Potential soil carbon sequestration in a semiarid Mediterranean agroecosystem under climate change: Quantifying management and climate effects

Jorge Álvaro-Fuentes[1*], Keith Paustian[1,2]

[1] Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523, USA; [2] Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO 80523 USA

* Corresponding author. Tel.: +1-(970)-491-5580 ; fax: +1-(970)-491-1965.
E-mail address: jalvaro.fuentes@gmail.com / jorgeaf@nrel.colostate.edu

Keywords

Soil Organic Carbon; Climate Change; Modeling; Tillage; Mediterranean systems

Abstract

Climate change is projected to significantly impact vegetation and soils of managed ecosystems. In this study we used the ecosystem Century model together with climatic outputs from different atmosphere-ocean general circulation models (AOGCM) to study the effects of climate change and management on soil organic carbon (SOC) dynamics in semiarid Mediterranean conditions and to identify which management practices have the greatest potential to increase SOC in these areas. Five climate scenarios and seven management scenarios were modeled from 2010 to 2100. Differences in SOC sequestration were greater among management systems than among climate change scenarios. Management scenarios under continuous cropping yielded greater C inputs and SOC gain than scenarios under cereal-fallow rotation. The shift from rainfed conditions to irrigation also resulted in an increase of C inputs but a decrease in the SOC sequestered during the 2010-2100 period. The effects of precipitation and temperature change on SOC dynamics were different depending on the management system applied. Consequently, the relative response to climate and management depended on the net result of the influences on C inputs and decomposition. Under climate change, the adoption of certain management practices in semiarid Mediterranean agroecosystems could be critical in maximizing SOC sequestration and thus reducing CO_2 concentration in the atmosphere.

Abbreviations

AOGCM, atmosphere-ocean general circulation models
BF, barley-fallow
CB, continuous barley
IRRI, irrigated
CT, conventional tillage
NT, no-tillage
SOC, soil organic carbon
SOM, soil organic matter
SR, straw removal

Introduction

Soil organic carbon (SOC) stocks in Mediterranean semiarid agroecosystems are constrained by different factors. Limited C input because of low precipitation and high evapotranspiration rates; centuries of agriculture under intensive tillage systems combined with the use of long bare fallows (16-18 months between crops) and the removal of crop residues for animal feed are some of these factors (Austin et al. 1998; Hernanz et al. 2009). In the Mediterranean region, several long-term experiments were initiated in the 1980´s and 1990´s to determine the effects of different management practices on crop development and soil properties (i.e. Hernanz et al. 1995; López and Arrúe 1997; Moreno et al. 1997). These experiments were originally established to study crop growth and soil fertility characteristics under different tillage and cropping systems. In the past decade, data on management effects on SOC sequestration and dynamics in these agroecosystems have been collected. For example, López-Fando et al. (2007), in central Spain, reported 13% more SOC in no-tillage (NT) compared to conventional tillage (CT) in the 0-30 cm depth. Also, Ordóñez-Fernández et al. (2007) in southern Spain measured 20% more SOC stock under NT than under CT in the top 26 cm soil depth. Álvaro-Fuentes et al. (2008) in northeast Spain observed up to 15% more SOC in a continuous barley (CB) system compared to a barley-fallow (BF) system in the 0-30 cm layer. These studies support the potential for SOC sequestration as a result of the adoption of alternative management practices in Mediterranean regions. To our knowledge, there are no region-specific assessments of the potential effects that climate change could have in SOC dynamics in semiarid Mediterranean agroecosystems.

Applications of atmosphere-ocean general circulation models (AOGCM) in the Mediterranean region suggest that climate change could result in significant warmer conditions and lower precipitations (Gibelin and Déqué 2003). Results from the PRUDENCE project using regional climate models in Europe showed that the largest warming is projected to occur in the Mediterranean region, with an increase of greater than 6 ºC in the Iberian Peninsula during summer (Christensen et al. 2007). Recently, the effects of warming on SOC dynamics have received particular attention (e.g., Davidson and Janssen 2006; Conant et al. 2008). Despite some remaining uncertainty about the effects of warming on different compartments of SOC (Kirschbaum 2006), there is scientific consensus that soil organic matter (SOM) overall is sensitive to an increase in temperature (Knorr et al. 2005; Conant et al. 2008). However, temperature is not the only factor affecting soil microbial activity and SOM turnover but the soil water content also plays a major role (e.g. Linn and Doran 1984; Skopp et al. 1990). Furthermore, in semiarid regions climate change could have a significant impact not only on soil microbial processes but also on crop growth and the return of C inputs to the soil (Mínguez et al. 2007). Previous model analyses suggest that climate impacts on both SOM turnover and crop growth may be modified by management practices (e.g. Paustian et al. 1996). For example, Lugato and Berti (2008), in northeast Italy, observed significant differences in SOC sequestration under climate change depending on the management applied.

Since the soil C sink could take even 100 years to reach a new equilibrium, simulation models are a valuable tool to study the interactions of climate change, management practices and ecological processes (Rosenzweig 1990; Ojima et al. 1993; Paustian et al. 1997). In this study we used the Century ecosystem model together with climatic outputs from different AOGCM´s to study the effects of climate change and management on SOC dynamics in semiarid Mediterranean conditions and to identify what management practices have the greatest SOC sequestration potential in these areas.

Materials and methods

Experimental site and model description

An experimental site located in the Zaragoza province NE Spain (41º44’30´´N, 0º46’18´´W, 270 m) was chosen as broadly representation of conditions in the semiarid cropland of Spain. The climate is semiarid, with an average annual precipitation of 340 mm and an average annual air temperature of 14.7 ºC. The soil is a fine-loamy, mixed, thermic Xerollic Calciorthid (Soil Survey Staff, 1975) with the following main properties for the 0-20 cm soil layer: pH (H_2O, 1:2.5): 8.3; electrical conductivity(1:5): 0.25 dS m^{-1};

$CaCO_3$: 432 g kg^{-1}; sand (2000-50 µm), silt (50-2 µm), and clay (<2 µm) content: 293, 484 and 223 g kg^{-1}, respectively. The long-term experiment was established in 1989 and consisted of a long-term tillage (three tillage systems: CT, reduced tillage and NT) and two cropping systems (BF vs. CB) comparison experiment. In the present study, data was only presented from the CT and BF system, as the baseline historical management performed in the area during decades. Primary tillage consisted of mouldboard ploughing to a depth of 30 cm implemented in early spring every two seasons during the fallow phase of the rotation. Secondary tillage was implemented in late spring with a cultivator pass to a depth of 15-20 cm. Inorganic nitrogen was applied in all the treatments since 1998. The N fertilization rates have been changed every season and ranged from 26 to 60 kg N ha^{-1}. From the records found, it is known that prior to the establishment of the long-term experiments fields had been under CT and BF rotation for several decades.

We chose this experiment mainly for two reasons. Firstly, the experiment was located in a representative Mediterranean semiarid area with typical soil, climate and landscape. The second is that we previously used the Century model in this same long-term experiment to validate the Century model in Mediterranean semiarid areas (Álvaro-Fuentes et al. 2009).

The Century model is a general ecosystem model designed to simulate C, N, S and P dynamics in a monthly time step. The model was described in detail by Parton et al. (1987, 1994). The parameterization and initialization of the model for the same experimental plots was done in a previous study (Álvaro-Fuentes et al. 2009). Briefly, passive and slow SOM pools were initialized simulating a 5000-yr period with a tree-grass system and a 100-years period with a barley-fallow rotation with intensive tillage, respectively. Furthermore, parameter constants controlling crop growth (e.g. harvest index (HIMAX), the effect of water deficit on harvest index (HIWSF and HIMONN), the fraction of N which goes to the grain (EFGRN) or potential aboveground production (PRDX)) were calibrated to better represent crop growth according with the values measured during the experimental period. Also, we implemented the procedure proposed by Metherell et al. (1993) to simulate SOC dynamics in the 0-30 cm soil depth. For this experiment, both simulated and measured SOC values from the BF-CT treatment during the 1989-2005 period were taken from Álvaro-Fuentes et al. (2009).

The Century model is able to simulate the impacts of increased atmospheric CO_2 on plant processes. Century considers the following effects 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, (4) increase in C allocation to roots (Metherell et al. 1993; Paustian et al. 1996). The effects of CO_2 change on plant growth can be parameterized for each crop. In our study where we only modeled barley we used the same parameterization used by Paustian (1996) for a wheat crop. This parameterization considered a 30% increase in the potential enhanced photosynthesis and a decrease in transpiration per unit canopy biomass of 23%. These values are in the range of responses found for C3 crops in Free Air Carbon-dioxide Enrichment (FACE) studies (Ainsworth and Long 2005).

Climate and management scenarios

In order to evaluate the effects of climate change on SOC dynamics seven management scenarios and five climate scenarios were built and simulated over a 90 yr period (from

2010 to 2100). Management scenarios are summarized in Table 1. The planting and harvest dates and the N fertilization rates were similar in all the management scenarios. Barley crop were planted in November and harvested in June and fertilized with 45 kg N ha^{-1} at planting. In the irrigated scenarios (IRRI), 400 mm of water was applied from March to June in every cropping season. Tillage and cropping system practices in the management scenarios were the same used during the experimental period (1989-2005).

Climate scenarios included a baseline scenario with neither CO_2 increase nor climate change. The climate data used for this baseline scenario was obtained from the average monthly temperature and monthly accumulated precipitation measured during the 1989-2005 period. The other four scenarios were obtained from two AOGCM simulations (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 a CO_2 concentration at the end of the simulation period of 856 and 621 ppmv. We assumed a linear CO_2 concentration increase over time. The climate data was produced by the Meteorology State Agency (Ministry of the Environment and Rural and Marine Environs of Spain) using a regionalization technique explained in Brunet et al (2008) to better adjust the climate change scenarios to the conditions of the area studied. In all the four climate change scenarios, precipitation decreased in the next order compared to the baseline scenario in the order: CGCM2-A2 > CGCM2-B2 > ECHAM4-A2 > ECHAM4-B2 (Table 2). Also the mean maximum and minimum air temperature increased in all of the climate change scenarios in the order: ECHAM4-A2 > ECHAM4-B2 > CGCM2-A2 > CGCM2-B2. The only exception was the maximum air temperature in the CGCM2-B2 scenario which was lower than in the baseline scenario. In addition to the variation in total annual precipitation, the annual distribution pattern was significantly modified in the climate change scenarios (Fig. 1). Basically, in this semiarid area, the two typical rain peaks (in fall and spring) decline, in particular the fall peak. In contrast there was a precipitation increase during the summer period. However, the annual temperature distribution was not modified by climate change (Fig. 1).

Results

The average annualized grain yield, C inputs and SOC variation predicted during the 2010-2100 period for the different management scenarios are shown in Table 3. The lowest grain yield and C inputs were predicted in the BF-CT-SR scenario. Also, this was the only management scenario with SOC loss (Table 3). Management scenarios under CB had greater grain yields, C inputs and SOC gain than scenarios under BF rotation. The shift from rainfed conditions (CB-CT and CB-NT) to irrigation (CB-CT-IRRI and CB-NT-IRRI) also resulted in an increase of grain yields and C inputs but a decrease in the SOC sequestered during the 2010-2100 period (Table 3). Also, within the same cropping system, NT had lower C input compared to CT but greater SOC gain (Table 3).

In the BF management scenarios, C inputs were similar among climate scenarios. However, greater differences were obtained in the SOC variation during the 2010-2100 period (Fig. 2). In general, the model predicted the lowest SOC gain (in the BF-CT-SR rotation the greatest SOC loss) in the baseline scenario followed by the CGCM2-A2. The exception was in the BF-CT in which the lowest SOC gain was in the CGCM2-A2 followed by the baseline. The greatest SOC gain was predicted in the ECHAM4 scenarios in all the three BF management scenarios.

In the CB scenarios under rainfed conditions (i.e. CB-CT and CB-NT), differences in C inputs and SOC gain among climate scenarios were similar. The greatest C inputs and SOC gain were predicted in the baseline and both CGCM2 scenarios and the lowest in the ECHAM4-A2 and ECHAM4-B2 (Fig. 3).

In the CB scenarios under irrigated conditions (i.e. CB-CT-IRRI and CB-NT-IRRI), similar C inputs were observed among scenarios (Fig. 4). However, the greatest SOC gain was obtained in the CGCM2-A2 and CGCM2-B2 scenarios in both management scenarios (Fig. 4).

The temporal SOC dynamics in the CGCM2-B2 and ECHAM4-A2 climate scenarios during the 2010-2100 period are shown in Fig. 5. Both climate scenarios had similar SOC dynamics among management scenarios. The BF-CT-SR showed an initial SOC decrease and a stabilization of the SOC by the end of the study period. The BF-CT management scenario kept almost steady over the entire study period (Fig. 5). In both climate scenarios, the CB management showed an almost linear SOC increase during the entire studied period. However, in the latest 10 years of the simulation, the SOC gain in CB under ECHAM4-A2 scenario kept almost steady (Fig. 5). However, this trend was not shown in the CGCM2-B2 scenario.

Discussion

In semiarid Mediterranean areas, the effects of cropping intensification and tillage reduction on SOC sequestration under current climate conditions have been widely studied (i.e. Virto et al. 2007; Álvaro-Fuentes et al. 2008; Hernanz et al. 2009). In the same study area, we used the Century model to simulate SOC dynamics in a tillage-cropping system long-term experiment under current climate conditions (Álvaro-Fuentes et al. 2009). In a previous study (Álvaro-Fuentes et al. 2009), we observed threefold higher SOC sequestration rates under a NT-CB system than under a CT-CB system and under a NT-BF system. Similarly, in our present study under climate change conditions both CB and NT also showed greater SOC gain than the scenarios under BF and CT. However, greater C input was predicted under CT than under NT in both current climate and climate change conditions. Moret et al. (2007) in the same experimental plots concluded that the greater biomass production observed under CT than under NT was explained by higher soil evaporation in NT compared to CT due to lower ground cover provided by the crop during growth.

In the study area selected, climate change scenarios predicted an increase in air temperature and a reduction in total annual precipitation. As commented previously, annual precipitation distribution was modified under climate change. In the four climate change scenarios, precipitation increased during summer compared with the baseline. Furthermore, reduction in precipitation was predicted during the two water recharge periods (autumn and spring), which are critical for crop growth. However, in the BF and IRRI management scenarios, the average C inputs were reasonably steady among climate change scenarios. Though in semiarid Mediterranean agroecosystems crop production is strongly dependant on rainfall (Austin et al. 1998), the drop in precipitation due to climate change did not have a strong effect on C inputs. Increase in atmospheric CO_2 has been associated with both the stimulation of crop photosynthesis (i.e. CO_2 fertilization effect) (Friedlingstein et al. 1995; Lobell and Field 2008) and the increase in water use efficiency as a result of lower stomatal conductance (Morgan et al. 2004). Consequently, the effect of precipitation reduction on crop growth could be ameliorated by the increase in water use efficiency and crop photosynthesis due to atmospheric CO_2 increase. However, in the CB scenarios, there was a slight decrease in C inputs predicted for the two ECHAM4 scenarios compared to the CGCM2 scenarios. This fact could suggest that exceptional reductions in precipitation (e.g. more than 60 mm per year in the ECHAM4 scenarios compared to the baseline) could lead to situations in which water use efficiency improvement by increased atmospheric CO_2 could not completely ameliorate water stress effect on plant growth.

At the same time, climate modification due to increases in atmospheric CO_2 has a significant impact over SOC turnover (McGuire et al. 1995). A positive relationship between warming and SOC decomposition has been experimentally demonstrated (Kirschbaum, 1995; Trumbore et al., 1996; Conant et al., 2008). In our study, the effects of temperature increase on SOC decomposition was observed in the irrigated (IRRI) scenarios where despite similar C inputs slightly lower SOC gain was predicted in the ECHAM4 scenarios compared with the CGCM2 scenarios. Similar soil moisture among climate scenarios due to irrigation supply together with an increase in more than 3ºC in both minimum and maximum temperatures predicted in the ECHAM4 scenarios compared with the CGCM2 scenarios resulted in greater SOC decomposition. However opposite behavior was observed in the barley-fallow (BF) scenarios where lower SOC decomposition was predicted for the two ECHAM4 scenarios despite the similar C inputs among climate scenarios. Soil moisture limits SOC decomposition (Stott et al. 1986), particularly in semiarid conditions (Wildung et al. 1975; Paustian et al. 1996). Furthermore, in semiarid southeastern Spain but under current climate conditions, Almagro et al. (2009) established a threshold value of soil water content above which soil respiration was controlled basically by soil temperature and below which was controlled by precipitation only. In our study, it is likely that the low soil moisture in the ECHAM4 scenarios in the BF system led to limited conditions for soil microorganism to decompose SOC.

The increase in precipitation predicted during summer months in the four climate change scenarios led to increases on SOC decomposition compared to the baseline scenario. Despite this increased precipitation during the summer months (July and August), the model predicted a decline in SOC in all the climate and management scenarios; under climate change SOC losses were greater compared to the baseline scenario. For instance, in the CB-NT and CB-CT management scenarios under the ECHAM4-A2 climate change scenario, the average SOC loss during July and August was 9.9 and 7.4 gC m^{-2}, respectively. However, for the same period and management scenarios, under the baseline scenario SOC losses were 6.9 and 4.5 gC m^{-2}, respectively. The BF management scenarios showed a similar SOC loss between the climate change scenarios and the baseline scenarios. In the irrigated (IRRI) scenarios, during summer differences in SOC loss between climate change scenarios and the baseline scenario were negligible. Consequently, in the climate change scenarios higher precipitation and elevated soil temperatures during summer increased SOC decomposition compared to the baseline scenario. The increase on SOC decomposition can be assessed with the Century output factor *defac* (i.e. decomposition factor based on the temperature and the soil moisture). During July and August, the Century model predicted between 40% and 50% increases in the *defac* parameter of the CB and BF management scenarios under climate change scenarios compared to the same management scenarios under baseline conditions (data not shown).

As commented before, the CB management scenarios showed different C inputs among climate scenarios. The lower C inputs predicted in the ECHAM4 scenarios led to lower SOC gain under these climate scenarios compared to the CGCM2 scenarios. Consequently, under CB, climate effects on SOC dynamics were primarily due to an increase in C inputs. Basically, the relative response to climate and management in this study depended on the net result of the influences on C inputs and decomposition. Consequently, different management systems showed different responses to climate change scenarios.

Following a change of management practice, SOC content tends to reach a new steady state (West and Six 2007). The time it takes to achieve this new steady state varies between ecosystems, climate regimes and land management. In our study, different climate scenarios had different effects on the duration of SOC sequestration. The ECHAM4-A2 climate scenario with higher increase in temperature and lower annual precipitation achieved a steady state earlier than the CGCM2-B2 scenario. West and Six (2007) observed that sequestration activities with greater impacts on decomposition rates result in lower sequestration durations.

Results from simulation models are associated with imprecision and bias known as model uncertainty (Ogle et al. 2007). Lugato and Berti (2008), in a similar study in northeast Italy, identified three main sources of uncertainty: associated with the model, associated with the climate scenarios and associated with the management scenarios. These same authors pointed out that the uncertainty associated with the model is basically related with the fact that Century is a model based on a first-order decomposition kinetics, resulting in a SOC increase without limits as C input increases. However, as suggested by Stewart et al. (2007), some long-term experiments showed no change in SOC content in response to different C input levels. Therefore, in our experiment, the almost linear SOC gain in the four CB scenarios with significant increase in SOC stock in the 90 years of simulation (Fig. 5) could be overestimated. Another possible uncertainty source could be the climate scenarios. The use of AOGCM could result in significant biases in the precipitation and temperature predicted when used for regional studies, particularly in areas of complex topography and land use distribution like the Mediterranean basin (Christensen et al. 2007). However, in our study, as commented in the Methods section, the climate data used has been transformed with a regionalization technique (Brunet et al. 2008) by the Spanish Meteorology State Agency in order to better adjust the climate change scenarios to the physiographic conditions of the area studied. The third source of uncertainty was associated with the management scenarios. As suggested Lugato and Berti (2008), farmers would react to climate change in a dynamic way by adopting new management practices or by using new genetic material. In our simulation, management scenarios remained the same during the whole simulation period. This means that possible changes in fertilization, crop varieties or species, irrigation or event planting and harvest dates, were not contemplated in the study. However, we considered that maintaining the same management during the simulation period could help to better understand the interactions between climate and management, which was the purpose of this experiment. Another source of uncertainty could be related to the adjustment between measured and simulated baseline conditions. As discussed in a previous study

(Ávaro-Fuentes et al. 2009), during the experimental period (1989-2005) the Century model somewhat overestimated SOC gain in the BF-CT system. This fact could result in a slight bias of the final SOC value for all the management scenarios. However, this bias did not necessarily have an impact on the differences found in SOC among management and climate scenarios.

Because this study was only focused on one site, it is not necessarily representative of the entire region. Especially recently when new simulation tools and approaches are being created in order to simulate SOC stocks in regional/national scales (e.g. Milne et al. 2007; Tornquist et al. 2009). However, the main purpose of our study was to evaluate the effects of management on SOC dynamics under climate change in semiarid Mediterranean conditions. Therefore, an approach based on one specific site that was representative of the climate, historic management and soil characteristics could give us a better interpretation of the interaction between management and climate on SOC dynamics.

Conclusions

Our study investigated the role of management practices on SOC dynamics under climate change in a semiarid Mediterranean agroecosystem. The adoption of certain management practices could be essential in order to maximize SOC sequestration under climate change. In our study, differences on SOC sequestration were greater among management systems than among climate change scenarios. In general, cropping intensification and NT had greater SOC sequestration than cereal-fallow and CT, respectively. At the same time, rainfed systems compared to irrigated systems resulted in greater SOC gain and the removal of the straw resulted in SOC loss over time. The effect of precipitation and temperature change on SOC dynamics was different depending on the management system applied. Consequently, the relative response to climate and management depended on the net result of the influences on C inputs and decomposition. Under climate change, the adoption of certain management practices in semiarid Mediterranean agroecosystems could be critical in maximizing SOC sequestration and thus reducing CO_2 concentration in the atmosphere.

Acknowledgments

We would like to thank Mark Easter and Stephen Williams for helping and assistance on modeling. Jorge Álvaro-Fuentes was awarded with a Beatriu de Pinós Postdoctoral Fellowship by the Comissionat per a Universitats i Recerca del Departament d'Innovació, Universitats i Empresa, of the Generalitat de Catalunya.

REFERENCES

Ainsworth EA, Long SP (2005) What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. New Phytol 165:351-371.

Almagro M, Lopez J, Querejeta JI, Martinez-Mena M (2009) Temperature dependence of soil CO2 efflux is strongly modulated by seasonal patterns of moisture availability in a Mediterranean ecosystem. Soil Biol Biochem 41:594-605

Álvaro-Fuentes J, López MV, Arrúe JL, Moret D, Paustian K (2009) Tillage and cropping effects on soil organic carbon in Mediterranean semiarid agroecosystems: testing the Century model. Agr Ecosyst Environ 134:211-217

Álvaro-Fuentes J, López MV, Cantero-Martínez C, Arrúe JL (2008) Tillage effects on soil organic carbon fractions in Mediterranean dryland agroecosystems. Soil Sci Soc Am J 72:541-547

Austin RB, Cantero-Martínez C, Arrúe JL, Playán E, Cano-Marcellán P (1998) Yield-rainfall relationships in cereal cropping systems in the Ebro river valley of Spain. Eur J Agron 8:239-248

Brunet M, Casado MJ, de Castro M, Galán P, López JA, Martín JM, Pastor A, Petisco E, Ramos P, Ribalaygua J, Rodríguez E, Sanz I, Torres L (2008) Generación de escenarios regionalizados de cambio climático para España. Agencia Estatal de Meteorologia. Ministerio de Medio Ambiente, Medio Rural y Marino. Gobierno de España

Christensen JH, Carter TR, Rummukainen M, Amanatidis G (2007) Evaluating the performance and utility of regional climate models: the PRUDENCE project. Climatic Change 81:1-6

Conant R, Drijber RA, Haddix ML, Parton W, Paul EA, Plante A, Six J, Steinweg JM (2008) Sensitivity of organic matter decomposition to warming varies with its quality. Global Change Biol 14:868-877

Davidson EA, Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440:165-173

Friedlingstein P, Fung I, Holland E, John J, Brasseur G, Erickson D, Schimel D (1995) On the contribution of CO2 fertilization to the missing biospheric sink. Global Biogeochem Cycles 9:541-556

Gibelin AL, Déqué M (2003) Anthropogenic climate change over the Mediterranean region simulated by a global variable resolution model. Clim Dynam 20:327-339

Hernanz JL, Girón V, Cerisola C (1995) Long-term energy use and economic evaluation of three tillage systems for cereal and legume production in central Spain. Soil Till Res 35:183-198

Hernanz JL, Sanchez-Giron V, Navarrete L (2009) Soil carbon sequestration and stratification in a cereal/leguminous crop rotation with three tillage systems in semiarid conditions. Agr Ecosyst Environ 133:114-122

Kirschbaum MUF (1995) The temperature dependence of soil organic matter decomposition and the effect of global warming on soil organic carbon storage. Soil Biol Biochem 27:753–760

Kirschbaum MUF (2006) The temperature dependence of organic-matter decomposition - still a topic of debate. Soil Biol Biochem 38:2510-2518

Knorr W, Prentice IC, House JI, Holland EA (2005) Long-term sensitivity of soil carbon turnover to warming. Nature, 433:298-301

Linn DM, Doran JW (1984) Effect of water-filled pore-space on carbon-dioxide and nitrous-oxide production in tilled and nontilled soils. Soil Sci Soc Am J 48:1267-1272

Lobell D, Field C (2008) Estimation of the carbon dioxide (CO_2) fertilization effect using growth rate anomalies of CO_2 and crop yields since 1961. Global Change Biol 14:39-45

López, MV, Arrúe, JL (1997) Growth, yield and water use efficiency of winter barley in response to conservation tillage in a semi-arid region of Spain. Soil Till Res 44: 35-54

López-Fando C, Dorado J, Pardo MT (2007) Effects of zone-tillage in rotation with no-tillage on soil properties and crop yields in a semi-arid soil from central. Spain Soil Till Res 95:266-276

Lugato E, Berti A (2008) Potential carbon sequestration in a cultivated soil under different climate change scenarios: A modelling approach for evaluating promising management practices in north-east Italy. Agr Ecosyst Environ 128:97-103

McGuire AD, Melillo JM, Kicklighter DW, Joyce LA (1995) Equilibrium responses of soil carbon to climate change: Empirical and process-based estimates. J Biogeogr 22:785-796

Metherell AK, Harding LA, Cole CV, Parton WJ (1993) CENTURY Soil Organic Matter Model Environment Technical Documentation. Agroecosystem Version 4.0 Great

Plains System Research unit Technical Report No. 4. USDA-ARS, Fort Collins, Colorado. 245 p.

Milne E, Al Adamat R, Batjes NH, Bernoux M, Bhattacharyya T, Cerri C, Cerri C, Coleman K, Easter M, Falloon P, Feller C, Gicheru P, Kamoni P, Killian K, Pal DK, Paustian K, Powlson DS, Rawajfih Z, Sessay M, Williams S, Wokabi S (2007) National and sub-national assessments of soil organic carbon stocks and changes: The GEFSOC modelling system. Agr Ecosyst Environ 122:3-12

Mínguez M, Ruiz-Ramos M, Díaz-Ambrona C, Quemada M, Sau F (2007) First-order impacts on winter and summer crops assessed with various high-resolution climate models in the Iberian Peninsula. Clim Change 81:343-355

Moreno F, Pelegrín F, Fernández JE, Murillo JM (1997) Soil physical properties, water depletion and crop development under traditional and conservation tillage in southern Spain. Soil Till Res 41:25-42

Morgan JA, Pataki DE, Korner C, Clark H, Del Grosso SJ, Grunzweig JM, Knapp AK, Mosier AR, Newton PCD, Niklaus PA, Nippert JB, Nowak RS, Parton WJ, Polley HW, Shaw MR (2004) Water relations in grassland and desert ecosystems exposed to elevated atmospheric CO_2. Oecologia 140:11-25

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grubler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (2000) Special Report on Emissions Scenarios: A Special Report of Working Group III of the

Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Ogle SM, Breidt FJ, Easter M, Williams S, Paustian K (2007) An empirically based approach for estimating uncertainty associated with modelling carbon sequestration in soils. Ecol Model 205:453-463

Ojima DS, Parton WJ, Schimel DS, Scurlock JMO, Kittel TGF (1993) Modeling the effects of climatic and CO_2 changes on grassland storage of soil C. Water Air Soil Poll 70:643-657

Ordóñez Fernández R, González Fernández P, Giráldez Cervera JV, Perea Torres F (2007) Soil properties and crop yields after 21 years of direct drilling trials in Southern Spain. Soil Till Res 94:47-54

Parton WJ, Schimel DS, Cole CV, Ojima DS (1987) Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci Soc Am J 51:1173-1179

Parton WJ, Schimel DS, Ojima DS, Cole CV (1994) A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In: Bryant RB, Arnold RW (Eds.), Quantitative Modeling of Soil Forming Processes, SSSA Spec. Pub. 39. ASA, CSSA and SSSA, Madison, WI, p. 147-167

Paustian K, Elliott ET, Peterson GA, Killian K (1996) Modelling climate, CO2 and management impacts on soil carbon in semi-arid agroecosystems. Plant Soil 187:351-365

Paustian K, Levine E, Post WM, Ryzhova IM (1997) The use of models to integrate information and understanding of soil C at the regional scale. Geoderma 79:227-260

Rosenzweig C (1990) Crop response to climate change in the southern Great Plains: A simulation study. Prof Geogr 42:20-37

Skopp J, Jawson MD, Doran JW (1990) Steady-state aerobic microbial activity as a function of soil-water content. Soil Sci Soc Am J 54:1619-1625

Soil Survey Staff. 1975. Soil taxonomy, a basic system of soil classification for making and interpreting soil surveys. USDA-SCS Agric. Handbook 436. US Gov. Print. Office, Washington, DC, USA.

Stewart C, Paustian K, Conant R, Plante A, Six J (2007) Soil carbon saturation: concept, evidence and evaluation. Biogeochemistry 86:19-31

Stott DE, Elliott LF, Papendick RI, Campbell GS (1986) Slow-temperature or low water potential effects on the microbial decomposition of wheat residue. Soil Biol Biochem 18: 577-582

Tornquist CG, Giasson E, Mielniczuk J, Pellegrino Cerri CE, Bernoux M (2009) Soil organic carbon stocks of Rio Grande do Sul, Brazil. Soil Sci Soc Am J 73:975-982

Trumbore SE, Chadwick OA, Amundson R (1996) Rapid exchange between soil carbon and atmospheric carbon dioxide driven by temperature change. Science 272:393-396

Virto I, Imaz MJ, Enrique A, Hoogmoed W, Bescansa P (2007) Burning crop residues under no-till in semi-arid land, Northern Spain-effects on soil organic matter, aggregation, and earthworm populations. Aust J Soil Res 45:414-421

West T, Six J (2007) Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity. Clim Change 80:25-41

Wildung RE, Garland TR, Buschbom RL (1975) Interdependent effects of soil temperature and water-content on soil respiration rate and plant root decomposition in arid grassland soils. Soil Biol Biochem 7:373-378

Tables

Table 1. Summary of the management scenarios used for simulation during the 2010-2100 period.

Management scenarios	Description
BF-CT-SR	Barley-fallow system under conventional tillage and straw removal
BF-CT	Barley-fallow system under conventional tillage and straw incorporated into the soil
BF-NT	Barley-fallow system under no-tillage and straw left on soil surface
CB-CT	Continuous-barley system under conventional tillage and straw incorporated into the soil
CB-NT	Continuous-barley system under no-tillage and straw left on soil surface
CB-CT-IRRI	Continuous-barley system under conventional tillage and straw incorporated into the soil with irrigation
CB-NT-IRRI	Continuous-barley system under no-tillage and straw left on soil surface with irrigation

Table 2. Average total annual precipitation, maximum and minimum air temperature predicted by the different climate scenarios during the 2010-2100 period.

	Precipitation (mm yr^{-1})	Tmax (ºC)	Tmin (ºC)
Baseline	340	21.5	8.4
CGCM2-B2	300	20.9	8.9
CGCM2-A2	302	21.7	9.5
ECHAM4-B2	280	25.7	12.6
ECHAM4-A2	277	26.3	13.1

Table 3. Annualized grain yield, C input and SOC variation averaged across all climate scenarios during the 2010 to 2100 period for the management scenarios.

Management scenario	Grain yield (kg ha^{-1})	C inputs (g C m^{-2})	ΔSOC (g C m^{-2})	ΔSOC (%)
BF-CT-SR[b]	1458±257	54±4[a]	-459±64	-13
BF-CT	1778±307	215±4	437±148	13
BF-NT	1467±265	177±2	1485±166	42
CB-CT	1920±437	283±27	2749±209	79
CB-NT	1751±424	252±28	3827±337	109
CB-CT-IRRI	4000±193	356±13	2300±189	66
CB-NT-IRRI	3702±173	329±11	3179±243	91

[a] Average value ± standard deviation

[b] BF, barley-fallow rotation; CB, continuous barley system; CT, conventional tillage; IRRI, irrigation; NT, no-tillage; SR, straw removal

Figure captions

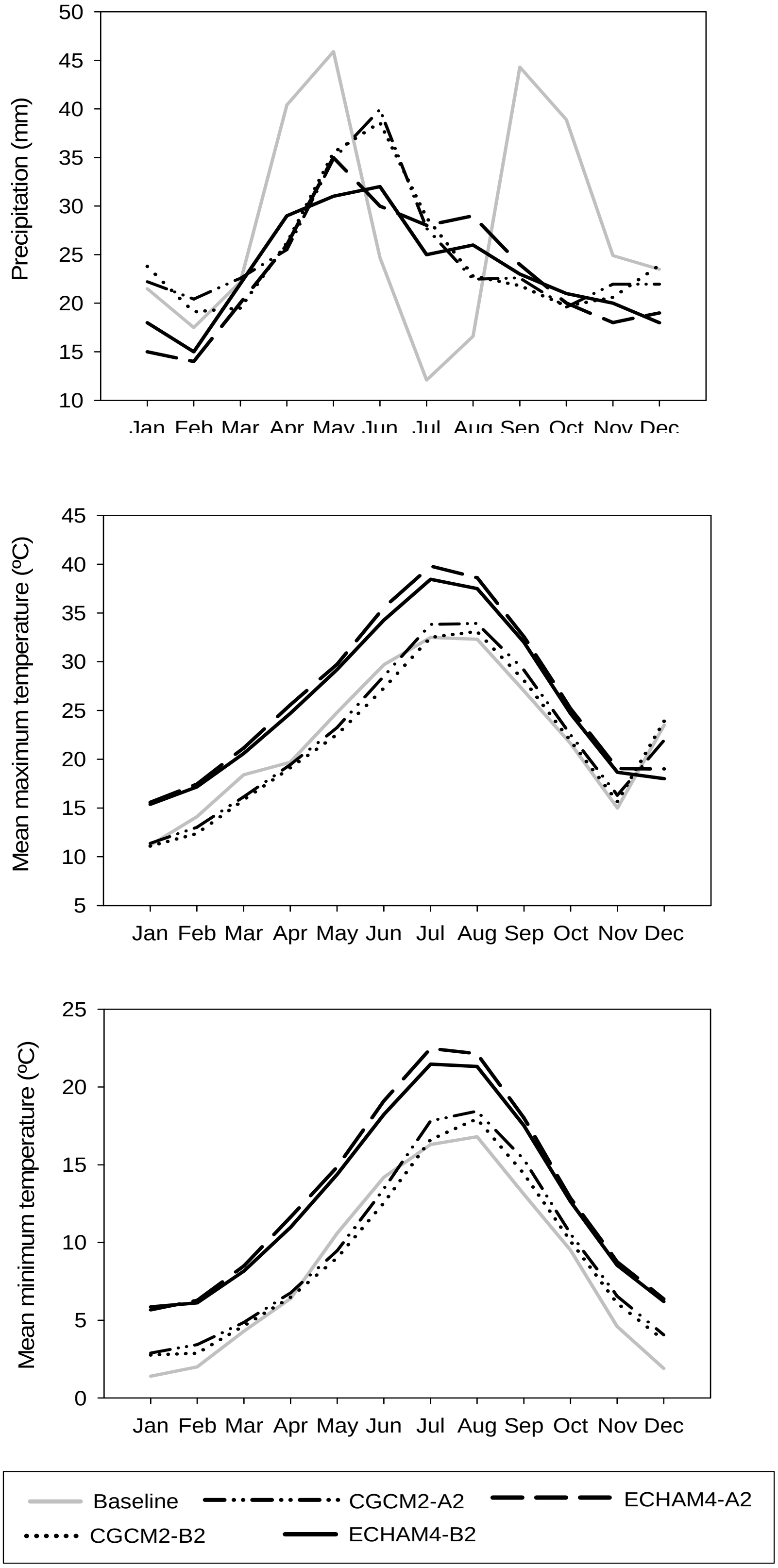
Fig.1. Precipitation, mean air maximum and minimum temperature distribution for the different climate scenarios (Baseline, CGCM2-A2, CGCM2-B2, ECHAM4-A2, ECHAM4-B2).

Fig. 2. Average C inputs and SOC change during the 2010-2100 period for the different climate scenarios (Baseline, CGCM2-A2, CGCM2-B2, ECHAM4-A2, ECHAM4-B2) and for the barley-fallow management scenarios (BF-CT-SR, Barley-fallow system under conventional tillage and straw removal; BF-CT, Barley-fallow system under conventional tillage and straw incorporated into the soil; BF-NT, Barley-fallow system under no-tillage and straw left on soil surface).

Fig. 3. Average C inputs and SOC change during the 2010-2100 period for the different climate scenarios (Baseline, CGCM2-A2, CGCM2-B2, ECHAM4-A2, ECHAM4-B2) and for the continuous barley under rainfed conditions scenarios (CB-CT, Continuous-barley system under conventional tillage and straw incorporated into the soil; CB-NT, Continuous-barley system under no-tillage and straw left on soil surface).

Fig. 4. Average C inputs and SOC change during the 2010-2100 period for the different climate scenarios (Baseline, CGCM2-A2, CGCM2-B2, ECHAM4-A2, ECHAM4-B2) and for the continuous barley under irrigated conditions scenarios (CB-CT-IRRI, Continuous-barley system under conventional tillage and straw incorporated into the soil with irrigation; CB-NT-IRRI, Continuous-barley system under no-tillage and straw left on soil surface with irrigation).

Fig. 5. Temporal SOC dynamics from 2010 to 2100 for the different management scenarios (BF-CT-SR, Barley-fallow system under conventional tillage and straw removal; BF-CT, Barley-fallow system under conventional tillage and straw incorporated into the soil; BF-NT, Barley-fallow system under no- tillage and straw left on soil surface; CB-CT, Continuous-barley system under conventional tillage and straw incorporated into the soil; CB-NT, Continuous-barley system under no-tillage and straw left on soil surface; CB-CT-IRRI, Continuous-barley system under conventional tillage and straw incorporated into the soil with irrigation; CB-NT-IRRI, Continuous-barley system under no-tillage and straw left on soil surface with irrigation) and for the CGCM2-B2 and ECHAM4-A2 climate scenarios.



Precipitation (mm)
10
15
20
25
30
35
40
45
50
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Mean maximum temperature (ºC)
5
10
15
20
25
30
35
40
45
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Mean minimum temperature (ºC)
0
5
10
15
20
25
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Baseline
CGCM2-A2
ECHAM4-A2
CGCM2-B2
ECHAM4-B2

Fig. 1

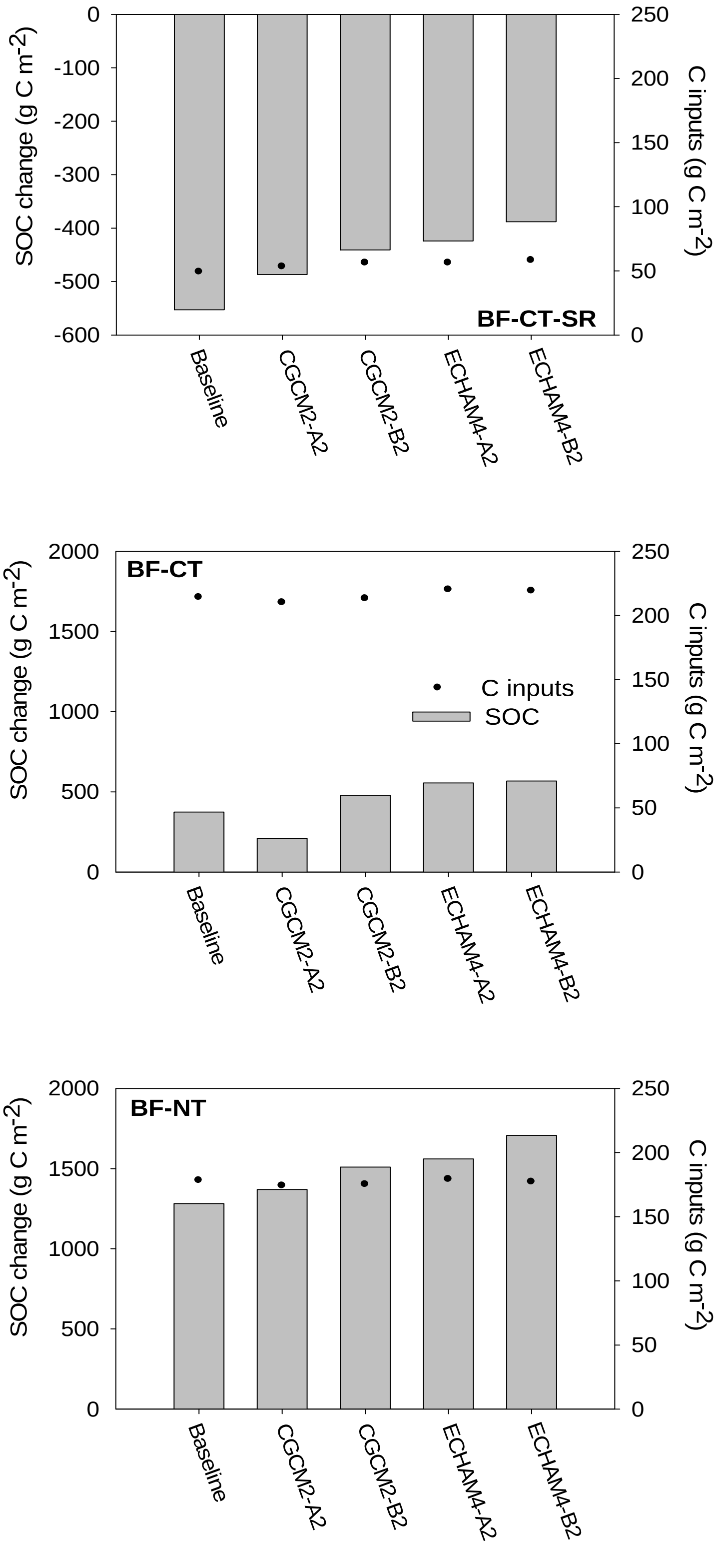

SOC change (g C m^{-2})
C inputs (g C m^{-2})
0
-100
-200
-300
-400
-500
-600
250
200
150
100
50
0
BF-CT-SR
Baseline
CGCM2-A2
CGCM2-B2
ECHAM4-A2
ECHAM4-B2
BF-CT
2000
1500
1000
500
C inputs
SOC
BF-NT

Fig. 2

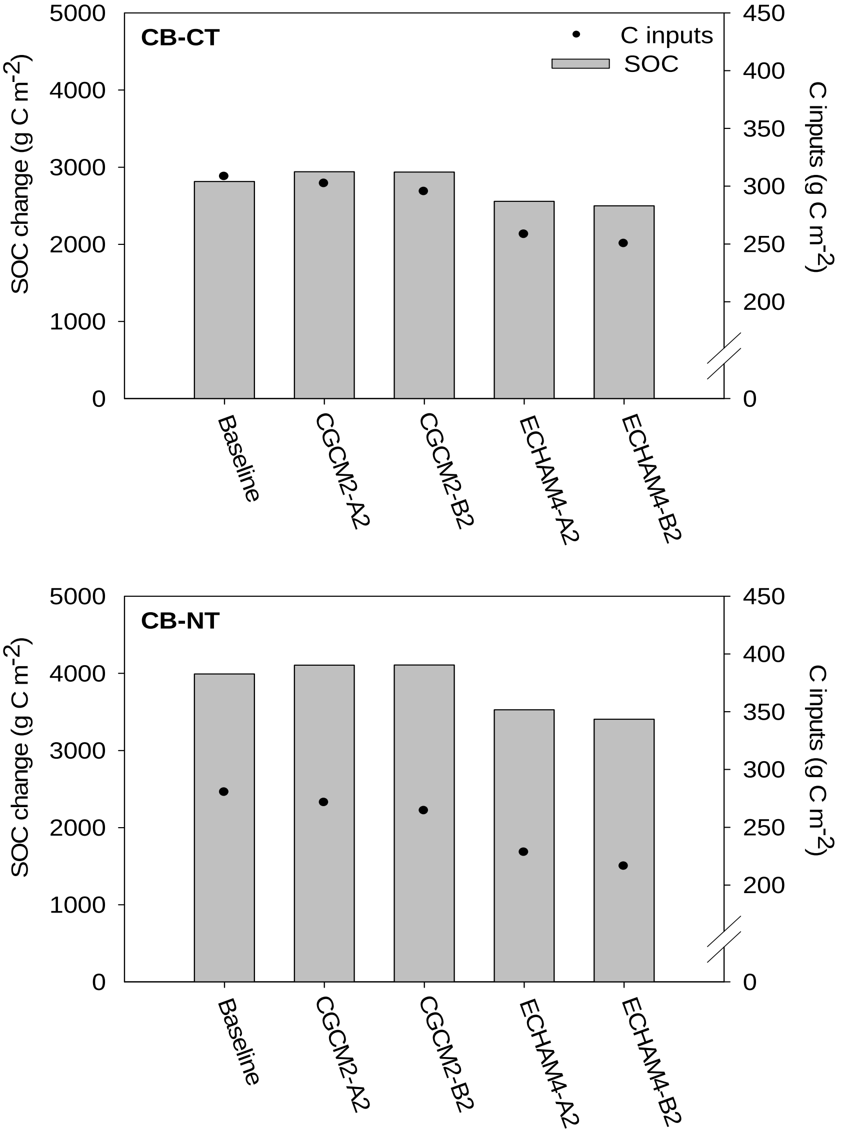

CB-CT
C inputs
SOC
SOC change (g C m^{-2})
C inputs (g C m^{-2})
0
1000
2000
3000
4000
5000
0
200
250
300
350
400
450
Baseline
CGCM2-A2
CGCM2-B2
ECHAM4-A2
ECHAM4-B2
CB-NT
SOC change (g C m^{-2})
C inputs (g C m^{-2})
0
1000
2000
3000
4000
5000
0
200
250
300
350
400
450
Baseline
CGCM2-A2
CGCM2-B2
ECHAM4-A2
ECHAM4-B2

Fig. 3

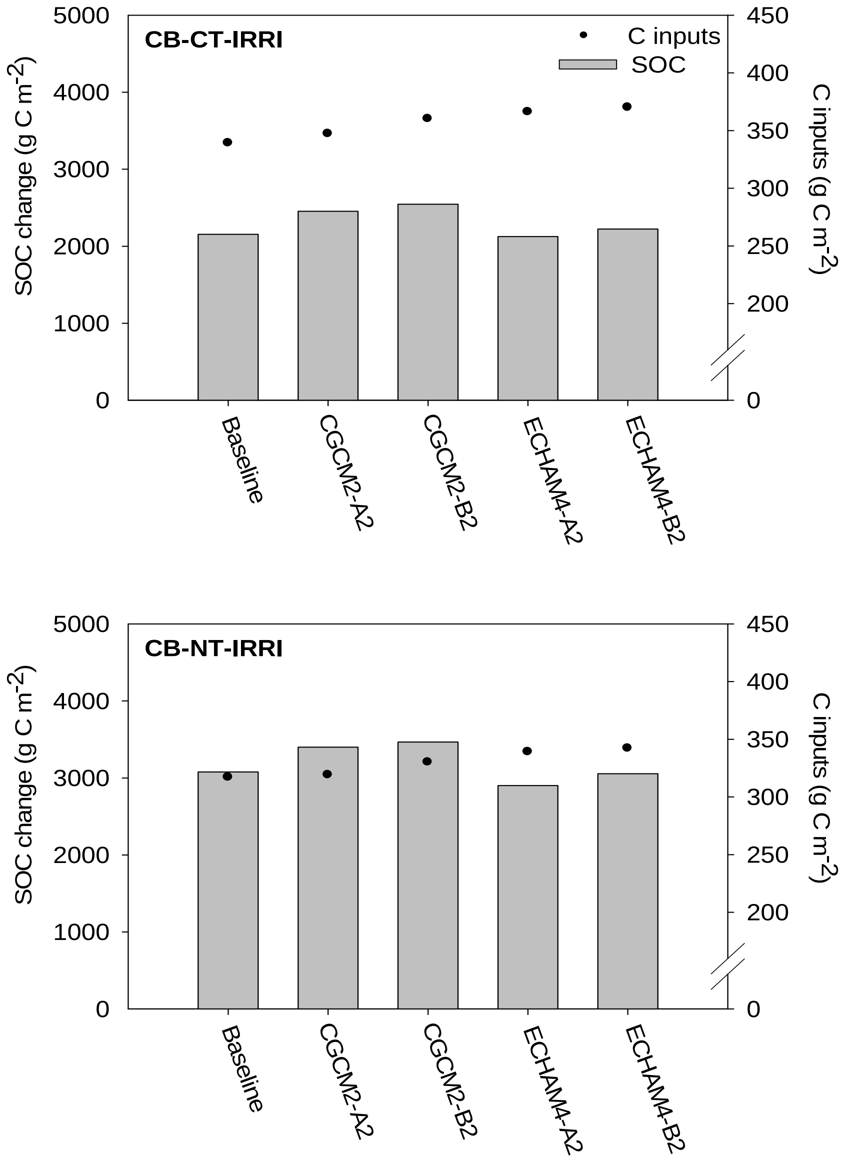

CB-CT-IRRI
C inputs
SOC
SOC change (g C m-2)
C inputs (g C m-2)
0
1000
2000
3000
4000
5000
0
200
250
300
350
400
450
Baseline
CGCM2-A2
CGCM2-B2
ECHAM4-A2
ECHAM4-B2
CB-NT-IRRI
SOC change (g C m-2)
C inputs (g C m-2)
0
1000
2000
3000
4000
5000
0
200
250
300
350
400
450
Baseline
CGCM2-A2
CGCM2-B2
ECHAM4-A2
ECHAM4-B2

Fig. 4

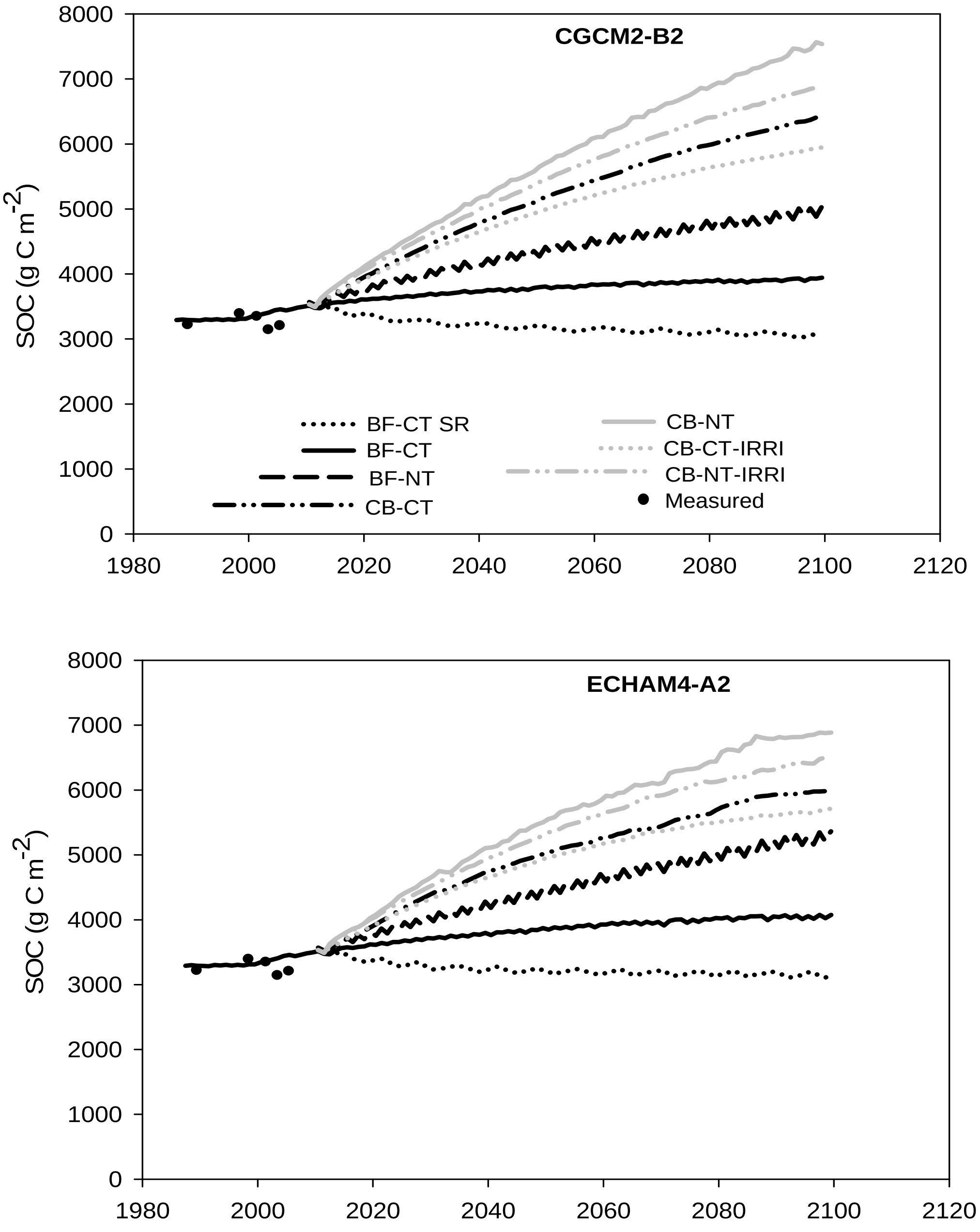

CGCM2-B2
SOC (g C m^{-2})
8000
7000
6000
5000
4000
3000
2000
1000
0
1980
2000
2020
2040
2060
2080
2100
2120
BF-CT SR
BF-CT
BF-NT
CB-CT
CB-NT
CB-CT-IRRI
CB-NT-IRRI
Measured
ECHAM4-A2
SOC (g C m^{-2})
8000
7000
6000
5000
4000
3000
2000
1000
0
1980
2000
2020
2040
2060
2080
2100
2120

Fig. 5