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LONG-TERM DURUM WHEAT-BASED CROPPING SYSTEMS RESULT IN THE RAPID SATURATION OF SOIL CARBON IN THE MEDITERRANEAN SEMI-ARID ENVIRONMENT

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ABSTRACT

Climate, soil physical–chemical characteristics, land management, and carbon (C) input from crop residues greatly affect soil organic carbon (SOC) sequestration. According to the concept of SOC saturation, the ability of SOC to increase with C input decreases as SOC increases and approaches a SOC saturation level. In a 12-year experiment, six semi-arid cropping systems characterized by different rates of C input to soil were compared for ability to sequester SOC, SOC saturation level, and the time necessary to reach the SOC saturation level. SOC stocks, soil aggregate sizes, and C inputs were measured in durum wheat monocropping with (Ws) and without (W) return of aboveground residue to the soil and in the following cropping systems without return of aboveground residue to soil: durum wheat/fallow (Wfall), durum wheat/berseem clover, durum wheat/barley/faba bean, and durum wheat/*Hedysarum coronarium*. The C sequestration rate and SOC content were lowest in Wfall plots but did not differ among the other cropping systems. The C sequestration rate ranged from 0.47 Mg C ha^{-1} y^{-1} in Ws plots to 0.66 Mg C ha^{-1} y^{-1} in W plots but was negative (−0.06 Mg C ha^{-1} y^{-1}) in Wfall plots. Increases in SOC were related to C input up to a SOC saturation value; over this value, further C inputs did not lead to SOC increase. Across all cropping systems, the C saturation value for the experimental soil was 57.7 Mg ha^{-1}, which was reached with a cumulative C input of 15 Mg ha^{-1}. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: SOC sequestration duration and rate; soil carbon saturation; durum wheat straw

INTRODUCTION

Land degradation is related to the soil quality and health (Brevik *et al.*, 2015) and he degradation of the soil system will change the hydrological, biological, and geochemical cycles in the Earth and the service the soils offers to the human societies (Keesstra *et al.*, 2012; Berendse *et al.*, 2015). Within the Earth System cycles the carbon is one that is more influenced by the human use of the land (de Graaff *et al.*, 2015; Köchy *et al.*, 2015; Ping *et al.*, 2015). Agriculture and intensive tillage have caused a 30 to 50% decrease in the carbon (C) content of many soils that have been cultivated for more than 100 years (Schlesinger, 1986; Lal & Kimble, 1997; Smith *et al.*, 2000; de Moraes Sá *et al.*, 2013). Given the ecological and agronomic importance of soil organic matter (Brevik *et al.*, 2015; de Graaff *et al.*, 2015; Vanlauwe *et al.*, 2015), a main objective for the sustainable use of soil resources should be an increase in the pool of soil organic C (SOC) (Paustian *et al.*, 1997).

The variables that influence C sequestration and consequently the SOC pool include climate, soil physical and chemical characteristics, land management, and the input and decomposition of plant residues, including leaves, roots, and root exudates. (Cely *et al.*, 2014; Parras-Alcántara & Lozano-García, 2014; Srinivasarao *et al.*, 2014; Weyers & Spokas, 2014; Kaleeem Abbasi *et al.*, 2015). The SOC pool can generally be increased by agricultural management that increases litter input and reduces tillage intensity (Bell *et al.*, 2003; Alvaro-Fuentes *et al.*, 2009a; Carr *et al.*, 2015). With respect to the size of the SOC pool, the quantity and quality of crop residues are especially important.

In soil subjected to intensive tillage in warmer or semi-arid regions, residues are readily decomposed (Rasmussen *et al.*, 1998), and belowground C inputs from roots are unable to maintain or increase soil C levels (Barbera *et al.*, 2012). The input and sequestration of C in soil can of course be affected by the crop. The C sequestration rate (Csr), for example, was greater with cereals than legumes in a study by Curtin *et al.* (2000). Incorporating straw from cereals into soil seems to be an effective way to increase SOC, particularly in dryland soils (Lugato *et al.*, 2006; Barbera *et al.*, 2012). In a study in China, a relatively high percentage (16.3%) of the cereal straw returned to soil was retained in the SOC pool (Lu *et al.*, 2009). At the global scale, the annual SOC sequestration by straw return in agricultural ecosystems was estimated to be 0.124 Pg C, about 1.4% of global fossil-fuel emissions (Le Quere *et al.*, 2009). This is similar to the estimated C sequestration potential resulting from the adoption of conservation tillage and crop residue management (0·150–0·175 Pg C y^{-1}; Lal & Bruce, 1999). The potentially significant contribution of this residual straw to the reduction in greenhouse gas (GHG) emissions and the mitigation of global warming, however, has been largely ignored.

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As described in the theory of soil C saturation, there may be a limit to how much C can be stored in soil relative to the C input rate (Gao *et al*., 2013). The C saturation limit and other variables including SOC turnover rates and stability are greatly affected by the degree of soil aggregation (Stewart *et al*., 2008). Soil aggregation can physically protect organic matter against rapid decomposition (Pulleman & Marinissen, 2004) and is strongly influenced by agricultural management intensity (Blanco-Canqui & Lal, 2008; Bono *et al*., 2008; Alvaro-Fuentes *et al*., 2009b; Blanco-Canqui *et al*., 2009; Simon *et al*., 2009; Debasish-Saha *et al*., 2014). SOC and soil aggregation enhance each other. SOC binds with mineral particles to form soil aggregates, and as noted earlier, soil aggregates can reduce the rate of decomposition of the SOC within (Tisdall & Oades, 1982; Gupta & Germida, 1988; Elliott *et al*., 1993; Beare *et al*., 1994a, 1994b; Li *et al*., 2009).

SOC is typically reduced by tillage because tillage breaks soil aggregates apart and exposes the SOC within, while SOC is typically increased by the input of organic residues (Tisdall & Oades, 1982; Elliott *et al*., 1993; Ouedraogo *et al*., 2005). In any case, whether the soil C saturation limit can be reached as a function of agricultural management in semi-arid environments and specifically in Vertisols has not been studied and therefore remains unknown. However, SOC concentrations in clay soils in Sicily are usually not lower than 15 g kg^{-1}, even though the high temperatures and rainfall support high decomposition rates; these clay soils seem to have a potential low limit for C storage (Stewart *et al*., 2008).

Soils in semi-arid areas generally have low SOC levels, and it is unclear to what degree the C stock in these soils can be increased by a change in land use or by improved soil management. In these soils, changes in C stocks are slow because of the high decomposition rate and high inputs of C do not typically result in proportional increases in SOC sequestration (Al-Kaisi & Grote, 2007).

This paper describes a long-term experiment that compared six cropping systems in a semi-arid environment in Sicily (Italy) characterized by different rates of C input. The main objective was to verify the limits and potentiality of cropping system to increase SOC stock. Soil C saturation levels were determined and the time required to reach the soil C saturation level as a function of cropping system was estimated.

MATERIAL AND METHODS

Study Area and Experimental Design

The 12-year experiment was conducted in Sparacia, which is located in the southern part of Sicily (37°37′74″N, 13°42′53″E; elevation 400 m). Mean annual precipitation 529 mm and mean annual air temperature 21·4 max and 9·0 min on a 50-year average. Soils of the test area are Vertic Cambisols according to World Reference Base (2014) or Vertic Haploxerepts according to Soil Taxonomy system (Soil Survey Staff, 2014). These are moderately deep soils that evolved on a gentle slope (6%) and are sub-alkaline (pH = 7.7) and clayey (57·7% clay, 16·2% silt, 26·1% sand). The average $CaCO_3$ content of the soil is 2·8%. The SOC and N contents at the beginning of the experiment were 16·4 and 1·2 g kg^{-1} respectively. Beginning in 1998, the following six rainfed cropping systems typical of semi-arid environments were compared: (1) durum wheat monocropping with return of aboveground residues to soil (Ws); (2) durum wheat monocropping (W); (3) durum wheat followed by fallow (Wfall) (2-years rotation); (4) durum wheat rotated with berseem clover (Wbc) (2 -ears rotation); (5) durum wheat rotated with barley and faba bean (Wbf) (3-years rotation); (6) and durum wheat (2 years) rotated with *Hedysarum coronarium* (WWhh) (2 years) (Figure 1, Table I). Aboveground residues were not incorporated into the soil except for Ws cropping system. The systems were compared in a randomized complete block design with three blocks or replications, covering an area of 6500 m^2 and a plot size of 250 m^2. Details on cropping system management are reported in Table I.

Soil Sampling and Fractionation

After wheat was harvested in June of each year, soil samples were collected (0–30 cm depth) using a cylinder (10 cm diameter), air-dried, and passed through a 2-mm sieve. To reduce the error tolerance to less than ±5%, about 2 to 4 kg of soil (Hitz *et al*., 2002) was collected per sample. Without prior chemical dispersion, three wet aggregate-size fractions were obtained by mechanically shaking 50 g of air-dried soil sample on a column with sieves of >75 μm(macro-aggregates), 75–25 μm(micro-aggregates), and <25 μm (silt and clay fraction); an AS 200 Sieve shaker (RETSCH analytical-203 mm diameter sieves) (amplitude of 2 cm, frequency of 1·6 Hz and a water flux of 2 l min^{-1}) was used. The relative weight distribution of the soil fractions and their

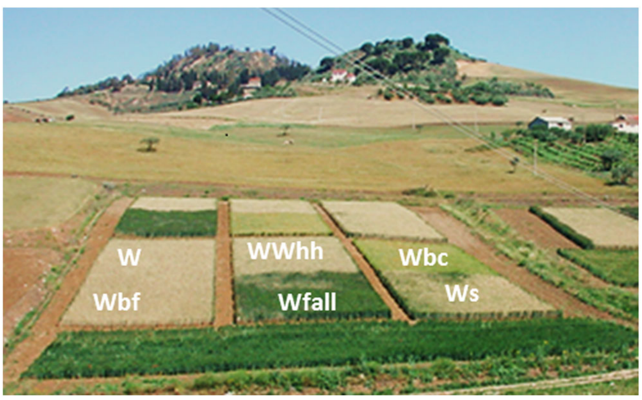

Figure 1. Photograph of one replicate block of the experiment. Ws = durum wheat monocropping with return of aboveground residues to the soil; W = durum wheat monocropping without return of aboveground residues to the soil; Wfall = durum wheat/fallow without return of aboveground residues to the soil; Wbc = durum wheat/berseem clover without return of aboveground residues to the soil; Wbf = durum wheat/barley/faba bean without return of aboveground residues to the soil; and WWhh = durum wheat/*Hedysarum coronarium* without return of aboveground residues to the soil. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Table I. Cropping systems management characteristics in a 12-year experiment in Sicily concerning C input and C storage in soil

Cropping system[a]	Crop[b]	Fertilization N ($kg\,ha^{-1}$) (sowing)	N ($kg\,ha^{-1}$) (five leaves stage)	P_2O_5 ($kg\,ha^{-1}$) (sowing)	Seeds (n m^{-2})	Row wide (cm)	Soil preparation	Weeds control
W	W	90	60	100	350	25	CT[c]	Her[e]
	W	60	60	100	350	25	CT	Her
Ws	W	90	60	100	350	25	CT	Her
	W	60	60	100	350	25	CT	Her
Wbc	bc	–	-	60	1200	16	ST[d]	-
	W	40	40	100	350	25	CT	Her
Wfall	fall	mm	-	-	-	-	-	-
	W	40	40	100	350	25	CT	Her
Wbf	b	50	50	90	300	25	ST	Her
	f	-	-	60	40	75	CT	Mec[f]
	W	40	40	100	350	25	CT	Her
WWhh	h	min	nim	60	700	50	ST	-
	h	min	num	-	—	°	—	d
	W	30	30	100	350	25	CT	Her
	W	60	60	100	350	25	CT	Her

[a]Cropping systems are described in the legend for Figure 1 and in the text.
[b]W = durum wheat, Ws = durum wheat with straws return, bc = berseem clover, fall = fallow; b = barley; f = faba bean; *h* = *Hedysarum coronarium.*
[c]Conventional tillage (CT) - ploughing (30 – 35 cm depth) and a surface tillage (5 cm depth);
[d]Surface tillage (ST) (5 cm depth);
[e]Pre-planting *glyphosate* treatment;
[f]Mechanical interow control at five leaves stage

C content was measured. SOC was determined using the Walkley and Black method (Walkley & Black, 1934).

Calculations

Annual aboveground biomass production was estimated each year by weighing the plant biomass in 1 m^2 in each replicate plot; the ratio aboveground/below biomass was determined for *Faba bean* and *Hedysarum coronarium* (ten plants/plot). For the other species, data from other publications were used to determine the ratio of aboveground to belowground biomass (Kong *et al*., 2005; Chung *et al*., 2008). After harvest, all aboveground crop residues were removed from the plot according to the farm practices of the area except in Ws plots; that is, straw residues were returned to the soil only in plots with durum wheat monocropping. Thus, only the biomass of the roots was considered as C input (Ci) to the soil except in the Ws plots, where straw was also added. Ci was calculated according to Kong *et al*. (2005) and Chung *et al*. (2008):

$$Ci\left(Mgha^{-1}\right) = Krs{*}Above \quad ground \quad biomass\left(Mgha^{-1}\right) \; {*}Root \quad carbon \quad content(\%) \quad (1)$$

Where: Krs is the ratio of belowground residue mass/aboveground residue mass (Table II). For all species, the root carbon content was assumed to be 43% of the dry root biomass (Laudicina *et al*., 2014).

The cumulative C input (CCi) was calculated for each cropping system by summing the C input for all years of the experiment.

SOC stock ($Mg\,ha^{-1}$) in the 0–30 cm layer was calculated using the equation:

$$SOC\left(Mg\ ha^{-1}\right) = SOC\left(g\ kg^{-1}\right){*}\ BD\left(Mg\ m^{-3}\right){*}\ d(m)/10 \quad (2)$$

Where: SOC is soil organic C content, BD is the bulk density, and *d* is the thickness of the soil layer.

BD was calculated using the volume of the collected samples and the weight of the dry soil (Blake & Hartge, 1986).

The Csr ($Mg^{-1}\,ha^{-1}\,y^{-1}$) was estimated for the topsoil by the following equation (Kong *et al*., 2005):

$$Csr = (SOC_t - SOC_0)/y \quad (3)$$

Where: SOC_t and SOC_0 are the stock of SOC at time *t* (2010) and at the beginning of the experiment (1998) and *y* is the duration of experiment. For determination of SOC_0, the mean C value of all of the plots at the beginning of the experiment

Table II. Ratio of belowground residue biomass/aboveground residue biomass (*Krs*) in the species used in the cropping systems and biomass characteristics (ADF, acid detergent fibre; NDF, neutral detergent **fibre**; and ADL, acid detergent lignin). Biomass ratios are from the Intergovernmental Panel on Climate Change (2006, Table 11·2) except for Faba bean and *Hedysarium coronarium* (measured data)

	Krs	ADF (%)	NDF (%)	ADL (%)
Durum wheat (W)	0·20	48·2(3·5)	76·4(5·2)	7·0(0·3)
Faba bean (f)	0·40(0·05)	42·3(2·3)	53·7(3·2)	7·7(0·5)
Berseem clover (bc)	0·70	37·8(2·5)	54·3(4·0)	6·8(0·2)
Barley (b)	0·21	48·2(3·0)	76·4(3·8)	7·0(0·5)
Hedysarum c. (H)	0·12(0·07)	46·4(2·1)	63·0(2·5)	9·5(0·5)

Values in parenthesis indicate standard deviation.

was used because the variability of SOC was low at the start (Rover & Kaiser, 1999; Kravchenko *et al*., 2006; de Oliveira *et al*., 2015). Positive and negative values were considered as SOC gains or losses for the cropping systems.

C sequestration efficiency (Cse) (%) was calculated by the following equation.

$$Cse = Csr/Ci*100 \quad (4)$$

Where: Ci is the annual C input via straw return and roots turnover ($Mg\,ha^{-1}\,y^{-1}$) and Csr is the SO Csr.

The potential C saturation deficit (SOC_{sat}) was calculated as follows:

$$SOC_{sat} = SOC_{sat<25\mu m} + SOC_{>25\mu m} \quad (5)$$

Where: $SOC_{sat>25\ \mu m}$ is the C content ($g\,kg^{-1}$) of coarser soil particles >25 μm (%), and $SOC_{sat<25\ \mu m}$ is the potential C saturation ($g\,kg^{-1}$) of fine soil particles <25 μm (%). $SOC_{sat<25\ \mu m}$ was calculated according to the equation of Hassink (1997) (Equation 7):

$$SOC_{sat<25\mu m} = 1 - SOC_{start}/Pc \quad (6)$$

Where: SOC_{start} is the SOC content at the start of the experiment and Pc is soil C protective capacity of <25 μm particles. Pc was calculated as follows:

$$Pc = 4.09 + 0.37*particles < 25\ \mu m\ (\%) \quad (7)$$

Statistical Analysis

The data for SOC content, aggregate size, and CCi were evaluated by analysis of variance for a completely randomized block design. Differences between means were tested with the LSD test at $*P < 0{\cdot}05$. SPSS statistical software was used.

RESULTS

SOC Response to Cumulative C Input (CCi)

The CCi values during the 12-year experiment ranged from 3·3 $Mg\,C\,ha^{-1}$ in Wfall plots to 35.5 $Mg\,C\,ha^{-1}$ in Ws plots (Table III). In spite of the wide range of CCi values, the Csr was significantly different in only one of the six cropping systems; that is, the Csr was significantly lower in Wfall plots than in the other five kinds of plots but did not differ among Ws, W, Wbc, Wbf, and WWhh plots (Table III).

In the five cropping systems with positive Csrs, the rates ranged from 0·47 $Mg\,C\,ha^{-1}\,y^{-1}$ in W plots to 0·66 $Mg\,C\,ha^{-1}\,y^{-1}$ in Ws plots. The negative rate in Wfall plots (−0·06 $Mg\ C\,ha^{-1}\,y^{-1}$) was associated with a low CCi value, a value that was apparently insufficient to balance the SOC reduction resulting from tillage and decomposition during fallow soil management. Among the five cropping systems with positive Csrs, Cse was highest in W plots (8·7%), followed by WWhh (5·6%) and Wbf (4·7%) plots. These findings indicate that the high values for Cse were obtained in cropping systems with low CCi but high neutral detergent fibre (NDF) content (such as in the W cropping system) or in cropping systems with a high Ci from legumes (WWhh and Wbf) (Figure 2, Table II).

SOC Stock in Soil Aggregates and in Bulk Soil

Among the soil aggregate fractions, the <25 μm fraction was the most abundant, followed by the 25–75 μm fraction and then by the >75–250 μm fraction (Table IV). Among cropping systems, the portion of the aggregates >75 μm tended to be smallest in Ws and Wbc plots (Table IV).

Regardless of cropping system, the SOC concentration was highest in the <25 μm aggregate fraction, followed by the 25–75 μm aggregate fraction and then by the >75 μm aggregate fraction (Table III). Regardless of cropping system, the <25 μm aggregate fraction had the greatest mass among the aggregate fractions (Table IV). It follows that most of the SOC in the soil was present in the finest fraction. The concentration of SOC in the finest fraction tended to be highest in WWhh plots followed by Ws plots and was lowest in Wfall plots (Table III).

The low SOC concentration in Wfall plots was associated with a low input of C and N (Table I) and with soil tillage. The relatively high concentrations of SOC in the >75 μm aggregate fraction in W and Ws plots were perhaps because of the high level of NDF in wheat residues (Table II), which would reduce the decomposition rate.

Table III. Cumulative Carbon input (CCi), carbon sequestration rate (Csr) and SOC content of the bulk soil and aggregate-size fractions as a function of cropping system. Values are means of three replicates. Means in a column followed by a different letter are significantly different at $p \leq 0{\cdot}05$ (LSD test)

Cropping system	CCi (Mg C ha^{-1})	Csr ($Mg\,C\,ha^{1}\,y^{-1}$)	SOC ($g\,C\,kg^{-1}$) Bulk soil	>75 μm	25-75 μm	<25 μm
W	5·47ab	0·47b	18·30b	3·20d	3·6b	11·50b
Ws	35·5d	0·66b	19·02c	3·20d	3·1a	12·70cd
Wbc	13·82c	0·56b	18·60c	2·30c	4·69e	11·70bc
WFall	3·34a	−0·06a	16·14a	2·00b	4·52de	9·50a
Wbf	10·31bc	0·49b	18·40b	2·00b	4·28cd	12·10bc
WWhh	9·46bc	0·53b	18·50b	1·00a	4·09c	13·40d
Average	12·99	0·44	18·20	2·28	4·05	11·82

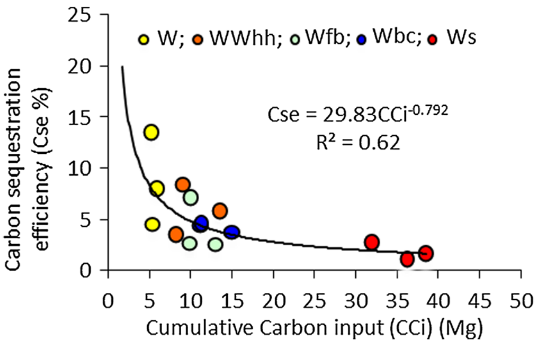

Figure 2. Cumulative Carbon input (CCi) vs. carbon sequestration efficiency (Cse) in the experiment (n = 15) ($R^2 = 0{\cdot}62^{**}$). Values for the Wfall cropping system were negative and are not included. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

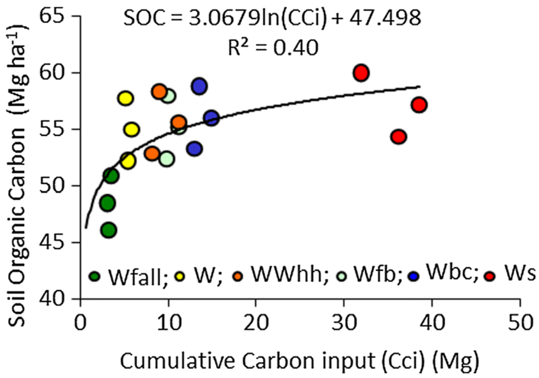

Figure 3. Cumulative carbon input (CCi) vs. soil Organic Carbon (SOC) in bulk soil for the six cropping systems (n = 18) ($R^2 = 0{\cdot}40^{**}$). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Quantitative Analysis of the C Saturation Rate

SOC increased as C input increased but the relationship was logarithmic rather than linear; that is, the rate of SOC increase dropped as CCi increased and as SOC apparently approached a saturation level (Figure 3). When calculated according to Equations 5 and 6 and based on data from all plots, the C saturation level was 57·7 Mg ha^{-1} (Figure 4A, vertical black line). Likewise, SOC tended to plateau as CCi increased to about 55 to 60 Mg ha^{-1} (Figure 3).

According to Figure 4A, the SOC saturation level was reached with a CCi value of 15 Mg ha^{-1}. As indicated by the area between the red dotted line and black dotted line in Figure 4A, C sequestration increased from 47·0 (the SOC content at the start of the experiment) to 57·7 Mg ha^{-1} (the SOC saturation value). Relating CCi to SOC stock at start of the experiment, calculated by exponential relationship (Figure 4A), was 4·7 Mg ha^{-1} (red dotted line, Figure 4). The lowest CCi values corresponded to the lowest SOC values (the area below the dotted red line in Figure 4A), which occurred in the three Wfall plots. The CCi values that exceeded 15 Mg ha^{-1} (the area above the black dotted lines in Figure 4A and B) correspond to C inputs that did not increase SOC because the SOC saturation level had been reached. The C saturation deficit ranged between 0·6 Mg ha^{-1} in Ws and 9·3 Mg ha^{-1} in Wfall.

Based on Figure 4A, the CCi value needed to reach the SOC saturation level was set at 15 Mg ha^{-1}. Plots of CCi against time (assuming that C input was linear over time) indicated the time required for each cropping system to reach the SOC saturation level (Figure 4B). Ws plots required only 5 years to reach the SOC saturation level, while the other plots required more than 12 years to reach the saturation level (Table V).

Table IV. Effect of cropping system on the amount of soil aggregates of different sizes. In the same column, means (n = 3) followed by a different letter are significantly different at $p \leq 0{\cdot}05$ (LSD test)

Cropping system	Aggregate size (g kg^{-1})		
	>75 µm	25–75 µm	<25 µm
W	107·0c	123·0ab	770·2b
Ws	91·0d	97·0c	811·2a
Wbc	99·0cd	134·0a	766·2bc
Wfall	123·7b	140·3a	735·7c
Wbf	138·0a	103·0c	758·2bc
WWhh	109·0c	109·0bc	781·2ab
Average	111·3	117·7	770·4

DISCUSSION

The C sequestration efficiencies in relation to C inputs were lower in the current study of Sicilian rain-fed cropping systems than in studies for other cropping systems (Miglierina *et al*., 2000; Bono *et al*., 2008; Simon *et al*., 2009) but were comparable to those reported for Mediterranean semi-arid agroecosystems (Alvaro-Fuentes *et al*., 2009c). The low annual level of C sequestration in the current study was probably because of high rates of decomposition and low C saturation deficits. For these reasons, the soil C sequestration threshold was low (steady state); that is, increases in C input did not greatly increase soil C accumulation because the C was rapidly mineralized rather than being incorporated into soil microaggregates (Six *et al*., 2002; Kong *et al*., 2005). If saturation occurred, further incorporated SOC, would be lost to erosion and mineralization processes.

The low saturation deficit found in our long-term study of cropping systems in Sicily indicates that once the CCi reaches a value of about 14 Mg ha^{-1}, no additional C will accumulate in the soil. These results, which are consistent with the views of West & Six (2007) on C sequestration and saturation, indicate that the quantity of C stored in semi-arid Vertisols will reach a steady-state level in a relatively short time. Our results confirmed that straw return is an effective measure to quickly enhance SOC stock under cropland. Liu *et al*. (2014) and West & Six (2007) estimated that soil C saturation might occur over a period of 12 years (straw return) and over 26 years (under intensive rotation) respectively, both longer than that under Ws of this study (5 years).

Several reports have indicated that soil C sequestration can be increased by N fertilization and especially by the planting of legumes (Paustian *et al*., 1992; Alvarez, 2005), especially if most of the other residues added to the soil have

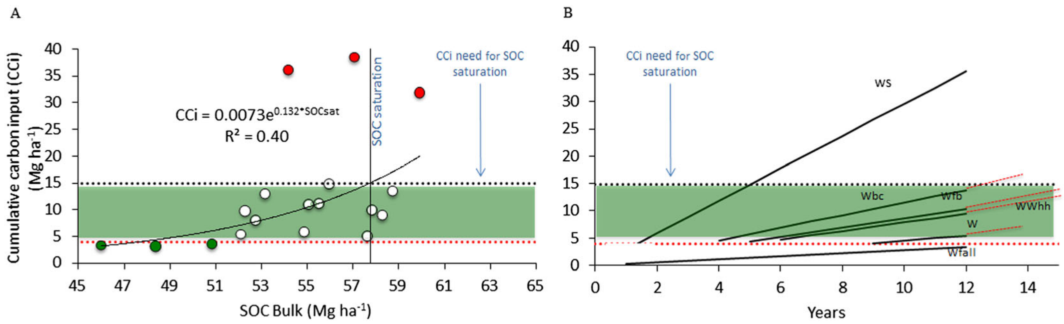

Figure 4. (A) Cumulative Carbon input (CCi) plotted against bulk Soil Organic Carbon (SOC) at the end of the experiment and (B) CCi versus the duration of the experiment. Red bullets and green bullets indicate Ws and W cropping system respectively. In A the vertical solid line represents the SOC stock at the saturation level (57·7 Mg ha^{-1}). In both A and B graphs, the horizontal black dotted line was drawn from the following equation: $CCi = 0{\cdot}0073e^{0{\cdot}132(SOCsat)}$ where SOCsat refers to the SOC saturation level; the red dotted line indicates the CCi before the start of the experiment. In graph 4B each point of the continuous lines is the annual Carbon input (Ci) (Cci divided by number of years) multiplied for the years from the trial start. Red dotted lines are the projections of the CCi toward hypothetical SOC saturation. In both graphs the green area represents the SOC saturation deficit. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

a low C/N. Our results indicated that residue quality was less important than residue quantity, perhaps because N was not a limiting factor for C sequestration in the current study (Barbera *et al*., 2012). In a similar semi-arid environment, Laudicina *et al*. (2014) found that leguminous rotations had more potential to enhance CO_2 emissions than cereal monocultures because of the higher quality of leguminous residues compared with cereal residues

Additional research is needed to clarify how C sequestration in soil is affected by interactions among soil type, residues quality, climate, and nitrogen fertilization. This information would help policymakers identify land uses that are responsible for long-term gains and losses in soil organic C.

The soil C saturation level could probably be increased by changing management; that is, by reducing tillage to limit decomposition rates and by using irrigation to increase C input rates and generally adopting management aimed to improve macroaggregate stabilization. Such changes may be difficult to achieve because climate limits the selection of crops and because local and traditional agricultural practices may be difficult to change. There are also economic challenges to adopting these changes (Alexander *et al*., 2015). Still, farmers should be encouraged to increase or at least maintain their soil C stocks. To do so, farmers will require information on the C input levels required to increase or maintain the soil C stock for their particular cropping system. The current study has provided that information for cereal crops grown in the semi-arid Vertisols of Sicily.

Table V. Years required to reach the SOC saturation level for six cropping systems. These estimates were based on the linear regressions of CCi on time (Figure 4B)

Cropping system	Regression slope	Years
W	0·45	33
Ws	2·96	5
Wbc	1·15	13
Wfall	0·28	50
Wbf	0·86	17
WWhh	0·78	19

CONCLUSION

Findings of this work showed that in a long-term experiment in a semi-arid climate the wide range of CCi and the trial period (12 years) dispelled any doubts about rapid steady state or saturation achievement because of the relatively high carbon input in all cropping systems and the low efficiency in term of SOC sequestration of the wheat fallow cropping system. The recommended mean C sequestration period of 20 years for national GHG according to the IPCC Guidelines (Houghton *et al*., 1997) are perhaps e suitable for most semi-arid cropping systems but not for durum wheat monocropping and fallow. Durum wheat cropping systems showed high ability in C saturation achievement (five years) only when supported by high C input return (Ws). Cropping systems with leguminous rotation did not show the same ability because of the low CCi and probably the faster residues decomposition because of high nitrogen input.

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