SOC stored in the upper 30 cm soil layer in the four climate change scenarios. Therefore, from our simulations, the increase in atmospheric CO_2 concentration together with the change in climate (i.e., higher temperatures and lower annual precipitation) would result in an increase in the C sequestered in Spanish agricultural soils up to 0.32 Tg C yr^{-1} (i.e., 0.08 Mg C ha^{-1} yr^{-1}).

In the last 15 years, SOC decomposition under climate change conditions has been a topic of debate (e.g., Kirschbaum, 1995; Knorr et al., 2005; Davidson and Janssens, 2006). Soil water content and soil temperature are major factors regulating SOC decomposition (Linn and Doran, 1984; Stott et al., 1986; Trumbore et al., 1996;

Conant et al., 2008; Craine et al., 2010). On the other hand, a faster SOC turnover associated with higher temperatures could result in the loss of significant amounts of C stored in agricultural soils. However, in our experiment, simulations did not agree with these experimental observations and significant SOC increases under warming conditions were predicted by the model. Therefore, from our results, SOC response to climate change cannot be entirely explained by changes in temperature. As commented before, decomposition is also controlled by soil moisture. The AOGCM scenarios used in this study predicted reductions in annual precipitation ranging from 6% up to 22% (Fig. 2). This drop in rainfall could be critical in our simulated area, a region with 600 mm of mean annual precipitation and where there exist areas with less than 350 mm. Consequently, under climate change conditions the decrease in soil moisture could constrain soil microbial activity. In the Century model, the effect of soil moisture and temperature on SOC decomposition can be assessed with the *Defac* factor. In our study, we evaluated the effect of different climate scenarios on the *Defac* factor considering two different areas within the 40,498 km^2 modelled with different mean annual precipitation (i.e., semiarid area with 310 mm and sub-humid with 1369 mm) (Table 5). Simulations were considering a monoculture, no-tillage system under rainfed conditions. In the semiarid area, the climate change scenarios showed a reduction in annual precipitation, which limited microbial decomposition and thus decreasing defac values compared to the baseline scenario (Table 5). However, in the sub-humid area the increase in temperature predicted in the climate change scenarios resulted in an increase in microbial decomposition since the decrease in precipitation was not a limited factor (Table 5). In a different semiarid area located in southern Spain, Almagro et al. (2009) established a threshold value of soil water content above which soil respiration is controlled basically by soil temperature and below which it is controlled only by precipitation. Smith et al. (2005) simulated SOC changes under climate change for the entire European croplands and observed differences in C change among European regions. They concluded that the combined direct effect of climate change on SOC dynamics is a balance between increasing temperature and decreasing soil moisture. Furthermore, soil management can also affect soil moisture dynamics. In dryland cropping systems in northeast Spain, Morell et al. (2011) observed that differences in soil water conservation among tillage systems resulted in differences in soil CO_2 emissions due to changes in microbial activity and crop growth. Therefore, in our simulations, the increase in SOC predicted by the Century model could be explained by a decrease in the decomposition rates and also by an increase in C inputs under climate change conditions as the model predicted (Fig. 4).

Increases in atmospheric CO_2 concentration reduce stomatal conductance and transpiration, thus improving water use efficiency and stimulating higher rates of photosynthesis and light-use efficiency (Drake et al., 1997). Consequently, as observed in free-air CO2 enrichment (FACE) experiments, under conditions of atmospheric CO_2 increase a stimulation of crop growth occurs (Ainsworth and Long, 2005). In the four climate change scenarios tested in our study, the model predicted greater C inputs compared with the baseline scenario in which C inputs remained constant over the overall simulation span. Among climate scenarios, differences in SOC stock gains over the 2007-2087 period were related to the amount of C inputs received. Thus, the Century model predicted both the greatest SOC sequestration and C inputs in the CGCM2-A2 and the lowest in the ECHAM4-B2 scenario (Table 3 and Fig. 4). Improving crop water use efficiency due to atmospheric CO_2 increase may be crucial in rainfall-limited conditions of northeast Spain. Guereña et al. (2001), simulating crop growth under climate change conditions in Spain with the CERES model, predicted an increase in water use efficiency under a 2xCO_2 scenario for both wheat and barley. Consequently, climate change would favour increases in NPP resulting in greater SOC stocks (Schlesinger and Andrews, 2000). In FACE experiments conducted in diverse ecosystems, increases in SOC have been demonstrated, with values exceeding 40 g C m^{-2} yr^{-1} in grassland and forest soils due to increases in C inputs (Jastrow et al., 2005). In Spain, modelling studies predicted variable effects of climate change on crop growth (i.e., Guereña et al., 2001; Mínguez et al., 2007). In northeast Spain and according to different climate change scenarios, changes in rainfed wheat yield could vary between -30% to more than 100% (Mínguez et al., 2007). Similarly, in our experiment, for the rainfed arable land classes (i.e., MC-CT; MC-NT; MC-RT) under climate change conditions, the Century model predicted changes in grain yield ranging from -20% to 140% (data not shown). FACE experiments compiled by Ainsworth and Long (2005) showed mean wheat yield increases of 15%.

The greatest SOC gain was achieved in the CGCM2-A2 scenario. In the CGCM2-A2 scenario, the decrease in annual rainfall was higher than the CGCM2-B2 scenario (i.e., 10 mm lower compared to the Baseline scenario). But, at the end of the simulation period, atmospheric CO_2 concentration achieved higher level in the CGCM2-A2 scenario than in the CGCM2-B2 scenario (Table 2). This higher increase in atmospheric CO_2 concentration in the CGCM2-A2 scenario could result in the higher SOC gain despite the slightly lower annual precipitation in this scenario compared to the CGCM2-B2 scenario. Similarly, in the ECHAM4 scenarios, the model predicted higher SOC increase in the ECHAM4-A2 scenario compared to the ECHAM4-B2 scenario. Thus, despite the ECHAM4-B2 presented 20 mm more annual rainfall compared to the ECHAM4-A2, it sequestered less SOC due to the lower atmospheric CO_2 increase than the ECHAM4-A2 scenario (Table 2).

The interactive effects of warming, soil moisture and CO_2 increase on SOC turnover were further revealed among agricultural classes. The supply of water in the irrigated land classes (i.e., AF, IR, and OR) predicted a slightly lower C gain than the classes under rainfed conditions (i.e., CF, GO, MC-CT, MC-NT, and MC-RT). Therefore, an additional water supply together with an increase in temperature could stimulate soil microorganisms. Gillabel et al. (2007) estimated faster SOC turnover rates under irrigation than under rainfed conditions due to higher soil moisture conditions that limited microbial activity. In northeast Spain, irrigated crops (e.g., corn, alfalfa, fruit trees) have their maximum growth and water demand during the summer season. Therefore, irrigation events are concentrated during the warmest months of the year resulting in optimal soil conditions for soil microbial activity. The AF and OR classes were the only two agricultural classes with lower SOC stocks in the climate change scenarios compared to the baseline scenario in 2087. Although the model predicted somewhat greater biomass in the AF and OR classes under climate change than under baseline conditions (data not shown), climate change conditions stimulated microbial decomposition, compensating the higher C inputs predicted by the model.

Under climate change conditions, soil moisture limitation resulted in differences in SOC stock change among rainfed arable land classes (i.e., MC-CT, MC-NT and MC-RT). In the four climate change scenarios, the C input was higher in MC-NT than in the MC-CT (data not shown). This difference in SOC increased over the simulated time period and it was greater in the climate scenarios with the highest decrease in rainfall (i.e., ECHAM4-B2 and ECHAM4-A2) (Table 4). No-tillage systems have been recognized for their effect on soil and water conservation (Lal, 1989; Unger et al., 1991). Surface residues under no-tillage systems avoid soil water losses from evaporation and retain soil surface water improving water infiltration (Cantero-Martínez et al., 2007). Furthermore, the lack of tillage under MC-NT reduces soil C decomposition rates (Paustian et al., 1997). Accordingly, greater soil C inputs together with lower decomposition rates under MC-NT led to the greatest SOC stocks predicted by the model for this class in the four climate change scenarios (Table 4).

Results from simulation models are associated with imprecision and bias known as model uncertainty (Ogle et al. 2007). Uncertainty should particularly be considered when results are used for policy and decision-making (Smith and Heath, 2001). In Mediterranean Spain, uncertainty sources in SOC simulation experiments with the Century model have been explained not only at field scale level (Álvaro-Fuentes and Paustian, 2011) but also at regional scale level (Álvaro-Fuentes et al., 2011). Since the main objective in our experiment was to compare the effects of climate change on SOC dynamics in agricultural lands of Spain, possible management and land use changes over the next 80 years were not considered. Obviously, changes in management, crop genetics, cropping systems and land use are expected to occur in the next decades especially if climate change predictions are realised (IPCC, 2007). Another possible uncertainty source could be attributable to the climate scenarios. As commented in Álvaro-Fuentes and Paustian, (2011), the use of AOGCM scenarios could result in significant biases in precipitation and temperature. Moreover, when used for regional studies, these biases could be significant in areas of complex topography and land use distribution like the Mediterranean basin (Christensen et al., 2007). Moreover, AOGCM scenarios predict changes in air temperature when SOC turnover is controlled by soil temperature. Despite soil temperature is affected by air temperature, the relationship between both variables is complex (Beltrami and

Kellman, 2003) and geographically variable (Zhang et al., 2005) resulting in a potential source of uncertainty.

In ecosystem-level models, the simulation of warming effects on SOM decomposition could also be another source of uncertainty. Recent studies suggest that temperature sensitivity on SOC decomposition changes according to SOC pools (see review by Smith et al., 2008). In the Century ecosystem model, the impact of temperature on decomposition is identical in the different C pools (Parton et al., 1994). Consequently, changes in the response of different C pools to warming could not be predicted by the model. Furthermore, climate change could lead to changes in litter composition and thus affecting microbial decomposition. Changes in both the C:N ratio (Hocking and Meyer, 1991) and the lignin content (Booker et al., 2005) of the plant tissues have been observed under climate change conditions. Under elevated CO_2 conditions, the Century model permits changes in the C:N ratio but not in the lignin content. Additionally, it has been suggested that warming could also alter the composition of the microbial community (Allison et al., 2010). Therefore, despite recent modelling approaches incorporate new factors affecting SOC turnover under climate change conditions (e.g., Conant et al., 2010), more effort needs to be put into better simulating SOC dynamics in changing environments.

5. Conclusions

In northeast Spain agroecosystems, the Century model predicted an increase in SOC storage under climate change. In all four climate scenarios tested, the decrease in annual precipitation and the increase in temperature resulted in SOC gains compared to the baseline scenario (i.e., absence of CO_2 increase and climate change). Although it has been experimentally demonstrated that warming stimulates soil microbial activity, in our study the main driven factor for microbial activity was soil moisture. The semiarid conditions prevailing in the most part of the modelled area constrained microbial activity when the amount of water supplied by rainfall was reduced. Furthermore, the model predicted an increase in C inputs under climate change for all the agricultural classes assessed due to the rise in atmospheric CO_2 concentration. Consequently, the greater C inputs together with the decrease in the decomposition rates due to water limitation resulted in the general increase in SOC stored in agricultural soils of northeast Spain. However, SOC sequestration potential was different among agricultural classes. The greatest SOC sequestration rates were found in the rainfed arable land under monoculture. In contrast, the alfalfa cropping systems were the unique with SOC losses in all climate change scenarios. The supply of water in the irrigated land classes resulted in a slightly lower SOC gain compared to the classes under rainfed conditions, thus supporting the hypothesis that soil moisture is the major factor controlling SOC sequestration potential in agroecosystems of northeast Spain. Consequently, under climate change conditions, the Spanish agricultural soils could act as potential sinks for atmospheric CO_2. Nevertheless, both the magnitude of the change in climate and the adoption of certain management practices could be decisive in maximizing SOC sequestration.

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Figure captions

Fig. 1. Map of Spain with the area modelled in this study.

Fig. 2. Average monthly precipitation (2007-2087) distribution for the different climate scenarios (Baseline, CGCM2-A2, CGCM2-B2, ECHAM4-A2 and ECHAM4-B2).

Fig. 3. Temporal SOC stock evolution from 2007 to 2087 for the different climate scenarios (Baseline, CGCM2-A2, CGCM2-B2, ECHAM4-A2 and ECHAM4-B2) in the 0-30 cm soil depth.

Fig. 4. Temporal C inputs evolution during the 2007-2087 period for the different climate scenarios (Baseline, CGCM2-A2, CGCM2-B2, ECHAM4-A2, ECHAM4-B2).

Tables

Table 1. Surface occupied by agricultural classes in 2007.

Agricultural classes[a]	Surface in 2007 (km^2)
AF	1757
CF	11765
GO	4524
IR	4253
MC-CT	5661
MC-RT	4805
MC-NT	5390
OR	2343
Total	40498

[a] AF, alfalfa; CF, cereal-fallow; GO, grape-olive; IR, irrigated arable land; MC-CT, rainfed arable land under monoculture and conventional tillage; MC-NT, rainfed arable land under monoculture and no-tillage; MC-RT, rainfed arable land under monoculture and reduced tillage; OR, orchard.

Table 2. Total annual precipitation and mean maximum and minimum air temperatures (Tmax and Tmin, respectively) predicted for the different climate scenarios during the 2007-2087 period.

Climate scenario	Precipitation (mm)	Tmax (ºC)	Tmin (ºC)	CO_2 concentration (ppmv)[a]
Baseline	600	16.3	5.5	370
CGCM2-A2	552	19.5	7.6	856
CGCM2-B2	562	18.8	7.1	621
ECHAM4-A2	467	24.3	10.8	856
ECHAM4-B2	486	23.6	10.4	621

[a] Atmospheric CO_2 concentration in 2100.

Table 3. Simulated SOC stock change in the 0-30 cm soil layer during the 2007-2087 period for the different climate scenarios.

Climate scenario	SOC stock change (Tg C yr^{-1})
Baseline	0.01
CGCM2-A2	0.32
CGCM2-B2	0.23
ECHAM4-A2	0.21
ECHAM4-B2	0.15

Table 4. Modelled SOC stocks (Mg C ha^{-1}) in 2007, 2047 and 2087 for different agricultural classes and climate scenarios.

Year	Climate scenario	Agricultural classes[a]							
		AF	CF	GO	IR	MC-CT	MC-NT	MC-RT	OR
					Mg C ha^{-1}				
2007	Baseline	65	58	73	68	59	69	64	66
2047	Baseline	59 (-9)[b]	57 (-2)	74 (1)	67 (-1)	58 (-2)	76 (10)	64 (0)	71 (8)
	CGCM2-A2	60 (-8)	58 (0)	81 (11)	68 (0)	60 (2)	83 (20)	68 (6)	69 (5)
	CGCM2-B2	60 (-8)	58 (0)	78 (7)	68 (0)	60 (2)	82 (19)	67 (5)	69 (5)
	ECHAM4-A2	58 (-11)	58 (0)	73 (0)	68 (0)	61 (3)	84 (22)	69 (8)	64 (-3)
	ECHAM4-B2	58 (-11)	58 (0)	71 (-3)	69 (1)	60 (2)	83 (20)	68 (6)	65 (-2)
2087	Baseline	57 (-12)	56 (-3)	74 (1)	66 (-3)	56 (-5)	77 (12)	63 (-2)	73 (11)
	CGCM2-A2	59 (-9)	58 (0)	89 (22)	69 (1)	61 (3)	93 (35)	72 (13)	71 (8)
	CGCM2-B2	58 (-11)	57 (-2)	87 (19)	68 (0)	60 (2)	88 (28)	69 (8)	70 (6)
	ECHAM4-A2	56 (-14)	57 (-2)	75 (3)	68 (0)	61 (3)	95 (38)	72 (13)	61 (-8)
	ECHAM4-B2	55 (-15)	57 (-2)	75 (3)	68 (0)	60 (2)	90 (30)	70 (9)	60 (-9)

[a] AF, alfalfa; CF, cereal-fallow; GO, grape-olive; IR, irrigated arable land; MC-CT, rainfed arable land under monoculture and conventional tillage; MC-NT, rainfed arable land under monoculture and no-tillage; MC-RT, rainfed arable land under monoculture and reduced tillage; OR, orchard.

[b] In parenthesis, percentage of SOC change according to the initial (i.e., 2007) SOC stock.

Table 5. Mean *Defac* Century factor predicted for the 2007-2087 period in two different geographical areas and five climate scenarios.

Geographical area[a]	Climate scenario	*Defac* factor
Semiarid	Baseline	0.15
	CGCM2-A2	0.12
	CGCM2-B2	0.12
	ECHAM4-A2	0.10
	ECHAM4-B2	0.11
Sub-humid	Baseline	0.22
	CGCM2-A2	0.26
	CGCM2-B2	0.26
	ECHAM4-A2	0.32
	ECHAM4-B2	0.32

[a] For the Baseline scenario, mean annual precipitation (2007-2087 period) in the semiarid and sub-humid areas were 310 and 1369 mm, respectively.

Fig. 1.

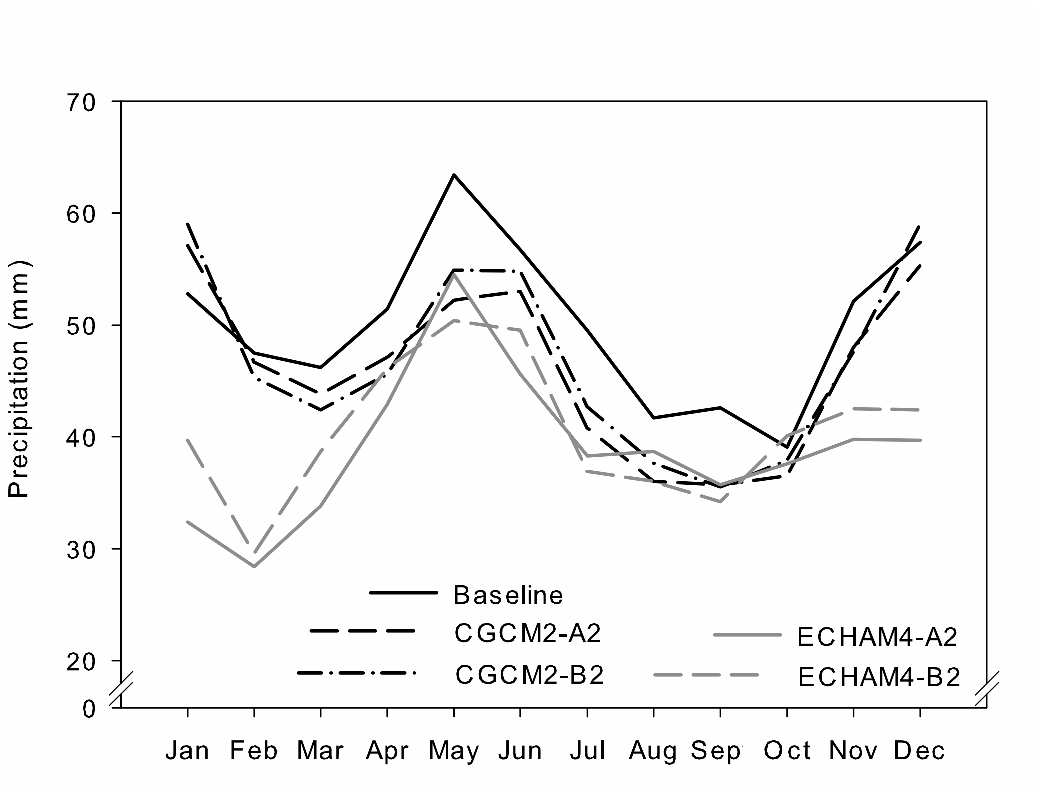
Precipitation (mm)
70
60
50
40
30
20
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Baseline
CGCM2-A2
CGCM2-B2
ECHAM4-A2
ECHAM4-B2

Fig. 2.

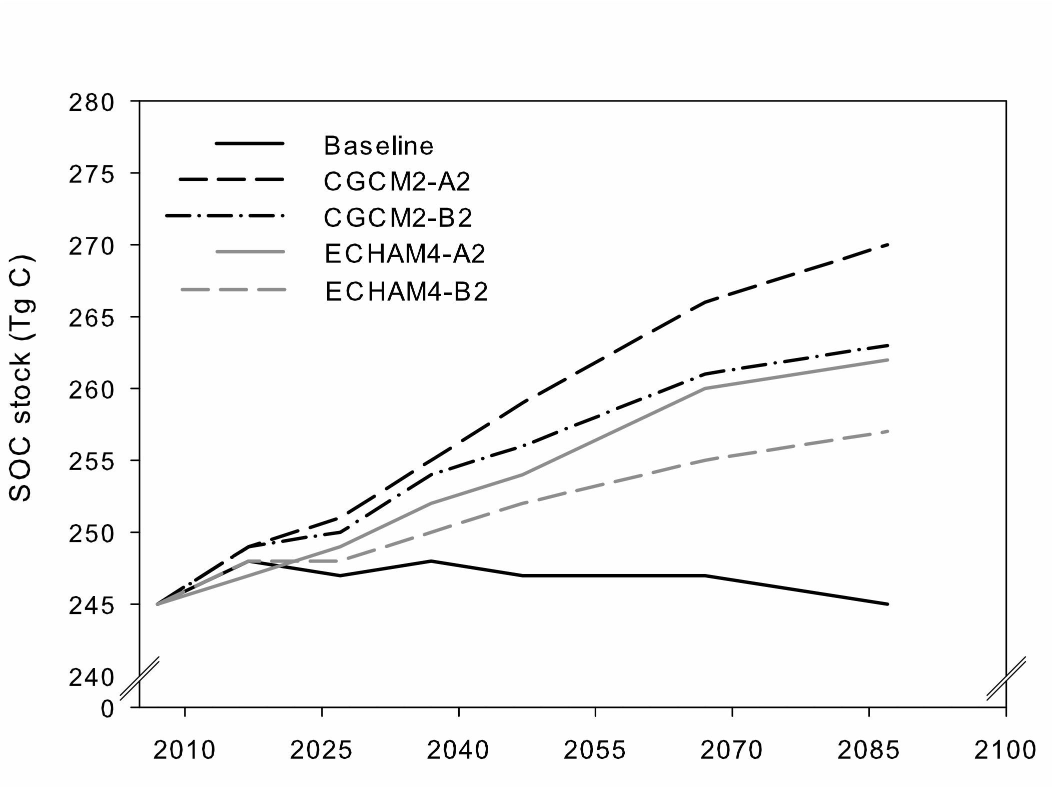
280
275
270
265
260
255
250
245
240
0
SOC stock (Tg C)
2010
2025
2040
2055
2070
2085
2100
Baseline
CGCM2-A2
CGCM2-B2
ECHAM4-A2
ECHAM4-B2

Fig. 3.

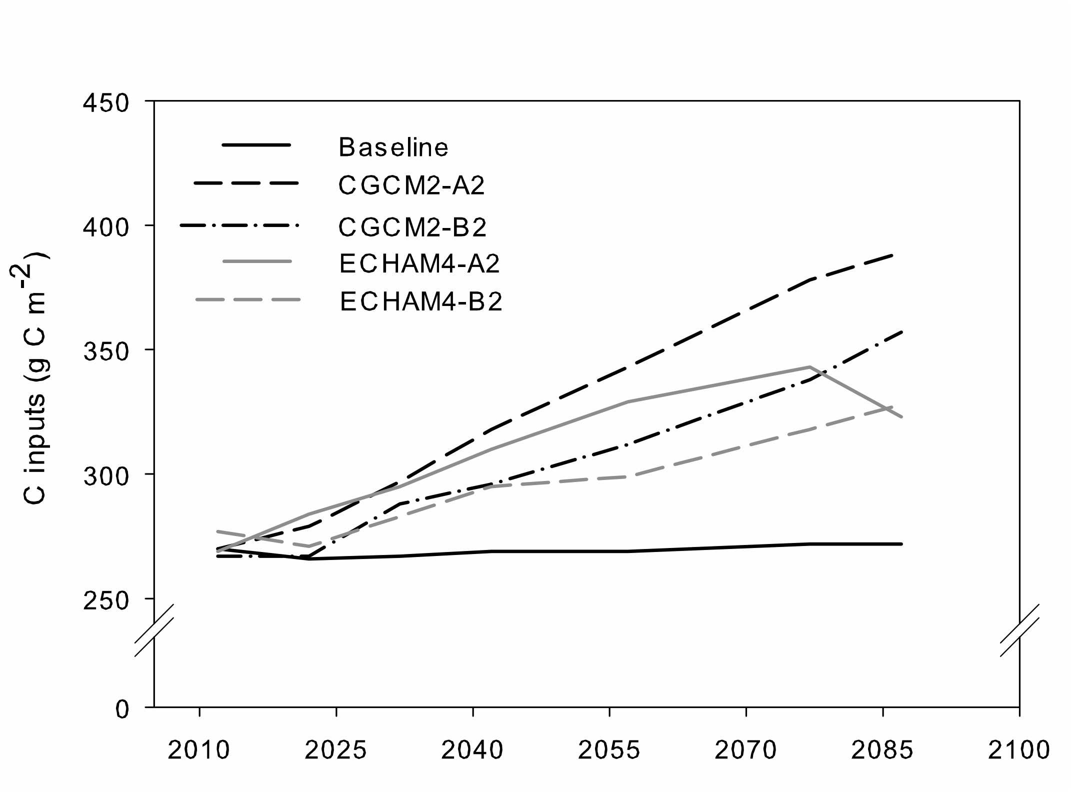
C inputs (g C m^{-2})
450
400
350
300
250
0
2010
2025
2040
2055
2070
2085
2100
Baseline
CGCM2-A2
CGCM2-B2
ECHAM4-A2
ECHAM4-B2

Fig. 4.