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Review

Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture

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ABSTRACT

Conservation agriculture (CA) helps to mitigate climate change. Firstly, the modifications introduced by CA on the carbon dynamics in the soil directly result in an increase of the carbon (C) in the soil fraction. Secondly, CA drastically reduces C oxidation processes by diminishing the mechanical manipulation of the soil.

Spain's position in relation to the Kyoto Protocol must be improved, as is one of the European countries in a non-compliance situation. With the aim of providing knowledge about the potential of CA as C sink in Spain, 29 articles on this subject were reviewed. According to 2010 CA uptake, the results demonstrated that conservation practices have the potential to promote the fixation in soil of about 2 Gg year^{-1} more C than traditional tillage (TT) systems. As indicated by Tebrügge (2001), 3.7 Mg of CO_2 are generated from 1 Mg of C through microbial oxidation processes taking place in the ground, meaning that through CA almost 7.5 Gg of CO_2 could be sequestered from the atmosphere every year until the equilibrium is reached.

C fixation was found to be irregular over time. C fixation rates were high in newly implemented systems during the first 10 years, reaching top values of 0.85 Mg ha^{-1} year^{-1} for no-tillage (NT) and 1.54 Mg ha^{-1} year^{-1} for cover crops (CC) implemented in-between perennial tree rows. After those first 10 years, it followed a period of lower but steady growth until equilibrium was reached. Nevertheless, C decreases of 0.16 Mg ha^{-1} year^{-1} in the first 10 years may be expected when practicing minimum tillage (MT). C sequestration rate resulted higher in case farmers do crop rotations in NT and MT rather than monoculture. In woody crops, studies reported higher C fixation values for native species when compared to sowed CC. Also, climate conditions seem to affect C sequestration rate in Spain. Although in NT differences observed between maritime and continental climates are not pronounced, as approximately 25% of the values recorded in both climates are equal, in the case of MT about 75% of maritime climate values result higher than the continental situation.

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1. Introduction

The consequences of the effects of climate change resulting from the uncontrolled emission of greenhouse gases (GHGs) and additional pressure from the international scientific community has required most countries to adopt an international agreement to implement a series of commitments to be fulfilled by the cooperating countries. These commitments, included in the so-called ''Kyoto Protocol,'' establish a limit for the net GHG emissions based on the economic, scientific and technological development of each country (United Nations, 2011). Analysis of the major GHG types indicates that carbon dioxide (CO_2) is the dominant component in terms of absolute weight, generally above 80% overall. In a breakdown by activity sectors, in 2009 agriculture emitted 10.5% GHGs overall. The Kyoto Protocol provides several mechanisms to try to reduce GHGs, among them is the promotion of activities with a C sink effect as a solution to reduce CO_2 concentrations (West and Post, 2002).

The sink effect is any process that can fix atmospheric C. Agriculture and forestry are virtually the only activities that can achieve this effect through photosynthesis and the C incorporation into carbohydrates. Crops capture CO_2 from the atmosphere during photosynthesis by converting C forms associated with soil organic matter (SOM) for microbial decomposition processes (Johnson et al., 2007). Although agriculture is sometimes excluded from environmental regulations, its ability to offset the emissions of GHGs identifies some agricultural activities as key partner in climate policies (Claassen and Morehart, 2009).

Soil management is one of the best tools for climate change mitigation and adaptation (Lal et al., 2011). In fact, agricultural soils occupy about 35% of the global land surface (Betts et al., 2007). CA introduces important changes in the dynamics of soil C sequestration and promotes this process as well (Carbonell-Bojollo et al., 2011). Crop residues left on the soil surface and no mechanical soil disturbance reduce the rate of mulch decomposition and decrease the mineralization of SOM due to reduced air flow, resulting in a lower accessibility of microorganisms and increased soil C. Therefore, the reduction of tillage reduces and slows the decomposition of plant matter, which promotes the storage of CO_2 fixed in the plant as C and returned to the soil as plant debris. Thus, soils have the potential of storing CO_2, thereby helping to mitigate the emission of GHGs generated by other activities (Reeves, 1997). Generally, there are major differences in organic matter (OM) content between NT, CA best agri-environmental approach for arable land, and TT (Paustian et al., 1997). Hence, CA is an alternative that can help reduce GHGs, mainly due to that C-fixation in the soil through an increase of the OM (Nelson et al., 2009) and to the decrease in the intensity of tillage (FAO, 2011).

Spain, as a signatory of the Protocol, has committed to limiting the average annual net emissions of GHGs to a level of a 15% increase over the net emissions recorded in the base year (1990) during 2008–2012. Data presented at the Fifth National Communication of Spain to the UN Framework Convention on Climate Change, published in December 2009 by the Secretariat General for the Prevention of Pollution and Climate Change of the Ministry of Environment, Rural and Marine Affairs (MERMA), showed that the total emissions in 2007 were 53% over the base-year value. CA is recognized as a C sink by the MERMA and the Spanish Office for Climate Change. Indeed, reduced tillage intensity, increased arable hectares under CA, especially NT, and the use of CC were suggested for the establishment of the CO_2 absorption potential throughout Spanish territories.

Reduced tillage trials were started in Spain at the beginning of the eighties with the purpose of introducing simple conservation methods for soil, keeping a protective cover to mitigate erosion stresses, and to save water. Later, farmers detected the advantage of their reduced production costs (González-Sánchez et al., 2010) and several research groups conducted studies to evaluate the benefits of CA systems on the fixation of C.

As the Spanish National Plan for the Allocation of GHG Emissions Rights assumes that emissions may be reduced by 2% due to C sinks, the purpose of the present study is to provide knowledge with a solid scientific base on the potential of CA in Spain in addressing the task of reducing the concentration of CO_2 in the atmosphere through C sequestration by the review of the published works on this subject by different research groups in the Spanish Autonomous Communities of Andalusia, Aragon, Catalonia, Castille-La Mancha, Castille and Leon, Extremadura, Madrid and Navarra (Fig. 1).

2. Materials and methods

For this study, 29 research papers were reviewed, from 20 locations, covering 11 research group papers from various areas of Spain, as listed in Table 1. According to the literature review, the potential for C sequestration in a particular CA practice is not always equal and depends on several factors. Therefore, this study considered the following characteristics:

- Climate of the area;
- Soil type;
- Crop rotation in arable crops.

In many cases the initial values obtained were not directly comparable. Hence, certain simplifications were made in some variables to calculate a single coefficient for each CA practice. These simplifications are described below.

Fig. 1. Map of Spain. Stars represent areas where the studies were carried out.

Table 1
List of locations and soil management systems compared.

Region	Province	Location	Soil classification	Soil management system
Andalusia	Seville	Coria del Rio	Xerofluvent	MT vs. TT
	Seville	Carmona	Chromic Haploxerept	NT vs. TT MT vs. TT
	Cordoba	Castro del Rio	Calcic Haploxerept	CC vs. TT
	Cordoba	Obejo	Ruptic-Lhitic Xerorthent	CC vs. TT
	Cordoba	Nueva Carteya	Calcic Haploxerept	CC vs. TT
	Huelva	Chucena	Typic Haploxerept	CC vs. TT
	Seville	La Campana	Typic Calcexerept	CC vs. TT
	Jaen	Torredonjimeno	Calcic Haploxerept	CC vs. TT
	Jaen	Torredelcampo	Calcic Haploxerept	CC vs. TT
	Cordoba	Cordoba	Vertisol	CC vs. TT
	Jaen	Arquillos	Anthropic Xerortent	CC vs. TT
Extremadura	Caceres	Madrigalejo	Ultic Haploxeralf	NT vs. TT
Castille-La Mancha	Toledo	Santa Olalla	Calcic Haploxeralf	NT vs. TT MT vs. TT
Madrid	Madrid	Aranjuez	Vertic Haploxeralf	NT vs. TT MT vs. TT
	Madrid	Alcala de Henares	Calcic Haploxeralf	NT vs. TT MT vs. TT
Castille and Leon	Burgos	Torrepadierne	Typic Calcixerols	NT vs. TT MT vs. TT
Aragon	Zaragoza	Penaflor	Xerollic Calciorthid	NT vs. TT MT vs. TT
Catalonia	Lleida	Selvanera	Typic Xerofluvent	NT vs. TT MT vs. TT
	Lleida	Agramunt	Fluventic Xerocrept	NT vs. TT MT vs. TT
Navarra	Navarra	Olite	Calcic Haploxerept	NT vs. TT MT vs. TT

Classified according to Soil Taxonomy (Soil Survey Staff, 1999).
CC, cover crop; MT, minimum tillage; NT, no tillage; TT, traditional tillage.

2.1. Time variable

Several studies have suggested that the soil organic carbon (SOC) content increases rapidly during the first 10 years after the change from TT to CA. After this period, the increases slow until near zero growth in the OM content is reached, indicating soil equilibrium (Yang and Wander, 1999; Puget and Lal, 2005). Consequently, coefficients given for the calculation of the potential fixation of the atmospheric C refer to two time periods. One coefficient is valid for those techniques whose implementation period does not exceed 10 years, and an additional coefficient will apply to those whose implementation period exceeds 10 years.

2.2. Depth of study variable

The potential fixation values associated with each type of CA refer to the greatest depth at which the SOM study was performed, with depths ranging from 40 to 52 cm in the cases of NT and MT and 25 to 30 cm in the case of CC. There were also two CA implementation periods studied: less than 10 years and over 10 years.

2.3. Study area variable

The studies reviewed in this paper represent areas with different soil and climates, indicating that the C fixing potential for the same agricultural practices would vary considerably from one case to another, making it risky to assign the whole country a single rate of C sequestration. Thus, starting from the major climatic zones in Spain, we grouped the coefficient calculations into the following two areas based on the location of the soils studied in each work:

- Areas with a continental Mediterranean climate, including Extremadura, Castille-La Mancha, Castille and Leon, Navarra, Madrid, and Aragon.

  This kind of climate affects most of the Iberian Peninsula. The climate of these areas is characterized by significant differences in temperature between day and night and the different seasons of the year. It has two rainy seasons, in autumn and spring, with annual averages between 300 mm and 500 mm. There are very hot summers with high temperatures, and cold winters with frequent frosts. Summer temperatures have important variations between day and night, ranging from 30 °C to 40 °C in the day to 10 °C at night.
- Areas with a maritime Mediterranean climate, comprising Andalusia and Catalonia.

  The maritime area is characterized by mild winters, long dry summers and rainy autumns and springs. The average winter temperatures along the coast about 10–13 °C, while inland of Andalusia are a few degrees lower. In summer average temperatures are around 22–27 °C along the coast and often exceed 40 °C in the Andalusian inland. Average rains are between 400 and 600 mm.

2.4. How to calculate the C fixation coefficient

The analysis of the C sink effect of CA was performed through a literature review of existing research in Spain through the year 2009, in studying the effects various soil management systems have had on the OM content over different periods. These systems included NT and MT in arable crops and in woody crops the use of CC. To estimate the potential of CA for C sequestration, in each study, the increase of observed OM in the conservation management systems was evaluated in relation to TT. For each soil depth interval studied i, C increases are proposed in terms of quantities of C from the organic carbon (OC) in the soil, according to the following formulae:

$$\mathrm{OC}_i(\mathrm{kg/ha}) = \mathrm{OC}_i(\mathrm{kg_{OC}}/100\ \mathrm{kg_{soil}}) \times \rho_i(\mathrm{kg_{soil}}/\mathrm{m}^3) \times D_i(\mathrm{m}) \times 10^4\ \mathrm{m}^2/\mathrm{ha} \quad (1)$$

$$OC_i(Mg/ha) = 10^{-3}OC_i(kg/ha) \quad (2)$$

where ρ_i is the bulk soil density and D_i is the depth of the interval studied.

Total C content is determined for the studied total depth Dt, making the sum of the amounts obtained for each soil depth interval sampled, as follows:

$$OC_{Dt}TT(Mg/ha) = \sum_{1}^{n} OC_iTT \quad (3)$$

$$OC_{Dt}CA(Mg/ha) = \sum_{1}^{n} OC_iCA \quad (4)$$

where n is the total number of depth intervals studied in the experience being analyzed. This number of intervals varies from one study to another as each author decides the total depth to sample. Thus, in a determinate reviewed study j, the average annual increase in C stored in soils under CA compared to TT soil to the total studied depth D_{tj}, after Y_j years of experience is obtained as follows:

$$\Delta OC_{Dtj}(Mg/ha\,year) = \frac{(OC_{Dtj}CA(Mg/ha) - OC_{Dtj}TT(Mg/ha))}{Y_j} \quad (5)$$

where ΔOC_{Dtj} is the C annual fixation coefficient for the reviewed study j.

For each climatic zone there are two groups, on one side those works whose term of study is less than 10 years and on the other, those exceeding 10 years of experimentation. On this basis, for each climatic zone and duration of the study, a matrix associates increases in OC for the different total depths D_t of each study j reviewed. The calculation of the annual average C fixation rate, FC, comes from the weighted average of these increases, taking into account the maximum depth of study in each area and time period considered, as follows:

$$FC(Mg/ha\,year) = \frac{\sum_{j=1}^{j=S} \Delta OC_{Dtj} x (D_{tj}/D_{tmax})}{S} \quad (6)$$

where FC is the annual average C fixation coefficient. Dt_{max} is the Maximum total sampling depth of all studies corresponding to the climatic zone and time period considered. S is the total number of studies corresponding to the climatic zone and time period considered.

3. Results and discussion

In recent years, the OC pool in cultivated land and the practices that contribute to its increase have been widely studied because of the potential influence on the reduction of CO_2 (Schlesinger, 2000). Contents of SOC are influenced either directly or indirectly by human activities (Fantappiè et al., 2010; Farina et al., 2011; Hernanz Martos et al., 2009) but also in an important way, that storage volume is affected by soil variability of the farm, physic-chemical characteristics of soil and environmental conditions affecting the absorption and release of C.

Changes in land management systems directly affect soil C content (Guo and Gifford, 2002). A C cycle modeling study has shown that changes in soil management have a greater impact on the soil C content than predicted by climate change (Smith et al., 2005). The results presented by authors may be quite different depending on the area where is carried out the study, due to the importance of climate in the C cycle. Other factors that influence and may differentiate the results are the depth of the profile considered in the study and the crop rotations.

According to Paustian et al. (1997), the increasing in OM levels that result under CA depends on the soil management system and other factors that are involved, such as the soil climatic conditions (temperature and humidity), the biochemical composition of the organic material, the nutrient availability and the level of soil disturbance. There is great variability in the potential of these techniques to fix C; thus, there is no single value of C sequestration that applies to a particular CA practice. In addition, based on the observations reported in these research studies, the increases that occur are not constant over time: at the beginning of the experiment, the SOM growth rate is high and decreases over time to achieve an eventual equilibrated rate of zero growth.

The results of our study confirm those reported by other authors on the idea that the amount of C that can store a soil is not unlimited. Experiments have shown how the increases are higher just after a change in use or land management and decrease over time to approach a new steady state (Freibauer et al., 2004). From that moment it is said that the storage capacity of the soil is saturated (IPCC, 2000). In a long-term study in two olive farms with soils classified as Calcic Vertisol and Chromic Calcisol, Nieto et al. (2010) reported annual increases in C concentration of 25.3 Mg ha^{-1} and 23.6 Mg ha^{-1} respectively at 6 and 5 years of installation of a pruning cover. After that, decreases to 1 Mg ha^{-1} $year^{-1}$ are to be considered in a whole period of 26 years. Accordingly, those works in which are presented results of studies for a period of time exceeding 10 years, will be more representative of the evaluated area.

Another aspect to consider is the unequal distribution in the profile of the SOC for TT and CA. The overall view of all studies reviewed indicates that the C fixation data provided by those experiences which provides a greater volume of soil will be more reliable when making the comparison between different systems evaluated in the study. According Franzluebbers (2000), stratification of SOC calculated as the ratio of the concentration in the surface layer from a deeper, can be used as C fixation index to compare different soil management systems.

3.1. Coefficients of C fixation for NT

Tables 2 and 3 show the C increase for NT compared to TT, for different climatic zones. Articles reviewed demonstrate that NT stimulates soil C sequestration. Indeed, NT is the practice included in CA with a higher level of soil conservation for arable crops, where the absence of tillage favors C sequestration. In NT, the OC increase is evident in the surface soil layer. Ismail et al. (1994) reported significant changes in the upper 5 cm of the soil profile. In-depth effect of NT has not been observed in other studies, Rhoton (2000) constrained the positive effect of NT only in the top 2.5 cm layer. Ordóñez-Fernández et al. (2007), reported substantial differences in the OC content in the first 13 cm, with an increase of 23% in comparison to TT. The growing trend was maintained for a longer period than the 4 years observed by Rhoton et al. (2002), as SOC was still improving after 20 years. In the Andalusian countryside, after 21 years of trials, Ordóñez-Fernández et al. (2007) have reported an increase of 18 Mg ha^{-1} in the OC content under NT of a wheat (*Triticum aestivum* L. and *Triticum durum* Desf.), sunflower (*Helianthus annuus* L.) and legume plants, broad beans (*Vicia faba* L.), chickpea (*Cicer arietinum* L.), vetch (*Vicia sativa* L.), and pea (*Pisum sativum* L.) rotation, whereas TT did not result in any increase. However, the differences between the tillage systems disappeared with depth, showing more OC under TT beyond 25 cm. In an experiment in semi-arid conditions in Navarra, Bescansa et al. (2006) have reported a significantly higher OM content in the first 15 cm of soil under NT systems, compared to TT. López-Fando et al. (2007) have observed significant differences in the amount of C stored in the top 10 cm of untilled soils, compared with those traditionally managed, but there was no significant difference at greater depths. These results are similar to those reported by

Table 2
List of studies referred and C-fixation rates of no tillage for the continental Mediterranean climate zone.

Study	Study period (years)	Maximum soil depth sampled (cm)	Increase over traditional tillage C ($Mg\,ha^{-1}\,year^{-1}$)	Type of crop[a]
EX1 (Muñoz et al., 2005)	5	30	0.61	Monoculture of maize
EX2 (Muñoz et al., 2007)	5	30	0.71	Monoculture of maize
CM1 (Lacasta and Meco, 2005)	9	20	1.00	Monoculture of barley
CM2 (López-Fando and Almendros, 1995)	2	20	1.79	Monoculture of barley
CM3 (López-Fando and Pardo, 2001)	12	30	0.02	Monoculture of barley
CM2 (López-Fando and Almendros, 1995)	2	20	1.73	Barley-vetch
CM3 (López-Fando and Pardo, 2001)	12	30	0.10	Barley-vetch
CM2 (López-Fando and Almendros, 1995)	2	20	2.12	Barley-sunflower
CM3 (López-Fando and Pardo, 2001)	12	30	0.09	Barley-sunflower
CM4 (López-Fando et al., 2005, 2007)	10	30	0.40	Barley-pea
MA1 (AEAC.SV, 2006)	7	40	1.69	Wheat-maize
MA1 (AEAC.SV, 2006)	7	40	2.01	Fallow-barley-Legume
MA2 (Hernanz Martos et al., 2002)	11	40	0.16	Monoculture of Cereal
MA2 (Hernanz Martos et al., 2002)	11	40	0.21	Wheat-vetch
MA3 (Hernanz Martos et al., 2005)	19	40	0.36	Wheat-vetch
MA4 (Hernanz Martos et al., 2009)	20	40	0.41	Wheat-vetch
CL1 (De Benito and Sombrero, 2006)	10	30	0.24	Wheat-vetch
AR1 (Álvaro-Fuentes et al., 2004)	15	5	0.13	Monoculture of barley
AR1 (Álvaro-Fuentes et al., 2004)	15	5	0.12	Barley-vetch
NA1 (Bescansa et al., 2006)	12	30	0.56	Monoculture of barley
Mean			0.72	
SE mean ($p < 0.05$)			0.16	

EX, Extremadura; CM, Castille-La Mancha; MA, Madrid; CL, Castille and Leon; AR, Aragon; NA, Navarra.
[a] Scientific names: barley, *Hordeum vulgare* L.; maize, *Zea mays* L.; pea, *Pisum sativum* L.; sunflower, *Helianthus annuus L.;* vetch, *Vicia sativa* L.; wheat, *Triticum* L.

Aguilera et al. (1996) where authors evaluated the OC and bioactivity in an Andisol soils.

Martino (2001) has shown that the NT system is one of the main mechanisms by which C is sequestered in agriculture. However, the sequestration increases until it reaches a new equilibrium for the system used (20 or more years). Changes in soil management practices require time to detect variations in the soil organic carbon (SOC), adding some difficulties to evaluate short-term field experiments (Álvarez and Álvarez, 2000). Furthermore, the short-term (<10 years) effects of management on the SOC are complex and vary with soil conditions, such as the soil texture, climate, cropping system and kind of crop residue, as well as with the management system itself (Muñoz et al., 2007). NT practices generally increase the sequestration of C, but this increase might not be apparent for approximately 5–10 years (West and Post, 2002).

The quantity and quality of the mulch in the soil is a consequence of the alternation of the previous crops, because crop rotations produce a higher quality and quantity of dry matter than monoculture do (Copeland and Crookston, 1992). Table 2 demonstrates, in general, that higher soil fixation values are found in soils in which crops are rotated. These results are consistent with those reported by Martino (2001), who had observed over a 30-year study that the soil under a rotation of crops and pastures had between 15 and 20 Mg of C per ha more than under monoculture farming.

A statistical analysis of NT reviewed studies show that those with crop rotations obtained a C sequestration mean of 0.64 $Mg\,ha^{-1}\,year^{-1}$ ($p < 0.05$, SE mean = 0.17), while those under monoculture reached 0.54 $Mg\,ha^{-1}\,year^{-1}$ ($p < 0.05$, SE mean = 0.17). Therefore, C sequestration rate resulted about 19% higher in case farmers do crop rotation in NT rather than monoculture. Finally, if all C sequestration data is analyzed by climates, in the case of NT (Fig. 2) differences observed between two climates are not pronounced, as approximately 25% of the values recorded in both climates are equal. However, both the

Table 3
List of studies referred and C-fixation rates of no tillage for the maritime Mediterranean climate zone.

Study	Study period (years)	Maximum soil depth sampled (cm)	Increase over traditional tillage C ($Mg\,ha^{-1}\,year^{-1}$)	Type of crop[a]
AN6 (Ordóñez-Fernández et al., 1997)	11	52	0.96	Wheat-sunflower-Legume
AN7 (Ordóñez-Fernández et al., 2007)	19	52	0.47	Wheat-sunflower-Legume
CA1 (Álvaro-Fuentes et al., 2006)	18	5	0.16	Monoculture of barley
CA2 (Álvaro-Fuentes et al., 2007)	18	20	0.25	Monoculture of barley
CA1 (Álvaro-Fuentes et al., 2006)	18	5	0.11	Barley-fallow
CA2 (Álvaro-Fuentes et al., 2007)	18	20	0.15	Barley-fallow
CA1.1 (Álvaro-Fuentes et al., 2006)	15	5	0.08	Cereal-rape
CA2.1 (Álvaro-Fuentes et al., 2007)	15	20	0.05	Cereal-rape
CA1.2 (Álvaro-Fuentes et al., 2006)	15	5	0.25	Cereal-rape
CA2.2 (Álvaro-Fuentes et al., 2007)	15	20	0.38	Cereal-rape
Mean			0.29	
SE mean ($p < 0.05$)			0.09	

AN, Andalusia, CA1.1, Catalonia, Selvanera farm; CA1.2, Catalonia, Agramunt farm.
[a] Scientific names: barley, *Hordeum vulgare* L.; rape, *Brassica napus* L.; sunflower, *Helianthus annuus L.;* wheat, *Triticum* L.

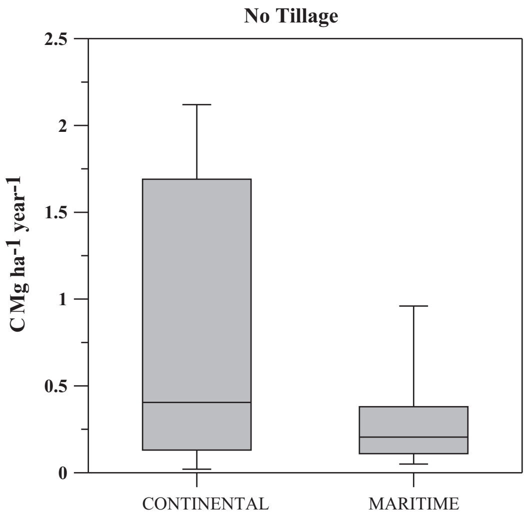

Fig. 2. C fixation in no tillage in maritime and continental Mediterranean climates.

median and the rest of the three headquarters are higher in the case of the maritime climate.

3.2. Coefficients of C sequestration for MT

In Tables 4 and 5, the regional coefficients of C sequestration are compared, from which are calculated the standard rates of C sequestration for the practice of MT. MT is an agronomic practice with a lower conservation effect than NT, that is why results in a lower increase in the C fixation. As shown in Table 4, compared to TT, the fixation rate is even negative in some cases.

In an experiment in the province of Seville, Moreno et al. (2006) have found a higher OC content in the first 10 cm of the soil under MT compared to a TT system. Higher fixation values were also evident in an 11-year study following the rotation of wheat-sunflower-legume where the controlled depth was 52 cm (Ordóñez-Fernández et al., 1997), whereas the worst case reported was an 11-year study on a wheat-corn rotation where the controlled depth was 40 cm (AEAC.SV, 2006) where tilled soils fixed a higher amount of C relative to those subjected to MT. In the case of MT is not very clear the influence of time, depth, and cultivation on the increase in C sequestration, compared to TT.

In the case of MT, C sequestration rate is higher in case farmers do crop rotation rather than monoculture. A statistical analysis of MT reviewed studies show that those with crop rotations obtained a C sequestration mean of 0.27 Mg ha^{-1} year^{-1} ($p < 0.05$, SE mean = 0.11), while those who carry out monoculture reached 0.04 Mg ha^{-1} year^{-1} ($p < 0.05$, SE mean = 0.16).

If all C sequestration data is analyzed by climates, in the case of MT (Fig. 3) differences observed between two climates are very pronounced. In the maritime climate almost all registered values are higher than 75% of the values that have occurred in the case of the continental climate and the value of its median is close to their maximum observed in the continental climate.

Table 4
List of studies referred and coefficients of C-fixation of minimum tillage for the continental Mediterranean climate zone.

Study	Study period (years)	Maximum soil depth sampled (cm)	Increase over traditional tillage C (Mg ha^{-1} year^{-1})	Type of crop[a]
CM4 (López-Fando et al., 2005, 2007)	10	30	−0.18	Barley-pea
MA1 (AEAC.SV, 2006)	7	40	−0.50	Wheat-maize
MA2 (Hernanz Martos et al., 2002)	11	40	−0.31	Monoculture of Cereal
MA2 (Hernanz Martos et al., 2002)	11	40	0.17	Wheat-vetch/pea
MA3 (Hernanz Martos et al., 2005)	19	40	−0.01	Wheat-vetch/pea
MA4 (Hernanz Martos et al., 2009)	20	40	0.02	Wheat-vetch/pea
CL1 (De Benito and Sombrero, 2006)	10	30	0.18	Wheat-vetch/pea
AR1 (Álvaro-Fuentes et al., 2004)	15	5	−0.01	Monoculture of barley
AR1 (Álvaro-Fuentes et al., 2004)	15	5	0.03	Barley-fallow
NA1 (Bescansa et al., 2006)	12	30	0.45	Monoculture of barley
Mean			−0.01	
SE mean ($p < 0.05$)			0.08	

CM, Castille-La Mancha; MA, Madrid; CL, Castille and Leon; AR, Aragon; NA, Navarra.
[a] Scientific names: barley, *Hordeum vulgare* L.; maize, *Zea mays* L.; pea, *Pisum sativum* L.; sunflower, *Helianthus annuus L.;* vetch, *Vicia sativa* L.; wheat, *Triticum* L.

Table 5
List of studies consulted and coefficients of C-fixation of minimum tillage for the Mediterranean climate zone.

Study	Study period (years)	Maximum soil depth sampled (cm)	Increase over traditional tillage C (Mg ha^{-1} year^{-1})	Type of crop[a]
AN1 (Murillo et al., 1998)	6	30	0.66	Wheat-sunflower
AN2 (Moreno et al., 2005)	11	25	0.60	Wheat-sunflower
AN3 (Moreno et al., 2006)	11	25	0.54	Wheat-sunflower
AN4 (Murillo et al., 2006)	13	25	0.27	Wheat-sunflower
AN5 (Madejón et al., 2007)	14	25	0.72	Wheat-sunflower
AN6 (Ordóñez-Fernández et al., 1997)	11	52	0.77	Wheat-sunflower-Legume
CA2 (Álvaro-Fuentes et al., 2007)	18	20	0.02	Monoculture of barley
CA2 (Álvaro-Fuentes et al., 2007)	18	20	0.08	Barley-fallow
CA2 (Álvaro-Fuentes et al., 2007)	15	20	0.22	Wheat-barley
Mean			0.43	
SE mean ($p < 0.05$)			0.10	

AN, Andalusia, CA, Catalonia.
[a] Scientific names: barley, *Hordeum vulgare* L.; sunflower, *Helianthus annuus L.;* wheat, *Triticum* L.

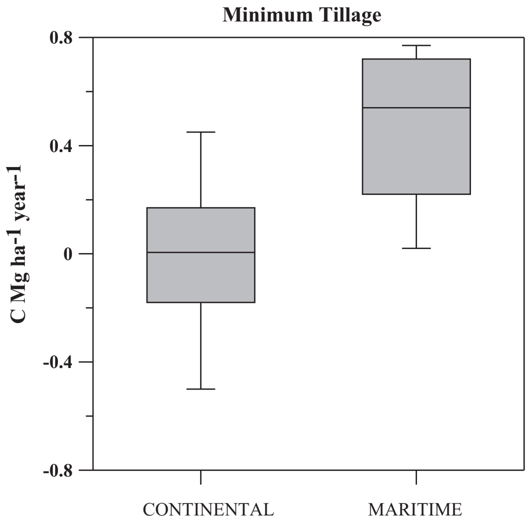

Fig. 3. C fixation in minimum tillage in maritime and continental Mediterranean climates.

3.3. Coefficients of C sequestration for CC

The benefits reported in the literature related to CC are very broad and include the reduction of surface water pollution (Rodríguez-Lizana et al., 2007), the improvement of the balance of water in the soil (Bowman and Bilbrough, 2001), the aid in the control of weeds (Hatcher and Melander, 2003), and the recycling of unused soil N (Weiner et al., 2002). However, C fixation rates are favored by not tilling the soil under CA with woody crops and the ability of CC to capture CO_2 and deliver C to the soil as during decomposition, when compared with TT. In Table 6, the coefficients of CO_2 are listed by region, from there were calculated the standard rates for the use of CC.

The C storage capacity of a soil depends on its characteristics and the weather, which is a reason for the high variability in the values for fixation in the various studies reviewed. However, more important than the sampling depth is the time to control the test CC that has given the major difference between management systems. Furthermore, CC using native grass generally gave higher rates of C fixation (Table 6). A statistical analysis of CC reviewed studies show that those with native species obtained a C sequestration mean of 1.78 Mg ha^{-1} year^{-1} ($p < 0.05$, SE mean = 0.52), while those with sowed species reached 1.16 Mg ha^{-1} year^{-1} ($p < 0.05$, SE mean = 0.50).

3.4. Average potential CO_2 fixation based on the soil surface under CA in Spain

An evaluation of the estimated coefficients was performed and represents the reduction of GHG emissions in Spain, taking into account the percentage of arable land occupied by crops under CA.

In this regard, the official data available in Spain for the case of NT and CC are presented in the Survey Areas and Crop Yields, from the MERMA (2009, 2010). In the case of MT, the estimates by the Spanish Association for Conservation Agriculture Living Soils

Table 6
List of studies cited and coefficients of C-fixation for cover crops.

Study	Study period (years)	Depth (cm)	Increase over traditional tillage C (Mg ha^{-1} year^{-1})	Location	Type of cover crop[a]
AN9 (Márquez et al., 2008)	4	25	0.41	Cordoba (Castro del Río)	Native species
AN9 (Márquez et al., 2008)	4	25	4.64	Cordoba (Nueva Carteya)	Native species
AN9 (Márquez et al., 2008)	4	25	3.11	Cordoba (Obejo)	Native species
AN10 (Gómez et al., 2004)	4	5	0.28	Cordoba	Barley
AN11 (Gómez et al., 2009)	4	10	0.35	Cordoba	Barley
AN9 (Márquez et al., 2008)	4	25	2.26	Jaen (Torredonjimeno)	Ryegrass
AN9 (Márquez et al., 2008)	4	25	1.75	Jaen (Torredelcampo)	Ryegrass
AN12 (Castro et al., 2008)	28	30	0.11	Jaen (Arquillos)	Native species (chemical mowing)
AN12 (Castro et al., 2008)	28	30	0.27	Jaen (Arquillos)	Native species (mechanical mowing, brush cutter)
AN12 (Castro et al., 2008)	28	30	0.69	Jaen (Arquillos)	Native species (mechanical mowing, brush cutter + cultivator)
AN9 (Márquez et al., 2008)	4	25	1.88	Sevilla (La Campana)	Native species
AN9 (Márquez et al., 2008)	4	25	1.79	Huelva (Chucena)	Native species
AN9 (Márquez et al., 2008)	4	25	3.08	Huelva (Chucena)	Native species
Mean			1.59		
SE mean ($p < 0.05$)			0.39		

AN, Andalusia.
[a] Scientific names: barley, *Hordeum vulgare* L.; ryegrass, *Lolium* L.; wheat, *Triticum* L.

Table 7
Area under conservation agriculture in Spain.

	Woody crops (2010)	%	Woody crops (2009)	%
Total (ha)	4,986,046	100	5,043,896	100
CC (ha)	1,218,726	24.4	1,066,182	21.1
	Arable crops (2010)	**%**	**Arable crops (2009)**	**%**
Total (ha)	7,182,050	100	7,341,709	100
NT (ha)	428,638	6.0	274,528	3.7
MT (ha)	1,500,000	20.9	1,200,000	16.3

Table 8
Area cultivated in Spain under conservation agriculture (2010) and potential C fixation over traditional tillage.

Agricultural practice	C coefficient of fixation (Mg ha^{-1} $year^{-1}$)	Period	Area (ha)	Fixation potential of C (Mg $year^{-1}$)
NT	0.85	<10 years	378,638	321,842
	0.16–0.40	>10 years	50,000	8000–20,000
MT	−0.16	<10 years	800,000	−128,000
	0.03–0.30	>10 years	700,000	21,000–210,000
CC	1.54	<10 years	1,128,559	1,737,981
	0.35	>10 years	90,167	31,558
Total				1,992,381–2,193,381

(AEAC.SV, 2011) suggested an adoption by farmer figure for 2009 of 1.3 Mha and 1.5 Mha for 2010.

The MERMA data for NT and CC, together with the estimates by the AEAC.SV for the MT for the 2009 and 2010 seasons are presented in Table 7. Given these values of land use in Spain of crops under CA and the years of duration that the experiment was performed, the calculated potentials for C fixation in Spain are presented in Table 8. Based on the research conducted and the data of agricultural area in Spain dedicated to the CA, we conclude that around 2 Gg C would be fixed per year over TT, due to the soil C sink effect promoted by CA.

4. Conclusions

CA implementation would help Spain's Government to meet the targets set in the Kyoto Protocol. The potential for C fixation in CA systems is not constant over time. Thus, in newly implemented systems, fixation rates are high during the first 10 years or so, followed by a period of lower but steady growth to reach an equilibrated rate.

Due to the influence of climatic and soil characteristics on potential C fixation, it is not advisable to report the absolute mitigation of GHGs related to CA practices, therefore potential fixation must always be described relative to TT. NT for arable crops and CC for woody crops leads to increased C sequestration in any period. In contrast, MT in the short term may lead to a slight decrease in C, although in long-term experiences favors C sequestration.

The more homogeneous the climate area, total depth sampled and crop rotation followed, the more accurate the C fixation rate would be. Crop rotations presented higher values of C fixation coefficients than monocultures in arable crops. In woody crops, native cover crop species lead to higher values of C fixation coefficients than sowed species.

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References

Aguilera, S.M., Borie, G., Del Canto, P., Peirano, P., 1996. Contribución del sistema conservacionista cero labranza en los niveles de C, P y bioactividad de suelo Santa Bárbara. Agric. Téch. 56, 250–254.
Álvarez, C.R., Álvarez, R., 2000. Short-term effects of tillage systems on active soil microbial biomass. Biol. Fertil. Soil 31, 157–161.
Álvaro-Fuentes, J., López, M.V., Gracia, R., Arrúe, J.L., 2004. Effect of tillage on short-term CO_2 emissions from a loam soil in semiarid Aragon (NE Spain). In: Arrúe, J.L., Cantero-Martínez, C. (Eds.), Third Mediterranean Meeting on No Tillage, vol. 60. Options Mediterranées, pp. 51–54.
Álvaro-Fuentes, J., Cantero-Martínez, C., López, M.V., Arrúe, J.L., 2007. Soil carbon dioxide fluxes following tillage in semiarid Mediterranean agroecosystems. Soil Till. Res. 96, 331–341.
Álvaro-Fuentes, J., López, M.V., Cantero-Martínez, R., Gracia, R., Arrúe, J.L., 2006. No-tillage, soil organic matter and soil structure: relationships and implications. In: Arrúe, J.L., Cantero-Martínez, C. (Eds.), Third Mediterranean Meeting on No Tillage, vol. 69. Options Mediterranées, pp. 149–153.
Asociación Española Agricultura de Conservación/Suelos Vivos (AEAC.SV), 2006. Parcelas de Demostración de Técnicas de Agricultura de Conservación en la finca La Chimenea. Campaña 2006. Informe de seguimiento. AEAC.SV, Córdoba, Spain.
Asociación Española Agricultura de Conservación/Suelos Vivos (AEAC.SV), 2011. La agricultura de conservación en el mundo. http://www.agriculturadeconservacion.org/quienes-somos/la-ac-en-el-mundo.html, viewed 29 December 2011.
Bescansa, P., Imaz, M.J., Virto, I., Enrique, A., Hoogmoed, W.B., 2006. Soil water retention as affected by tillage and residue management in semiarid Spain. Soil Till. Res. 87, 19–27.
Betts, R.A., Falloon, P., Goldewijk, K.K., Ramankutty, N., 2007. Biogeophysical effects of land use on climate: model simulations of radioactive forcing and large-scale temperature change. Agric. For. Meteorol. 142, 216–233.
Bowman, W.D., Bilbrough, C.J., 2001. Influence of a pulsed nitrogen supply on growth and nitrogen uptake in alpine graminoids. Plant Soil. 233, 283–290.
Carbonell-Bojollo, R., González-Sánchez, E.J., Veroz-González, O., Ordóñez-Fernández, R., 2011. Soil management systems and short term CO_2 emissions in a clayey soil in southern Spain. Sci. Total Environ. 409, 2929–2935.
Castro, J., Fernández-Ondoño, E., Rodríguez, C., Lallena, A.M., Sierra, M., Aguilar, J., 2008. Effects of different olive-grove management systems on the organic carbon and nitrogen content of the soil in Jaén (Spain). Soil Till. Res. 98, 56–67.
Claassen, R., Morehart, M., 2009. Agricultural Land Tenure and Carbon offsets. Economic Brief-14. Department of Agriculture, Economic Research Service.
Copeland, P.J., Crookston, R.K., 1992. Crop sequence affects nutrient composition of corn and soybean grow under high fertility. Agron. J. 84, 503–509.
De Benito, A., Sombrero, A., 2006. Changes in soil chemical properties under three tillage systems in a long-term experiment. In: Arrúe, J.L., Cantero-Martínez, C. (Eds.), Third Mediterranean Meeting on No Tillage, vol. 69. Options Mediterranées, pp. 155–159.
Fantappiè, M., L'Abate, G., Costantini, E.A.C., 2010. Factors influencing soil organic carbon stock variations in Italy during the last three decades. In: Zdruli, P., Pagliai, M., Kapur, S., Cano, A.F. (Eds.), Land Degradation and Desertification: Assessment, Mitigation and Remediation. Springer, New York, pp. 435–466.
FAO, 2011. Conservation Agriculture Website. http://www.fao.org/ag/ca/1a.html, viewed 23 November 2011.
Farina, R., Seddaiu, G., Orsini, R., Steglich, E., Roggero, P.P., Francaviglia, R., 2011. Soil carbon dynamics and crop productivity as influenced by climate change in a rainfed cereal system under contrasting tillage using EPIC. Soil Till. Res. 112 (1), 36–46.
Franzluebbers, A.J., 2000. Soil organic matter stratification ratio as an indicator of soil quality. Soil Till. Res. 66, 95–106.
Freibauer, A., Rounsevell, M.D.A., Smith, P., Verhagen, J., 2004. Carbon sequestration in the agricultural soil of Europe. Geoderma 122, 1–23.
Gómez, J.A., Romero, P., Giráldez, J.V., Fereres, E., 2004. Experimental assessment of runoff and soil erosion in an olive grove on Vertic soil in southern Spain as affected by soil management. Soil Use Manage. 20, 426–431.
Gómez, J.A., Sobrinho, T.A., Giráldez, J.V., Fereres, E., 2009. Soil management effects on runoff, erosion and soil properties in an olive grove of southern Spain. Soil Till. Res. 102, 5–13.
González-Sánchez, E.J., Pérez-García, J.J., Gómez-Ariza, M., Márquez-García, F., Veroz-González, O., 2010. Sistemas agrarios sostenibles económicamente: el caso de la siembra directa. Vida Rural 312, 24–27.
Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biol. 8, 345–360.
Hatcher, P.E., Melander, B., 2003. Combining physical, cultural and biological methods: prospect for integrated non-chemical weed management strategies. Weed Res. 43, 303–322.
Hernanz Martos, J.L., López, R., Navarrete, V., Sánchez-Girón, V., 2002. Long-term effects of tillage systems and rotations on soil structural stability and organic carbon stratification in semiarid central Spain. Soil Till. Res. 66, 129–141.
Hernanz Martos, J.L., Sánchez-Girón, V., Navarrete Martínez, L., 2005. Evolución del carbono orgánico del suelo con tres sistemas de laboreo, Convencional, Mínimo y Siembra Directa, para una rotación cereal leguminosa en experimentos de larga duración (1985–2004). In: III Congreso Nacional de Agroingeniería: Libro de Resúmenes, Universidad de León, Secretariado de Publicaciones, León, Spain.
Hernanz Martos, J.L., Sánchez-Girón, V., Navarrete Martínez, L., 2009. Soil carbon sequestration and stratification in a cereal/leguminous crop rotation with three tillage systems in semiarid conditions. Agric. Ecosyst. Environ. 133, 114–122.
Intergovernment Panel of Climate Change (IPCC), 2000. Special Report of Land Use, Land-use Change and Forestry. Cambridge University press, Cambridge.

Ismail, I., Blevins, R.L., Frye, W.W., 1994. Long-term no-tillage effects on soil properties and continuous corn yields. Soil Sci. Soc. Am. J. 58, 193–198.
Johnson, J.M., Franzluebbers, A.J., Lachnicht-Weyers, S., Reicosky, D.C., 2007. Agricultural opportunities to mitigate greenhouse gas emissions. Environ. Pollut. 150, 107–124.
Lacasta, C., Meco, R., 2005. Efecto de la incorporación de la paja de cereal sobre la productividad de la cebada y sobre algunos parámetros químicos y bioquímicos del suelo. In: Congreso Internacional sobre Agricultura de Conservación: El reto de la agricultura, el medio ambiente, la energía y la nueva Política Agraria Común. Libro de Actas, AEAC.SV, ECAF, Diputación de Córdoba, Córdoba, Spain.
Lal, R., Delgado, J.A., Groffman, P.M., Millar, N., Dell, C., Rotz, A., 2011. Management to mitigate and adapt to climate change. J. Soil Water Conserv. 66 (4), 276–285.
López-Fando, C., Almendros, G., 1995. Interactive effects of tillage and crop rotations on yield and chemical properties of soils in semi-arid central Spain. Soil Till. Res. 36 (1–2), 45–57.
López-Fando, C., Pardo, M.T., 2001. The impact of tillage systems and crop rotations on carbon sequestration in a Calcic Luvisol of central Spain. In: García-Torres, L., Benites, J., Martínez-Vilela, A. (Eds.), 1st World Congress on Conservation Agriculture: Conservation Agriculture, a worldwide challenge, vol. II. FAO, ECAF, Córdoba, Spain, pp. 135–139.
López-Fando, C., Dorado, J., Pardo, M.T., 2005. Soil organic dynamics under no-tillage, zone tillage, minimum tillage and conventional tillage in a semiarid soil from central Spain. In: Congreso Internacional sobre Agricultura de Conservación: El reto de la agricultura, el medio ambiente, la energía y la nueva Política Agraria Común. Libro de Actas, AEAC.SV, ECAF, Diputación de Córdoba, Córdoba, Spain, pp. 47–451.
López-Fando, C., Dorado, J., Pardo, M.T., 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 (1–2), 266–276.
Madejón, E., Moreno, F., Murillo, J.M., Pelegrín, F., 2007. Soil biochemical response to long-term conservation tillage under semi-arid Mediterranean conditions. Soil Till. Res. 94, 346–352.
Márquez, F., Ordóñez-Fernández, R., Carbonell, R., Veroz, O., Sánchez, F., 2008. Contenido de materia orgánica en el perfil del suelo. In: Informe General 2003/2007 de Desarrollo de un Programa de Seguimiento para la Evaluación de la Aplicación de las medidas de fomento de Cubiertas Vegetales en Olivar de Andalucía. Asociación Española Agricultura de Conservación/Suelos Vivos, Córdoba, Spain.
Martino, D., 2001. Generación de créditos de carbono por cambios en el uso de la tierra. Revista Mercoopsur http://www.mercoopsur.com.ar/agropecuarias/notas/generaciondecreditos.htm, viewed 1 July 2011.
Ministry of Environment and Rural and Marine Affairs (MERMA), 2009. Encuesta Nacional de Superficies y Rendimientos. http://www.mapa.es/estadistica/pags/encuestacultivos/EstudioMantenimientoSuelo2009.pdf, viewed 1 July 2011.
Ministry of Environment and Rural and Marine Affairs (MERMA), 2010. Encuesta Nacional de Superficies y Rendimientos. Análisis de las técnicas de mantenimiento del suelo y métodos de siembra en España 2010. http://www.marm.es/es/estadistica/temas/encuesta-sobre-superficies-y-rendimientos-de-cultivos-esyrce-/EstudioMantenimientoSuelo2010_tcm7-147011.pdf, viewed 4 July 2011.
Moreno, F., Murillo, J.M., Madejón, E., Pelegrín, F., Girón, I.F., 2005. Mejoras agrícolas derivadas del laboreo reducido bajo condiciones semi-áridas, vol. 1. AC Agricultura de Conservación, pp. 18–21.
Moreno, F., Murillo, J.M., Girón, I.F., Pelegrín, F., 2006. Long-term impact of conservation tillage on stratification ratio of soil organic carbon and loss of total and active $CaCO_3$. Soil Till. Res. 85, 86–93.
Muñoz, A., Lopez-Piñeiro, A., García, A., Rato, J.M., Barreto, C., 2005. Short and long-term effect of direct sowing on aggregate stability, compaction and organic matter in semi-arid Mediterranean soils. In: Proceedings International Congress on Conservation Agriculture: The Challenge of Agriculture, Environment, Energy and the new CAP, AEAC.SV, ECAF, Diputación de Córdoba. Córdoba, Spain, pp. 531–535.
Muñoz, A., López-Piñeiro, A., Ramírez, M., 2007. Soil quality attributes of conservation management regimes in a semi-arid region of south western Spain. Soil Till. Res. 95, 255–265.
Murillo, J.M., Moreno, F., Pelegrín, F., Fernández, J.E., 1998. Responses of sunflower to traditional and conservation tillage under rainfed conditions in southern Spain. Soil Till. Res. 49, 233–241.
Murillo, J.M., Moreno, F., Madejón, E., Girón, I.F., Pelegrín, F., 2006. Improving soil surface properties: a driving forcé for conservation tillage under semi-arid conditions, Span. J. Agric. Res. 4, 97–104.
Nieto, O.M., Castro, J., Fernández, E., Smith, P., 2010. Simulation of soil organic carbon stock in a Mediterranean olive grove under different soil-management systems using the RothC model. Soil Use Manage. 26, 118–125.
Nelson, R.G., Hellwinckel, C.M., Brandt, C.C., West, T.O., Ugarte De La, T., Marland, G., 2009. Energy uses and carbon dioxide emissions from cropland production in the United States, 1990–2004. J. Environ. Qual. 38, 418–425.
Ordóñez-Fernández, R., González Fernández, P., Giráldez Cervera, J.V., 1997. Efecto del laboreo sobre la materia orgánica y fertilidad de los suelos. In: García Torres, L., González Fernández, P. (Eds.), Agricultura de Conservación: Fundamentos Agronómicos, Medioambientales y Económicos. Asociación Española Agricultura de Conservación/Suelos Vivos, Córdoba, Spain, pp. 41–49.
Ordóñez-Fernández, R., González Fernández, P., Giráldez Cervera, J.V., 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.
Paustian, K., Andren, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Vannoordwijk, M., Woomer, P.L., 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Manage. 13, 230–244.
Puget, P., Lal, R., 2005. Soil organic carbon and nitrogen in a Mollisol in central Ohio as affected by tillage and land use. Soil Till. Res. 80, 201–213.
Reeves, D.W., 1997. The role of organic matter in maintaining soil quality in continuous cropping systems. Soil Till. Res. 43, 131–167.
Rhoton, F.E., 2000. Influence of time on soil response to no-till practices. Soil Sci. Soc. Am. J. 64, 700–709.
Rhoton, F.E., Shipitalo, M.J., Lindbo, D.L., 2002. Runoff and soil loss from midwestern and southeastern US silt loam soils as affected by tillage practice and soil organic matter content. Soil Till. Res. 66, 1–11.
Rodríguez-Lizana, A., Ordóñez-Fernández, R., Espejo-Pérez, A.J., González, P., 2007. Plant cover and control of diffuse pollution from P in olive groves. Water Air Soil Pollut. 181, 17–34.
Schlesinger, W.H., 2000. Carbon sequestration in soils: some cautions amidst optimism. Agric. Ecosyst. Environ. 82, 121–127.
Smith, P., Andren, O., Karlsson, T., Perala, P., Regina, K., Rounsevells, M., Van Wesemaels, B., 2005. Carbon sequestration potential in European croplands has been overestimated. Global Change Biol. 11, 2153–2163.
Soil Survey Staff, 1999. Soil Taxonomy. A Basic System of Soil Classification for Making and Interpreting Soil Surveys. USDA-NRCS, Washington, DC.
Tebrügge, F., 2001. No-tillage visions—protection of soil, water and climate and influence on management and farm income. In: García-Torres, L., Benites, J., Martínez-Vilela, A. (Eds.), I World Congress on Conservation Agriculture: Conservation Agriculture, a worldwide challenge, vol. I, FAO, ECAF, Córdoba, Spain, pp. 303–316.
United Nations, 2011. Kyoto Protocol to the United Nations Framework Convention on Climate Change. http://unfccc.int/essential_background/kyoto_protocol/items/1678.php, viewed 23 November 2011.
West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates for crops with reduced tillage and enhanced rotation. Soil Sci. Soc. Am. J. 66, 1930–1946.
Weiner, T.L., Pan, W.L., Moneymaker, M.R., Santo, G.S., Stevens, R.G., 2002. Nitrogen recycling by nonleguminous winter crops to reduce leaching in potato rotations. Agron. J. 88, 860–866.
Yang, X.M., Wander, M.M., 1999. Tillage effects on soil organic carbon distribution and storage in a silt loam soil in Illinois. Soil Till. Res. 52, 1–9.