

**Modelling the effect of land management changes on soil organic carbon stocks in  
a Mediterranean cultivated field**

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## **Abstract**

Land management in agricultural lands has important effects on soil organic carbon (SOC) dynamics. These effects are particularly relevant in the Mediterranean region, where soils are fragile and prone to erosion. Increasing interest of modelling to simulate SOC dynamics and the significance of soil erosion on SOC redistribution has been linked to the development of some recent models. In this study, the SPEROS-C model was implemented in a 1.6 ha cereal field for a 150-year period covering 100 years of minimum tillage by animal traction, 35 years of conventional tillage followed by 15 years of reduced tillage by chisel to evaluate the effects of changes in land management on SOC stocks and lateral carbon fluxes in a Mediterranean agroecosystem. The spatial patterns of measured and simulated SOC stocks were in good agreement and their spatial variability appeared to be closely linked to soil redistribution. Changes in the magnitude of lateral SOC fluxes differed between land management showing that during the conventional tillage period the carbon losses is slightly higher ( $0.06 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) compared to the period of reduced till using chisel ( $0.04 \text{ g C m}^{-2} \text{ yr}^{-1}$ ).

Although the results showed that the SPEROS-C model is a potential tool to evaluate erosion induced carbon fluxes and assess the relative contribution of different land management on SOC stocks in Mediterranean agroecosystems, the model was not able to fully represent the observed SOC stocks. Further research (e.g. input parameters) and model development will be needed to achieve more accurate results.

**Keywords:** Spatial modelling; SPEROS-C; Soil organic carbon; Soil redistribution;

Land use history

## **Introduction**

The exchange of carbon between the atmosphere, biosphere and pedosphere occurs through complex interactions as plant photosynthesis, soil respiration and soil organic carbon decomposition (Cao & Woodward, 1998). Because these processes are temperature sensitive and potentially affected by rising CO<sub>2</sub> levels in the atmosphere, the worldwide concern of the potential climatic impact on ecosystem carbon fluxes and the need for strategies to mitigate its effects has triggered a vast amount of research (Mukhopadhyay *et al.* 2016; Kerr, 2007).

The role of soil erosion on terrestrial carbon fluxes has also received increased attention over the last decades, but its potential contribution to the greenhouse gas effect and changing climate remains largely unknown at the global scale (Muluneh *et al.*, 2015; Köchy *et al.*, 2015a; 2015b; García-Díaz *et al.*, 2016). Human-induced land use changes from forest to cultivated landscapes have been a significant source of atmospheric CO<sub>2</sub> (Smith *et al.*, 2000). Particularly, human influence on soils has been more intense in the Mediterranean region because of the long history of cultivation together with overgrazing and deforestation (Novara *et al.*, 2011; García-Ruiz, 2010).

Mediterranean soils are highly susceptible to erosion because of long dry periods followed by erosive rainfall falling on steep slopes with erodible soils, and resulting in high soil erosion rates (Navas *et al.*, 2014; López-Vicente *et al.* 2015). Patterns of erosion, transport and deposition of soil particles are closely linked to those of soil nutrients in agricultural landscapes, (Navas *et al.*, 2012; Quinton *et al.*, 2010) representing a major concern for crop productivity and agriculture sustainability.

Agricultural land use and management has an impact on soil organic carbon (SOC) by modifying carbon inputs (Bruce *et al.*, 1999; Novara *et al.*, 2015a; Parras-Alcantara *et*

*al.*, 2015a). As a consequence, estimates of SOC stocks and their changes over the time in agricultural soils are essential to understand SOC dynamics and identify the management practices that may contribute to sequestering carbon in soils and the temporal scale at which they may do so, which will mainly depend on how and where C is stored in soils (Álvaro-Fuentes and Paustian, 2011).

A number of SOC dynamics models have been developed to understand the short and long-term impact of land management on SOC stocks and fluxes (e.g. CENTURY, Roth-C, ICBM, DNDC) and monitoring changes in carbon fluxes in soil over temporal and spatial scales. Although these models omitted the impact of erosion and deposition on SOC dynamics, effort has been made to increasingly include its effect as in CENTURY5 version, the EDEM model (Liu *et al.*, 2003) or the SOrCERO model (Billings *et al.*, 2010). Despite the progress, these models remain based on a single profile or landscape unit, not allowing the full characterization of landscapes. To overcome this spatial limitation, combined soil erosion and SOC dynamics models are increasingly being used to understand the temporal and spatial significance of the impact of soil erosion on SOC and the carbon cycle.

This is the case of the SPEROS-C model (Van Oost *et al.*, 2005) that combines the soil erosion SPEROS model (Van Oost *et al.*, 2003) and the SOC dynamics Introductory Carbon Balance Model (ICBM, Andrén and Kätterer, 1997). The model has been successfully implemented to simulate soil redistribution and its effect on SOC dynamics within the soil profile in agricultural lands ranging from small catchments (Van Oost *et al.*, 2005, Dlugoß *et al.*, 2012) to the regional scale (Nadeu *et al.*, 2015).

Data concerning SOC dynamics are needed to elucidate the carbon fluxes between soil and atmosphere and its relationships in order to know if an agricultural system acts as a

sink or source of carbon. In this study we apply and evaluate the SPEROS-C model on a rain-fed field characteristic of Mediterranean mountain agroecosystems that has been cultivated for cereals since at least 1860 with two different management practices: minimum and conventional tillage. Minimum tillage practices were implemented from 1860 to 1960's using chisel with animal traction and for the last fifteen years (1995–2010) using chisel with tractor. Conventional tillage was done in the study field from 1960 to 1995 using mouldboard with tractor. Our objective is to assess the model performance and its ability to represent the effect of land management on SOC stocks, SOC fluxes and changes in their spatial distribution.

## **Materials and methods**

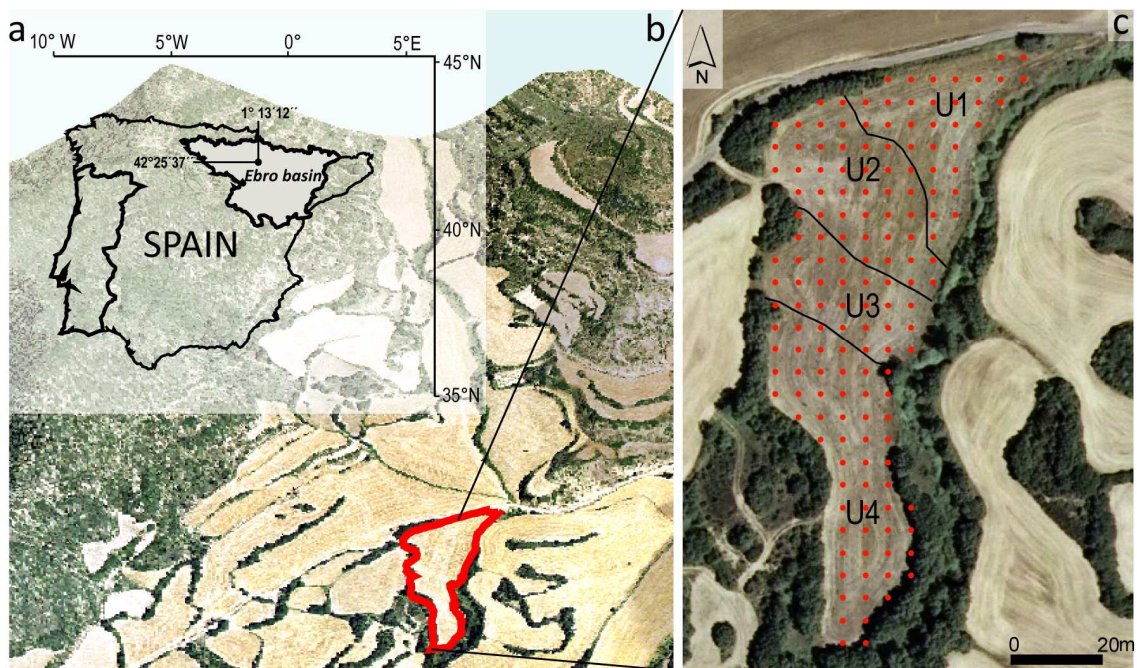
### *2.1. Study area*

The study was conducted on a 1.6 ha rain-fed cereal field situated in the central part of the Ebro Basin (NE Spain) (Fig. 1a). The field has a contrasting topography, the elevation ranges between 622 and 636 m a.s.l. and the slope from 1.1% to 19% (Fig. 1b).

According to the drainage pattern, four hydrological units with different hydrological behaviour are identified associated to particular topographic characteristics (Fig. 1c). The hydrological units U1 and U2 in the northern part of the field have higher slope and elevation. The unit U2 is characterized by the development of a gully system whereas the hydrological units U3 and U4 are in the relatively flat southern part of the field (Quijano et al., 2016b).

The field has been cultivated with winter cereals for the last 150 years as documented by the owner. The main crop was winter barley (*Hordeum vulgare*) and occasionally wheat (*Triticum aestivum L.*). Agricultural practices have changed during the study period (1860–2010) from conservation agriculture done with animal traction and humans, to conventional tillage after introduction of agricultural machinery in 1960. Since 1995 minimum tillage has been implemented using a chisel.

The climate in the study area is continental Mediterranean. Rainfall events mainly occur in spring (April and May) and autumn (September and October). Soils classified as Calcisols, are developed on Quaternary deposits.



**Fig. 1.** a) Location of the study field in the central part of the Ebro basin (NE Spain), b) 3D view of the study area, c) sampling points on a 10x10 m grid (n=156) and limits between the four hydrological units.

## 2.2. Sampling sites and soil analysis

Soil sampling was carried out in 2010. Soil samples (n=156) were collected on a 10 m grid (Fig. 1c) to a depth of 30 cm using a 7 cm diameter automatic core driller. The sampling depth was extended up to 50 cm in the sampling points (n=26) identified as depositional sites according to field observations.

Soil samples were air-dried and passed through a 2-mm sieve. The fine fraction (<2 mm) were used for soil analyses. Particle-size analysis was carried out with a Beckman Coulter LS 13 320 laser. SOC was measured using a LECO RC-612 multiphase carbon analyser. Soil organic carbon stock ( $\text{kg m}^{-2}$ ) for a fixed soil volume was calculated as the product of the organic carbon content (%) by the weight of the <2 mm fraction contained in the volume of the core and divided by the cross section of the core sampler (Quijano *et al.* 2016c).

## 2.3. SPEROS-C model

The SPEROS-C model is a spatially distributed and topography driven soil erosion model which results from the combination of the process-based erosion SPEROS model (Van Oost *et al.*, 2003), and the ICBM model (Andr n and K tterer, 1997). It keeps track of changes in SOC storage within the soil profile and of soil and SOC fluxes from eroded to depositional sites. A detailed description of the SPEROS-C model is included in Van Oost *et al.* (2005) and here we provide a brief explanation of the basic concepts. The model simulates induced soil redistribution by water and tillage using the WATEM model (Van Oost *et al.*, 2000) based on the Revised Universal Soil Loss Equation (RUSLE; Renard *et al.*, 1997) in combination with a sediment transport equation. The

local transport capacity TC ( $\text{kg m}^{-1} \text{a}^{-1}$ ) is assumed to be proportional to the erosion potential:

$$TC = ktc \cdot R \cdot C \cdot P \cdot K \cdot LS \quad (1)$$

Where  $ktc$  (m) is the transport capacity coefficient,  $R$ ,  $C$ ,  $P$ ,  $K$ ,  $L$  and  $S$  are the RUSLE factors.  $R$  is the rainfall erosivity ( $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$ ),  $C$  is the cover-management (dimensionless),  $P$  is the conservation support practice (dimensionless),  $K$  is the soil erodibility ( $\text{Mg ha h ha}^{-1} \text{MJ}^{-1} \text{mm}^{-1}$ ),  $L$  is the slope length (dimensionless) and  $S$  is the slope gradient ( $\text{m m}^{-1}$ ).

The ICBM model (Andrén and Kätterer, 1997) characterizes SOC dynamics considering two state variables, young (Y) and old (O) organic carbon pools, that follow first order kinetics and four carbon fluxes (carbon input from plants, mineralisation from the young and old pools and transformation of young into old pool). Young C pool consists of undecomposed plant residues and roots and old C pool is the slow and passive pool. The C input into the soil by plant residues is estimated as a ratio of crop yield and added to the plough layer, while the C input by roots is assumed to decrease with soil depth. Carbon inputs from crop and roots are derived from the crop-specific aboveground dry biomass which is calculated dividing the annual crop yield by the crop harvest index (Nadeu *et al.*, 2015).

Net vertical carbon fluxes result from the difference between C input to soil and mineralized young and old carbon pools. External factors such as climatic and edaphic are condensed in ICBM into one parameter ( $r$ ). The differential equations describing the dynamics of the two SOC pools are:

$$\frac{dY}{dt} = i - k_y r Y \quad (2)$$



$$\frac{dO}{dt} = hk_y rY - k_o rO \quad (3)$$

Where  $i$  represents the combined inputs from manure, roots and crop residues,  $k_y$  and  $k_o$  are the rate constants for decomposition and  $h$  is the humification coefficient which depends on clay content and the source of C input. Further,  $h$  controls the fraction of the outflux from Y that enters O (Kätterer and Andrén, 1999).

SOC redistribution over the landscape is modelled in SPEROS-C considering vertical changes in the soil profile from the topsoil layer and soil redistribution using the results of the water and tillage erosion.

### 2.3.1. Model inputs and implementation

A single execution of the SPEROS-C model has been applied for the study period (1860 – 2010) assuming a total soil depth of 0.3 m and a plough layer depth of 0.20 m. The model operates in an annual time step with a detailed spatial resolution of 2.5 m. The input parameters of the RUSLE model were calculated according to a previous study by Quijano *et al.* (2016b) who applied the WATEM model in the study field. The length slope factor (LS-factor) was simulated throughout the model run based on the digital elevation model. A temporally and spatially constant value of R-factor was considered for the study field, it was set to  $881 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$  which was calculated using available data at a time resolution of 15 min from the SAIH system of the Hydrographic Confederation of the Ebro River for the period 2005 – 2014. The K-factor was calculated using the equation by Wischmeier and Smith (1978) ranging from 0.010 to  $0.043 \text{ Mg ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$  with a mean value of  $0.035 \text{ Mg ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$ . The C-factor was computed by taking the average of the C factor values for winter barley and wheat and set to 0.2 (NS Department of Agriculture and Fisheries, 2001). The

support practice factor (P-factor) was considered 1.0 (Wall *et al.*, 2002). The main input data required to run SPEROS-C were supplied in the form of IDRISI GIS (Clark Labs Inc.) raster layers.

The ICBM model parameters related to SOC turnover rates for the plough layer were set to  $kY=0.8a^{-1}$  and  $kO=0.006 a^{-1}$  for young and old SOC, respectively (Andrén and Kätterer, 1997). The humification coefficients were set to  $hc=0.125$  and  $hm=0.31$  for crop and manure, respectively (Kätterer and Andrén, 1999). An average, spatially uniform soil bulk density of  $1.68 \text{ g cm}^{-3}$  for the soil profile was implemented. The clay content was set as a spatially distributed map derived from grain size measurements. Clay content ranged between 4.2 and 68.3% with a mean value of 22%. The estimates of the yield data for winter cereal crops were approximately  $3.500 \text{ kg ha}^{-1}$  for the period 1965–2010 and  $2.500 \text{ kg ha}^{-1}$  for 1860 to 1965 according to the owner. Similar values were found from official data of the Regional Government available since 1900.

The ICBM model parameters related to the C input by manure and the coefficient of SOC turnover with depth were parameterized by comparing the measured SOC contents (%) in each soil layer at five sectioned reference profiles with modelled SOC concentrations without running the soil redistribution component. A high Pearson's correlation coefficient between them was found ( $r=0.985$ ,  $p<0.05$ ) resulted in an annual manure C input of  $0.01 \text{ kg m}^{-2}$  and the exponent for the reduction of turnover rate with depth was set to 5.

### *2.3.2. Model calibration*

The SPEROS-C model was calibrated comparing the values of modelled SOC stocks for each combination of input parameters with the SOC stocks measured in the study

samples. Following several set-up runs, the transport capacity coefficient was iteratively adjusted to obtain the best fit between modelled and measured SOC stocks. We assessed the model performance based on the goodness of fit between measured and modelled SOC stocks at the same locations. Two approaches were considered: (i) a comparison for SOC stock distributed throughout the entire field and (ii) a comparison of SOC stock for each of the four defined hydrological units.

The goodness of fit of the model results was evaluated using the Nash–Sutcliffe (NS) model efficiency (Nash and Sutcliffe, 1970). In addition to NS model efficiency, two error statistics as R-squared ( $R^2$ ) and mean error (ME) have been used for the evaluation of model performance.

The transport capacity coefficient was calibrated at 15 m for the study period using a set of values ranging between 0 to 55 m (Nadeu *et al.*, 2015). Soil redistribution rates were estimated by applying the conversion models by Soto and Navas (2004, 2008). The resulting mean soil erosion rate was  $12.2 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  that matched with the derived  $^{137}\text{Cs}$  estimates of soil erosion for the study field with a mean value of  $19.7 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ .

#### *2.4. Statistical analysis*

Data were analysed using SPSS 19.0 (Chicago, IL, USA). One-way analysis of variance (ANOVA) was performed to assess the statistical significance of the effects of soil redistribution and land management on SOC stocks.

The spatial distribution of SOC stocks was derived by ordinary kriging, using a spherical semivariogram model with trend. The output maps and interpolations were performed using ESRI ArcGIS 10.2.1 software.

## Results

### 3.1. Model performance

The results of the goodness of fit between measured and modelled SOC stocks (Table 1) showed a better model performance for hydrological unit U2, which had a better goodness of fit of the model than the rest of hydrological units and also for the whole field. The NS statistic for hydrological units 1, 3 and 4 were 0.06, -0.26 and -0.11, respectively, the NS values close to 0 or negative indicated a poor model performance.

**Table 1.** Model evaluation statistics for the entire field and the hydrological unit U2.

	Field	U2
ME	-5.64	-14.09
NS	0.14	0.32
R <sup>2</sup>	0.15	0.53

### 3.2. Measured versus modelled SOC stocks

The measured stocks of SOC for the entire soil profile ranged between 0.9 and 7.3 kg m<sup>-2</sup> with a mean value of 3.5±0.9 kg m<sup>-2</sup>. The most frequent values (74%) ranged from 2.5 to 4.5 kg m<sup>-2</sup>. Modelled SOC stocks for the same exact locations and soil depth at the end of the simulation (i.e. year 2010) showed a range of values between 2.8 and 4.5 kg SOC m<sup>-2</sup> with a mean SOC stock value of 3.6±0.9 kg m<sup>-2</sup> (Table 2).

**Table 2.** Basic statistics of the observed (SOCobs) and modelled SOC (SOCmod) stocks (kg m<sup>-2</sup>) in the field.

n=156	Mean	S.D.	CV%	Min	Max
SOC obs	3.49	0.97	27.82	0.96	7.34
SOC mod	3.59	0.26	7.25	2.82	4.55

S.D. standard deviation; CV coefficient of variation

The average of the modelled SOC stocks at the end of the study period were significantly different between the three depth layers ( $p < 0.01$ ) which were 1.65, 1.58 and 0.36  $\text{kg m}^{-2}$ , in the layer I (0–10 cm), layer II (10–20 cm) and layer III (20–30 cm), respectively (Fig. 2).

Modelled SOC stocks increased during the study period for all soil layers, reaching the highest values for the 1994–2010 period of minimum tillage. Fluctuations in SOC stocks over time were less important in layer III and particularly at eroded sites (Table 3).

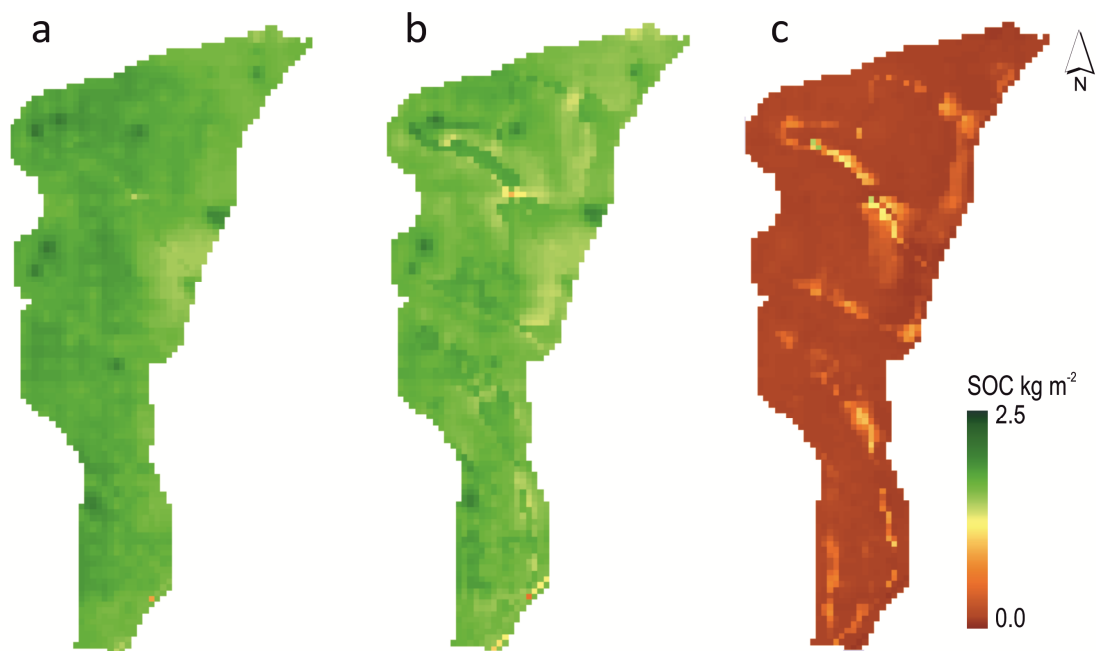


Fig. 2. a) Spatial distribution of the modelled SOC stocks in the layer I (0 – 10 cm), b) in the layer II (10 –20 cm), c) in the layer III (20 – 30 cm) at the end of the study period.

**Table 3.** Mean and standard deviation of SOC ( $\text{kg m}^{-2}$ ) in the soil layers by soil redistribution at the end of the three studied periods.

	Year	Eroded points	Depositional points
Layer I	1959	0.33±0.01a	0.34±0.02b
	1994	1.35±0.06a	1.33±0.07b
	2010	1.66±0.07a	1.63±0.08a
Layer II	1959	0.34±0.01a	0.33±0.02b
	1994	1.29±0.07a	1.32±0.07a
	2010	1.56±0.09a	1.63±0.09b
Layer III	1959	0.27±0.01a	0.27±0.02a
	1994	0.29±0.01a	0.45±0.15b
	2010	0.29±0.01a	0.58±0.24b

Different letters indicate significant differences at  $p < 0.05$  level

### 3.3. Modelled soil and SOC redistribution

The map of the modelled soil redistribution showed that the study field was mainly affected by erosion (Fig. 3a). According to model outputs, 78% ( $n=2037$  cell grid of 2610) of the field was affected by erosion (Table 4). Gross erosion rates at these sites averaged  $0.36 \text{ mm yr}^{-1}$  while the remaining area was considered depositional with an average soil deposition rate that almost tripled the average erosion rate.

**Table 4.** Statistics of modelled soil erosion and deposition within the test sites ( $n=2610$ ) for the whole simulation period (1860–2010).

	Soil erosion( $\text{mm a}^{-1}$ )	Soil deposition ( $\text{mm a}^{-1}$ )
Mean	0.36	0.96
SD	0.30	1.37
CV%	85.71	146.72
Max	8.62	14.63

Modelled soil redistribution in agreement with field surveys pointed out that soil deposition occurred along the gully ( $>4 \text{ mm yr}^{-1}$ ) and in the southern part of the field in concave areas where larger measured SOC stocks were found.

Lower and significantly different modelled SOC stocks were found at erosion sites (n=119) with a mean value of  $3.5 \pm 0.16 \text{ kg m}^{-2}$  than at depositional sites (n=37) with mean SOC stocks of  $3.8 \pm 0.35 \text{ kg m}^{-2}$  and higher dispersion (CV=9%) than at erosion sites (CV=4%).

The general spatial patterns of the measured and modelled SOC stocks were coincident (Figs 3b and c). The highest SOC stocks were found along the gully and the lowest SOC stocks at the end of the gully. However, in the southern part of the field with lower mean slope value (5.5%) than the northern part (8.3%) the modelled SOC stocks were slightly higher than the measured ones.

The superimposition of the flow lines was highly coincident with the spatial distribution of SOC (Fig. 3b). SOC stocks are closely linked with clay content ( $r=0.360$ ,  $p<0.01$ ).

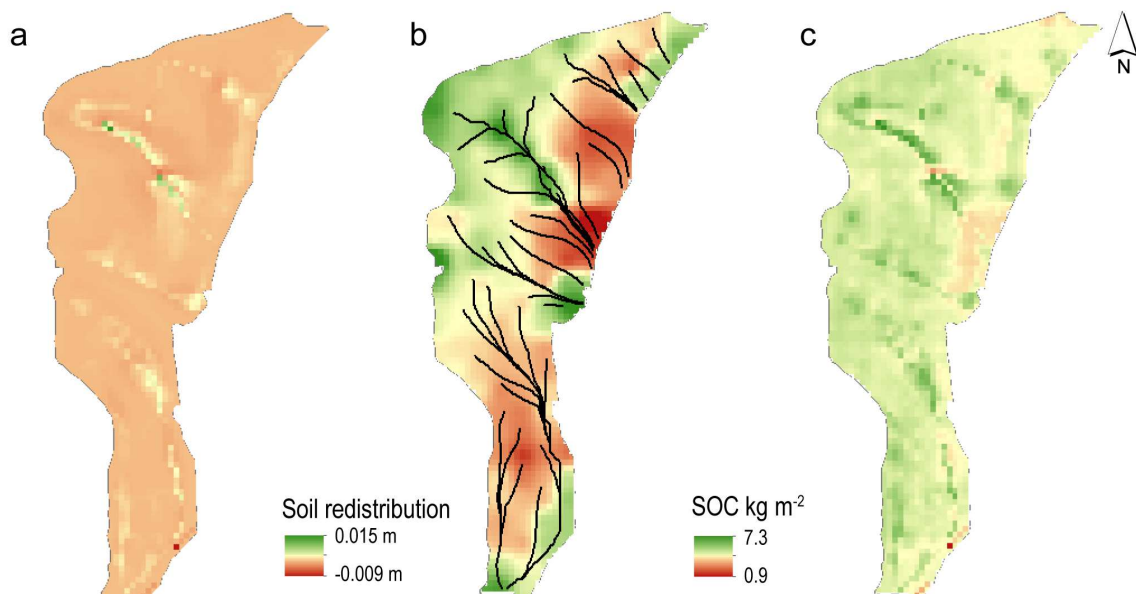


Fig. 3. a) Modelled soil redistribution (positive values indicate deposition and negative ones indicate erosion), b) Kriging of the measured SOC stocks with flow lines, c) Modelled SOC stocks for the study period (1860–2010).

### *3.4. Temporal evolution of SOC stocks and carbon fluxes*

Modelled SOC stocks ranged between 6.8 and 32.5 Mg ha<sup>-1</sup> yr<sup>-1</sup> in the plough layer and between 9.6 and 35.9 Mg ha<sup>-1</sup> yr<sup>-1</sup> for the entire soil profile at the end of the simulation period (Table 5). The SOC concentration in the plough layer (0–0.20 m) was in all cases lower for the three land management practices compared to the entire soil profile. The coefficients of variation (CV %) for SOC concentration in the plough layer ranged from 4.5% to 4.8% for the whole field and the CV for the entire soil profile were 4.6%, 5.9% and 7.3% for the periods 1860–1959, 1960–1994 and 1995–2010, respectively, showing an increase over time. The lowest values corresponded to the first period resulting in a higher SOC spatial variability linked to soil redistribution patterns because of the use of machinery.

SOC stocks increased over the study period both in the plough layer and considering the entire soil profile (Table 5). This increase was higher for plough layer SOC stocks than for the rest of the profile, as indicated by an increasing ratio between SOC stocks in the plough layer and total SOC stocks, and occurred mainly in the period under conventional tillage (1860–1959). During the 1960 – 2010 period, the difference of SOC stocks in the plough layer relative to the entire soil profile was lower than in the previous period.

Changes in lateral SOC fluxes differed between land management practices and showed the largest increase during the transition from animal traction to conventional tillage. Figure 4 shows the lateral carbon fluxes, where negative values represent a loss of carbon and positive values a carbon gain. Furthermore, the conventional tillage period with carbon losses of 0.06 g C m<sup>-2</sup> yr<sup>-1</sup> was slightly higher than the period of minimum till using chisel (0.04 g C m<sup>-2</sup> yr<sup>-1</sup>).



**Table 5.** Average modelled SOC values in the soil profile (SOCsp) and plough layer (SOCpl) and the ratio between them for the three periods with different land management.

	SOCsp (Mg ha <sup>-1</sup> )	SOCpl (Mg ha <sup>-1</sup> )	SOCpl/SOCsp
1860 - 1959	9.6±0.45	6.8±0.32	0.71
1960 - 1994	29.8±1.64	26.6±1.24	0.89
1995 - 2010	35.9±2.31	32.5±1.61	0.90

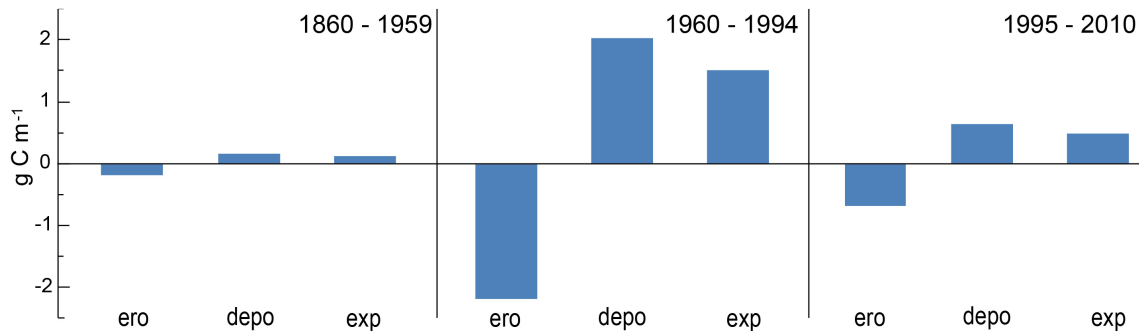


Fig. 4. Lateral carbon fluxes induced by soil redistribution processes for the different modelled periods of minimum (1860-1959), conventional (1960-1994) and minimum using chisel (1995-2010). Negative fluxes represent a C loss (ero) and positive fluxes a C gain (depo) and C exported (exp).

## Discussion

### 4.1. Model performance

The model performance was better for the hydrological unit U2 than when considering the whole field. For the remaining three hydrological units, the simulation was poor ( $NS \leq 0$ ). These results highlight the model's sensitivity to topography. Moreover, the low model performance in hydrological units U1, U3 and U4 can be explained by anthropogenic topographic changes based on field observations and the information given by the owner (Quijano *et al.*, 2016b). These changes in topography have

implications on the patterns of soil movement and can strongly influence soil distribution when accounted for in model simulations (Follain *et al.*, 2006). Given that the soil redistribution component in SPEROS-C is topography driven and focused on the contemporary geomorphic processes occurring on arable land, the impact of these anthropogenic activities had a larger impact on model output than expected and has to be taken into account when analyzing and interpreting the data.

The observed spatial dependence of SOC redistribution and runoff pathways that are determined by the topography revealed that spatial variability of SOC was mainly linked to water erosion processes. The runoff flow lines determined the path of soil redistribution and that of SOC as shown in Figure 3b and c.

The model is able to reproduce the relation between soil and SOC redistribution evidenced by the depletion of SOC at soil erosion sites mainly located upslope while soil deposition accumulates in concave areas. The preferential detachment of the lighter carbon fractions at eroded sites located upslope are typically enriched in carbon compared with the bulk soil as also reported Gregorich *et al.* (1998). The subsequent downslope transport and deposit occurs preferentially in areas with concave morphology as in the field gully. Factors such as the topographic position and slope affect the intensity of soil erosion and sediment redistribution and, thereof, SOC distribution in agreement with observations by Sun *et al.* (2015).

#### *4.2. Soil redistribution: water erosion versus tillage erosion*

In some agricultural landscapes, water erosion mainly controls soil redistribution (Jacinthe *et al.*, 2004; Taguas *et al.*, 2015; Quijano *et al.*, 2016b; Rodrigo-Comino *et al.* 2016). In our field, the predominance of water erosion processes diminished the

contribution of tillage erosion to total soil redistribution. In contrast, Van Oost *et al.* (2006) indicated that cultivated soils are affected by water and tillage erosion at approximately the same order of magnitude.

The SPEROS-C model has been successfully implemented in agricultural areas where tillage induced erosion was the main erosion process with a minor contribution from water erosion (Dlugoß *et al.*, 2012). However, little is known about the model implementation in rainfed Mediterranean agrosystems where the influence of water erosion on soil redistribution processes and SOC dynamics are predominant. A previous study by Quijano *et al.* (2016a) in the same field suggested that similar redistribution processes affected the spatial patterns of fine particles including  $^{137}\text{Cs}$  and SOC.

Runoff was identified as the main factor for soil redistribution in the study field. Although the field was considered isolated from a hydrological point of view during exceptional rainfall events the gully activates favouring the exportation of sediment to the ephemeral stream through several outlets (López-Vicente *et al.*, 2015).

The general pattern of the modelled soil erosion and deposition showed a predominance of erosion over deposition within the field, as observed in previous studies by Quijano *et al.* (2016a; 2016b). For the study period, the mean soil erosion ( $12.8 \text{ Mg ha}^{-1} \text{ y}^{-1}$ ) and deposition ( $8.6 \text{ Mg ha}^{-1} \text{ y}^{-1}$ ) rates compared well with derived  $^{137}\text{Cs}$  estimates reported by Navas *et al.* (2014) in similar Mediterranean agroecosystems.

#### *4.3. Impact of land management on SOC stocks and fluxes*

Soil erosion processes induced the lateral redistribution of different magnitudes of carbon during the three study periods. The largest erosion-induced carbon fluxes took place during the conventional tillage period, followed by the minimum chisel tillage. At

the field scale, the impact of lateral C redistribution on soil productivity can be relevant and C uptake depends on the balance between the spatial extent of eroding and depositional sites over the landscape (Fiener *et al.*, 2015).

The land management has an impact on the carbon fluxes and SOC stocks. When comparing land management practices, differences in SOC stocks are larger between the first and second periods, when conventional tillage was established, than between the second and the third periods. However, higher SOC stocks in the plough layer under minimum tillage for the last fifteen years indicates that using a chisel, reducing the number of tillage operations and leaving the crop residues on the surface as mulch improves C sequestration in agreement with Lal (1997) and Álvaro-Fuentes *et al.* (2014).

Land use and land cover affect the SOC content by modifying the input of organic residues and the decomposition of SOC within the local soil environment in agreement with Novara *et al.* (2015b) and Jarecki *et al.* (2005). Studies (Kisić *et al.*, 2002; Puustinen *et al.*, 2005) have reported that conservation tillage practices reduce losses in soil and organic carbon as evidenced in our study. Although land management is known to have a large effect on SOC stocks (Eynard *et al.*, 2005) lower values of SOC within the plough layer are found for the three land management practices. The relative higher enrichment ratio between the plough layer and the entire soil profile found after shifting to conventional tillage suggest that the implementation of heavy machinery leads to an increase in SOC carbon content in the plough layer. This fact is likely related to an increase of crop production.

#### 4.4. Limitations of the study

The uncertainty related to the use of an average value of RUSLE rainfall erosivity, which may not account for highly erosive events in medium term simulation as performed by the model might have an important effect on the low range of variation of the modelled SOC stocks in comparison with the measured ones. Beguería *et al.* (2015) found under different agricultural Mediterranean soils an enrichment of SOC in splashed materials. The amount of splash generated was determined by precipitation characteristics and associated rainfall erosivity.

In rainfed agrosystems, the potential erosion and its impacts on SOC dynamics is especially important because of the existing poor vegetation cover during the initial period of crop growth of winter cereals is in autumn and the harvest is in spring when precipitation events are frequent and intense. In Mediterranean soils, land use and management is definitive to understand long term SOC dynamics (Parras-Alcántara *et al.* 2015b). In agreement with Nadeu *et al.* (2014) the sensitivity of soil erosion and carbon redistribution was likely related to the transport capacity coefficient. Thus, under transport-limited conditions, detachment was controlled by sediment concentration and its sensitivity to slope was low because the limitations imposed by the ktc coefficient as a consequence SOC transport was low. Furthermore, the underestimation of SOC stocks may be related with the assumption that the point values are representative of the grid cells.

Some characteristics that were not related to processes integrated in the model may affect model performance as the SPEROS-C model was designed for 1 m soil depth whereas the soil in the study field does not exceeds 60 cm. In addition, some model uncertainties were associated to the calibration process when considering average or

constant values for some of the inputs such as transport coefficient. The sensitivity of the model to changes in transport coefficient and diffusion transport processes has not been analyzed in this research and could also explain the underestimation of SOC stocks. Furthermore, in our implementation of the SPEROS-C model we assumed that no selective transport occurred. The model is not currently capable of offering an adequate description of the processes taking place in the study field related to soil redistribution and grain size redistribution as the model assumes homogenous sediment distribution.

## **Conclusions**

This modelling constitutes a first approach to simulate the effect of long-term agricultural activity on soil redistribution and SOC dynamics in a characteristic cultivated field of Mediterranean agroecosystems located at the bottom slope of a mountain catchment. A combination of human induced changes on topography had a significant contribution in landscape evolution with implications on soil redistribution processes. The modelled SOC stocks and carbon fluxes were highly influenced by land management and soil redistribution processes, mainly water erosion. The SOC strongly linked to fine soil particles was preferentially transported downslope by water erosion leading to higher SOC contents in concave areas. Conventional tillage practices were the main sources of exported carbon that tripled those of minimum tillage.

The SPEROS-C model can contribute to increase our understanding on the interactions between geomorphology and soil properties such as SOC. Our research demonstrates the usefulness of SOC modelling to evaluate the effects of land management changes on SOC stocks over the last 150 years at detailed spatial scale. This is especially important

in Mediterranean areas where SOC concentrations are low but essential to maintain agricultural productivity and contribute to future agriculture sustainability. On this behalf, the modelling approach used in this study is a potential tool to monitor the state and evolution of SOC in soils. Further research is needed at the field level to support model development and parameterization.

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