Italian Journal of Agronomy 2018; volume 13:1101

Straw uses trade-off only after soil organic carbon steady-state

Agata Novara,[1] Mauro Sarno,[1] Paulo Pereira,[2] Artemi Cerdà,[3] Eric C. Brevik,[4] Luciano Gristina[1]

[1]Dipartimento di Scienze Agrarie, Alimentari e Forestali, University of Palermo, Palermo, Italy; [2]Environmental Management Centre, MykolasRomeris University, Vilnius, Lithuania; [3]Soil Erosion and Degradation Research Group, Department of Geography, University of Valencia, Valencia, Spain; [4]Department of Natural Sciences, Dickinson State University, Dickinson, ND, USA

Abstract

Soil organic matter (SOM) is the key for a healthy soil and a relevant property to achieve the sustainability on soil management. However, soils are still net exporters of organic matter. One example is the use of wheat straw residue for industrial and energy applications, which has gained attention in the last years. The off-farm use of this abundant and low cost resource should follow sustainability criteria to avoid soil degradation and SOM losses. Straw residue incorporation is recognized as a recommended management practice to control erosion and mitigate CO_2 emissions by increasing SOM. The goal of this work was: i) to evaluate the steady-state carbon (C) level in relation to C input and estimate the minimum residue input needed to maintain this SOC level in a durum wheat-based cropping system in long-term experiment; and ii) estimate the potential availability of durum wheat straws for alternative use. Results showed that a C steady-state can be achieved after 3.4 years with an annual organic C input of 4.5 $Mgha^{-1}$. Only after reaching a steady-state, straws can be used for trade-off, leaving 1.03 $Mgha^{-1}y^{-1}$ of C input remain in the soil.

Introduction

The soil system is a key component of the Earth System as it controls the flow of matter and energy within the hydrological, erosional, biological, ecological and geochemical cycles (Smith *et al*., 2015). Soil also contributes key resources, goods, and services to human kind, which makes soil a crucial factor in achieving sustainability of human societies. Human activities change the fate of the carbon cycle and can trigger degradation of the land (Chen *et al*., 2016; de Moraes Sá *et al*., 2015). Contemporaneously, a social interest to protect the soil system is increasing. Returning residues into the soil (straw, pruned branches, leaves) is a key strategy to help achieve this challenge (Lafond *et al*., 2009: Johnson *et al*., 2014; Cerdà *et al*., 2016). Straw return into the soil, in fact, has been suggested as a recommended management practice to increase soil organic carbon (SOC) stocks in agricultural lands leading to consequent mitigation of atmospheric CO_2 emissions (Liu *et al*., 2014; Xia *et al*., 2014). As indicated by Lal (2005), the indiscriminate removal of crop residues can lead to a reduction in soil quality due to the loss of organic matter (Wilhelm *et al*., 2004), resulting in an overall decline of the soil structure (Samahadthai *et al*., 2010), water retention and altering the nutrient cycle (Lal, 2005). Straw incorporation as a sustainable management practice for SOC increase has been widely demonstrated by short and long-term experiments and by simulation models for predicting soil carbon (C) stock (Saffih-Hdadi and Mary, 2008; Dikgwatlhe *et al*., 2014; Bleuler *et al*., 2017; Farina *et al*., 2017).

Differences in the magnitude of SOC increase are attributable to many factors, including straw C input, C/N ratio and soil condition (*e.g.* texture, temperature, and water content), nitrogen application, methods of incorporation, and tillage practices.In general, the increase of SOC stock is limited by the capacity of the soil to store additional C (C steady-state), and therefore no linear relationship between C residue input and SOC sequestration rate has been demonstrated in previous works (Garcia-Diaz *et al*., 2016; Novara *et al*., 2016). After reaching the C steady-state level, there is equilibrium between C input humification and C losses through mineralization and erosion. The amount of biomass residue that is needed to maintain a given SOC level is defined as C input maintain (Johnson *et al*., 2014). Assessing C input maintain is a critical need, considering that the removal of crop straw from soil has gained attention for alternative uses in the last few years (energy source or industrial processing) (Wamukonya and Jenkins, 1995; Qureshi *et al*., 2010; Scarlat *et al*., 2010).

The common management of the straw in the past was to bale and remove it from soils for use in livestock feed rations and as animal bedding, or marginally buried into the soil. Over the last 15-20 years, studies on the potential of lignocellulosic material for the production of biofuels, chemicals, and other by-products and the rising cost of petroleum (prior to 2016) resulted in a growing interest in the use of straw for energy production (Gray *et al*., 2006; Antoni *et al*., 2007). If on the one hand, some studies emphasize the important economic potential of the use of wheat straw as an energy source, on the other hand, environmental sus-

Correspondence: Luciano Gristina, Dipartimento di Scienze Agrarie, Alimentari e Forestali, University of Palermo, ed. 4, viale delle Scienze, 90128 Palermo, Italy.
E-mail: luciano.gristina@unipa.it

Key words: Carbon input maintain; Mediterranean durum wheat-based system; soil carbon sequestration; regional straw assessement.

Received for publication: 29 August 2017.
Revision received: 12 February 2018.
Accepted for publication: 13 February 2018.

*Italian Journal of Agronomy 2018; 13:1101
doi:10.4081/ija.2018.1101*

tainability and in particular, the depletion of SOM (Powlson *et al*., 2011) must be taken into account. In fact, the off-farm use of wheat straw has to follow sustainability criteria in order to avoid soil degradation. Hence, the goal of this work is to evaluate the soil C steady-state and C input maintain in a Mediterranean wheat system and to assess the potential availability of straw residue for alternative uses while avoiding negative impacts on SOC stock.

Materials and methods

Study area biomass and soil analysis

The SOC stock dynamic in relation to Cinput was analysed in a durum wheat-based cropping system under a semiarid environment. The data from a long-term experiment (12 years) carried out in Sparacia (27°37′N, 13°42′E; Sicily, Italy) were used in previous-research to determine the soil organic carbon behaviour under typical Mediterranean climatic conditions (Novara *et al*., 2016). In this study, the selected cropping systems were: i) durum wheat monocropping with aboveground residues return into soil (Ws); ii) durum wheat monocropping (W) with aboveground residues moved from the soil; and iii) durum wheat with aboveground residues moved from the soil followed by bare fallow (Wfall) (2-years rotation). The mean annual precipitation is 529 mm, and the mean annual temperature 16ºC, with 21.4ºC as maximum and 9ºC as minimum. The annual C input was estimated as the sum of C contained in stubble, straw, root, and rhizodeposition. At maturity, for all systems, straw and stubble were manually harvested and separated. The sampling took place in two 10 m^2 in the middle of each plot. After air-drying, portions of the grain, straw, and stubble were randomly selected to be oven-dried at 60°C until the weight stabilised for biomass weight determination. The root plant-derived biomass and C were estimated from the straw biomass and the ratio of stubble/root (Kong *et al*., 2005). In this research, the average proportions of stubble to straw biomass were estimated to be 20% and the rhizodeposition-derived C was assumed to be equal to the root-derived C (Bolinder *et al*., 1999).

The total regional straw availability was calculated by multiply durum wheat harvest area in Sicily and the straw yield per hectar.

The C content was assumed to be 40% for all considered inputs (Johnson *et al*., 2006).

The cumulative C input (CCi) was calculated for each cropping system by summing the C input for all years of the experiment. After wheat was harvested 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 th an ±5%, about 2 to 4 kg of soil (Hitz *et al*., 2002) was collected per sample. SOC was determined according to Walkley and Black (1934). Soil bulk density was measured with core method.

Soil organic carbon steady-state determination by segmented regression

The response between a dependent variable (SOC) and an explanatory variable (cumulative carbon input, CCI) can shows more than one linear relationship at different ranges of CCI, therefore a single linear model was not adequate as well as a nonlinear model. In this case a segmented regression approach can be used to better fit the experimental data. Contemporary the breakpoint can rapresents an estimation of the SOC steady-state in realation to CCI. The unknown value of the breakpoint (Bp) was estimated at CCI=Bp using the following model:

$$\begin{cases} SOC_1 = a_1 + b_1 CCI \; for \; CCI \le Bp \\ SOC_2 = a_2 + b_2 CCI \; for \; CCI \ge Bp \end{cases} \qquad (1)$$

where: SOC_1 and SOC_2 are soil organic carbon values below and above the break point (Bp) values respectively; *a* and *b* are the regression intercept and angular coefficient of regressions and CCI is the cumulative carbon input. In order for the regression function to be continuous at the breakpoint, the two equations for SOC need to be equal at the breakpoint (when CCI = Bp):

$$a_1 + b_1 Bp = a_2 + b_2 Bp \qquad (2)$$

Solving for a_2:

$$a_2 = a_1 + Bp(b_1 - b_2) \qquad (3)$$

Then by replacing a_2 with the equation above, the result is a piecewise regression model that is continuous at CCI = Bp:

$$SOC = a_1 + b_1 CCI \text{ for } CCI \le Bp \qquad (4)$$

$$SOC = \{a_1 + Bp(b_1 - b_2)\} + b_2 CCI \text{ for } CCI > Bp \qquad (5)$$

Regressions parameters and regressions ANOVA were carried out both on the single regression and on the two segmented regressions using STATA software at 90% confidence interval (STATA StataCorp., College Station, TX, USA).

C input maintain

The C input maintain (C_m), referring to the amount of C input from biomass residue that is needed on a soil to maintain SOC steady-state levels, was calculated using the basic equation of the AMG model (Saffih-Hdadi and Mary, 2008) (Eq. 6). The AMG model estimates SOC stock change with time, considering the annual C input and mineralization coefficient.

$$SOC_t = SOC_s + (SOC_i - SOCs)e^{-kt} + \frac{C_m h}{k}(1 - e^{kt}) \qquad (6)$$

where SOC_t is the SOC at time t; SOC_s is the stable fraction of the initial SOC content, SOC_i is the initial content of SOC, k is the mineralization rate constant, m is the amount of Cinput, and h is the humification coefficient. A value of 60% was used for the stable C fraction, as previous studies in the same environment showed that this is the percentage of SOC which is mainly stored in the finest soil aggregate fraction (<25 µm) and therefore the most recalcitrant (Barbera *et al*., 2012; Novara *et al*., 2016). The humification coefficient of durum wheat straw was assumed to be 0.15 (Marraccini *et al*., 2012). The k constant, which is affected by air average temperature, clay and carbonate content, was calculated according to Boiffin *et al*. (1986) and Bockstaller and Girardin (2003). The C input maintain (C_m) was calculated assuming the difference of SOC between two subsequent years after reaching the steady-state level was equal to 0 and solving the equation for C_m.

$$C_m = \frac{(SOC_i - SOC_s)e^{-kt+1} - (SOC_i - SOC_s)e^{-kt}}{h(1-e^{-kt+1}) - h(1-e^{-kt})} * K \qquad (7)$$

Results and discussion

Soil carbon steady-state

In durum wheat-based cropping system, the SOC stock is not directly correlated to CCI. The different cropping systems showed the lowest CCI in Wfall (10.2 Mg ha^{-1}), followed by W (17.8 Mg ha^{-1}) and Ws (48.1 Mg ha^{-1}). Therefore, it is needed to assess the lower CCI to maintain SOC at steady-state. Many researches have looked for critical thresholds associated with ecological studies (Andren, 1994; Fahrig, 2001). Critical thresholds occur when the responses of an ecological process are not linear, but changes sharply and suddenly (breakdown) at a determined level that can be considered the threshold level. Soil ecological processes, and in particular SOM sequestration, adheres to these basic principles, with the threshold after breakdown being considered the soil C steady-state level. In fact, changes in management regimes may have different threshold type effects if processes are evaluated through time.

Analysis of the segmented regression determined a breakpoint at 16.1 Mg ha^{-1} of CCI, corresponding to 37.3 Mg ha^{-1} of SOC. Regressions ANOVA showed the segmented regressions fit data better than a single regression. Less than fifty percent of total variance was explained if the single regression was applied. On the contrary, segmented regression was able to explain more than ninety percent of the total variance. Both analyses were characterized by a high significance level (Table 1).

Regression under the breakpoint showed a high SOC sequestration rate (R^2=0.96), whereas after the breakpoint the slope regression was not significantly different than 0 (P=0.06) (Figure 1 and Table 2). For this reason the constant in the >Bp regression can be considered the SOC steady-state level. Constant in the <Bp regression is the theoretical SOC stock at zero C input. The slope regression under the breakpoint can be used to estimate the soil C sequestration duration in relation to cropping system C input. The duration represents the ratio between SOC (SOC = SOC at Bp - theoretical SOC stock at zero C input) and annual C input (Figure 2). According to annual C input, the C steady-state was achieved after 3.4 years and 9 years with an annual C input of 4.5 Mg ha^{-1}and 1.7 Mg ha^{-1} (corresponding to 11.3 and 4.3 Mg ha^{-1} of wheat residue), respectively. In this 12 years long term experiment, the C steady-state level was not reached with the annual C input determined by Wfall cropping system (0.9 Mg ha^{-1}) (Figure 2, dotted line). Knowledge of time over which SOC steady-state occurs for a specific cropping system could be useful for SOC prediction and designing environmental policy based on C accounts.

Carbon input maintain

The C maintain, calculated after the breakpoint, was 3.15 Mg ha^{-1} yr^{-1} of wheat biomass, corresponding to 1.03 Mg ha^{-1} y^{-1} of C input. This value represents the critical C input to maintain the C steady-state level and is affected mainly by pedoclimatic characteristics and input quality. Johnson *et al*. (2014), for instance, estimated that the average minimum residue return of corn stover needed to maintain SOC levels was 5.74±2.4 Mg ha^{-1}yr^{-1} using a dataset from 19 field in USA. In India Srinivasarao *et al*. (2012) found that a minimum input of 1.13 Mg C ha^{-1} yr^{-1} was required for sustenance of SOC levels in rainfed fingermillet.

The value of C maintain estimated in this work was lower than the value of 2 Mg C ha^{-1} yr^{-1} estimated by Wang *et al*. (2016) in another wheat system using the RothC model. However, the Wang *et al*. study reported high variability depending on soil and climatic

Table 1. ANOVA table for the linear regression without and with breakpoint. Significant regressions were considered at P≤0.05.

	SS	DF	Var	F	P
Without breakpoint					
Explained	64.3	1	64.3	12.29	0.004
Unexplained	83.7	16	5.23		
With breakpoint					
Explained	139.4	3	46.49	76.12	0.000
Unexplained	8.54	14	0.61		

Table 2. Results of regression of SOC (Mg ha^{-1}) against CCI (Mg ha^{-1}) with optimal breakpoint (Bp).

	Bp	d.f.	SOC	s.d.	CCI	s.d.
Without Bp	8.72	18	35.5	2.9	25.4	1.72
x<Bp	16.01	7	32.4	2.3	10.9	2.20
x>Bp	16.01	11	37.5	0.8	34.6	0.16

CCI, independent variable; s.d., standard deviation; d.f., freedom degree.

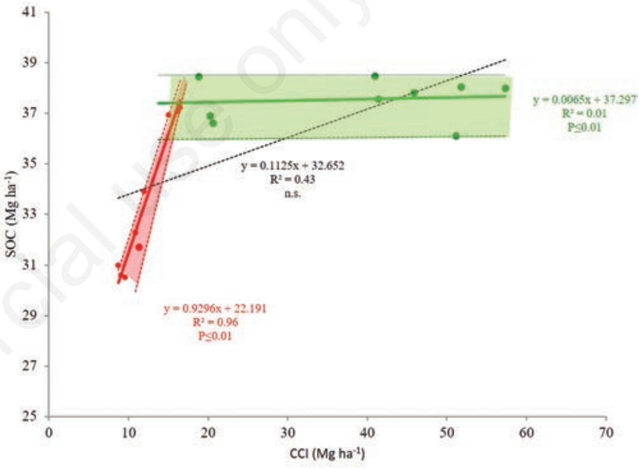

Figure 1. Regressions with (red and green line) and without (black dotted line) breakpoint. Red and green areas are confidence intervals at 10 and 90% for the breakpoint regression.

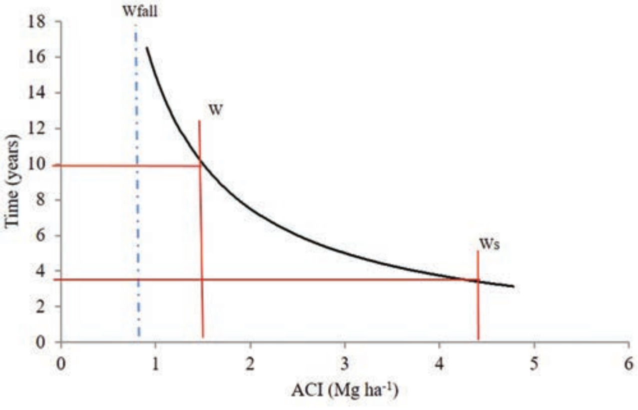

Figure 2. Annual carbon input (ACI) in relation to years needed to reach the C steady-state level. The dotted line represents an annual C input of 0.9 Mg ha^{-1}, that is not enough to reach the steady-state after 12 years. Wfall, wheat-fallow cropping system; W, wheat monocropping without straw return; Ws, wheat monocropping with straw return.

characteristics; the values were highest in the United States and Western Europe, indicating that more C input is needed to maintain C steady-state in wetter and warmer regions. Better mapping and modelling of soil properties distribution and incorporating those soil properties into models could help eliminate some of this variability. In this study the low C maintain value is related to the dry climatic condition and the low current soil C stock present in this area. Moreover, a high percentage of the soil C stock can be considered stable because is mineralogically protected by the high clay content of the soil fraction and therefore the potential mineralizable C pool is low (Barbera *et al*., 2011).

Regional wheat straw assessment and potential availability

Determining an amount of straw that can be removed from soil without altering C stocks must take into account that the straw is important both from an ecological point of view and in economics terms, considering the increasing interest in straw for alternative uses. In Sicily, in the last seven years the durum wheat cultivated area was stable at about 290,000 ha with an average grain yield of 2.8±0.9 Mg ha^{-1} (ISTAT, 2016). Total durum wheat residue yield (straw, roots, rhizodeposition,and stubble) is estimated as 5.3 Mg ha^{-1}year^{-1} (Carbon input= 2.12 Mg ha^{-1} yr^{-1}) with a total regional value of 15,472,217 Mg yr^{-1}. As far as straw availability, it is estimated about 3.2 Mg ha^{-1}yr^{-1} (Carbon input= 1.28 Mg ha^{-1} yr^{-1}) and therefore there are 9,283,330 Mg yr^{-1} of total straws produced in Sicily each year.

Considering a durum wheat straw harvest efficiency of 85%, an effective availability of 7,890,830 Mg yr^{-1} seems to be more realistic. Therefore, the effective C input (1.03 Mg C ha^{-1} yr^{-1}) is determined by the contribution of roots, rhizodeposition and stubble (0.84 Mg C ha^{-1} yr^{-1}) and by the 15% of straw left into the soil after harvest (0.19 Mg C ha^{-1} yr^{-1}).

Because the durum wheat higher heating value (HHV) is 17.9 MJ kg^{-1}, around 141 million of MJ represents the regional potential energetic contribution from durum straw (Channiwala and Parikh, 2002). Although the relatively lower HHV of wheat straw in comparison to other material (*i.e.*, the HHV of diesel oil is 45.7 MJ kg^{-1}), the remain straw over C input maintain could be a valid contribution to alternative energy source to reduce petroleum consumption (Channiwala and Parikh, 2002).

Upscaling estimates for a whole region based on a long term experiment conducted over a limited geographic extent could be affected by the same uncertainties that affect the models. In fact, stocastical models used to estimate soil C stock show large variability due to uncertainties in climate, soils, cropping systems, etc. and a lack of long term empirical data.

Conclusions

Straw return into the soil is essential to rapidly reaching and then maintaining a SOC steady-state level in wheat systems, and therefore it should be encouraged as a recommended management practice in Mediterranean types ecosystems. Results of this study showed that a C steady-state can be achieved after 3.4 years with an annual C input of 4.5 Mg ha^{-1}. Only after reaching a steady-state is possible to use the straw yield for alternative uses, because 1.03 Mg C ha^{-1} yr^{-1} is needed to maintain the SOC level and more than 1.03 Mg ha^{-1} are provided by roots, stubble, and rhizodeposition. Estimating the duration to reaching SOC steady-state is affected by climatic and pedological uncertains, that should deeply investigated for a more reliable evaluation of the ecological contribution of the proposed wheat straw management at regional level.

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