Soil organic carbon storage in a no-tillage chronosequence under Mediterranean conditions

J. Álvaro-Fuentes [a,*], D. Plaza-Bonilla [b], J. L. Arrúe [a], J. Lampurlanés [c], C. Cantero-Martínez [b]

[a] Departamento de Suelo y Agua. Estación Experimental de Aula Dei. Consejo Superior de Investigaciones Científicas (EEAD-CSIC). P.O. Box 13034, 50080, Zaragoza, Spain.

[b] Departamento de Producción Vegetal y Ciencia Forestal (Unidad Asociada EEAD-CSIC), Universidad de Lleida, Avda. Rovira Roure 191, 28198 Lleida, Spain.

[c] Departamento de Ingeniería Agroforestal (Unidad Asociada EEAD-CSIC), Universidad de Lleida, Avda. Rovira Roure 191, 28198 Lleida, Spain

* Corresponding author. Tel.: +34-976-71-6123; fax: +34-(976)-716145

E-mail address: jorgeaf@eead.csic.es

Abstract

Background and Aims

The duration of soil organic carbon (SOC) sequestration in agricultural soils varies according to soil management, land-use history and soil and climate conditions. Despite several experiments have reported SOC sequestration with the adoption of no-tillage (NT) in Mediterranean dryland agroecosystems scarce information exists about the duration and magnitude of the sequestration process. For this reason, 20 years ago we established in northeast Spain a NT chronosequence experiment to evaluate SOC sequestration duration under Mediterranean dryland conditions.

Methods

In July 2010 we sampled five chronosequence phases with different years under NT (i.e., 1, 4, 11, and 20 years) and a continuous conventional tillage (CT) field, in which management prevailed unchanged during decades. Soil samples were taken at four depths: 0-5, 5-10, 10-20 and 20-30 cm. The SOC stocks were calculated from the SOC concentration and soil bulk density. Furthermore, we applied the Century ecosystem model to the different stages of the chronosequence to better understand the factors controlling SOC sequestration with NT adoption.

Results

Differences in SOC stocks were only found in the upper 5 cm soil layer in which 4, 11 and 20 years under NT showed greater SOC stocks compared with 1 year under NT and the CT phase. Despite no significant differences were found in the total SOC stock (0-30 cm soil layer) there was a noteworthy difference of 5.7 Mg ha^{-1} between the phase with the longest NT duration and the phase under conventional tillage. The maximum annual SOC sequestration occurred after 5 years of NT adoption with almost 50% change in the annual rate of SOC sequestration. NT sequestered SOC over the 20 years following the change in management. However, more than 75% of the total SOC sequestered was gained during the first 11 years after NT adoption. The Century model predicted reasonably well SOC stocks over the NT chronosequence.

Conclusions

In Mediterranean agroecosystems, despite the continuous use of NT has limited capacity for SOC sequestration, other environmental and agronomic benefits associated to this technique may justify the maintenance of NT over the long-term.

Keywords: No-tillage; Mediterranean agroecosystems; Soil organic carbon sequestration duration; Soil carbon modelling; Century model

Introduction

In agricultural systems, increases in soil organic carbon (SOC) after no-tillage (NT) adoption have been observed in several studies worldwide (e.g., see review by West and Post 2002). SOC sequestration by NT can be a successful strategy to both increase crop yield (Lal 2010) and offset anthropogenic CO_2 emissions (Álvaro-Fuentes and Cantero-Martínez 2010). However, the impact of periodic tillage of NT fields on SOC storage can be variable. Thus, whereas in some studies no significant changes have been reported (Grandy and Robertson 2006), other authors found that tilling of fields under NT causes the loss of previous SOC stored (Conant et al. 2007). In Mediterranean Spain, for instance, a pass of mouldboard plough after 8 years under NT resulted in SOC losses close to 20% of the initial levels (Melero et al. 2011).

SOC sequestration is not an endless process (Powlson et al. 2011). Soils have a finite capacity for SOC storage. Accordingly, after a change in soil management the time needed to achieve a new SOC level is called sequestration duration. Likewise, the new equilibrium level achieved will last until a new management change is adopted (West and Six 2007). The sequestration duration varies between agroecosystems due to differences in soil management, historical land-use and climate (West et al. 2004). For example, in a modelling study, Álvaro-Fuentes and Paustian (2011) observed that for the same climate change conditions the Century model predicted different SOC sequestration durations according to different management scenarios. The model predicted longer SOC sequestration durations in a conventional-tillage cropping system under irrigation than under rainfed conditions (i.e., whereas after 90 years soil in the irrigated system continued sequestering SOC, the rainfed system sequestered SOC for 70 years). In a global meta-analysis, West and Post (2002) estimated that an enhancement in the complexity of crop rotation resulted in longer sequestration durations compared to a decrease in tillage intensity. According to Follett (2001), new steady-state conditions can be achieved after 25-50 years of a change in tillage.

In addition to sequestration duration, the time at which maximum sequestration rate occurs should be known to determine the suitability of NT in different agroecosystems. The capability of a soil to sequester C varies over time. Thus, according to estimations of West and Six (2007), with a change in management, the annual SOC sequestration rate increases during the initial years until a maximum, from which onwards the annual sequestration rate decreases. It has been suggested that several factors such as soil properties, climate, C input, initial SOC levels and management practices adopted, control the maximum SOC sequestration rate (Janzen et al. 1998; McConkey et al. 2003).

In semiarid Mediterranean conditions, where extensive information exists on the effects of tillage system on SOC sequestration (e.g., Álvaro-Fuentes et al. 2009a; Hernanz et al. 2009; Moreno et al. 2010), almost no data are available on either the

SOC sequestration duration and the time to achieve maximum rate of SOC sequestration. Thus, the main aim of this study was to determine the SOC sequestration duration and the maximum SOC sequestration rate after adoption of NT in dryland Mediterranean conditions. In order to achieve this objective we established a NT chronosequence over a 20-yr period in a representative dryland Mediterranean agroecosystem. The chronosequence procedure has also been used in similar studies carried out in other agroecosystems (e.g., Sá et al. 2001; Ochoa et al. 2009). In our region, where precipitation is highly variable in both total precipitation and seasonal distribution, the establishment of a NT chronosequence to study SOC dynamics was considered to be particularly appropriate. The chronosequence approach permited us to overcome the limitation of year-specific weather effects on SOC dynamics.

Material and Methods

Site and chronosequence characteristics

The NT chronosequence was established at Agramunt in northeast Spain (41º48´N, 1º07´E, 330 masl). The area is characterized by widespread adoption of conservation tillage systems during the last two decades. The climate is semiarid with an average annual precipitation of 432 mm and an average air temperature of 13.8 ºC. Rainfall is distributed bimodally with peaks in autumn and late spring and little rainfall in winter and summer (Morell et al. 2011a). The soil is a Typic Xerofluvent (Soil Survey Staff 1994) with a loam texture (465 g kg^{-1} sand, 417 g kg^{-1} silt and 118 g kg^{-1} clay) and a pH of 8.5 in the top 28 cm of soil. In 1990, the SOC stock to 30 cm soil depth was 31.5 Mg C ha^{-1}.

The chronosequence was established in 1990 on a total surface of 7500 m^2 under conventional tillage (CT) (Fig. 1). The area chosen was historically mouldboard ploughed for more than 40 years and planted annually with either wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.). Commonly, ploughing was done to 25 cm depth. Furthermore, pig slurry applications were historically done due to the high density of swine farms in the study area. During the chronosequence, fertilization consisted of 15 m^3 ha^{-1} of swine slurry applied annually.

In 1990, NT was established in 1500 m^2 area of the total chronosequence surface (i.e., 7500 m^2) and the rest of the surface (i.e., 6000 m^2) continued under CT. In 1999, another 1500 m^2 area previously under CT was converted to NT. Similarly, in 2006 and 2009 another 1500 m^2 area of CT surface was converted to NT. Thus, in 2010 the total surface under CT was 1500 m^2 and the remaining 6000 m^2 of the chronosequence was under NT with four different ages: 1, 4, 11 and 20 years. A conceptual scheme of the NT chronosequence is presented in Fig. 1. Over the 20-yr experimental period, the different chronosequence phases followed the same management except for tillage in the CT phase in which mouldboard ploughing to 25 cm depth was done every fall before planting.

Soil sampling, SOC measurements and statistical analyses

In July 2010, soil samples were collected at four soil depths: 0-5, 5-10, 10-20 and 20-30 cm. Within each phase of the chronosequence three sampling areas (pseudoreplicates) were identified. In each sampling area, one dug pit (0.25 m^2) was excavated to 35 cm soil depth. Soil samples were taken per soil depth from a composite sampling around the pit (~ 0.5 kg). Once in the laboratory, soil was air dried and ground to pass a 2-mm sieve. Total SOC content was measured by the wet oxidation method of Walkley and Black (Nelson and Sommers 1982). In each sampling area, soil bulk density was determined by the core method (Grossman and

Reinsch 2002). To avoid possible bias in the estimation of SOC stocks due to differences in soil bulk densities among chronosequence phases, SOC stocks were corrected for equivalent soil mass (Ellert and Bettany 1995). The cumulative soil mass in the 0-30 cm soil layer was 4516 Mg ha^{-1}. After SOC stocks for each chronosequence phase were calculated, the change in the annual rate of SOC sequestration was estimated according to Eq. 1, similar to West and Post (2002).

$$\Delta SOC\%\ yr^{-1} = \frac{\dfrac{\left(SOC\_NT_t - SOC\_CT_t\right) - (SOC\_NT_{t-x} - SOC\_CT_{t-x})}{(SOC\_NT_{t-x} - SOC\_CT_{t-x})}}{years}\ x\ 100 \quad \text{(Eq.1)}$$

where SOC_NT_t : SOC stock in the NT phase *t*; SOC_CT_t: SOC stock under CT in the phase *t*; SOC_NT_{t-x} : SOC stock in the NT phase previous to *t*; SOC_CT_{t-x}: SOC stock under CT in the phase previous to *t*; and *years*: duration in years of the *t* phase.

Over the 20-yr period, SOC stocks under CT were not at steady state. Thus, between 1990 and 2010 there was a SOC difference of 1.52 Mg C ha^{-1}, which we decided to take into account in Eq. 1. However, over the 20-yr period in the CT phase SOC measurements were not taken. For that reason, SOC stock change over time for the CT phase was estimated considering a linear SOC change between 1990 and 2010.

In the field in which the chronosequence was established, the soil was homogeneous and the slope nearly level. Therefore, we considered the experiment as a randomized experiment for statistical analyses. The three sampling locations within each chronosequence phase were used as pseudo-replicates. Data were analysed using the SPSS software. The effects of chronosequence phases on SOC were compared with analyses of variance. Differences between means were tested with the Tukey's HSD mean separation test.

Chronosequence modelling

The SOC changes in the NT chronosequence were simulated with version 4.0 of the Century model (Parton et al. 1987). The model, which is a general ecosystem model designed to simulate C, N, S and P dynamics in a monthly time step, was described in detail by Parton et al. (1987, 1994). We chose the Century model because we had previously parameterized and validated this model to simulate SOC dynamics in Mediterranean semiarid agroecosystems (Álvaro-Fuentes et al. 2009b; 2011). Weather data for model runs were obtained from a meteorological station located in the same field. Initialization of soil organic matter (SOM) pools was similar to the procedure followed in other SOC modelling studies carried out in similar conditions (i.e., Álvaro-Fuentes et al. 2009b; Álvaro-Fuentes and Paustian 2011). Briefly, an equilibrium period of 10,000 years with a tree-grass system and a 20-yr fire frequency was run to initialize the most recalcitrant SOM pool (i.e., the passive pool). Next, a base history of 190 years was simulated to initialize the slow SOM pool. The base history was divided in two periods. During the first 150 years, a barley-fallow rotation with intensive tillage and low additions of manure was simulated. However, during the previous 40 years to the start of the chronosequence, we simulated a continuous barley system with intensive tillage and with 60% increase in the amount of manure applied compared to the previous 150-yr period. In the base history period, agricultural management was simulated according to historical records of the experimental field.

Results

SOC levels

As observed in Table 1, SOC stocks differed among chronosequence phases. Differences were only found in the upper 5 cm soil layer in which 4, 11 and 20 years under NT (i.e., 4-NT, 11-NT and 20-NT phases, respectively) showed greater SOC stocks compared with the 1-NT and 0-NT phases. Below 5 cm depth, SOC stocks were similar with values ranging from 5.4 to 12.3 Mg ha^{-1} (Table 1). Total SOC stock in the overall 0-30 cm layer sampled was also similar among chronosequence phases (Table 1).

SOC sequestration change and duration

Change in the annual rate of SOC sequestration in the 0-30 cm soil layer is shown in Fig. 2a. After NT adoption, the annual rate of SOC sequestration rapidly increased over the first years. The maximum annual SOC sequestration occurred after 5 years of NT adoption with almost 50% change. From 5 years onwards, the change in the annual rate of SOC sequestration decreased until 20 years after NT adoption when the change was about 3% (Fig. 2a).

Annual rate of SOC sequestration by NT followed a different trend when it was analysed by soil layers (Fig. 3). In the soil surface (0-5 cm depth), the percentage change followed a similar trend as the observed for the whole 0-30 cm soil layer (Fig. 2a), with a maximum annual SOC sequestration rate after 5 years and a decrease afterwards. However, in the 5-10 cm soil layer, it was observed an initial loss of SOC, represented by a negative percentage, followed by an increase in the annual SOC sequestration rate during the following 4 years (Fig. 3). In the lowest soil layer

sampled (i.e., 20-30 cm depth), the change in the annual rate of SOC sequestration was close to zero indicating that SOC levels under NT were similar to CT levels.
According to Fig. 2b, in our experiment, NT sequestered SOC over the first 20 years following the change in management. However, from the year 11 onwards, SOC sequestration rates were lower than 0.20 Mg C ha^{-1} yr^{-1} (Fig. 2b). Thus, more than 75% of the total SOC sequestered was gained during the first 11 years after NT adoption.

Chronosequence modelling

The Century model was used to simulate temporal SOC changes over the chronosequence (Fig. 4). The model performed well in simulating SOC stocks at the end of the study period. In 2010, measured SOC values were similar to the SOC stocks predicted by the Century model (Fig. 4). The highest difference between observed and predicted SOC values was obtained in the 11-NT phase in which the model predicted 2.8% lower SOC content compared to the observed SOC stock value. The good performance of the Century model simulating the chronosequence was reflected in the significant relationship obtained between observed and predicted SOC values ($P<0.01$; $R^2 = 0.961$) (data not shown). Furthermore, the estimated root mean square error (RMSE) of the simulation was low (i.e., 1.7), indicating a good adjustment between simulated and observed values.
We created a long-term NT scenario (i.e., 100 years) in which we simulated the same existing conditions as those existing in the chronosequence experiment (Fig. 5). The only difference was climate variables, which were set as mean values. It is important to remark that in the future scenario, changes due to either climate change or atmospheric CO_2 increase were not considered. The model predicted a decrease in the

rates of SOC sequestration with time since NT adoption. Thus, during the first 20 years the model predicted an increase of 5.4 Mg C ha^{-1} meanwhile in the following 20 years (i.e., from year 20 to year 40) the model predicted a SOC gain of 4.3 Mg C ha^{-1} (Fig. 5). The lowest increase was predicted for the last 20 years (i.e., from year 80 to year 100) in which SOC stock increased about 2.0 Mg C ha^{-1}.

Discussion

The NT chronosequence gave an excellent opportunity to study both SOC sequestration change and duration after NT adoption. Despite no significant differences were found in SOC stocks over the entire soil sampled profile (i.e., 0-30 cm depth), there was a noteworthy trend in SOC of 5.7 Mg ha^{-1} between the phase with the longest NT duration (i.e., the 20-NT phase) and the phase under conventional tillage (i.e., the 0-NT phase). In the 0-5 cm soil layer, the SOC stock difference between 20-NT and 0-NT was significant at 6 Mg ha^{-1} (Table 1). Thus, this difference in SOC stock found in the soil surface was responsible for all of the increase in SOC stock in the entire 30 cm. Similarly, Sá et al. (2001) observed that total SOC accumulated in a NT chronosequence in a Brazilian Oxisol could be attributed to SOC accumulated in the upper 10 cm soil depth.

The effect of sampling depth on SOC sequestration by NT has been widely debated in the literature (e.g., Baker et al. 2007; VandenBygaart et al. 2011). Shallow soil sampling could lead to misinterpretation of the SOC sequestration potential after changes in soil management. Baker et al. (2007) suggested soil sampling deeper than 30 cm in order to account for any changes in soil C due to mouldboard ploughing. In our experiment, since mouldboard ploughing was performed up to 25 cm depth, we sampled to 30 cm to account for possible effects of tillage implementation on SOC accrual in lower soil layers. In the 20-30 cm soil layer, SOC levels were similar among NT phases (Table 1). Therefore, we could assume that in our experiment the effect of mouldboard ploughing on SOC accumulation in deeper soil was minimal.

The increase in SOC with longer NT duration can be attributable to the effects of NT increasing C inputs and decreasing decomposition. In the same region, higher crop biomass has been reported in NT compared to CT due to better soil water conservation (Cantero-Martínez et al. 2007). Furthermore, the lack of soil disturbance permits longer physical protection of SOC within aggregates reducing SOC accessibility to soil microorganisms (Six et al. 1999). Álvaro-Fuentes et al. (2009a), studying physical SOC stabilization under NT in semiarid agroecosystems in northeast Spain, concluded that the slower aggregate turnover in NT compared to CT resulted in greater microaggregate formation within macroaggregates and to the stabilization of SOC within these microaggregates occluded within macroaggregates. Consequently, we hypothesize that the longer the years under NT the higher the SOC stabilized within soil macroaggregates and protected against microbial decomposition.

As observed in Fig. 2, the maximum annual SOC sequestration occurred after 5 years of NT adoption. West and Post (2002) in a global analysis of 93 tillage comparisons, estimated a maximum annual SOC sequestration at about 7 years since the adoption of NT. During the first year under NT, the SOC sequestered was almost nil (Fig. 2). In water-limited regions, it is frequent the absence of SOC storage during the first years after the adoption of NT (Six et al. 2004). As commented by these authors, the slower incorporation of crop residues under NT systems through soil fauna compared to mechanical incorporation in CT systems may result in the lack of C sequestration over the first years of NT. Furthermore, NT adoption in dryland Spain can be associated with a slightly decline in crop yields during the first years of implementation (López-

Fando and Almendros 1995; López and Arrúe 1997), which could lead to lower C inputs during the first years under NT.

Interestingly, the annual amount of SOC sequestered was different among soil layers. The adoption of NT had a significant effect on the distribution of SOC over the soil profile. The SOC stock profile of the CT phase (i.e., 0-NT) differed considerably from the SOC profile of the chronosequence phases with the longest NT duration (i.e., 11-NT and 20-NT) (Table 1). Therefore, variations in the distribution of SOC along the soil profile between chronosequence phases resulted in different patterns of annual amount of SOC sequestered among the different soil layers studied.

In our representative Mediterranean conditions, NT sequestered SOC over the 20 years studied. However, more than 75% of the total SOC sequestered during the 20 years was gained during the first 11 years after NT adoption. In dryland conditions of central Spain, Hernanz et al. (2009) observed SOC equilibrium conditions 11 years after the adoption of NT. However, our sequestration duration could be also compared to the data showed in the study of West and Post (2002) in which they estimated a sequestration duration of 20 years after adoption of NT. These authors pointed out that different C sequestration durations are expected to occur under different climate, ecosystems, land-use history and management. In semiarid dryland conditions, limited crop growth restricts SOC sequestration (Halvorson et al. 2002). Furthermore, in Mediterranean semiarid conditions, both soil water-limiting conditions and elevated soil temperatures affect soil microbial activity during long periods of time (Almagro et al. 2009; Morell et al. 2011b). Consequently, different SOC sequestration durations in Mediterranean conditions could be attributed to the interactive effects of the above mentioned determining factors (i.e., low C inputs, soil water-limiting conditions and elevated soil temperatures).

The Intergovernmental Panel on Climate Change (IPCC) method for estimating SOC stock changes at a regional scale is computed over a 20-yr period (IPCC 2006). This implies that the SOC change rate is considered linear over this period of time (Milne et al. 2007). However, according to our study, the use of the IPCC method in semiarid Mediterranean agroecosystems could be overestimating the SOC stock changes since more than 75% of the total SOC gain was achieved during the first 11 years after NT adoption.

The Century model was able to simulate well the NT chronosequence (Fig. 5). The parameterization used was similar to that described in Álvaro-Fuentes et al. (2009b); in which the Century model was parameterized and validated in a long-term tillage experiment also located in northeast Spain. In this case, model uncertainty estimated with the RMSE was also low (i.e., between 3.2% and 5.8%) indicating the good performance of the Century model simulating tillage effects in semiarid agroecosystems of northeast Spain.

The NT long-term scenario simulated with the Century model showed a non-linear SOC with time. Thus, during the first 20 years the model predicted the greatest SOC sequestration rates with values higher than 0.25 Mg C ha^{-1} yr^{-1}. The predicted SOC change rate during the first 20 years after NT adoption was somewhat lower than the SOC change rate measured in the chronosequence (i.e., 0.36 Mg C ha^{-1} yr^{-1}). After 80 years, the model predicted SOC sequestration rates of 0.10 Mg C ha^{-1} yr^{-1}. This non-linear SOC gain over time is explained with the first-order decomposition kinetics that the model employs (Paustian et al. 1997). This first-order kinetics implies that soil C level increases according to C input changes until an equilibrium level is achieved (Stewart et al. 2007).

According to the simulation, SOC stock would still increase over the next 100 years. As commented previously, fertilization in the chronosequence consisted of 15 m^3 ha^{-1} of swine slurry applied annually. The addition of manure results in the increase of SOC stocks over time (Paustian et al., 1997). In a long-term experiment conducted at Rothamsted (Harpenden, UK), SOC stocks increased continuously during 100 years of barley cropping with annual addition of 35 Mg ha^{-1} of manure (Johnston, et al. 2009). Similarly to our chronosequence experiment, the Rothamsted experiment SOC increased rapidly during the first years and then more slowly.

Conclusions

Under dryland Mediterranean conditions, NT increased SOC compared to CT only in the soil surface (i.e., 0-5 cm). The NT chronosequence experiment allowed us to determine both SOC sequestration duration and change in annual amount of SOC sequestered over a 20-yr period. According to SOC stocks measured in the chronosequence, NT gained SOC during the overall 20-yr period with a maximum annual SOC sequestration rate estimated to occur 5 years after adoption of NT. However, more than 75% of the total SOC sequestered was gained during the first 11 years after NT adoption. Differences existed in the annual SOC sequestered among different soil layers. The Century model predicted reasonably well SOC stocks over the whole NT chronosequence. Although continuous use of NT has a limited capacity for SOC sequestration in Mediterranean agroecosystems, other beneficial environmental and agronomic effects associated with this practice (e.g., soil erosion control) may last for longer periods and justify the value of maintaining NT in those systems.

Acknowledgements

This work was supported by the Comisión Interministerial de Ciencia y Tecnología of Spain (Grants AGL2007-66320-CO2-02/AGR and AGL2010-22050-C03-01/02) and the European Union (FEDER funds). We acknowledge the Consejo Superior de Investigaciones Cientificas (CSIC) for the contract granted to Jorge Álvaro-Fuentes within the "Junta para la Ampliación de Estudios" (JAE-DOC) programme co-financed by the European Social Fund. Furthermore, Daniel Plaza-Bonilla was awarded with a FPU fellowship by the Spanish Ministry of Education. We thank Carlos Cortés and Silvia Martí for their technical assistance. We would like to thank the two anonymous reviewers for their helpful comments on earlier versions of this manuscript.

References

Almagro M, López J, Querejeta JI, Martínez-Mena M (2009) Temperature dependence of soil CO_2 efflux is strongly modulated by seasonal patterns of moisture availability in a Mediterranean ecosystem. Soil Biol Biochem 41:594–605

Álvaro-Fuentes J, Cantero-Martínez C (2010) Potential to mitigate anthropogenic CO_2 emissions by tillage reduction in dryland soils of Spain. Span J Agric Res 8:1271–1276

Álvaro-Fuentes J, Paustian K (2011) Potential soil carbon sequestration in a semiarid Mediterranean agroecosystem under climate change: Quantifying management and climate effects. Plant Soil 338:261–272

Álvaro-Fuentes J, Easter M, Cantero-Martínez C, Paustian K (2011). Modelling soil organic carbon stocks and their changes in the northeast of Spain. Eur J Soil Sci 62, 685–695

Álvaro-Fuentes J, Cantero-Martínez C, López MV, Paustian K, Denef K, Stewart CE, Arrúe JL (2009a) Soil Aggregation and Soil Organic Carbon Stabilization: Effects of Management in Semiarid Mediterranean Agroecosystems. Soil Sci Soc Am J 73:1519–1529

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

Baker JM, Ochsner TE, Venterea RT, Griffis TJ (2007) Tillage and soil carbon sequestration – What do we really know?. Agr Ecosyst Environ 118:1–5

Cantero-Martínez C, Angás P, Lampurlanés J (2007) Long-term yield and water use efficiency under various tillage systems in Mediterranean rainfed conditions. Ann Appl Biol 150:293–305

Conant RT, Easter M, Paustian K, Swan A, Williams S (2007) Impacts of periodic tillage on soil C stocks: A synthesis. Soil Till Res 95:1–10

Ellert BH, Bettany JR (1995) Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can J Soil Sci 75:529–538

Follett RF (2001) Soil management concepts and carbon sequestration zin cropland soils. Soil Till Res 61:77–92

Grandy AS, Robertson, GP (2006) Aggregation and organic matter protection following tillage of a previously uncultivated soil. Soil Sci Soc Am J 70:1398–1406

Grossman RB, Reinsch TG (2002) Bulk density and linear extensibility. In: Dane JH, Topp GC (eds) Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, pp 201–228

Halvorson AD, Peterson GA, Reule AC (2002) Tillage system and crop rotation effects on dryland crop yields and soil carbon in the central Great Plains. Agron J 94:1429–1436

Hernanz JL, Sánchez-Girón V, Navarrete 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

IPCC (2006) IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds). IGES, Japan

Janzen HH, Campbell CA, Izaurralde RC, Ellert BH, Juma N, McGill WB, Zentner RP (1998) Management effects on soil C storage on the Canadian prairies. Soil Till Res 47:181–195

Johnston AE, Poulton PR, Coleman K (2009) Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. Adv Agron 101:1–57

Lal R (2010) Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration. Food Sec 2:169–177

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, 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 36:45–57

McConkey BG, Liang BC, Campbell CA, Curtin D, Moulin A, Brandt SA, Lafond GP (2003) Crop rotation and tillage impact on carbon sequestration in Canadian prairie soils. Soil Till Res 74:81–90

Melero S, Panettieri M, Madejón E, Gómez Macpherson HG, Moreno F, Murillo J. (2011) Implementation of chiselling and mouldboard ploughing in soil after 8 years of no-till management in SW Spain: Effect on soil quality. Soil Till Res 112:107–113

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. Agric Ecosyst Environ 122:3–12

Morell FJ, Cantero-Martínez C, Álvaro-Fuentes J, Lampurlanés J (2011a) Root growth of barley as affected by tillage systems and nitrogen fertilization in a semiarid mediterranean agroecosystem. Agron J 103:1270–1275

Morell FJ, Cantero-Martínez C, Lampurlanés J, Plaza-Bonilla D, Álvaro-Fuentes J (2011b) Soil carbon dioxide flux and organic carbon content: effects of tillage and nitrogen fertilization. Soil Sci Soc Am J 75:1874-1884

Moreno F, Arrúe JL, Cantero-Martínez C, López MV, Murillo JM, Sombrero A, López-Garrido R, Madejón E, Moret D, Álvaro-Fuentes J (2010) Conservation agriculture under Mediterranean conditions in Spain. In : Lichtfouse E (ed) Biodiversity, Biofuels, Agroforestry and Conservation Agriculture. Sustainable Agriculture Reviews, vol 5, Springer, pp 175–193

Nelson DW, Sommers LE (1982) Total carbon, organic carbon and organic matter. In: Page AL et al. (ed) Methods of soil analysis. Chemical and microbiological properties. Agronomy No. 9, Part 2, ASA-SSSA, Madison, pp 539–579

Ochoa CG, Shukla MK, Lal R (2009) Macroaggregate-associated physical and chemical properties of a no-tillage chronosequence in a Miamian soil. Can J Soil Sci 89:319–329

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, pp 147–167

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

Paustian K, Collins HP, Paul EA (1997) Management controls on soil carbon. In: Paul EA et al. (eds) Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America. Lewis Publishers, CRC Press, Boca Raton, pp 15–49

Powlson DS, Whitmore AP, Goulding WT (2011) Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. Eur J Soil Sci 62:42–55

Sá JCM, Cerri CC, Dick WA, Lal R, Filho SPV, Piccolo MC, Feigl BE (2001) Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian Oxisol. Soil Sci Soc Am J 65:1486–1499

Six J, Ogle SM, Breidt FJ, Conant RT, Mosier AR, Paustian K (2004) The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Global Change Biol 10:155–160

Six J, Elliot ET, Paustian K (1999) Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci Soc Am J 63:1350–1358

Soil Survey Staff (1994) Keys to Soil Taxonomy. United States Department of Agriculture, Soil Conservation Service, Washigton, pp 306

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

Vandenbygaart AJ, Bremer E, McConkey BG, Ellert BH, Janzen HH, Angers DA, Carter MR, Drury CF, Lafond GP, McKenzie RH (2011) Impact of Sampling Depth on Differences in Soil Carbon Stocks in Long-Term Agroecosystem Experiments. Soil Sci Soc Am J 75:226–234

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

West TO, Post WM (2002) Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci Soc Am J 66:1930–1946

West TO, Marland G, King AW, Post WM, Jain AK, Andrasko K (2004) Carbon management response curves: estimates of temporal soil carbon dynamics. Environ Managem 33:507–518

Figure captions

Fig. 1. Conceptual scheme of the no-tillage (NT) chronosequence. White areas represent field surface occupied by the conventional tillage (CT) phase (NT-0) and grey squares indicate phases under NT (1-NT, 1 year under NT; 4-NT, 4 years under NT; 11-NT, 11 years under NT; 20-NT, 20 years under NT). Each grey rectangle represents 1500 m^2 surface.

Fig. 2. (a) Percentage change in the annual rate of soil organic carbon (SOC) sequestration in the 0-30 cm soil layer over the 20-yr period after the adoption of no-tillage (NT), calculated as the percentage of SOC sequestered in the NT system within a given time period in relation with the sequestered in the previous period (see Eq. 1); and (b) Total SOC sequestered in the 0-30 cm soil layer after NT adoption.

Fig. 3. Percentage change in the annual rate of soil organic carbon (SOC) sequestration in the 0-5, 5-10, 10-20 and 20-30 cm soil layers over the 20-yr period after the adoption of no-tillage (NT), calculated as the percentage of SOC sequestered in the NT system within a given time period in relation with the sequestered in the previous period.

Fig. 4. Evolution of measured and simulated soil organic carbon content in the 0-30 cm soil layer for the different no-tillage (NT) chronosequence phases (1-NT, 1 year under NT; 4-NT, 4 years under NT; 11-NT, 11 years under NT; 20-NT, 20 years under NT). Errors bars represent standard errors.

Fig. 5. Soil organic carbon (SOC) evolution in the 0-30 cm soil layer predicted by the Century model for a long-term no-tillage (NT) scenario.

Tables

Table 1. Soil organic carbon (SOC) stocks (Mg ha^{-1}) corrected for equivalent soil mass in the different no-tillage (NT) chronosequence phases (0-NT, 0 years under NT; 1-NT, 1 year under NT; 4-NT, 4 years under NT; 11-NT, 11 years under NT; 20-NT, 20 years under NT).

Soil depth (cm)	0-NT	1-NT	4-NT	11-NT	20-NT
0-5	6.1 (0.1)b*	6.3 (0.6)b	10.1 (1.4)a	12.3 (0.4)a	12.1 (0.2)a
5-10	6.0 (0.1)	5.4 (0.2)	6.7 (0.4)	7.8 (1.1)	7.3 (0.5)
10-20	10.7 (1.1)	12.4 (0.7)	9.6 (0.5)	9.6 (0.5)	12.0 (1.0)
20-30	10.2 (0.2)	9.1 (1.0)	8.7 (1.3)	8.0 (0.5)	7.4 (1.4)
0-30	33.0 (1.3)	33.1 (2.2)	35.1 (3.3)	37.8 (2.3)	38.7 (2.9)

* In parenthesis standard errors. Means followed by the same lowercase letter within a row are not statistically different at $P \leq 0.05$ according to Tukey´s HSD mean separation test.

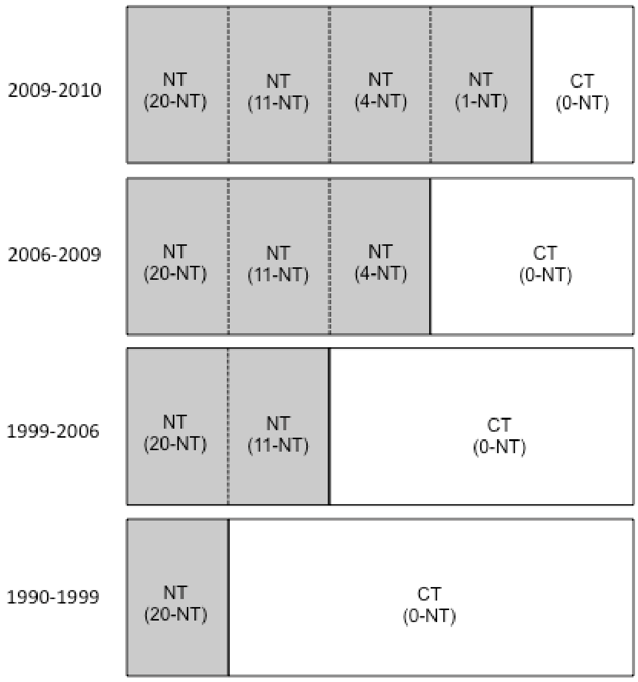

2009-2010
NT (20-NT)
NT (11-NT)
NT (4-NT)
NT (1-NT)
CT (0-NT)
2006-2009
NT (20-NT)
NT (11-NT)
NT (4-NT)
CT (0-NT)
1999-2006
NT (20-NT)
NT (11-NT)
CT (0-NT)
1990-1999
NT (20-NT)
CT (0-NT)

Fig. 1.

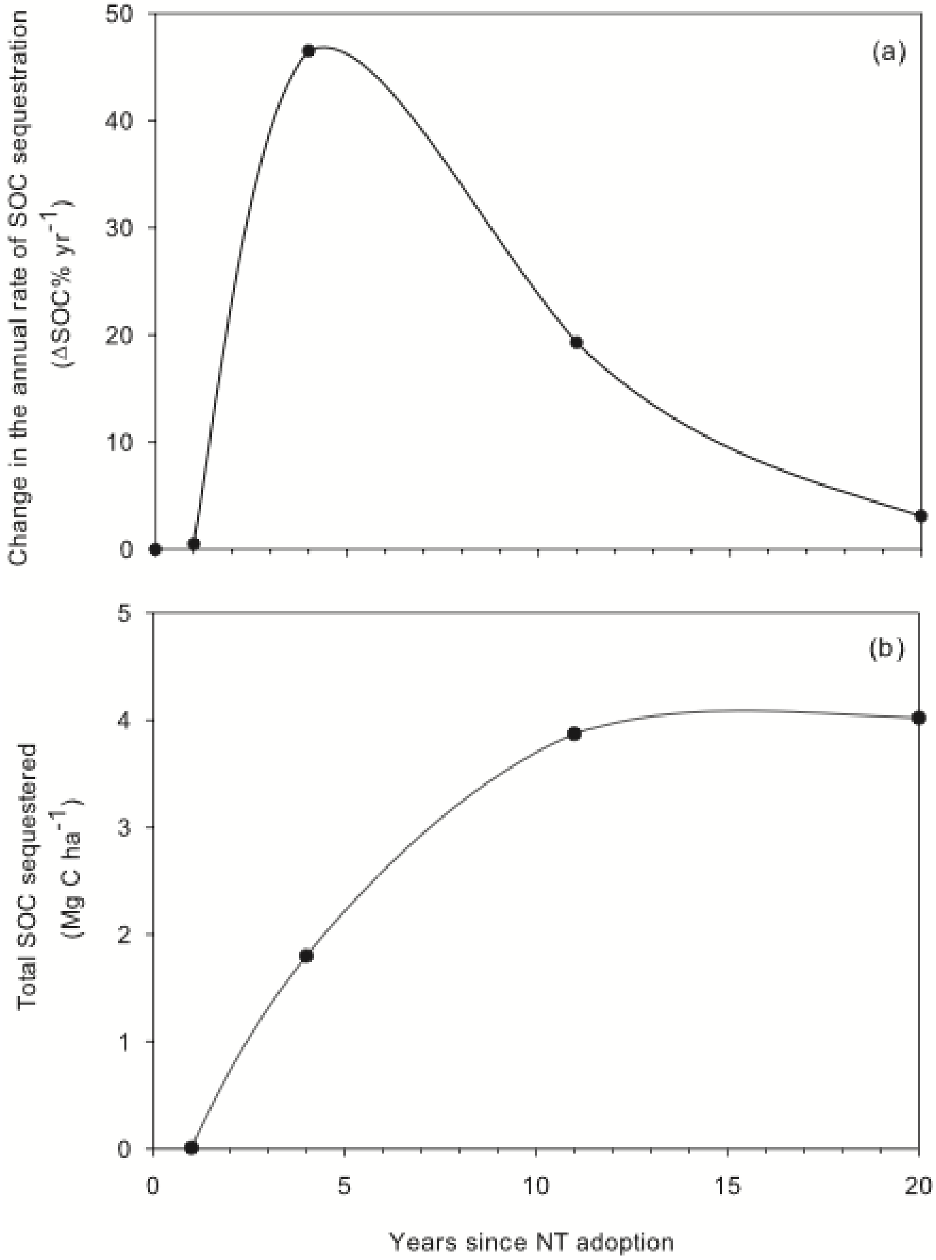

(a)
Change in the annual rate of SOC sequestration
(ΔSOC% yr^{-1})
0
10
20
30
40
50
(b)
Total SOC sequestered
(Mg C ha^{-1})
0
1
2
3
4
5
0
5
10
15
20
Years since NT adoption

Fig. 2.

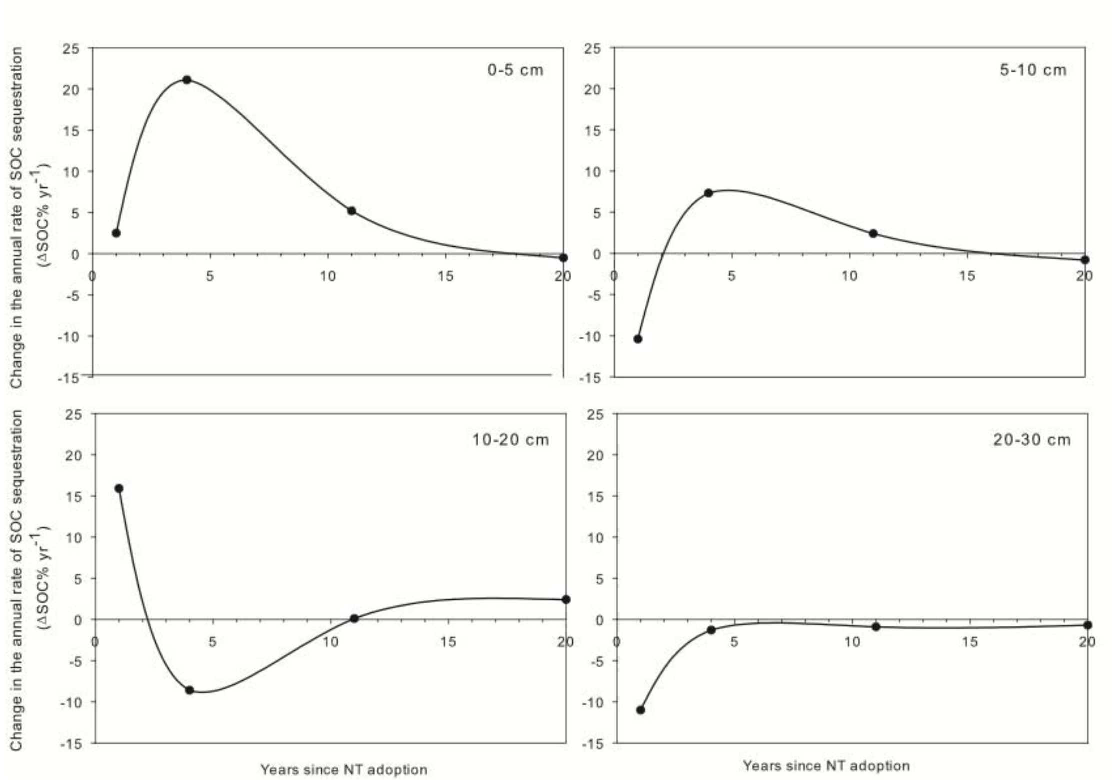

0-5 cm
5-10 cm
10-20 cm
20-30 cm
Change in the annual rate of SOC sequestration (ΔSOC% yr^{-1})
Years since NT adoption

Fig. 3.

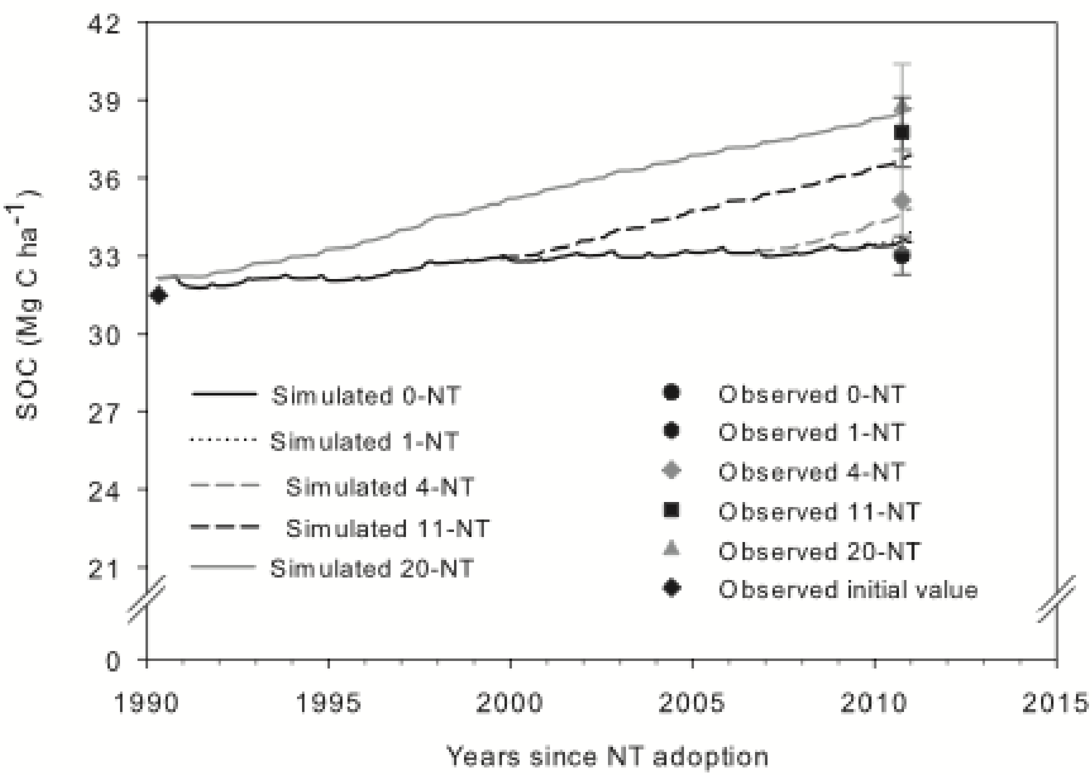
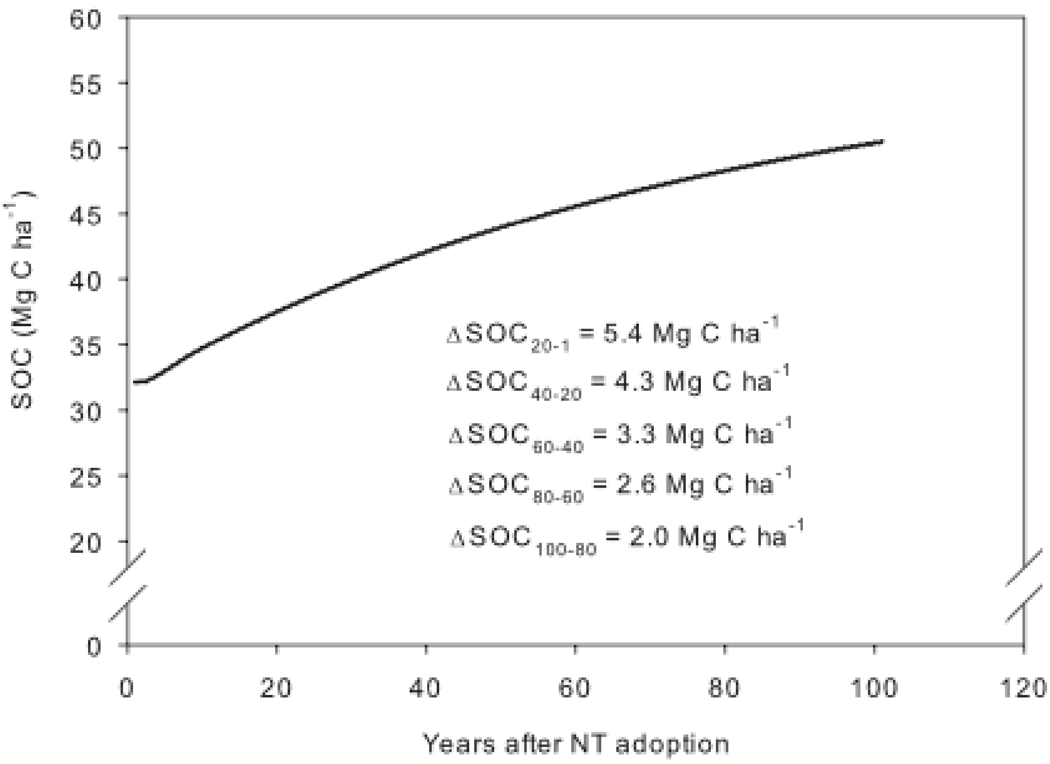

SOC (Mg C ha-1)
42
39
36
33
30
27
24
21
0
1990
1995
2000
2005
2010
2015
Years since NT adoption
Simulated 0-NT
Simulated 1-NT
Simulated 4-NT
Simulated 11-NT
Simulated 20-NT
Observed 0-NT
Observed 1-NT
Observed 4-NT
Observed 11-NT
Observed 20-NT
Observed initial value

Fig. 4.



SOC (Mg C ha-1)
60
55
50
45
40
35
30
25
20
0
ΔSOC20-1 = 5.4 Mg C ha-1
ΔSOC40-20 = 4.3 Mg C ha-1
ΔSOC60-40 = 3.3 Mg C ha-1
ΔSOC80-60 = 2.6 Mg C ha-1
ΔSOC100-80 = 2.0 Mg C ha-1
0
20
40
60
80
100
120
Years after NT adoption

Fig. 5.