Modelling soil organic carbon stocks and their changes in the northeast of Spain

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Running title: Soil organic carbon in northeast Spain.

Summary

Currently, there is little information about soil organic carbon (SOC) stocks and changes in Mediterranean areas at a regional scale. We modelled 9.5 Mha in northeast Spain using the Global Environmental Facility Soil Organic Carbon (GEFSOC) system to predict SOC stocks and changes in pasture, forest and agricultural soils. The spatial distribution of the different land use categories and their change over time was obtained by using the Corine database and official Spanish statistics on land use from 1926 to 2007. The model predicted the largest current SOC stock in forest soils at 578 Tg C. Agricultural soils were the second largest SOC reservoir containing 244 Tg C. During the last 30 years, the model predicted a total SOC gain in the 0–30 cm soil layer of 34 Tg C. Forest and grassland-pastures soils had a decline in their stored SOC by 5 and 3 Tg C, respectively, because the reduction in the soil surface occupied by both classes. The greatest SOC gain was predicted in agricultural soils with 42 Tg C caused by changes in management which led to increases in C inputs. Although model uncertainty was not quantified, some hypothetical assumptions on the initialization and parameterization of the model could be made of potential sources of uncertainty. Our simulations predicted that in northeast Spain soil management has contributed to the sequestration of substantial amounts of atmospheric CO_2 sinks during the last 30 years. More research is needed in order to study the potential role of soils as atmospheric CO_2 sinks under different managements and climatic conditions.

Introduction

The Kyoto Protocol allows carbon (C) sinks to be selected in the categories of grazing, cropland and forest management (Smith, 2004). Thus, it is necessary to generate accurate estimates of soil organic carbon (SOC) stocks and changes for the major land-use and management conditions. However, because of the lack of reliable data, Spain has not yet reported agricultural soil carbon dioxide (CO_2) emissions in the annual National Inventory Report (NIR).

In Spain, several studies have reported SOC stocks and changes at a plot scale in agricultural (Álvaro-Fuentes *et al.*, 2008; Virto *et al.*, 2007; Nieto *et al.*, 2010), forest and grassland systems (Garcia-Pausas *et al.*, 2007). The potential for SOC sequestration varied according to the local climate, soil and management conditions where the experiment was set up. Álvaro-Fuentes *et al.* (2009) measured SOC sequestration rates greater than 0.45 Mg C ha^{-1} $year^{-1}$ under no-tillage (NT) in a rain-fed semiarid agro-ecosystem in Aragón. However, when studying the effects of olive plantation management on SOC sequestration in Andalucía, Nieto *et al.* (2010) reported gains of up to 0.6 Mg C ha^{-1} $year^{-1}$ in soil under a mulch of pruning residues. In summary, SOC sequestration caused by management and land-use change is viable in Spain, as reported in a number of plot scale studies carried out across the country.

Regional-scale approaches are needed in order to integrate the spatial variability of the variables that control soil organic matter dynamics (Paustian *et al.*, 1997). Some regional level methodologies have involved sampling large areas of territory over a given period of time to determine SOC stocks (Arrouays *et al.*, 2001). Also, SOC changes over large areas have been estimated by measuring SOC over different time periods (Goidts & van Wesemael, 2007) and by using dynamic process-based SOC models linked to spatial data through geographical information systems (GIS)

(Paustian *et al.*, 1997). The use of process-based SOC models takes account of the underlying process that determines SOC stocks and changes (Milne *et al.*, 2007). Recently, the Global Environmental Facility Soil Organic Carbon (GEFSOC) modelling system (Milne *et al.*, 2007) linked the Century ecosystem model (Parton *et al.*, 1988) to GIS layers to provide datasets that are spatially distributed as the model needs (Easter *et al.*, 2007). The GEFSOC system has been successfully applied in different regions of the world to estimate SOC stocks and change under different land-use and management conditions (Bhattacharyya *et al.*, 2007; Cerri *et al.*, 2007). However, the GEFSOC system has not yet been applied to European soils.

In Mediterranean areas, some studies have presented SOC values collected over large areas to determine the effects of climate, soil types and land use on SOC contents (Rodríguez-Murillo, 2001; Garcia-Pausas *et al.*, 2007). However, information on SOC changes at a regional/sub-national level has not been yet been reported. Moreover, in Spain, process-based SOC models have been only applied to the plot scale (e.g., Álvaro-Fuentes *et al.*, 2009; Nieto *et al.*, 2010).

Consequently, the aim of the present study was to predict soil C stocks and changes at a regional scale in Mediterranean conditions. For this purpose the GEFSOC modelling system was used to simulated SOC changes stocks and changes during the last 30 years in a characteristic Mediterranean area of 95 269 km^2 located in northeast Spain.

Materials and methods

Study area

The study area covers four Autonomous Communities (Aragón, Catalunya, La Rioja and Navarra) in the northeast of Spain, representing a total of 95 269 km^2 (Figure 1). The area is bounded in the north by the Pyrenees mountain range, in the south by the Iberian mountain range and in the east by the Mediterranean Sea. The western part of the area borders the Basque Country. The area extends to close to 450 km from west to east and 300 km from north to south (Figure 1). The Ebro River, the second longest river in the Iberian Peninsula divides the study area from west to east. The Ebro River basin encloses 85 362 km^2 most of which is located within our study area. The study area, as in the whole Spain, has a complex orography. More than 55% of the Iberian Peninsula is at an altitude above 600 m (Guereña *et al.* 2001). Consequently, the irregularity of the landscape leads to a large range of local climates. For instance, in the area close to the Pyrenees the annual precipitation can be greater than 2000 mm. However, in the middle of the Ebro River valley (the central part of the study area) annual precipitation is only 300 mm. Air temperatures also follow large gradients with mean annual temperatures varying from 3.3º C to 14.0º C (Ninyerola *et al.*, 2005).

The central area is a sedimentary basin formed from the eroded materials from the two mountain ranges (i.e., the Pyrenees in the north and the Iberian mountains in the south). The materials are mainly limestone which lead to the formation of loam, clay loam and silty clay loam soils. The main soil orders are: Aridisols, Inceptisols and Entisols (Arrúe, personal communication). Aridisols are located in the centre of the study area where the driest conditions occur. However, Inceptisols and Entisols can also be found randomly over almost the whole region (Cantero-Martínez, personal communication).

Forestry and agriculture are the two main land-use classes (Table 1). The forest surface occupies 50% of the total area (MARM, 2007a). Forests are both coniferous and broadleaf species. The major coniferous species pine (*Pinus nigra* L., *Pinus halepensis* L., *Pinus pinaster* L.), silver fir (*Abies alba* L.) and Spanish juniper (*Juniperus thurifera* L.) dominate. The main broadleaf species are oaks (e.g. *Quercus ilex* L., *Quercus robur* L., *Quercus faginea* L., *Quercus pyrenaica* L.), ash (*Fraxinus spp.*), chestnut (*Castanea sativa* L.), alder (*Alnus glutinosa* L.) and birch (*Betula spp.*) (MARM, 2007a). Agricultural land occupies 45% of the total surface (MARM, 2007b) (Table 1). Irrigated land comprising irrigated arable land (IRR), orchards (OR) and alfalfa (AF) cover almost 20% of the total agricultural area (Table 1) and are located in the centre of the study area where water is scarce. The major crops in dryland systems are cereals, grapes and olives and in irrigated systems corn, alfalfa and orchards (MARM, 2007b).

The GEFSOC Modelling system

The GEFSOC modelling system was extensively described by Easter *et al.* (2007). The system estimates SOC stock and SOC stock changes at a regional scale using different models (Milne *et al.,* 2007). In this study, we mainly used the Century general ecosystem model and, only for comparison purposes, we also used the Intergovernmental Panel on Climate Change (IPCC) method for assessing soil C at regional scales (IPCC, 2004). We previously parameterized and validated the Century model for Mediterranean conditions using data from long-term experiments located within the study area (Álvaro-Fuentes *et al.*, 2009). Originally, the Century model was parameterized to simulate SOC dynamics in the 0–20 cm depth. However, we modified the model to simulate SOC dynamics in the 0–30 cm soil depth in a similar way to Álvaro-Fuentes *et al*. (2009). Intensive tillage is still implemented to 25–30-cm depth in some areas of NE Spain (Álvaro-Fuentes *et al*., 2008). Therefore, in our experiment, modelling SOC turnover only up to 20-cm depth could have lead to mis-interpretation of the predicted results. .

Five geographic dataset layers of driving variables were provided to the modelling system, namely, native vegetation, climate, soils, land-use (historical and current) and latitude/longitude. The intersection of the five GIS dataset layers resulted in a table with all the specific attributes for each unique polygon. This table was incorporated into the model input database (Easter *et al.*, 2007).

Native vegetation

To initialize the proportion of SOC in the most recalcitrant pool (passive pool) an equilibrium period was simulated for 7000 years with a tree-grass system with a 40-year fire return interval. This simulation scheme was the same as that we previously used to validate the Century model under Mediterranean conditions (Álvaro-Fuentes *et al.*, 2009). Previous paleobotanic studies carried out in the area showed the coexistence of both coniferous and evergreen species with grasses (González-Samperiz *et al.*, 2008).

Climate

Monthly precipitation, mean monthly minimum air temperature and mean monthly maximum air temperature data were obtained from the Digital Climatic Atlas of the Iberian Peninsula produced by the Autonomous University of Barcelona (Ninyerola *et* *al.*, 2005). The Atlas consisted in raster layers with 200 m spatial resolution that provided unique climatic mean values for each month. Because of the high resolution of the dataset, we developed a procedure to reduce the number of climatic values to facilitate the intersection of the different GIS layers. For each unique polygon obtained from the intersection of the five GIS dataset layers, we calculated an average climate value. Consequently, we reduced the number of climate values to only one value per month for each polygon.

Soils

We created a Soil and Terrain (SOTER) database for our study area and the associated SOTER GIS coverage. Because there is a lack of soil information at a national scale in Spain, we used soil data such as texture, hydraulic status and bulk density from the European Soils Database (ESDB; Van Liederkerke *et al.*, 2006). The ESDB database with 1 km^2 spatial resolution presents soil properties as classes representing ranges. For example, soil texture is divided into five classes of coarse, medium, medium fine, fine and very fine. Consequently, for modelling purposes, classes were transformed to numerical data according to the specifications given in the ESDB database.

Historic and current land use

Current land use was obtained from the Corine Land Cover 2000 (CLC2000) map. The CLC2000 is a vector format layer with a minimal mapping unit of 25 ha. The forty-four original land-use classes in CLC2000 were re-classified into eleven new classes. This procedure allowed us to adapt the land use classes in CLC2000 to the classes described in the 2007 Statistical Yearbook (MARM, 2007b). We considered eight agricultural classes according to the major crops and management systems in the area, as well as one forest class, one grassland class (Table 2) and another termed ‘other’ which integrated the remaining CLC2000 classes not already included. This latter class is not included in Table 2. CLC2000 class 211 which corresponds to ‘Non-irrigated arable land’ was divided into four classes: continuous annual cropping under conventional tillage (MC-CT); continuous annual cropping under reduced tillage (MC-RT), continuous annual cropping under no-tillage (MC-NT) and cereal-fallow (CF) (Table 2). Moreover, CLC2000 classes 241, 242 and 243 were divided into several land-use classes according to their CLC2000 definition (Bossard *et al.*, 2000). For instance, the class 241 defined in CLC2000 as ‘Annual crops associated with permanent crops’ was divided into two tree crop classes: fruit tree orchards (OR) and vineyards-olives (GO) (Table 2). We also created a unique land use and management class for both forest and grassland. CLC2000 defined three forest classes (311, 312 and 313) that corresponded to broad-leaved, coniferous and mixed, respectively. In order to simplify the simulation process, we used a general forest class (FR) (Table 2). For modelling purposes, we simulated tree forest growth according only to coniferous forest parameters since in the study area the surface occupied by this type of forest almost double that of the broadleaf forest (1 700 000 ha for coniferous and 950 000 ha for broadleaf forests; MARM, 2007a).

In addition to the land-cover map, we also used official Spanish agricultural statistics to define the historic land use according to five periods: 1737-1936; 1937-1956; 1957-1976; 1977-1996 and 1997-2007. For each period, we collected the proportion of area for each land-use class and the management associated in each class. The proportion of area was obtained from both the database of the Ministry of the Environment and Rural and Marine Affairs of Spain (http://www.mapa.es/es/estadistica/infoestad.html), which publishes the Agriculture

Statistics Yearbook since the 1980s, and the Historical Statistical Yearbooks of Spain published since 1858 by the National Statistical Institute (http://www.ine.es/prodyser/pubweb/anuarios_mnu.htm).

Agricultural management practices for the different time periods were obtained from two main sources. The first was the interviews with both farmers and technical advisors from the area. Farmers from different provinces and with different farm types were interviewed to get information not only about the current management but also the past management by their ancestors. The second source was a literature review to compile information about historical management in the area. We found a number of studies about agricultural history in Spain (Bringas, 1998; Millet i Bel, 2001) and some for specific regions (López, 2004). Also, the Aragón Conservation Agriculture Association (Agracon) provided information about the surface under conservation agriculture in the study area. Agricultural surface under conservation tillage varies significantly among provinces (Table 3). Some farmers stated that they started to use conservation tillage in late 1980s. However, we decided to simulate conservation tillage only for 1997–2007 because the expansion of conservation tillage in the area occurred in the mid-late 1990s (Cantero-Martínez, personal communication).

Results and discussion

Model validation

In the study area, SOC stocks had only been reported in experiments conducted at the plot level (Virto *et al.*, 2007; Álvaro-Fuentes *et al.*, 2008). The only SOC inventory that exists at a regional scale is that by Rodríguez-Murillo (2001), which gives SOC stock estimates for the entire surface of Spain. As noted before, the Spanish inland territory is characterized by a complex orography with a large diversity of vegetation and microclimates (Guereña *et al.*, 2001). Thus, we did not consider it appropriate to use the study of Rodríguez-Murillo (2001) for the validation of our study which covers only 20% of the total surface area of Spain. Consequently, we compiled the studies located within the study area, which reported SOC stocks at a field-plot scale (Table 4). We could find the particular simulated SOC that matches each measured SOC value from the geographical coordinates given in each study. As shown in Table 4, measured and simulated SOC stocks were similar. It is of note that the model simulated the effects of tillage on SOC stocks reasonably well. As explained in Material and methods section, we used the Century model parameterization from a previous simulation of a long-term tillage trial located within the same study area (Álvaro-Fuentes *et al.*, 2009).

SOC stocks

Figure 2 shows the current SOC stock distribution in the northeast of Spain for the 0–30 cm soil layer obtained from the Century model. In 2007, the total SOC stock predicted in this layer was 920 Tg C (Table 5). These SOC stocks varied from 20 to 220 Mg C ha^{-1} and their distribution was in agreement with other information layers. For instance, the smallest SOC stocks were located in the central part of the study area, which is characterized by large evapotranspiration rates together with low precipitation and mostly occupied by rain-fed arable systems. In contrast, the model estimated the greatest SOC stocks in the north and south parts where the mountain ranges are located.

The predicted SOC stocks in 1977 and 2007 for the main land use classes are presented in Figure 3. The Century model predicted mean SOC stock values greater than 100 Mg C ha^{-1} in both years in the forest and grassland classes. Grassland and forest systems are known for their large SOC stocks (Guo & Gifford, 2002). The absence of soil disturbance together with significant belowground C inputs contributes to the storage of large amounts of C in both forest and grassland soils (Jobbágy & Jackson, 2000; Guo & Gifford, 2002). In northeast Spain, forests occupy almost half of the area simulated (Table 1). Consequently, this elevated SOC stock per unit area together with a large surface under forest resulted in a total SOC storage of 578 Tg C (63% of the total SOC stock). However, in spite of having the greatest SOC stock per unit area, the grassland-pastures soils stored only 98 Tg C just 11% of the total SOC stock (Table 5).

Initial cultivation resulted in large losses of SOC previously stored in native soils (Davidson & Ackerman, 1993). In our study, Century estimated mean SOC stocks in agricultural soils of nearly 60 Mg C ha^{-1} (Figure 3). Management practices that stimulated SOC losses such as export and burning of residues, low-input farming, long-fallowing and intensive tillage, were commonly practiced in the area over many decades (Millet i Biel, 2001). Currently a large part of the study area (30% of the total agricultural surface; Table 1) is still cultivated under the cereal- fallow (CF) system consisting of intensive tillage with mouldboard ploughing together with a long fallow period of 16–18 months (Álvaro-Fuentes *et al.*, 2008). The small C inputs in the CF system and the stimulation of SOC decomposition caused by tillage led to the smallest predicted SOC stock (Figure 4). However, because the CF system occupied most of the agricultural surface in both 1977 and 2007 (Table 1), soils under this system stored the greatest total amount of SOC (Table 5).

The Century model predicted the greatest SOC stocks in the GO, MC-NT and OR agricultural classes with values greater than 65 Mg C ha^{-1} (Figure 4). In some long-term experiments in the study area, adoption of no-tillage (NT) has successfully stored SOC (Virto *et al.*, 2007; Álvaro-Fuentes *et al.*, 2008). The positive effects of NT on SOC accumulation are explained by the absence of soil disturbance which results in both the modification of soil conditions reducing microbial activity and the accumulation of SOC because of a slower turnover (Peterson *et al.*, 1998). However, in our study area, some situations have been also reported in which NT did not increase SOC stocks (Álvaro-Fuentes *et al.*, 2008). Accumulation of SOC in deeper soil layers in the CT system may result in different effects depending on the total soil depth sampled (Angers & Eriksen-Hamel, 2008). Some studies recommend that soil sampling should extend deeper than 30 cm to fully account for differences between tillage systems (Baker *et al.*, 2007). The model was able to simulate SOC dynamics in the upper 30 cm but we were not able to consider possible differences in SOC stocks between tillage systems below this depth

Similarly, tree crops (fruit orchards, grapes and olives) are possible options to increase SOC through the adoption of cover crops (Nieto *et al.*, 2010). In a vineyard agro-ecosystem also located in northeast Spain, Peregrina *et al.* (2010) estimated SOC gains of up to 1.50 Mg C ha^{-1} year^{-1} in the 0–5 cm depth with cover crops compared with conventional tillage.

SOC change

The GEFSOC system allowed us to study the changes in SOC stocks during 1977–2007 and Figure 5 shows the SOC change rates for the main land-use classes modelled (forest, grasslands-pastures and agriculture). In this period, and for the whole study area, the Century model predicted a total SOC gain of 34 Tg C. However, in forest and grassland-pastures soils SOC declined by 5 and 3 Tg C, respectively (Table 5) because of the reduction in the soil surface occupied by these classes during this time (Table 1). Agricultural soils had the greatest SOC gain of 42 Tg C.

Furthermore, land-use change may result in significant changes on SOC stocks (Guo & Gifford, 2002). In our study, Century predicted a decrease in SOC stock when changing from either forest or grassland to tilled agricultural fields. In particular, changes from grasslands and forest to agricultural lands decreased SOC stocks by 37% and 30%, respectively (data not shown).

In the three main land-use classes, the model estimated SOC sequestration rates ranging from 0.10 to 0.30 Mg C ha^{-1} year^{-1} (Figure 5). The greatest SOC rate was predicted in the grasslands-pastures class followed by the agricultural class (Figure 5). Intensification of grasslands has been suggested as a viable option to increase SOC (Conant *et al*., 2001). Fertilization, improved grazing management, conversion from cultivation, sowing of legumes, earthworm introduction and irrigation have been identified as potential management practices to increase SOC (Conant *et al*., 2001). In our study, the Century model predicted a SOC increase rate of 0.30 Mg C ha^{-1} for the grassland-pasture class during the 1977–2007 period (Figure 5). Freibauer *et al.* (2004), reviewing viable potentials for C sequestration in European soils, highlighted the beneficial effects of grassland management on SOC sequestration. These authors estimated SOC sequestration rates in European grasslands of up to 0.50 Mg C ha^{-1} year^{-1} from improved management. During the latest 30 years, some studies in Spain have encouraged management improvement to increase grassland productivity (Ramírez Juidias, 2000). Nevertheless, despite having the greatest SOC increase rate, the model predicted losses of total SOC stored in grasslands-pastures soils because of the decrease in the area occupied by grassland from 1977 to 2007 (Table 1).

During this time, the agricultural soils of northeast Spain increased SOC at a rate of 0.27 Mg C ha^{-1} $year^{-1}$ (Figure 5). Figure 6 shows the rates of SOC change for the different agricultural classes. The Century model predicted an increase in SOC content in all eight classes. During the last five decades, the agricultural productivity in northeast Spain increased considerably. For instance, the grain yield of barley has shown a linear increase since 1960 (*http://www.mapa.es/es/estadistica/infoestad.html*). In 1977 the average barley grain yield in Spain was 1920 kg ha^{-1}, and in 2007 it had increased to 3410 kg ha^{-1}. The Century model also predicted an increase in crop productivity during the 1977–2007 period. Figure 7 shows the average estimated C inputs in 1977 and 2007 for the different agricultural classes. In all classes, larger C inputs were predicted for 2007 than for 1977 and, on average, in 2007 C inputs were more than two-fold greater than in 1977 (Figure 7). The greatest increases in C inputs were predicted for the IRR and the MC-NT classes (Figure 7). Similarly, the IRR and MC-NT classes had the greatest SOC increase among agricultural classes (Figure 6). Consequently, the increase in C inputs resulted in net SOC sequestration in the agricultural soils of northeast Spain. Other studies have also attributed recent SOC gains to enhanced agricultural production in others parts of the world, for example Liao *et al.* (2009) in China. In northeast Spain, changes in crop productivity could be attributed to many factors including improvement in crop growth potential, with the release of new varieties better adapted to drought (Royo *et al.*, 2008), and the increase in the amount of fertilizers applied as two major factors. Data compiled by the Ministry of the Environment and Rural and Marine Affairs of Spain (*http://www.mapa.es/es/estadistica/infoestad.html*) show that during the period 1997–2007 the amount of N fertilizer applied in the study area was almost double that applied during 1967–1977.

The Century model estimated the greatest SOC increase rate in the MC-NT class. However, the final contribution of MC-NT to the total SOC storage in whole area was not considerable large (Table 5) because the surface cultivated under no-tillage is small in comparison with conventional tillage (Table 1). Álvaro-Fuentes & Cantero-Martínez (2010) estimated that, hypothetically, the entire rain-fed area of Mediterranean Spain under no-tillage would offset 17% of the total CO_2 equivalent emissions generated from agricultural soils in Spain. Therefore, despite the potential of no-tillage for sequestering SOC, the area under this management is still small limiting the potential storage in these soils.

Comparison to other methods of the GEFSOC system

Total SOC stock estimation from both the Century model and the IPCC method is shown in Table 6. Both in 1977 and 2007, total SOC stock in the 0–30-cm layer predicted with the Century model was approximately 40% larger than that by the IPCC method. Nevertheless, both models showed the same SOC change trend with almost the same SOC change rate during this period (Table 6). Similarly, other SOC regional inventories with the GEFSOC system also predicted larger SOC stocks with the Century model than with the IPCC method (Cerri *et al*., 2007; Bhattacharyya *et al*., 2007). Cerri *et al*. (2007) simulating SOC changes in the Brazilian Amazon, predicted 18% larger SOC stocks to 20-cm depth with Century than with the IPCC method for 30-cm depth.

Sources of uncertainty

Results from simulation models are associated with imprecision and bias (model uncertainty; Ogle *et al.,* 2007). Uncertainty can be attributed to several sources including that from the model itself, the initialization of the SOC pools, and the lack of reliable input data. In our study, hypothetical assumptions on the initialization of the model could be potential sources of uncertainty. We initialized the most recalcitrant SOC pool (the passive pool) by simulating an equilibrium period of 7000 years with a tree-grass system with a 40-year fire return interval. This initialization was consistent with paleobotanical information reported in the literature (González-Samperiz *et al.*, 2008). Although this could represent the most of the area studied, local variations could exist leading to biases in the initial distribution of SOC pools. Likewise, to initialize more labile SOC fractions (the slow pool), we started the simulations from 1735. Because reliable data on land use in Spain were obtained from 1935, we assumed that land use and management did not change during the 200 years period prior to 1935. This assumption could result in another source of uncertainty because some slight changes in management and land use may have taken place over this period. Also, in order to simplify the simulations, forests were simulated as a general forest that included both coniferous and broadleaf species. This could be a further source of uncertainty since differences on SOC dynamics exist between broadleaf and coniferous forests (Rey & Jarvis, 2006). Similarly, we combined the pastures and natural grasslands (18 and 26 CLC2000 classes, respectively) in a single grassland class. According to the 2007 Statistical Yearbook (MARM, 2007b), the study area comprises different proportions of natural grasslands and pastures (85% and 15%, respectively). Furthermore, simulation of agricultural classes could also lead to uncertainty because it was impossible to model the entire combination of management, crops and cropping systems existing in the study area. Thus, N fertilizer rates and type, crop and tree type, tillage implementation, planting and harvest date, straw management, pruning type, cover crop management, manure applications and irrigation management were modelled according to the most common practices in each province within the study area.

Conclusions

The use of dynamic models linked to spatial databases may help to understand better the processes that control SOC dynamics at large scales. The present study represents the first estimation of SOC stocks and changes at a regional scale in Spain. The application of the Century model to an area of 95 269 km^2 in northeast Spain predicted that currently SOC is mostly stored in forest soils. The large SOC sequestration rate in forest soils together with the large area covered (almost 50% of the simulated area) resulted in this large SOC storage. Agricultural soils are the second largest SOC reservoir. Among the agricultural classes considered, the cereal-fallow class with the largest surface stored the largest total amount of SOC.

The Century model estimated SOC increases for the last 30 years for the whole study area. The forest and grassland-pastures soils declined in their SOC stored because of the decrease in the surface area occupied by both classes. Agricultural soils stored 42 Tg C due to changes in management. During the 1977–2007 period, the Century model predicted an increase in C inputs for all the agricultural classes resulting in SOC sequestration. The model predicted the largest SOC increase rate in the no-tillage (MC-NT) class. However, the final contribution of MC-NT to the total

SOC sequestration in the study area was not important because the area covered by no-tillage was small compared with other agricultural classes such as conventional tillage.

Results of this study should be taken with caution since some hypothetical assumptions on the initialization and parameterization of the model could be potential sources of uncertainty. Our simulations predicted that in northeast Spain soil management changes have contributed to the sequestration of large amounts of atmospheric CO_2 sinks during the latest 30 years. However, more research is needed in order to study the effects of management and climate on the potential role of soils as atmospheric CO_2 sink.

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Figure captions

Figure 1 Map of Spain with the simulated regions Barcelona, Girona, Huesca, La Rioja, Lleida, Navarra, Tarragona, Teruel and Zaragoza (in white).

Figure 2 Map of SOC stocks in 2007 estimated from the Century model for the 0–30 cm soil layer in northeast Spain.

Figure 3 Modelled SOC stock in the 0–30 cm soil layer in 1977 and 2007 for the main land use classes in northeast Spain.

Figure 4 Modelled SOC stock in the 0–30 cm soil layer in 1977 and 2007 for the different agricultural classes in northeast Spain (CF, cereal-fallow; MC-CT, rain-fed arable land under continuous annual cropping and conventional tillage; MC-RT, rain-fed arable land under continuous annual cropping and reduced tillage; MC-NT, rain-fed arable land under continuous annual cropping and no-tillage; GO, grape-olive; IRR, irrigated arable land; AF, alfalfa; OR, orchard).

Figure 5 Modelled SOC stock change rates in the 0–30 cm soil layer during the 1977–2007 period for the main land use classes in northeast Spain.

Figure 6 Modelled SOC stock change rates in the 0–30 cm soil layer during the 1977–2007 period for the different agricultural classes in northeast Spain (CF, cereal-fallow; MC-CT, rain-fed arable land under continuous annual cropping and conventional tillage; MC-RT, rain-fed arable land under continuous annual cropping and reduced tillage; MC-NT, rain-fed arable land under continuous annual cropping and no-tillage; GO, grape-olive; IRR, irrigated arable land; AF, alfalfa; OR, orchard).

Figure 7 Modelled C inputs in 1977 and 2007 for the different agricultural classes (CF, cereal-fallow; MC-CT, rain-fed arable land under continuous annual cropping and conventional tillage; MC-RT, rain-fed arable land under continuous annual cropping and reduced tillage; MC-NT, rain-fed arable land under continuous annual cropping and no-tillage; GO, grape-olive; IRR, irrigated arable land; AF, alfalfa; OR, orchard).

TABLES

Table 1. Surface occupied by each land use class in 1977 and 2007.

Land use	Surface in 1977 / km^2	Surface in 2007 / km^2
Forest	46285	44813
Grasslands-pastures	6182	5706
Agriculture	38766	40498
CF [a]	13537	11765
MC-CT	13867	5661
MC-RT	-	4805
MC-NT	-	5390
GO	5236	4524
IRR	4413	4253
AF	639	1757
OR	912	2343
Total	91233	91017

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

Table 2. Corine (CLC2000) land use classes and experimental land use and management classes.

CLC2000 code	CLC2000 label 3	Experiment code	Experiment label
211	Non-irrigated arable land	MC-CT	Rainfed arable land under continuous annual cropping and conventional tillage
		MC-RT	Rainfed arable land under continuous annual cropping and reduced tillage
		MC-NT	Rainfed arable land under continuous annual cropping and no-tillage
		CF	Cereal-fallow rotation
212	Permanently irrigated land	IRR	Irrigated arable land
		AF	Alfalfa
221	Vineyards	GO	Vineyards-olives
222	Fruit trees and berry plantations	OR	Orchards
223	Olive groves	GO	Vineyards-olives
231	Pastures	PS	Grassland-pastures
241	Annual crops associated with permanent crops	GO and OR	-
242	Complex cultivation pattern	GO, OR, PS, MC-CT, MC-RT, MC-NT and CF	-
243	Agricultural land with significant areas with natural vegetation	MC, OR, GO and CF	-
311	Broad-leaved forest	FR	Forest
312	Coniferous forest	FR	Forest
313	Mixed forest	FR	Forest
321	Natural grasslands	PS	Grassland-pastures

Table 3. Surface proportion occupied by different tillage systems (CT, conventional tillage; RT, reduced tillage; NT, no-tillage) in the provinces included in the simulated area during the period 1997-2007.

Province	CT	RT	NT
Huesca	0.88	0.02	0.10
Teruel	0.97	0.01	0.02
Zaragoza	0.88	0.04	0.08
Barcelona	0.40	0.35	0.25
Girona	0.75	0.20	0.05
Lleida	0.10	0.50	0.40
Tarragona	0.78	0.20	0.02
La Rioja	0.75	0.25	0.00
Navarra	0.30	0.40	0.30

Table 4. Measured and simulated SOC content in the 0-30 cm soil depth in different published experiments located within the study area.

Experiment	Location	Land use	Measured SOC / Mg C ha^{-1}	Simulated SOC / Mg C ha^{-1}
García-Pausas et al. (2007)[a]	Pyrenees	PS[b]	82-299	70-230
Blanco et al. (2009)	Navarra	FR	82	94
Álvaro-Fuentes et al. (2008)	Zaragoza	MC-CT	35	35
	Zaragoza	MC-RT	36	38
	Zaragoza	MC-NT	40	45
	Zaragoza	CF	32	36
	Lleida	MC-CT	37	40
	Lleida	MC-RT	39	42
	Lleida	MC-NT	41	44
Virto et al. (2007)	Navarra	MC-CT	46	50
	Navarra	MC-NT	49	55
Virto et al. (2006)[c]	Navarra	AF	36	38
	Navarra	IRR	42	46

[a] SOC from the entire soil profile.

[b] PS, grassland-pastures; FR, forest; MC-CT, rainfed arable land under continuous annual cropping and conventional tillage; MC-RT, rainfed arable land under continuous annual cropping and reduced tillage; MC-NT, rainfed arable land under continuous annual cropping and no-tillage; CF, cereal-fallow; AF, alfalfa; IRR, irrigated arable land.

[c] To calculate SOC stock, soil bulk density was estimated from the soil texture reported.

Table 5. Modelled total SOC stock in the 0-30 cm soil layer with the Century model in 1977 and 2007 for different land use classes.

Land use	Total SOC stock in 1977 / Tg C	Total SOC stock in 2007 / Tg C
Forest	583	578
Grasslands-pastures	101	98
Agriculture	202	244
CF [a]	69	65
MC-CT	70	32
MC-RT	-	29
MC-NT	-	36
GO	34	31
IRR	20	25
AF	4	11
OR	5	15

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

Table 6. Total SOC stock in the 0-30 cm soil layer in 1977 and 2007 for 9.1 Mha located in northeast Spain estimated with the Century model and the IPCC method.

Model	Total SOC stock in 1977 / Tg C	Total SOC stock in 2007 / Tg C	SOC change 1977-2007 / Tg C yr^{-1}
Century	886	920	1.13
IPCC	528	561	1.10

	Region	Surface / km^2
bcn	Barcelona	7728
grn	Girona	5910
hsc	Huesca	15636
lrj	La Rioja	5045
lld	Lleida	12172
nvr	Navarra	10391
trr	Tarragona	6303
trl	Teruel	14810
zgz	Zaragoza	17274

Fig. 1.

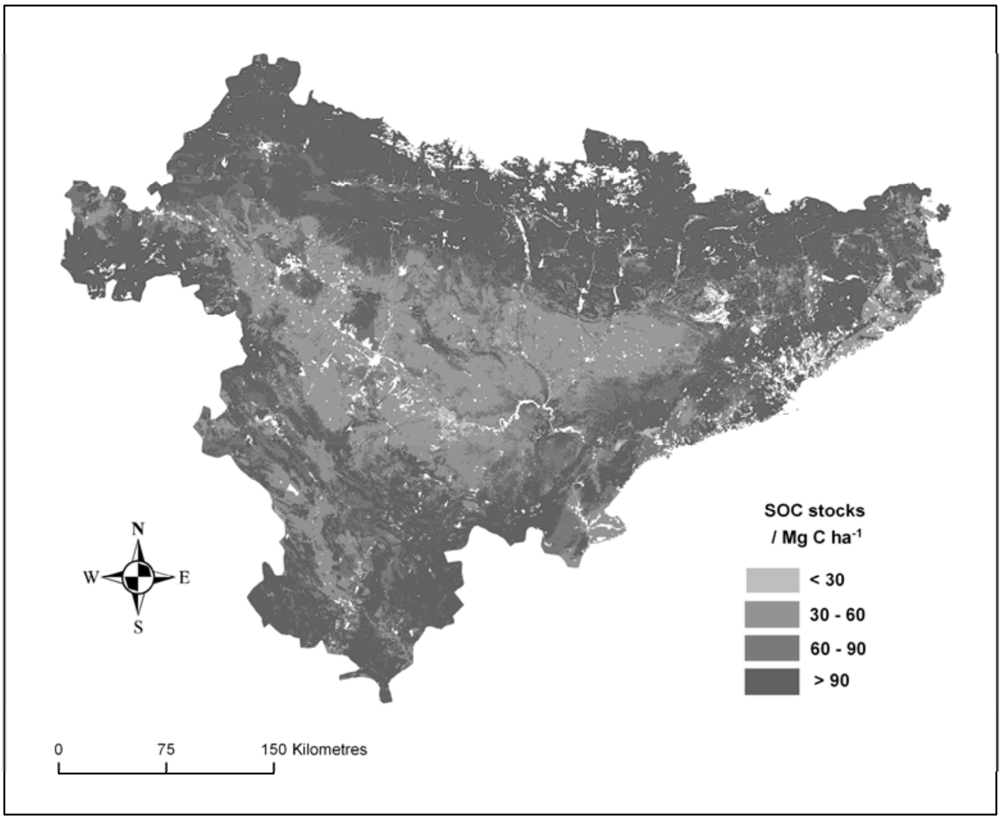


Fig. 2.

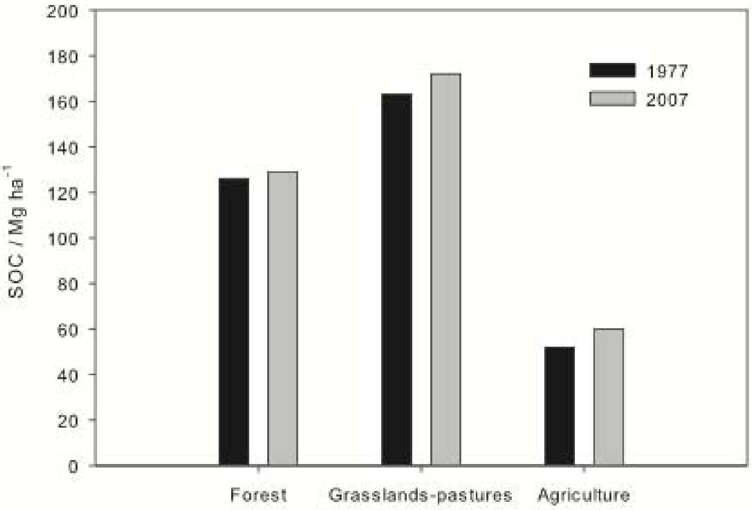

200
180
160
140
120
100
80
60
40
20
0
SOC / Mg ha^{-1}
1977
2007
Forest
Grasslands-pastures
Agriculture

Fig. 3.

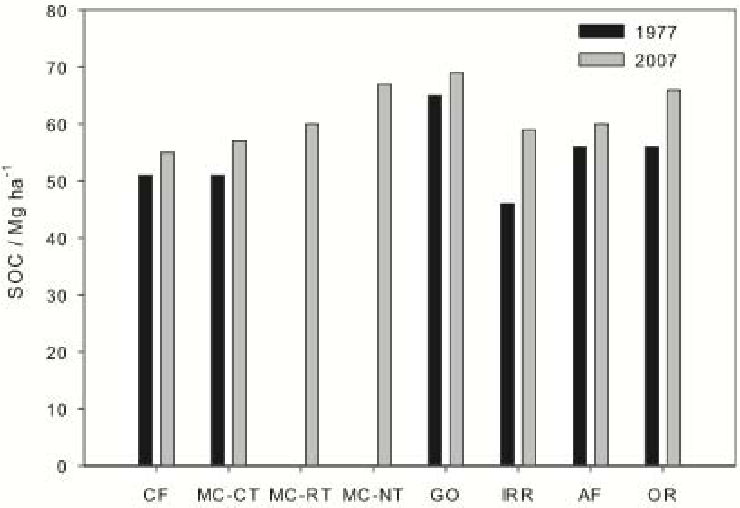

80
70
60
50
40
30
20
10
0
SOC / Mg ha^{-1}
1977
2007
CF
MC-CT
MC-RT
MC-NT
GO
IRR
AF
OR

Fig. 4.

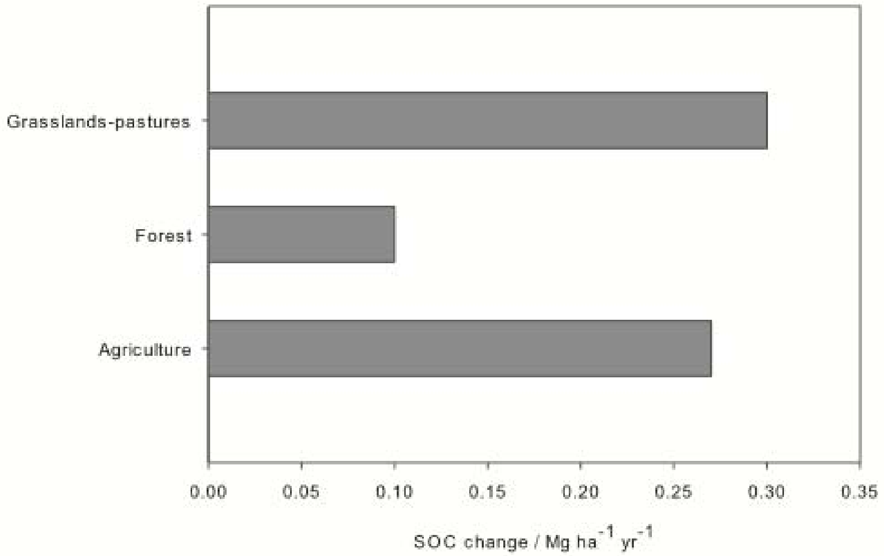
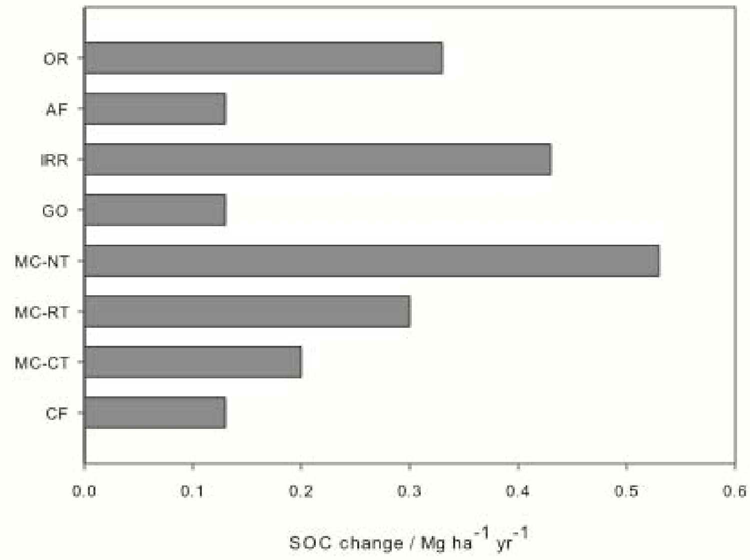

Grasslands-pastures
Forest
Agriculture
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
SOC change / Mg ha^{-1} yr^{-1}

Fig. 5


OR
AF
IRR
GO
MC-NT
MC-RT
MC-CT
CF
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0.1
0.2
0.3
0.4
0.5
0.6
SOC change / Mg ha^{-1} yr^{-1}

Fig. 6.

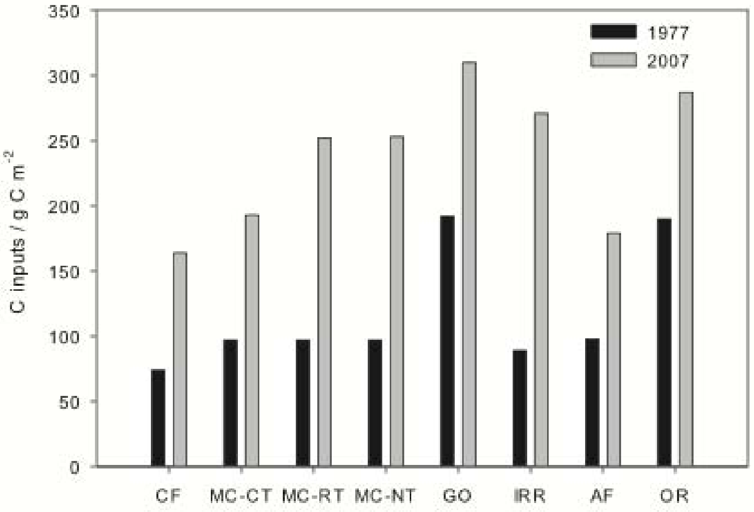
C inputs / g C m^{-2}
350
300
250
200
150
100
50
0
1977
2007
CF
MC-CT
MC-RT
MC-NT
GO
IRR
AF
OR

Fig. 7.