Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar
http://dx.doi.org/10.5424/sjar/2013113-3747
Spanish Journal of Agricultural Research 2013 11(3): 820-832
ISSN: 1695-971-X
eISSN: 2171-9292

Simulating improved combinations tillage-rotation under dryland conditions

M. Soldevilla-Martinez[1], D. Martin-Lammerding[2], J. L. Tenorio[2], I. Walter[2], M. Quemada[1] and J. I. Lizaso[1]*

[1] *Departamento de Producción Vegetal: Fitotecnia. ETSIA. Universidad Politécnica de Madrid. Ciudad Universitaria, s/n. 28040 Madrid, Spain*
[2] *Departamento de Medio Ambiente. Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA). Ctra. A Coruña, km 7,5. 28040 Madrid, Spain*

Abstract

Crop simulation models allow analyzing various tillage-rotation combinations and exploring management scenarios. This study was conducted to test the DSSAT (Decision Support System for Agrotechnology Transfer) modelling system in rainfed semiarid central Spain. The focus is on the combined effect of tillage system and winter cereal-based rotations (cereal/legume/fallow) on the crop yield and soil quality. The observed data come from a 16-year field experiment. The CERES and CROPGRO models, included in DSSAT v4.5, were used to simulate crop growth and yield, and DSSAT-CENTURY was used in the soil organic carbon (SOC) and soil nitrogen (SN) simulations. Genetic coefficients were calibrated using part of the observed data. Field observations showed that barley grain yield was lower for continuous cereal (BB) than for vetch (VB) and fallow (FB) rotations for both tillage systems. The CERES-Barley model also reflected this trend. The model predicted higher yield in the conventional tillage (CT) than in the no tillage (NT) probably due to the higher nitrogen availability in the CT, shown in the simulations. The SOC and SN in the top layer only, were higher in NT than in CT, and decreased with depth in both simulated and observed values. These results suggest that CT-VB and CT-FB were the best combinations for the dry land conditions studied. However, CT presented lower SN and SOC content than NT. This study shows how models can be a useful tool for assessing and predicting crop growth and yield, under different management systems and under specific edapho-climatic conditions.

Additional key words: CENTURY model; CERES-Barley; crop simulation models; DSSAT; sequential simulation; soil organic carbon.

Introduction

Intensive and continuous conventional tillage (CT) may cause loss of soil organic carbon (SOC), thus inducing an increase in soil erosion and a degradation of soil structure (Melero *et al*., 2009). Damages to soil biota, soil compaction, soil crusting and loss of soil fertility are also well known consequences of excessive tillage. In the last few decades, the search for practices that improve soil quality and agricultural sustainability has increased. Interest in conservation tillage practices (such as minimum and no-tillage) is growing because these practices reduce soil erosion, which is caused by conventional ploughed tillage, therefore preserving soil quality and fertility and improving the soil organic matter (SOM) content (Peigne & Roger-Estrade, 2007).

An increase in the soil quality by using conservation tillage systems has been reported in numerous studies (*e.g.* Verhulst *et al*., 2010). The increase in SOM in the first centimeters of soil in conservation tillage is one of the reasons for the improvement in soil quality (Lacasta & Meco, 1996; Buschiazzo *et al*., 1998; Hussain *et al*., 1999; Sombrero *et al*., 2007).

* Corresponding author: jon.lizaso@upm.es
Received: 14-11-12. Accepted: 18-07-13.

This work has one Supplemenary Table that does not appear in the printed article but that accompanies the paper online.

Abbreviations used: BB (continuous barley); CT (conventional tillage); DSSAT (Decision Support System for Agrotechnology Transfer); FB (fallow-barley); NT (no tillage); SN (total soil nitrogen); SOC (soil organic carbon); SOM (soil organic matter);VB (vetch-barley).

In arid and semi-arid zones, the low SOM content and the continuous losses due to the climate, makes conservation agriculture an interesting management option. The use of conservation tillage in semiarid climate, can improve the sustainability of the agricultural system in the long term by increasing the SOM and the soil biochemical quality in the first centimeters of soil (Madejón *et al*., 2007). Some authors reported that no tillage (NT) accumulates SOC and total soil nitrogen (SN) in the upper centimeters of soil some years after the beginning of the tillage system adoption (Rhoton, 2000; Motta *et al*., 2002). Minimum tillage (MT) and NT have been observed to contribute to the role of soil as a carbon sink, increasing SOC and SN when compared to CT (West & Post, 2002; Al-Kaisi & Yin, 2005).

Martín-Rueda *et al*. (2007) compared CT with MT and NT in a central Spain area. The results showed higher amounts of nitrogen, phosphorus, potassium and all the measured micronutrients in the first 15 cm of soil in conservation tillage treatments, being this boost in soil fertility more pronounced in the soils under NT than those under MT. In other study, Muñoz *et al*. (2007) compared different tillage systems in irrigated maize under dryland conditions. They found differences between tillage systems starting on the second year of trials, showing the NT systems higher amounts of SOC, water content, and SN as well as a higher stability of aggregates and a lower penetration resistance. Gal *et al*. (2007) compared the effects of NT and CT in soil fertility and they found an increase in the SN content for the first 15 cm of soil in the NT compared with the CT management, but similar SN content in deeper layers. Generally, fields under NT have a higher SOM in the top layer (< 10 cm) than soils under CT, but for the whole soil profile results can change. When a 30 cm upper layer was studied, some research showed that soils with NT or MT had greater SOM stocks than soils with CT (Halvorson *et al*., 2002; Huggins *et al*., 2007), while other studies reported the opposite (Blanco-Canqui & Lal, 2008), and some research found no significant differences (Dolan *et al*., 2006).

It is also well-known that NT conserves soil water by reducing direct evaporation and increasing water storage (Pryor, 2006). This is especially important in dryland areas, where water is the limiting factor for crop growth. The NT management can also improve the efficiency in the use of fertilizer, so that crops are better nourished under NT than under CT (Triplett & Dick, 2008). In some cases however, yield reduction has been observed under NT in specific climatic conditions. For example, López-Bellido *et al*. (1996) and Halvorson (2000) reported that wheat yield in dry years was higher in NT than in CT, but in wet years it was the opposite. Similarly, Bonari *et al*. (1994) found that CT was more effective increasing wheat yields, when precipitation was abundant.

The viability of dry land agriculture in Mediterranean zones could be increased by the adequate combination of reduced tillage and crop rotation (Martín-Rueda *et al*., 2007). Crop rotations are useful practices to control weeds and diseases, improve soil quality, increase the soil biological activity, or to maintain soil fertility (Altieri, 1999). Besides, the introduction of legumes in the rotation can be used to increase the available soil nitrogen by fixing atmospheric nitrogen and releasing it through microbial decomposition (Peel, 1998). The combination of tillage and crop rotations has significant influence on SOM due to changes in the mineralization processes (Martin-Rueda *et al*., 2007). In semi-arid central Spain, Sombrero & De Benito (2010) concluded that the combination of conservation tillage with rotations decreases SOM mineralization by minimizing soil disturbance, hence improving soil properties. They also showed that including a legume in the rotation increased SOC compared to monoculture. Therefore, is important to study tillage-crop rotation combinations in order to find the best strategy that optimizes high yield with preservation of SOM.

Wider-scale assessment of the potential of conservation agriculture across various agro-ecosystems, regions, and climates, can be facilitated by applying quantitative, system-dynamic tools such as crop-soil simulation modeling (Sommer *et al*., 2012). Crop models can complement ongoing agricultural research by assessing the integrated impact of environmental and management variables on productivity and resource conservation. For example, a better understanding of the effect of agricultural management practices on SOC could result from combining long-term field experimentation with simulation approaches (Smith *et al*., 2008). These crop simulation models could be used to evaluate various tillage-rotation combinations and explore management scenarios. The Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom *et al*., 2010), provides a suite of crop models and tools suitable for this task. DSSAT v4.5 includes tillage routines which modify soil variables and mix soil constituents (Hoogenboom *et al*., 2010). It integrates several crop system models, two alternative soil C and nitrogen (N) models, a daily soil water model, and a range of crop/land management options to simulate crop growth, yield and corresponding environmental impacts. Among the crop models included in DSSAT, CERES-Barley (Otter-Nacke *et al.*, 1991) simulates the daily development, growth, and yield of barley crops (Travasso & Magrin, 1998).

Many models of SOM have been developed and used for various purposes (McGill, 1996). The DSSAT system includes two options: the CERES-based SOM model (Godwin & Singh, 1998) and the DSSAT-CENTURY model (Parton *et al.*, 1992; Gijsman *et al.*, 2002). The CENTURY model simulates the dynamics of SOC and SN for a homogeneous land area. The incorporation of SOM models in DSSAT is particularly important for predicting yields in low input cropping systems and when analyzing the dynamics of cropping systems and soil quality over long periods of time. CENTURY has proved to simulate accurately long term SOM dynamics over a range of environments (Foereid & Hogh-Jensen, 2004; Lugato & Berti, 2008; Galdos *et al.*, 2009; Álvaro-Fuentes & Paustian, 2011).

The general objective of this work was to test the DSSAT modeling system (crops, SOC, SN) under the dryland conditions evaluated by a long term experiment (16 years) conducted in rainfed semiarid Central Spain. The focus of this paper is on the effects of tillage system (conventional/no-till) and rotation (cereal/legume/fallow) on the production and soil quality of the cropping system.

Material and methods

Field experiment

The field experiment started in 1993 and continued for 16 years in the experimental field La Canaleja (40° 32' N, 3° 20' W, 600 m altitude), near Madrid, Spain. Winter barley had been grown under CT for more than 10 years before the beginning of the experiment (Martín-Rueda *et al.*, 2007).

Meteorological information was recorded by a weather station located in the experimental field. The climate in the area is mild Mediterranean with dry summer and wet winter (Papadakis, 1966). For the studied period (1993-2009) average annual maximum and minimum daily air temperatures were 21 and 6°C, respectively and mean rainfall was 383 mm per year (Suppl. Table1 [pdf online]). The first two years of the experiment were extremely dry, and they were omitted from the simulation study.

The soil was a Calciortidic Haploxeralf characterized by a calcic horizon within a meter of the surface. It had a loam-sandy texture in the two upper horizons (Ap, Bt), changing to sandy with depth (Cca). It had 5% total carbonate, 1% active limestone and an average pH of 7.8 in the upper 60 cm at the beginning of the experiment (Martin-Rueda *et al.*, 2007). Soil characteristics relevant for the water balance were determined for each horizon in samples taken at the beginning of the study (Table 1).

The experimental design was a split plot with four random repetitions: tillage system was the main plot and rotation was the subplot. There were a total of 40 (10 m × 25 m) subplots. The two tillage systems were: i) conventional tillage (CT): soil was moldboard ploughed (20 cm depth) and then a field cultivator was used to prepare the seed bed; crops were sown with a seed drill; ii) no tillage (NT): herbicide (glyphosate, 12% w/v, 2 L ha^{-1}) was applied for weed control two weeks before sowing; under NT a direct seed drill was used. To maintain fallow subplots free of weeds, either ploughing (mouldboard or chisel) or herbicide (according to the management practices) were applied in February and,

Table 1. Soil characteristics measured in the field experiment and used in the simulations: volumetric water content at wilting point (LL), drained soil water limit (DUL), and water content at saturation (SAT), bulk density (BD) and soil hydraulic conductivity (Ksat)

Soil layer (cm)	LL[1] ($cm^3\ cm^{-3}$)	DUL[1] ($cm^3\ cm^{-3}$)	SAT[1] ($cm^3\ cm^{-3}$)	BD[2] ($g\ cm^{-3}$)	Ksat[3] ($cm\ h^{-1}$)
0-7.5	0.065	0.247	0.443	1.34	1.32
7.5-15	0.065	0.255	0.416	1.42	1.32
15-30	0.065	0.270	0.424	1.42	1.32
30-105	0.065	0.234	0.424	1.42	1.32

[1] LL, DUL and SAT were determined with the moisture retention curve measured with the pressure membrane apparatus (Richards, 1947). [2] BD was determined by the field core method (Blake & Hartge, 1986). [3] Ksat was determined with unaltered samples following Klute & Dirksen (1986).

if necessary, a cultivator (10-15 cm depth) or herbicide were applied in spring (May). Crops were sown at the end of October. Sowing rate was 170 kg ha^{-1} for barley (*Hordeum vulgare* L. cv.Tipper), 190 kg ha^{-1} for wheat (*Triticum aestivum* L. cv. Astral), 120 kg ha^{-1} for pea (*Pisum sativum* L. cv. Déclic), 100 kg ha^{-1} for vetch (*Vicia sativa* L. cv. Vereda) and 8 kg ha^{-1} for rapeseed *(Brassica napus* L. cv. Rafaela). Cereals were fertilized at sowing with 200 kg ha^{-1} of NPK 8-24-8. A second fertilization with 200 kg ha^{-1} of ammonium nitrate (27% N) was applied in March. At sowing, 300 kg ha^{-1} of 15-15-15 was applied to rapeseed. Ammonium nitrate (27% N) was applied after emergence at 300 kg ha^{-1}. Legumes were not fertilized. All crops were harvested in June. Biomass and yield were measured by manual sampling of two 0.7 m × 0.7 m representative squares on each subplot, separation and weighting of straw and grain. After harvest, the straw was chopped and spread all over the soil surface in all the treatments. A detailed description of the experiment can be found in Martin-Lammerding *et al*. (2011).

The experiment was divided into two periods separated by an all-fallow year. In the first period (1993-2001), a continuous barley crop (BB) was compared to two rotations of fallow-barley (FB) and vetch-barley (VB). Each rotation of FB and VB was replicated in alternate years, thus there is data for each crop of the rotation every year. In the 2004-2005 year, all plots were left to fallow. During the second period of the study (2005-2009), the continuous crop was wheat and a single crop rotation composed of fallow-wheat-pea-barley was replicated four times to have every year plots with each component of the rotation. Table 2 summarizes the rotation evolution during the whole study.

The SOC and SN were determined in samples taken at 0-7.5 cm 7.5-15 and 15-30 cm depth in different years over the studied period (1995 to 1997, and 2006 to 2008). Organic soil carbon (SOC) was determined by the Walkley-Black wet digestion method (Nelson & Sommers, 1996) and total soil nitrogen (SN) was measured by Kjeldalh digestion (Bremner & Mulvaney, 1982).

Crop and soil model simulations

Version 4.5 of DSSAT (Hoogenboom *et al*., 2010) was used in this study. The crop models tested were CERES-Barley (Otter-Nacke *et al*., 1991) and CERES-Wheat (Ritchie & Otter-Nacke, 1985; Godwin *et al*., 1990) for winter cereals and CROPGRO (Boote *et al*., 1998) for vetch and rapeseed. The DSSAT-CENTURY

Table 2. Crop rotation over the experimental period, for the continuous barley (BB), fallow-barley (FB) and vetch-barley (VB) treatments

Year	Crop rotation				
	BB	FB[2]		VB[2]	
		FB1	FB2	VB1	VB2
1993-1994[1]	Barley	Fallow	Barley	Vetch	Barley
1994-1995[1]	Barley	Barley	Fallow	Barley	Vetch
1995-1996	Barley	Fallow	Barley	Vetch	Barley
1996-1997	Barley	Barley	Fallow	Barley	Vetch
1997-1998	Barley	Fallow	Barley	Vetch	Barley
1998-1999	Barley	Barley	Fallow	Barley	Vetch
1999-2000	Barley	Fallow	Barley	Vetch	Barley
2000-2001	Barley	Barley	Fallow	Barley	Vetch
2001-2002	Fallow	Rapeseed	Wheat	Vetch	Barley
2002-2003	Wheat	Fallow	Vetch	Barley	Rapeseed
2003-2004	Vetch	Wheat	Barley	Rapeseed	Fallow
2004-2005	Fallow	Fallow	Fallow	Fallow	Fallow
2005-2006	Barley	Pea	Wheat	Wheat	Fallow
2006-2007	Fallow	Barley	pea	Wheat	Wheat
2007-2008	Wheat	Fallow	Barley	Wheat	Pea
2008-2009	Pea	Wheat	Fallow	Wheat	Barley

[1] Years too dry that were not included in the simulation study. [2] Each rotation of FB and VB was replicated in alternate years, thus there is data for each crop of the rotation every year.

Table 3. Genetic coefficients for barley and wheat in the CERES models

Symbol	Definition	Barley	Wheat
P1V	Days, at optimum vernalizing temperature, required for vernalization	26	26
P1D	Photoperiod response	145	52
P5	Grain filling phase duration (GDD)	100	520
G1	Kernel number per unit canopy weight at anthesis (No. g^{-1})	50	24
G2	Standard kernel size under optimum conditions (mg)	80	33
G3	Standard, non-stressed mature tiller wt (including grain) (g)	0.5	1.0
PHINT	Interval between successive leaf tip appearances (GDD)	89	95

GDD: growing degree-days (°C d).

model (Parton *et al*., 1992; Gijsman *et al*., 2002) was used for the soil organic matter. Simulations centered on barley biomass and yield for the period 1995-2001, and on SOC and SN in the VB1 rotation (see Table 2) for the whole period (1995-2009) .

Genetic coefficients of the barley variety were calibrated with data from the CT-BB plots on four climatic-representative years (1994-1998). CERES- Barley requires the estimation of seven cultivar dependent coefficients (Table 3). The seven coefficients were estimated on the basis of information on planting, anthesis, and harvest dates, together with observed biomass and yield. P1V and P1D coefficients were adjusted to predict the measured anthesis dates and P5 was adjusted according to the day of maturity. Measured yield and biomass were used to calibrate G1, G2 and G3 coefficients. The light extinction coefficient (KCAN) was also adjusted to improve DSSAT simulations. KCAN is set by default at 0.85 in the ecotype file in DSSAT V4.5. However, reported k-values for cereals based on PAR wave lengths, ranged from 0.41 to 0.66 for barley (Gregory *et al*., 1992; Goyne *et al*., 1993), so a value of 0.55 was employed for our simulations. Genetic coefficients of the wheat cultivar were also calibrated by using measured data from the CT-VB plots on one climatic-representative year (2006-2007) (Table 3). They were estimated according to field observations of planting and harvest dates together with measured biomass and yield. A KCAN coefficient of 0.55 was used. The calibrated coefficients for our barley and wheat varieties are shown in Table 3.

The photosynthesis factor (SLPF) used in the soil file was 0.75, to limit daily plant growth due to less than optimum soil conditions. The root growth factor (SRGF) was 1, 1, 0.8 and 0.6 for 8, 15, 30 and 105 cm of depth in the soil profile, allowing crops extend roots without an impeding soil layer.

CROPGRO model was used to simulate vetch and rapeseed in the barley-vetch rotations. As there is no specific model within DSSAT for these crops, the faba bean CROPGRO model was used. The genetic coefficients of the vetch variety were adapted from a comparable cultivar previously calibrated in a study (Gabriel & Quemada, 2011) in a nearby location in Aranjuez (Madrid) (40° 03' N, 3° 30' W and 570 m), with similar edapho-climatic conditions than our studied field. To calibrate vetch genetic coefficients only 2002-2003 biomass was available. Rapeseed coefficients were approximated using the yield registered in 2002-2003 season. Calibrated coefficients for vetch and rapeseed are shown in Table 4.

After calibration, the CERES-Barley model was used to simulate barley yield and biomass in a 6-year period (1996-2001) for all the tillage-rotation treat-

Table 4. Genetic coefficients modified for vetch and rapeseed in CROPGRO model

Symbol	Definition	Vetch	Rapessed
SD-PM	Time between first seed and physiological maturity (photothermal days)	30.8	32.80
Fl-LF	Time between first flower and end of leaf expansion (photothermal days)	42	45
LFMAX	Maximum leaf photosynthesis rate at 30 C, 350 vpm CO_2, and high light (mg CO2 m^{-2} s^{-1})	0.85	1
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	272	300
SIZLF	Maximum size of full leaf (three leaflets) (cm^2)	100	110
WTPSD	Maximum weight per seed (g)	1	1.04
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	21	20
THRSH	The maximum ratio of [seed/(seed + shell)] at maturity	77	70.9

ments. CERES- Wheat model was employed to simulate wheat. The sequence analysis utility in DSSAT was used to simulate the sequences or crop rotations.

The soil organic matter evolution was simulated with the DSSAT-CENTURY model in a 15 year-period (1995-2009) for the VB1 rotation under CT and NT. Simulated SOC and SN for the two tillage systems were compared to observed data. Initial soil C and N was estimated by changing the organic carbon percentage (SLOC), and the total nitrogen percentage (SLNI), in the soil profile until the total SOC and SN simulated at the beginning of the experiment, matched with the observations. Stover at harvest of previous crop was incorporated as residue of the following crop with model-simulated inputs of C and N.

Three statistical indices were calculated to evaluate the accuracy of model simulations: root mean square error (RMSE), index of agreement or d-stat (Willmott, 1982), and linear regression between observed and simulated parameters.

Results

Calibration

The barley model was calibrated with measurements on anthesis day, yield, and biomass. Mean observed anthesis date of barley was 192 days after planting (DAP). Calibration improved DSSAT simulated value from 146 DAP to 198 DAP, resulting in a great decrease in the RMSE between observed and simulated values (Table 5). Before calibration, the model overestimated yield and biomass. Setting the yield coefficients (G1, G2 and G3) improved simulated biomass and yield of barley. The RMSE of yield decreased by 82% and RMSE of biomass by 75% (Table 5). The indices of agreement also improved after calibration, reaching values close to one (0.95 for biomass and 0.98 for yield). The linear determination coefficient (R^2) after calibration was 0.92 for yield and 0.86 for biomass as shown in Fig. 1. After calibration, CERES-barley was validated for all the tillage-rotation treatments (Table 6). Wheat calibration employed the observed biomass and yield for the 2006-2007 year, reaching a 99.85% reduction of yield RMSE and a 99.97% reduction of biomass RMSE for that year (Table 5). Then, the wheat model was tested for the whole period under CT and NT (Table 7). Rapeseed was included in the field rotations only in three occasions but just one season (2002-2003) provided harvest measurements of grain yield. Vetch on the other hand, was included systematically in the rotations, yet it was harvested and biomass data collected only in 2002-2003.The results for vetch and rapeseed calibration are shown in Table 5.

DSSAT Model testing: barley yield and growth

The model correctly simulated barley yield of the VB rotation with an index of agreement of 0.9 in CT

Table 5. Observed and DSSAT simulated values and comparison statistics in the continuous barley plots for barley phenology and growth

Crop and year	Before calibration				After calibration			
	Obs.	Sim.	RMSE[1]	d-Stat[2]	Obs.	Sim.	RMSE	d-Stat
Barley 1994-1998								
Anthesis day (DAP)[3]	192	146	49	0.1	192	198	22	0.2
Tops weight (kg ha^{-1})	4,923	6,764	3,014	0.7	4,923	4,783	767	0.95
Maturity yield (kg ha^{-1})	2,579	3,427	1,820	0.7	2,579	2,586	335	0.98
Wheat 2007								
Tops weight (kg h^{-1})	5,644	11,642	5,998	—	5,644	5,642	2	—
Maturity yield (kg ha^{-1})	2,007	6,719	4,712	—	2,007	2,014	7	—
Vetch 2003								
Tops weight (kg ha^{-1})	2,605	3,164	559	—	2,605	2,605	0	—
Rapeseed 2003								
Maturity yield (kg ha^{-1})	1,121	1,243	122	—	1,121	1,121	0	—

[1] RMSE: root mean square error. [2] d-Stat: d-statistic or index of agreement (Willmott, 1982). [3] DAP: days after planting. —: not calculated because lack of enough data.

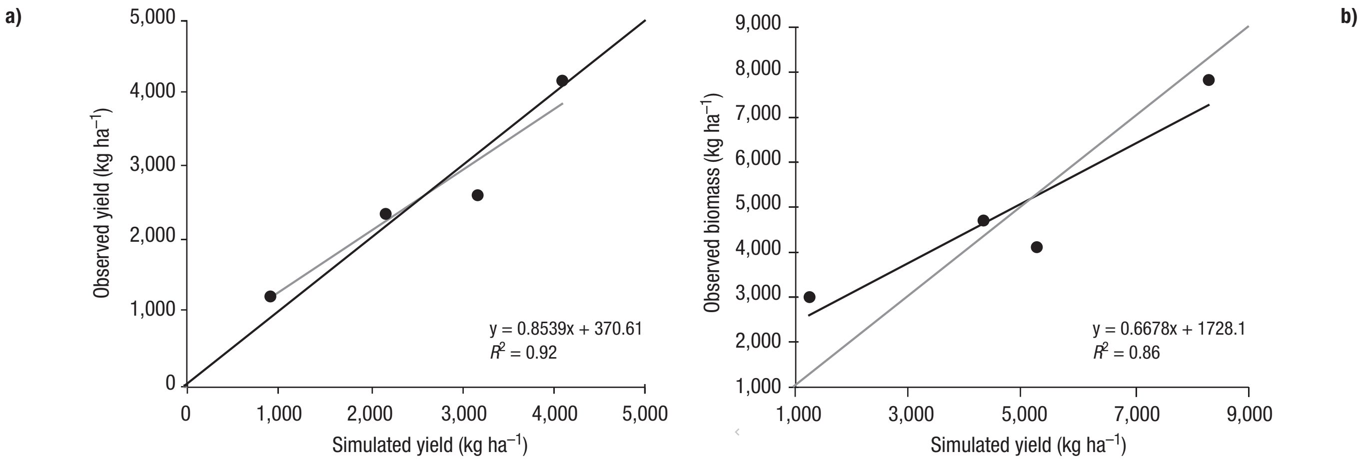

Figure 1. Barley yield (a) and biomass (b) after calibration in the CT-BB for seasons 1994-1995 through 1997-1998.

and 0.8 in NT. For total aboveground biomass, the best result was also found in the VB simulation with an index of agreement of 0.8 for both tillage systems. However in the simulations of BB and FB rotations, barley yield and biomass were overestimated by the model in both CT and NT. Observed data showed that rotations of FB (which includes FB1 and FB2 rotations) and VB (which includes VB1 and VB2 rotations), improved barley yield and biomass for both tillage managements compared to BB over the whole studied period. This trend was also observed in the simulated values (Table 6). Comparing by year (Fig. 2), the highest yield was found in the VB rotations reaching 8,152 kg ha^{-1} (simulated) and 7,489 kg ha^{-1} (observed) in the year 2000.The VB rotation showed the highest value of observed biomass (11,097 kg ha^{-1})

Table 6. Mean DSSAT simulated and observed barley yield and total aboveground biomass (kg ha^{-1}) per tillage-rotation. Data averaged across the 6 years (1996-2001), n = 24

	Yield (kg ha^{-1})								Biomass (kg ha^{-1})							
	CT				NT				CT				NT			
	Obs.	Sim.	RMSE	d-Stat	Obs.	Sim.	RMSE	d-Stat	Obs.	Sim.	RMSE	d-Stat	Obs.	Sim.	RMSE	d-Stat
BB	2,679	3,624	980	0.7	2,184	3,367	1,397	0.5	4,558	6,758	2,231	0.7	4,354	5,429	962	0.5
FB	3,863	4,124	1,855	0.6	3,574	3,661	984	0.5	6,458	8,300	3,665	0.1	6,616	6,387	1,209	0.5
VB	4,362	4,071	1,157	0.9	3,333	3,454	848	0.8	7,170	7,771	2,481	0.8	6,312	5,533	911	0.8

CT: conventional tillage. NT: no tillage. RMSE: root mean square error. d-Stat: d-statistic or index of agreement (Willmott, 1982). n = number of observations. FB: average between FB1 and FB2 for the 1996-2001 period. VB: average between VB1 and VB2 for the 1996-2001 period.

Table 7. Mean DSSAT simulated and observed wheat yield and total aboveground biomass (kg ha^{-1}) per tillage in the VB1 rotation. Data averaged across the 4 years (2005-2009), n = 16

Tillage	Yield (kg ha^{-1})				Biomass (kg ha^{-1})			
	Obs.	Sim.	RMSE	d-Stat	Obs.	Sim.	RMSE	d-Stat
CT	2,018	1,909	551	0.2	4,886	5,338	1,999	0.2
NT	1,533	1,882	804	0.3	4,293	5,283	2,282	0.2

RMSE: root mean square error. d-Stat: d-statistic or index of agreement (Willmott, 1982). n: number of observations. CT: conventional tillage. NT: no tillage.

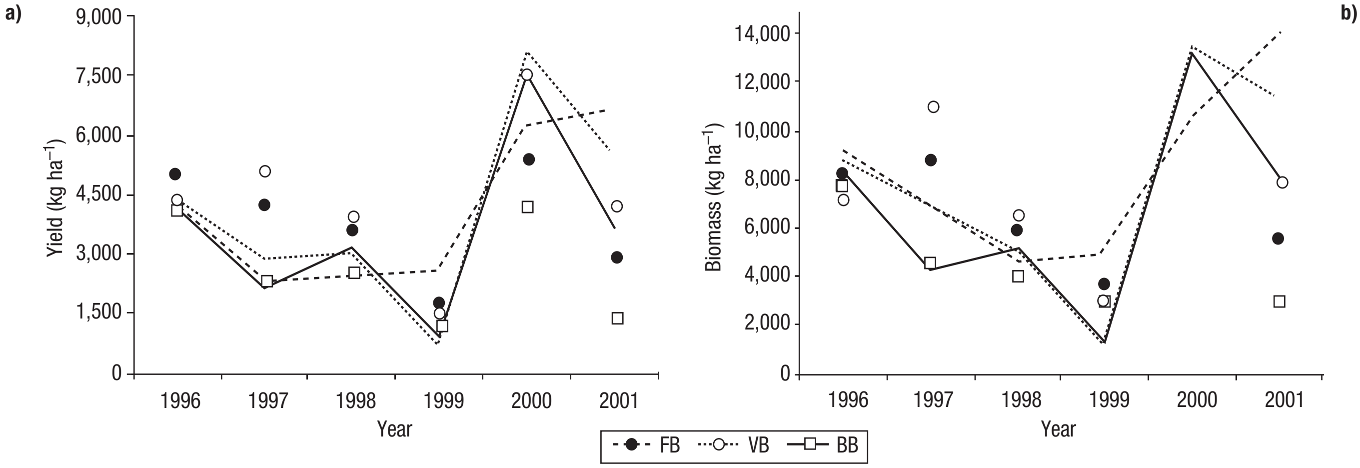

Figure 2. Observed (symbols) and simulated (lines) yield (a) and biomass (b) for continuous barley (BB), barley after fallow (FB = FB1 or FB2 rotation depending of the year) and barley after vetch (VB = VB1 or VB2 rotation depending of the year) during a 6-year period (1996-2001).

in the year 1997. For the other hand, the highest simulated biomass (14,085 kg ha^{-1}) was found in the FB rotation in 2001. Observed biomass for the year 2000 was unavailable, so these data are missing in Figs. 2 and 3.

Comparing by tillage system, field measurements indicated higher yields in CT than in NT treatments (Table 6). Observed biomass was also higher in CT than in NT except for FB that was the opposite. Simulations showed also higher yield and biomass in CT than in NT in all the rotations. Fig. 3, shows the comparison of tillage systems per year. Yield and biomass in both observed and simulated values were higher in CT than in NT except in the year 1999. The highest yield was found in CT on 2000 for both simulated and observed values (7389 kg ha^{-1} and 5729 kg ha^{-1}, respectively). The smallest yield and biomass was produced in 1999 for both tillage systems and for both observed and simulated values.

DSSAT Model testing: SOC and SN

SOC was satisfactorily simulated compared to the field observations, with a determination coefficient (R^2) of 0.96 for CT and 0.85 for NT (Table 8). The index of agreement between observed and simulated SOC was very high for both tillage systems (0.98 for CT and 0.99 for NT). The RMSE was 1,246 kg ha^{-1} in CT and 532 kg ha^{-1} in NT. The SN was also well simulated showing a good fit index (0.98 for CT and 0.95 for NT) and a high R^2 (0.96 for CT and 0.84 for NT). As shown in Fig. 4, field measurements of SOC and SN accumulated with time along the studied period. The simulations also showed this accumulation. At the beginning of the experiment, SOC simulated in the first 7.5 cm of soil was similar for both management systems. However, starting on the sixth year of the experiment SOC tended to be higher in NT than in CT, and these differences increased with time (Fig. 4a). The

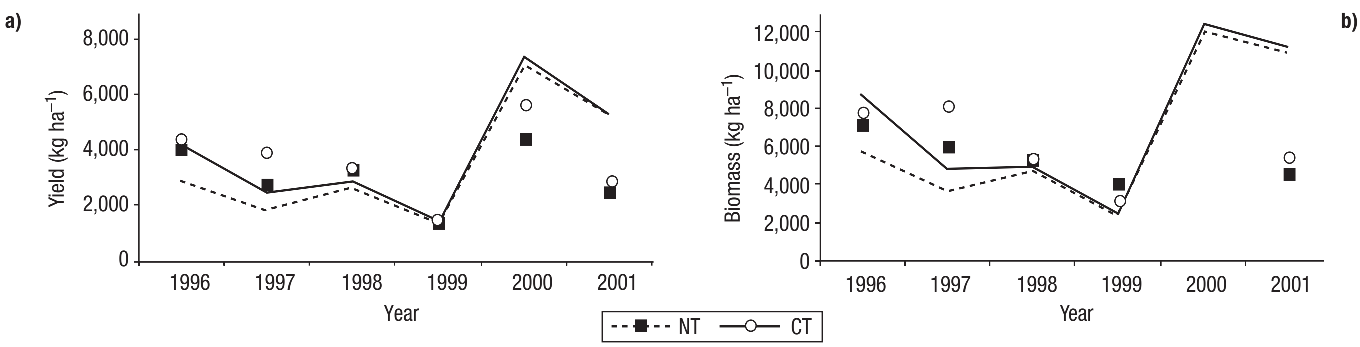

Figure 3. Observed (symbols) and simulated (lines) barley yield (a) and biomass (b) in no tillage (NT) and conventional tillage (CT). Each yearly value results from averaging all the rotations.

Table 8. Mean simulated and observed soil organic carbon (SOC) and soil organic nitrogen (SN) (kg ha^{-1}) in the 0-7.5 cm soil profile. Data averaged per tillage system across the whole period (1996-2009)

	SOC (kg ha^{-1})					SN (kg ha^{-1})				
	Obs.	Sim.	RMSE	d-Stat	R^2	Obs.	Sim.	RMSE	d-Stat	R^2
CT	4,556	5,776	1,246	0.98	0.96	544	658	152	0.98	0.96
NT	7,015	6,278	532	0.99	0.85	773	669	87	0.95	0.84

RMSE: root mean square error. d-Stat: d-statistic or index of agreement (Willmott, 1982). R^2: determination coefficient. CT: conventional tillage. NT: no tillage.

highest SOC was found at the end of the period in the NT (9,839 kg ha^{-1} observed and 8,820 kg ha^{-1} simulated in 2007). The SN resulted in a similar trend as SOC (Fig. 4b). The first seven years, the simulated SN under CT and NT was similar but it began to diverge from the eighth year. The tendency shows an increase in the SN in the first 7.5 cm of soil in the NT system over the CT system. The highest values of observed and simulated SN are found in the NT system at the end of the period. The SOC and SN content with depth were analyzed in Fig. 5. The biggest differences between tillage systems were found in the first centi-

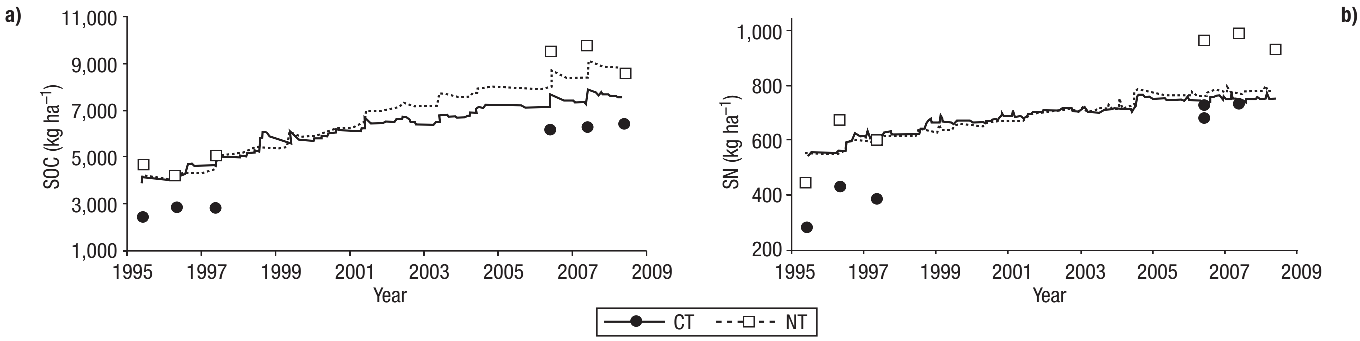

Figure 4. Observed (symbols) and simulated (lines) soil organic carbon (SOC) (a) and total soil nitrogen (SN) (b) in no tillage (NT) and conventional tillage (CT) in the 0 to 7.5 cm soil profile.

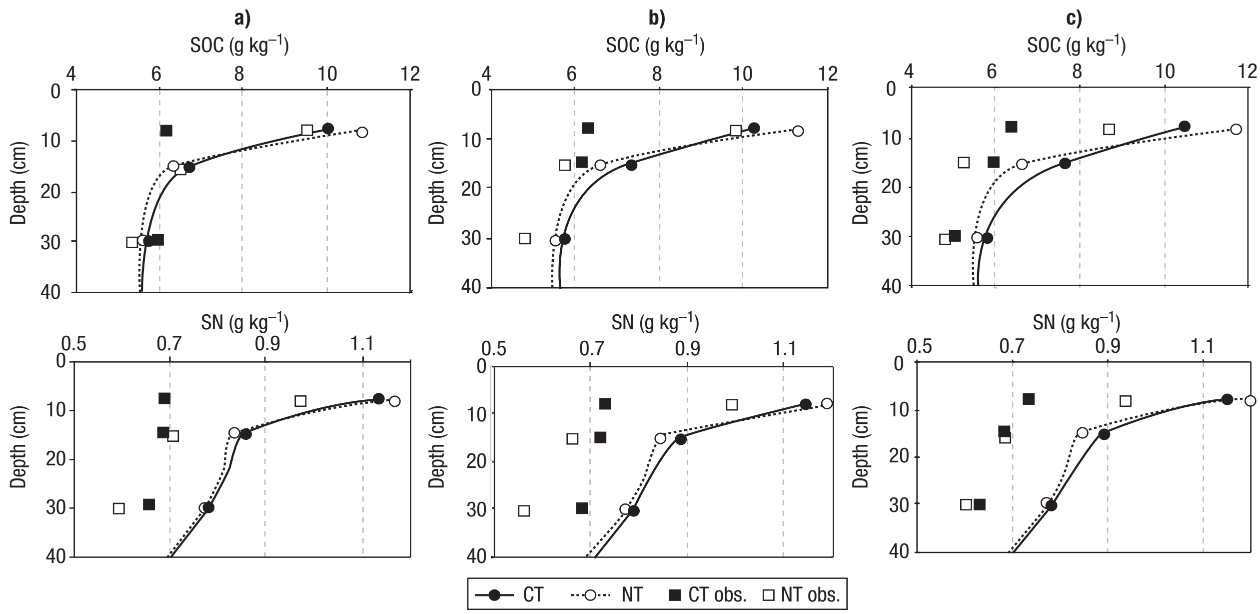

Figure 5. SOC and SN distribution (g kg^{-1}) with depth for 2006 (a), 2007 (b) and 2008 (c). Lines represent simulated values and symbols represent the observed values.

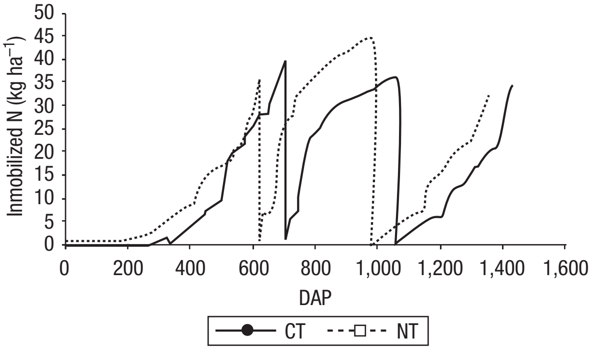

Figure 6. Evolution of the simulated immobilized N (kg ha^{-1}) in soil for conventional (CT) and no tillage (NT). DAP: days after planting.

meters of soil. In deeper layers, SOC and SN values for both systems were closer. In the first 10 cm of soil observed and simulated SOC and SN, were higher in NT than in CT for the plotted years. Simulated and observed SOC and SN concentration decreased with depth in both tillage systems, showing a sharper decrease in soils under NT than those under CT (Fig. 5). On the other hand, soil N simulations indicated that N immobilized in soil was higher in NT than in CT (Fig. 6).

Discussion

Simulations of barley yield and biomass greatly improved after model calibration. Yield and biomass were correctly simulated by the CERES-Barley model most of the period, resulting in simulated values close to observed. Similar results have been found previously under a wide range of conditions. For example, Travasso & Magrin (1998) working in Argentina under rainfed conditions with five cultivars and five sowing dates, concluded that CERES-Barley model was able to produce good yield estimates. Wheat calibration was also satisfactory, reducing the RMSE of yield and biomass around 99%. After calibration however, model testing results were poor and showed low indexes of agreement. Although previous authors have found inadequate estimates of wheat yields using CERES-Wheat (Landau *et al*., 1998), our uncertainty on observed wheat phenology (approximate dates of sowing, anthesis, and maturity) probably influenced our results.

Observed barley yield was lower in the BB rotations than in the FB (FB1 and FB2) and the VB (VB1 and VB2) rotations for the whole studied period. CERES-Barley reflected that trend as shown in Table 6, being the mean simulated yield higher in rotations than in monoculture. Similar results were found for barley biomass.

DSSAT model showed differences in yield and biomass associated to the tillage system. Similar to observations, CERES-Barley simulated higher yield and biomass in CT than in NT (Fig. 3). Using DSSAT we examined possible reasons for these results. One possibility could be that the soil water storage in CT was higher than in NT (data not shown). Simulated soil water content however, was similar in CT and NT. Soil N simulations indicated that N immobilized in soil was higher in NT than in CT. This could explain the lower yield in NT, due to limited N availability in that management. There are many studies suggesting enhanced N availability in CT since the microorganisms have more accessibility to crop residues (Silgram & Shepherd, 1999). Moreover, the presence of residues in NT could also promote N immobilization (Murillo *et al*., 2001). In addition to N immobilization, larger weed population observed in NT compared to CT plots may have also reduced yields, although this was not simulated with DSSAT.

SOC and SN were satisfactorily simulated compared to field observations, particularly SOC. It has been shown that the incorporation of CENTURY model in DSSAT made the model able to produce good long-term estimates of SOM (Gijsman *et al*., 2002). Basso *et al.* (2011) found excellent results comparing CENTURY simulations of SOC with measured data. In this study, we obtained an index of agreement close to one in all the simulations (Table 8). However, DSSAT overestimated SOC and SN in CT by 26% and 20% respectively but underestimated them in NT by as much as 10% in the case of SOC and 13% in SN. The analysis of the first 7.5 cm of soil showed that SOC and SN are accumulated over time in both simulated and observed values (Fig. 4). For that depth, simulated and observed values showed higher SOC and SN in NT than in CT after 6-8 years from the beginning of the experiment. Carter & Rennie (1982) and Rhoton (2000) also observed differences in SOC 4 to 5 years after the beginning of the NT system adoption. These results support the view that NT is a good choice to improve long-term soil quality, as shown in those experiments where there is time enough to observe its benefits. Other authors have found similar results showing an increase in the SOM in the first centimeters in soils with initially low organic matter content (Álvaro-Fuentes *et al*., 2008; Hernanz *et al*., 2009; Sombrero & De Benito, 2010). This is one of the advantages of using conservation tillage systems and makes it a very interesting option in low organic matter soils. Observed and simulated SOC and SN exhibited similar trends decreasing with depth (Fig. 5). The results from the observed and simulated values suggest that CT-VB and CT-FB were the best combinations for the dryland conditions studied. However, CT had the lowest SN and SOC while NT maintained higher SOC and SN. Both, simulated and observed values displayed these results. The ability of DSSAT to represent various tillage-rotation system scenarios makes it a good option to simulate cropping systems in dryland conditions, where the effects of tillage in water, nutrient, and soil organic matter, are extremely important. This is an example of how models can be a useful tool for estimating crop growth and yield under various managements, and assessing the mid-term impact of alternative tillage systems on soil quality.

In conclusion, the DSSAT-CERES model performed relatively well modeling barley biomass and yield in our experimental field. SOC and SN were also satisfactorily simulated compared with field observations. The beneficial effect of NT on SOC and SN under semiarid Mediterranean conditions can be identified by field observations and correctly reproduced by crop model simulations. Complementary economic and energy balance evaluations are needed to decide which are the best management practices for the area. However, the use of models to simulate combinations of tillage systems and crop rotations constitute a powerful tool assisting decision making to identify efficient system management options, increasing yields and decreasing environmental impacts, in specific edapho-climatic conditions.

Acknowledgements

This work was funded by Comunidad Autónoma Madrid (AGRISOST, S2009/AGR1630).

References

Al-Kaisi M, Yin X, 2005. Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn-soybean rotations. J Environ Qual 34: 437-445.

Altieri MA, 1999. The ecological role of biodiversity in agroecosystems. Agric Ecosyst Environ 74: 19-31.

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(1-2): 261-272.

Álvaro-Fuentes J, Arrúe JL, Cantero-Martínez C, López MV, 2008. Aggregate breakdown during tillage in a Mediterranean loamy soil. Soil Till Res 101: 62-68.

Basso B, Gargiulo O, Paustian K, Robertson GP, Porter CH, Grace PR, Jones JW, 2011. Procedures for initializing soil organic carbon pools in the DSSAT-CENTURY model for agricultural systems. Soil Sci Soc Am 75(1): 69-78.

Blake GR, Hartge KH, 1986. Particle density. In: Methods of soil analysis. Part 1 - Physical and mineralogical methods, 2nd ed (Klute A, ed). Am Soc of Agronomy, Madison, WI, USA.

Blanco-Canqui H, Lal R, 2008. No-tillage and soil-profile carbon sequestration: an on farm assessment. Soil Sci Soc Am J 72: 693-701.

Bonari E, Mazzoncini M, Caliandro A, 1994. Cropping and farming systems in Mediterranean areas. Proc III European Society of Agronomy Congress, Padova (Italy). pp: 636-644.

Boote KJ, Jones JW, Hoogenboom G, Pickering NB, 1998. The CROPGRO model for grain legumes. In: Understading options for agricultural production (Tsuji GY, Hoogenboom G, Thornton, eds). Kluwer Acad Publ, Boston, USA. pp: 99-128.

Bremner JM, Mulvaney CS, 1982. Nitrogen-Total. In: Methods of soil analysis, Part 2: Chemical and microbiological properties, 2nd ed (Page AL, Miller RH, Keeney DR eds). Agronomy Society of America, Madison, WI, USA.

Buschiazzo DE, Panigatti JL, Unger PN, 1998. Tillage effects on soil properties and crop production in the subhumid and semiarid Argentinean Pampas. Soil Till Res 49: 105-116.

Carter MR, Rennie DA, 1982. Changes in soil quality under zero tillage farming systems: distribution of microbial biomass and mineralizable C and N potentials. Can J Soil Sci 62: 587-597.

Dolan MS, Clapp CE, Allmaras RR, Baker JM, Molina JA, 2006. Soil organic carbon and nitrogen in a Minnesota soil as related to tillage, residue and nitrogen management. Soil Till Res 89: 221-231.

Foereid B, Hogh-Jensen H, 2004. Carbon sequestration potential of organic agriculture in northern Europe – A modelling approach. Nutr Cycl Agroecosys 68: 13-24.

Gabriel JL, Quemada M, 2011. Replacing bare fallow with cover crops in a maize cropping system: yield, N uptake and fertiliser fate. Eur J Agron 34: 133-143.

Gál A, Vyn TJ, Michéli E, Kladivko EJ, McFee WW, 2007. Soil carbon and nitrogen accumulation with long-term no-till *versus* moldboard plowing overestimated with tilled-zone sampling depths. Soil Till Res 96: 42-51.

Galdos MV, Cerri CC, Cerri CEP, Paustian K, Van Antwerpen R, 2009. Simulation of soil carbon dynamics under sugarcane with the CENTURY model. Soil Sci Soc Am J 73: 802-811.

Gijsman AJ, Hoogenboom G, Parton WJ, Kerridge PC, 2002. Modifying DSSAT crop models for low input agricultural systems using a soil organic matter-residue module from CENTURY. Agron J 94: 462-474.

Godwin DC, Singh U, 1998. Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems. In: Understanding options for agricultural production (Tsuji GY, Hoogenboom G, Thornton, eds). Kluwer Acad Publ, Boston. pp: 55-77.

Godwin D, Ritchie JT, Singh U, Hunt L, 1990. A user's guide to CERES Wheat-V2.10. Int Fertiliz Develop Center, Muscle Shoals, AL, USA.

Goyne PJ, Milroy SP, Lilley JM, Hare JM, 1993. Radiation interception, radiation use efficiency and growth of barley cultivars. Aust J Agric Res 44: 1351-1366.

Gregory PJ, Tennant D, Belford RK, 1992. Root and shoot growth, and water and light use efficiency of barley and wheat crops grown on a shallow duplex soil in a mediterranean-type environment. Aust J Agric Res 43: 555-573.

Halvorson AD, 2000. Spring wheat response to tillage and nitrogen fertilization in rotation with sunflower and winter wheat. Agron J 92: 136-144.

Halvorson AD, Wienhold BJ, Black A, 2002. Tillage, nitrogen, and cropping systems effects on soil carbon sequestration. Soil Sci Soc Am J 66: 906-912.

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.

Hoogenboom G, Jones JW, Porter CH, Wilkens PW, Boote KJ, Hunt LA, Tsuji GY, 2010. Decision support system for agrotechnology transfer, Vers 4.5. Volume 1: Overview. University of Hawaii, Honolulu, HI, USA.

Huggins DR, Allmaras RR, Clapp CE, Lamb JA, Randall GW, 2007. Corn soybean sequence and tillage effects on soil carbon dynamics and storage. Soil Sci Soc Am J 71: 255-258.

Hussain J, Olson KR, Ebehar SA, 1999. Long-Term tillage effects on soil chemical properties and organic matter fractions. Soil Sci Soc Am J 63: 1335-1341.

Klute A, Dirksen C, 1986. Hydraulic conductivity and diffusivity: Laboratory methods. In: Methods of soil analysis, Part 1. Physical and mineralogical methods (Klute A, ed). ASA and SSSA, Madison, WI, USA. pp: 635-662.

Lacasta C, Meco R, 1996. Influencia del laboreo en las propiedades químicas de los suelos. Congreso Nacional de Agricultura de Consevación: rentabilidad y medio ambiente. Córdoba, 2-4 de Octubre. pp: 153-155.

Landau S, Mitchell RAC, Barnett V, Colls JJ, Craigon J, Moore KL, Payne RW, 1998. Testing winter wheat simulation models' predictions against observed UK grain yields. Agr Forest Meteorol 89: 85-99.

López-Bellido L, Fuentes M, Castillo JE, López-Garrido FJ, Fernández EJ, 1996. Long-term tillage, crop rotation, and nitrogen fertilizer effects on wheat yield under rainfed Mediterranean conditions. Agron J 88: 783-791.

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

Madejón E, Moreno F, Murillo JM, Pelegrín F, 2007. Soil biochemical response to long-term conservation tillage under semi-arid Mediterranean conditions. Soil Till Res 94: 346-352.

Martin Lammerding D, Hontoria C, Tenorio J.L, Walter I, 2011. Mediterranean dryland farming: effect of tillage practices on selected soil properties. Agron J 103(2): 382-389.

Martín-Rueda I, M.Muñoz-Guerra L, Yunta F, Esteban E, Tenorio JL, Lucena JJ, 2007. Tillage and crop rotation effects on barley yield and soil nutrients on a Carciortidic Haploxeralf. Soil Till Res 92: 1-9.

McGill WB,1996. Review and classification of ten soil organic matter (SOM) models. In: Evaluation of soil organic matter models using existing long-term datasets. NATO ASI Series I, vol 38 (Powslon DS, Smith P, Smith JU, eds). Springer-Verlag, Heidelberg. pp: 111-132.

Melero S, López-Garrido R, Murillo J.M, Moreno F, 2009. Conservation tillage: short- and long-term effects on soil carbon fractions and enzymatic activities under Mediterranean conditions. Soil Till Res 104: 292-298.

Motta ACV, Reaves DW, Touchton JT, 2002. Tillage intensity effects on chemical indicators of soil quality in two coastal plain soils. Commun Soil Sci Plant Anal 33: 913-932.

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 JM, Moreno F, Pelegrin F, 2001. Respuesta del trigo y girasol al laboreo tradicional y de conservación bajo condiciones de secano (Andalucía Occidental). Invest Agr: Prod Prot Veg 16: 395-406.

Nelson DW, Sommers LE, 1996. Total carbon, organic carbon, and organic matter. In: Methods of soil analysis. Part 3. Chemical methods (Sparks DL, ed). SASSSA, Madison, USA. pp: 961-1010.

Otter-Nacke S, Ritchie JT, Godwin DC, Singh U, 1991. A user's guide to CERES Barley-v 2.1. Int Fertiliz Develop Center, Muscle Shoals, AL, USA.

Papadakis J, 1966. Climates of the world and their agricultural potentialities. Editorial Albatros, Buenos Aires. 174 pp.

Parton WJ, McKeown B, Kirchner V, Ojima DS, 1992. CENTURY user's manual. Colorado State Univ, NREL Publ, Fort Collins, CO, USA.

Peel MD, 1998. Crop rotations for increased productivity. North Dakota State Univ Ext Serv, Fargo, ND, USA.

Peigne B, Roger-Estrade D, 2007. Is conservation tillage suitable for organic farming? A review. Soil Use Manage 23: 129-144.

Pryor R, 2006. Switching to no-till can save irrigation water. Univ Nebraska-Lincoln Ext Pub EC196-3. Available in http://ianrpubs.unl.edu/epublic/live/ec196/build/ec196-3.pdf [12 June 2012].

Rhoton FE, 2000. Influence of time in soil response to no-till practices. Soil Sci Soc Am J 64: 700-709.

Richards LA, 1947. Pressure membrane apparatus construction and use. Agr Eng 28: 451-454.

Ritchie JT, Otter-Nacke S, 1985. Description and performance of CERES-Wheat: a user-oriented wheat yield model. USDA-ARS, ARS 38: 159-175.

Silgram M, Shepherd MA, 1999. The effects of cultivation on soil nitrogen mineralization. Adv Agron 65: 267-311.

Smith P, Fang C, Dawson JJC, Moncrieff JB, 2008. Impact of global warming on soil organic carbon. Adv Agron 97: 1-43.

Sombrero A, De Benito A, 2010. Carbon accumulation in soil. Ten-year study of conservation tillage and crop rotation in a semi-arid area of Castile-Leon, Spain. Soil Till Res 107: 64-70.

Sombrero A, De Benito A, González I, Álvarez MA, 2007. Influencia del laboreo sobre las propiedades químicas del suelo en agricultura de conservación. ITACYL. Innovación y Tecnología Agroalimentaria 1: 71-78.

Sommer R, Piggin C, Haddad A, Hajdibo A, Hayek P, Khalil Y, 2012. Simulating the effects of zero tillage and crop residue retention on water relations and yield of wheat under rainfed semiarid Mediterranean conditions. Field Crops Res 132: 40-52.

Travasso MI, Magrin GO, 1998. Utility of CERES-barley under Argentine conditions. Field Crops Res 57(3): 329-333.

Triplett GB, Dick WA, 2008. No-tillage crop production: a revolution in agriculture. Agron J 100: 153-165.

Verhulst N, Govaerts B, Verachtert E, Castellanos-Navarrete A, Mezzalama M, Wall P, Deckers J, Sayre KD, 2010. Conservation agriculture, improving soil quality for sustainable production systems? In: Advances in soil science: food security and soil quality (Lal R, Stewart BA, eds). CRC Press. Boca Raton, FL, USA. pp: 137-208.

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.

Willmott Cort J, 1982: Some comments on the evaluation of model performance. Bull Amer Meteor Soc 63: 1309-1313.