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Projection of Soil Organic Carbon Reserves in the Argentine Rolling Pampa Under Different Agronomic Scenarios. Relationship of these Reserves with Some Soil Properties

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Abstract: The soil organic carbon (SOC) of the Argiudolls of the Argentine Rolling Pampa evolves rapidly. Currently, the soils richest in SOC are cultivated with intensified crop sequences (e.g. maize-double cropped wheat/soybean, MWS) under no tillage (NT) and the poorest ones with soybean monoculture (S) under NT. There are great uncertainties about the future projections of SOC reserves and soil fertility associated with changes in land use and management. The aim of this study was to predict soil fertility in 2032, by: a) validating the simple AMG model in long-term experiments of the Rolling Pampa, b) correlating the SOC and active carbon pools (*SOCm* and *Ca*, respectively) modeled for 2008 with some soil properties, and c) simulating the evolution of SOC reserves under different agronomic scenarios, using the AMG model, starting from rich and poor SOC soils of the Rolling Pampa. The AMG model was able to provide satisfactory simulation of the SOC reserves (R^2 = 0.87) and showed good quality of fit between *Ca* and particulate organic carbon (POC) and *SOCm* and structural stability index (SSI), indicating that the AMG model could project SOC reserves and soil fertility. In rich SOC soils, the maintenance or increase in mean crop yields (MWS NT and MWS with high yields under NT, MWS opt., respectively) caused no changes, whereas the conversion to S under NT reduced the SOC reserves by 12%. Maize residue removal caused 4.5% SOC loss in MWS NT and no changes in MWS opt. In poor SOC soils, the continuity of S under NT and the conversion to MWS NT produced no changes; the passage to continuous or periodic shallow tillage caused 6% SOC loss; and the conversion to *Miscanthus x giganteus* produced an increase of 9% in SOC.

Keywords: Soil organic carbon, AMG model, agronomic scenarios, soil properties.

INTRODUCTION

The soil organic carbon (SOC) reserves of the Argiudolls of the Argentine Rolling Pampa (a subregion of the Humid Pampas) evolve rapidly. The introduction of agriculture in the originally rich silty loam grassland soils of the Rolling Pampa not subjected to erosion has led, 120 years later, to a loss of ~40% of their SOC reserves [1]. Changes in land use and management in the 1970s included progressive conversion from the crop/beef production system to agriculture under continuous tillage and introduction of soybean crop often double cropped with wheat, whereas those at the end of the 1980s included the replacement of mechanical by chemical weed control, bound or not to the appearance of conservation tillage. In the 1990s, after the introduction of no tillage (NT), the most important change in land use and management was the massive spread of the soybean crop, pulled by the rising global demand due to the industrial revolutions of China and India. At the local level, this revolution caused the rapid expansion and adoption in a large part of the surface of simplified crop systems, characterized by a high frequency of soybean and the technological package of transgenic soybean plus glyphosate herbicide. This led to soils with poor SOC reserves (<40 Mg SOC ha^{-1} at a soil mass of 2500 Mg ha^{-1}). However, a small area (13%) is still occupied by medium- to large-sized enterprises (500-2000 ha) which practice intensified crop sequences [2] that lead to maintaining soils rich in SOC reserves (>45 Mg SOC ha^{-1} at a soil mass of 2500 Mg ha^{-1}). Thus, the different agricultural practices carried out during this period have led to soils with different SOC reserves [1, 3-6].

In the sites with many years of continuous soybean, the occurrence of weeds tolerant/resistant to chemical control (such as *Lolium multiflorum*, *Conyza bonariensis*, *Amaranthus quitensis*) has increased in recent years [7, 8]. This has caused an incipient return to tillage for weed management.

On the other hand, in recent decades, the Argentine monogastric livestock production (poultry and hogs) has become industrialized [9], following the tendency of other developing countries [10] because pork and poultry products tend to be less expensive than cattle ones. Industrial monogastric livestock production is expected to meet most of the income-driven doubling in meat demand in the

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coming decades [11]. With the industrialization of livestock, land use changes are being increasingly directed towards feed crop production rather than towards grazing [12]. Hence, with livestock industrialization, feed crop production will be increased mainly from higher maize yield and/or higher surface planted with maize.

Finally, the agricultural and energetic sectors show an increasing linkage internationally, which, in the local market, is reflected in the production of biodiesel from soybean and with ethanol produced from sugar cane and corn [13]. Although no advances have been recorded in bioenergy produced from plant biomass in the Rolling Pampa, the exportation of cereal residues, mainly of maize, is being considered because it exceeds the biomass production of other cereals [14, 15]. The food security and release of SOC are the two important issues related to the resilience of the food production system when the grains and/or their residues are used for energy production [12]. A key to enhancing this resilience is the use of technologically and economically feasible sources of lignocellulosic fuels that can be grown on degraded lands [16]. Some perennial crops such as *Miscanthus x giganteus*, *Panicum virgatum* and *Pennisetum purpureum* have also received particular attention during the last years because they may increase land use efficiency and reduce greenhouse gas emissions and are able to sequester SOC. *Miscanthus x giganteus* is particularly interesting due to its high yield potential and low N requirements and its ability to lead to high C inputs in soil organic matter (SOM) [17].

These possible changes in land use and management cause great uncertainties about the future of the SOC reserves and soil fertility of the region. Medium/long-term mathematical models to simulate SOC are effective tools to reduce this uncertainty [18].

Taking into account the dynamics of different pools, their relationship with some soil properties is of great interest to predict the impact of the changes listed above [19]. The term “pool” is used to describe the theoretically separated, kinetically delineated component of SOC and the term “fraction” is used to describe measurable organic matter components [20, 21]. Models designed to predict SOC dynamics have incorporated at least two contrasting pools: a passive or stable pool and a labile or active pool [22-24]. Although the size, number and turnover rates of the pool used in multicomponent models vary, common divisions include compartments with time constants ($1/k$), where k is the mineralization coefficient measured in years, decades, centuries or millennia from the most active to the most persistent pool [25]. In the past few years, several methods have been developed to isolate and characterize relatively undecomposed particulate or macro-organic matter [21, 26]. The particulate organic carbon (POC) fraction is derived from above- and belowground inputs of plant residues. It includes labile substrates like litter, microbial biomass, residue fragments and partially decomposed residues, and decay products [27]. POC represents the slow pool of organic matter [28], with a turnover time that is intermediate between that of the active and passive pools of organic matter [29]. Efforts are being made to relate such kinetically defined pools to the biophysical or chemical features of the measurable organic fraction and to associate nutrient with carbon dynamics [21, 30]. The organic matter fractions related to the active and slow pools influence nutrient supply, determine soil aggregation and reflect management practices [21, 28, 31]. More recalcitrant SOM fractions that are equated with the slow, passive or resistant pools are more relevant for long-term C sequestration, sorption, cation exchange capacity, and soil water-holding capacity [21]. Some attempts have been made to match measurable SOC fractions with modeled pools [32-35]. Good agreement has been found between the conceptual compartments of the Roth-C model and some measurable SOM fractions for a wide range of environmental conditions related to sharp changes in tillage systems [35]. We have previously found good agreement between the size of the active SOC pool (*Ca*) of the AMG model obtained by the natural δ13C abundance technique with the fractions obtained by physical and biological fractionation under different tillage systems and crop sequences [20]. The AMG model is a simple three-compartment model. This model has been calibrated and validated in the Rolling Pampa in two long-term experiments under conventional tillage and NT by applying the natural δ^{13}C abundance technique [1] and in different long-term tillage systems and crop sequences experiments under different soil and climate conditions [22, 36-39]. Lal [19] reported that although significant progress has been made in predicting the SOC compartment under different changes in land use and management, efforts should be made to include in such models predictions concerning changes in soil quality regarding variations in the SOC compartments and flows. Given the lack of this possibility, as a first approximation, it would be interesting to correlate the results of modeling (sizes of SOC pools) with some soil properties to project soil fertility under future scenarios. The aim of this study was to predict soil fertility in 2032, by: a) validating the simple AMG model in long-term experiments of the Rolling Pampa, b) correlating the SOC and active carbon pools (*SOCm* and *Ca*, respectively) modeled for 2008 with some soil properties, and c) simulating the evolution of SOC reserves under different agronomic scenarios, using the AMG model, starting from rich and poor SOC soils of the Rolling Pampa.

MATERIALS AND METHODOLOGY

Study Site and Experimental Design

This study was carried out in the Argentine Rolling Pampa. The climate can be defined as temperate humid without a dry season and with a very hot summer [40]. Monthly mean temperatures range from 9 ºC in July to 24 ºC in February. The minimum soil temperature never reaches 0 ºC; therefore, soils do not freeze, and biological activity is never severely depressed. Rainfall varies from 900 to 1000 mm year^{-1}.

Soil data were obtained from long-term experiments conducted at the Pergamino Experimental Station of the Instituto Nacional de Tecnología Agropecuaria of Argentina (INTA) (33º 51’ S; 60º 40’W). The site is covered by a fine, illitic, thermic Typic Argiudoll (US Soil Taxonomy), Luvic

Table 1. Data set and sampling year of soil organic carbon (SOC) and soil bulk density (BD) used for model validation.

Crop Sequences	Tillage Systems	Year									
		1979	1983	1984	1987	1991	1997	1999	2004	2008	2012
WSM	CP	X		X		X				X	X
	NT	X		X			X	X		X	X
MWS	CP	X						X	X	X	X
	NT	X							X	X	X
WS	CP		X						X	X	X
	NT		X						X	X	X
M	CP				X				X	X	X
	NT				X				X	X	X
S	CP				X				X	X	X
	NT				X				X	X	X

WSM: double cropped wheat/soybean-maize MWS: maize-double cropped wheat/soybean. WS: double cropped wheat/soybean. M: maize monoculture. S: soybean monoculture. CP: chisel plow. NT: no tillage. X: indicates the sampling year.

Phaeozem (WRB) of the Pergamino Series, without water erosion phases (soil slope < 0.3%), and the texture of the A horizon (0-20 cm) is silty loam with 23% clay and 64% silt [3]. Five long-term experiments of crop sequences and tillage systems were carried out in a 9-ha plot: the double cropped wheat/soybean-maize (WSM) and maize-double cropped wheat/soybean (MWS) sequences (three crops in two years, where the summer crops are sown in the same year), which began in 1979, the double cropped wheat/soybean (WS), which started in 1983, and the maize and soybean monocultures (M and S), which were added in 1987. Each experiment presented a completely randomized block design. The main plot was 45 m long by 14 m wide, and the tillage systems were randomized in the main plots. The treatments analyzed were chisel plow (CP) and NT in all rotations. Under CP, the soil was chiseled, as primary tillage, at a depth of 15 cm and disk- and teeth-harrowed at a depth of 10 cm in late June every year. In all tillage systems, weeds were chemically controlled and no previous old plowed soil was recorded under the farm work depth. Wheat and maize were fertilized with 90 and 100 kg N ha^{-1}, respectively. In addition, maize, wheat and soybean were fertilized with 12 kg P ha^{-1}.

Soil and Plant Measurements

The data set used to validate the model was obtained from SOC, soil bulk density (BD), particle size distribution and crop yield measurements. Soil samples were taken before tillage at three depths: 0–5, 5–10, and 10–20 cm. Three sites were chosen at random for subsampling in each of the treatments, avoiding visible wheel tracks. The periods analyzed and the sampling years for each experiment are shown in Table **1**. Samples were dried and sieved finer than 2 mm. Particle size distribution was measured according to the pipette method [41]. SOC contents were determined by dry combustion with a mass spectrometer (Fisons/Isochrom) coupled with a C/N analyzer (Carlo Erba NA 1500). BD was determined by the cylinder method [42], except at the start of the experiments which were calculated using the equation of Chen et al. [43]. BD measurements were used to transform mass-based measurements into volume-based ones. A mass of 2500 Mg ha^{-1} was chosen to calculate SOC reserves.

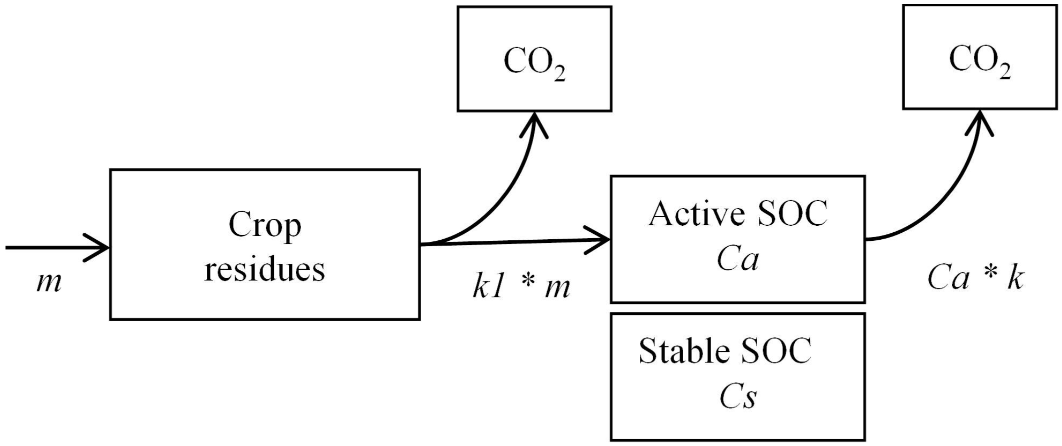
To estimate crop yields, two samples of each crop were randomly extracted at harvest from the whole plant (1 m^2 per plot) of each treatment. These were dried in an oven at 40 °C, the grains of each sample were threshed and weighed, and then yields obtained.

Relationships between Modeled Pools and some Soil Properties

The structural stability index (SSI) at the 0-5 cm layer and the POC at the 0-5 and 5-20 cm layers were chosen from the 2008 sampling to correlate with *SOCm* and *Ca* modeled in the same year, respectively, under CP and NT. POC (fraction > 53 µm) was determined by the method of Cambardella and Elliot [28] modified by replacing the chemical dispersion of the original method by mechanical water agitation with glass balls [44]. POC contents were analyzed by dry combustion using a C/N analyzer. The SSI for aggregates >0.5 mm in diameter was determined with the Douglas and Goss method [45] with slight modifications. SSI was calculated with Kemper´s procedure [46]:

$$SSI = \frac{Dry\,weight\,aggregates > 0.5\,mm}{Initial\,dry\,weight\,aggregates} * 100$$

where SSI is the structural stability index (%). The values assigned to SSI were as follows: SSI < 20%: unstable, SSI



m: annual C input (Mg ha^{-1} yr^{-1}). *k1*: humification coefficient (unitless). *k*: mineralization coefficient of the active pool (yr^{-1}).

Fig. (1). Diagram of the AMG model.

between 20 and 40%: moderately stable, and SSI > 40%: stable.

Simple linear correlation was used to relate the modeled pools with the soil properties.

Model Description

The diagram of the AMG model is presented in Fig. (**1**).

The basic equations of the AMG model are the following [22]:

$$SOCm = Cs + Ca \ , \quad (1)$$

$$\frac{dCa}{dt} = m \cdot k1 - k \cdot Ca \ , \quad (2)$$

where *SOCm* is the SOC pool (Mg ha^{-1}), *Cs* is the stable SOC pool (Mg ha^{-1}), *Ca* is the active SOC pool (Mg ha^{-1}), *m* is the annual C input (Mg ha^{-1} yr^{-1}), *k1* is the humification coefficient (unitless), and *k* is the mineralization coefficient of the active pool (yr^{-1}).

These equations can be integrated if *m* is considered constant every year. Then, the evolution of the carbon reserve may be described by the following equation:

$$SOCm = Cs + Ca_0 \cdot e^{-kt} + \frac{m \cdot k1}{k} \cdot (1 - e^{-kt}) \ , \quad (3)$$

$$Ca_0 = C0 - Cs \ , \quad (4)$$

where *SOCm* is the SOC pool (Mg ha^{-1}), *Cs* is the stable SOC pool (Mg ha^{-1}), *Ca* is the active SOC pool (Mg ha^{-1}), *m* is the mass of annual C input, *k1* is the humification coefficient (unitless) and *k* is the mineralization coefficient of the active pool (yr^{-1}), Ca_0 is the initial active *C* pool (Mg ha^{-1}), and *C0* is the initial SOC reserve (Mg ha^{-1}). In Eq. (3), the second term on the right represents the decomposition of the 'old carbon' (i.e. existing at time 0) while the third term represents the newly humified carbon, which reaches an asymptote:

$$Cmax = \frac{m \cdot k1}{k} \ , \quad (5)$$

$$Ceq = Cmax + Cs \ , \quad (6)$$

where *Cmax* is the maximum quantity of soil *C* originated from crop sequences (Mg ha^{-1}), *m* is the mass of annual C input, *k1* is the humification coefficient (unitless) and *k* is the mineralization coefficient of the active pool (yr^{-1}), *Ceq* is the total reserve of SOC at equilibrium (Mg ha^{-1}) and *Cs* is the stable SOC pool (Mg ha^{-1}).

Model Parameters during Validation

The *m* values were estimated from crop yields. The harvest indexes used were 0.50, 0.42 and 0.38 [47] for maize, wheat and soybean, respectively. The assumed root masses were 30% for all crops in relation to total aboveground biomass, including rhizodeposition [48]. The C content of all crop residues was assumed to be 40% of the total dry matter.

The *k1* values used were only dependent on the quality of the crop residues and were taken from international references taking into account the different tillage systems for three crop residues: 0.13 for wheat and maize under NT, 0.17 for soybean under NT, and 0.20 for wheat and maize under CP [1, 49]. Because the *k1* value for soybean under CP was not found in the literature, it was fitted in the soybean monoculture. The *k* values were estimated using the environmental functions proposed by Saffih-Hdadi and Mary [36].

The size of *Cs* should be independent of the culture system. However, Milesi Delaye *et al.* [1] found that the quality of fit of the AMG model, during the validation period, could be significantly improved with small variations of the *Cs* value among crop sequences under NT in comparison with the size of *Cs*. Thus, the size of *Cs* was fitted for each treatment.

The relative and absolute root mean square error (RRMSE and RMSE, respectively), in % and Mg ha^{-1} respectively, were used to describe the goodness of fit of the SOC model and is defined as follows:

$$RRMSE(j) = \frac{100}{\bar{X}_{ij}} \sqrt{\frac{1}{n_j} \sum_{i=1}^{n} \Sigma (X_{ij} - \hat{X}_{ij})^2} \ ,$$

Table 2. Agronomic scenarios simulated for 2032.

SOC Reserve	Agronomic Scenarios Simulated for 2032		
	Spread of Soybean Monoculture	**Increased Demand of Maize for Animal Feed**	**Linkage between Agriculture and Energetic Sectors**
Rich SOC soils (45.9 Mg C ha^{-1}) 2012: MWS NT	S NT	MWS NT MWS opt.	MWS NT R MWS opt. R
Poor SOC soils (38.7 Mg C ha^{-1}) 2012: S NT	S NT Mechanical weed control: S ST 3 S NT : 1 S ST	MWS NT	*Miscanthus x giganteus*

SOC: soil organic carbon. MWS: maize-double cropped wheat/soybean. S: soybean monoculture. MWS opt.: maize-double cropped wheat/soybean with high crop yields. NT: no tillage. ST: shallow tillage. R: removal of 30% of maize residue for bioenergy production. 3 S NT : 1 S ST: 3 years of soybean under no tillage and 1 year of soybean under shallow tillage.

$$RMSE(j) = \sqrt{\frac{1}{n_j}\sum_{i=1}^{n}\Sigma(X_{ij} - \hat{X}_{ij})^2} \ ,$$

where *nj* is the number of observations of each data set *j*, and *Xij* and $\hat{X}_{ij}$ are the observed and simulated values of SOC, respectively. Optimization was conducted using the Newton's method of Excel solver.

Agronomic Scenarios

The agronomic scenarios were built taking into account the main driving forces originated in the possible future of the Argentine agrifood system, for rich and poor SOC soils of the region (Table **2**). Commonly, 20 years is a time period used to evaluate SOC changes by land conversion [50- 52]. The year 2032 (20 years since 2012, the last year of validation) was selected to analyze the magnitude of the medium-term effects caused by changes in agricultural practices on SOC reserves.

The validated parameter values were used to simulate the different scenarios. When ST was included, the validated parameter values for CP were used. In MWS opt. under NT, *m* was 7 Mg ha^{-1} $year^{-1}$. The maize residue removal rate was fixed according to Andrews [53], who showed that up to 30% of the surface residue can be removed from some NT systems without increased erosion or runoff.

When *Miscanthus x giganteus* was considered, a value of 7.5 Mg C ha^{-1} yr^{-1} for *m* was obtained as follows: a) the mean aerial biomass production was 20 Mg ha^{-1} yr^{-1}, which, after export was reduced to 3.7 Mg ha^{-1} yr^{-1} [54, 55]; b) the belowground biomass was divided into dead rhizomes (1.5 Mg ha^{-1} yr^{-1}), dead roots (3.6 Mg ha^{-1} yr^{-1}) [17] and rhizodeposits, assuming that these represented 50% of the total biomass rhizomes + roots. The values of *k1* and *k* used (0.126 and 0.07 $years^{-1}$) are typical values for C4 crops under NT for the Pergamino soil series [1].

The following assumptions were used both for the simulation model and agronomic scenarios, to mark the boundaries within which the projections of SOC reserves are limited:

Simulation Model

- the size of *Cs* remained as such during the simulation period,

- breeding did not affect the allometric relationships of crops (yield / total biomass, root biomass / total biomass, C content of plant biomass),

- climate change scenarios were not considered,

- within a crop sequence, differences in SOC reserves regarding the baseline found in the interval ±2.0 Mg C ha^{-1} were not considered as change.

Agronomic Scenarios

- MWS was considered as a representative intensified crop sequence of the region,

- increases of 20% in the mean annual yields of soybean, wheat and maize was used in MWS opt.,

- increases in crop yields due to breeding are not taken into account,

- crop productivity is maintained within the limits of projected SOC contents,

- under maize residue removal, the remaining residue is sufficient to fulfill the NT functions (water conservation, reduced soil temperature, no compaction from wheel traffic) and has not effect on crop yields,

- disease-producing organisms are not enhanced by residue removal,

- water erosion is not a significant process,

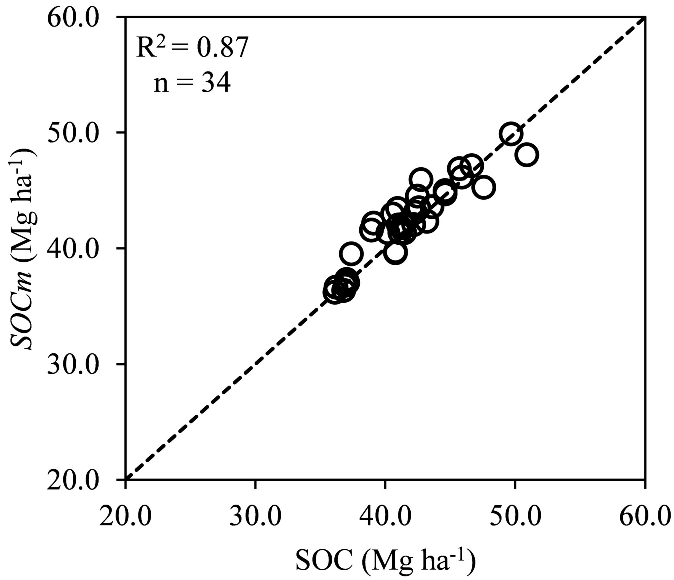


Fig. (2). Comparison of observed and modeled soil organic carbon (SOC and *SOCm*, respectively) during validation.

Table 3. Results of the AMG model validation in the experiments of crop sequences and tillage systems of INTA Pergamino.

Treatment	*C0*	*m*	*k1*	*k*	*Cs*	*Cmax*	*Ceq*	ΔCeq	SOC 2012	RMSE	RRMSE
	Mg ha^{-1}	Mg ha^{-1}yr^{-1}		year^{-1}		Mg ha^{-1}		%	Mg ha^{-1}		%
WSM CP	51.8	5.6	0.20	0.105	32.0	10.7	42.7	-18	40.9	2.0	4.1
WSM NT	51.8	5.8	0.14	0.070	33.8	11.4	45.3	-13	43.2	1.4	1.6
MWS CP	45.3	5.2	0.20	0.105	32.0	9.9	41.9	-7	41.2	1.5	3.0
MWS NT	45.3	5.4	0.14	0.070	32.6	10.6	43.2	-5	41.6	1.3	1.5
WS CP	49.2	5.8	0.21	0.110	30.2	11.1	41.2	-16	38.6	1.3	2.7
WS NT	49.2	6.4	0.15	0.079	31.8	12.2	44.0	-11	42.5	1.0	1.6
M CP	41.3	4.5	0.20	0.105	30.8	8.5	39.4	-5	37.4	1.3	3.4
M NT	41.3	4.7	0.13	0.070	32.5	8.8	41.3	0	40.2	0.6	1.1
S CP	40.5	3.1	0.20	0.105	30.0	5.9	35.8	-11	34.8	0.3	1.8
S NT	40.5	3.1	0.17	0.079	29.6	6.6	36.2	-11	37.2	0.2	0.7

WSM: double cropped wheat/soybean-maize. MWS: maize-double cropped wheat/soybean. WS: double cropped wheat/soybean. M: maize monoculture. S: soybean monoculture. CP: chisel plow. NT: no tillage. *C0*: initial soil organic carbon reserve. *m*: mass of annual C input. *k1*: humification coefficient. *k*: mineralization coefficient of the active pool. *Cs*: stable soil organic carbon pool. *Cmax*: maximum quantity of soil *C* originated from crop sequences. *Ceq*: soil organic carbon reserve at equilibrium. *ΔCeq*: percentage variation between *C0* and *Ceq*. SOC 2012: soil organic carbon observed in 2012. RMSE: root mean square error. RRMSE: relative root mean square error.

- the relationships obtained between modeled pools and soil properties are maintained during the projection period.

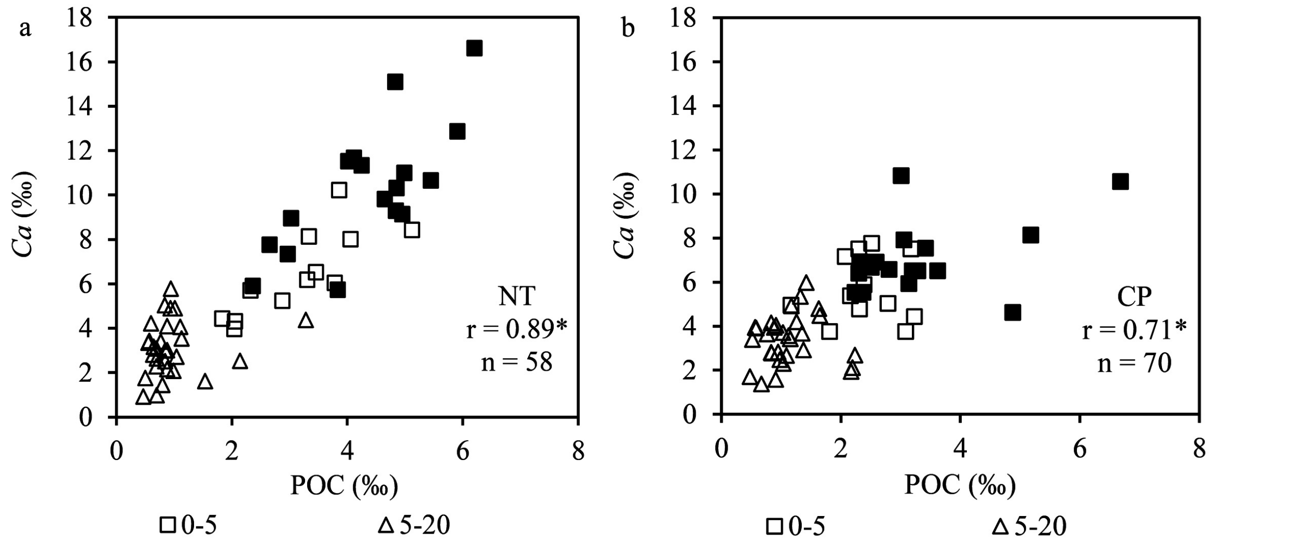
RESULTS

The AMG model showed good simulation of the evolution of SOC reserves. R^2 was 0.87 and RMSE and RRMSE values obtained for SOC were 1.1 ± 0.7 Mg C ha^{-1} and 2.15 ± 1.1 %, respectively (Fig. **2** and Table **3**).

The average size of *Cs* for all the treatments was 31.5 ± 1.3 Mg ha^{-1}. The richest SOC soils at the beginning of the experiments were associated with greater SOC losses (Table **3**). All crop sequences and tillage systems were near equilibrium in 2012. The greater the *m*, the greater the *Ceq* ($p < 0.01$) achieved. This can be observed in *Cmax*.

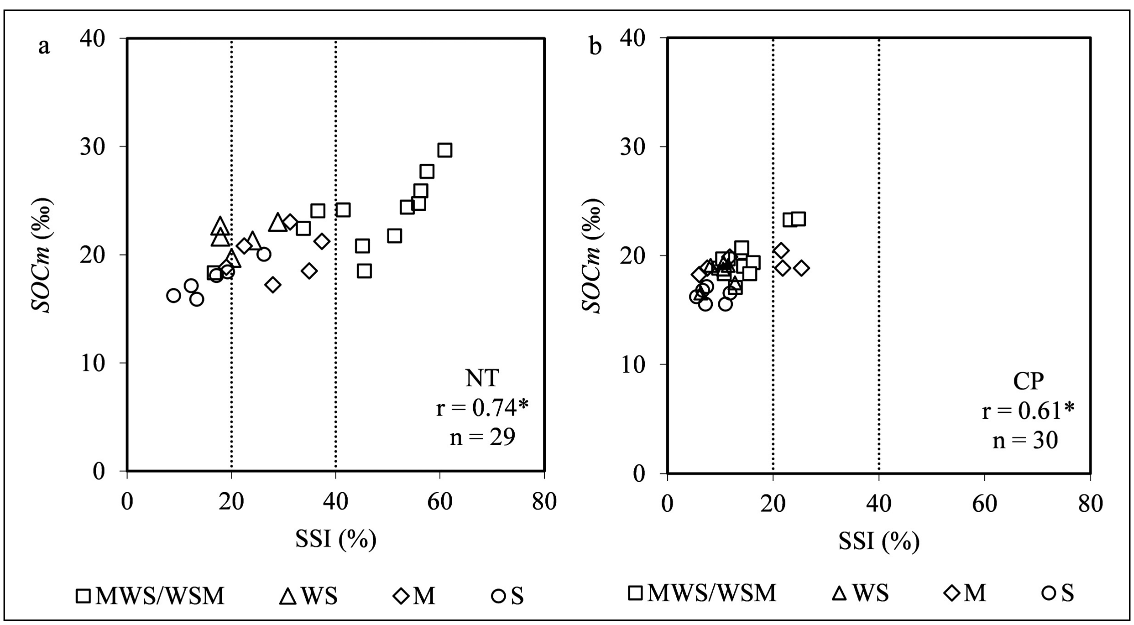
Relationships between Modeled Pools and Soil Properties in 2008

Good agreement between *Ca* and POC was found in all crop sequences under CP and NT for the 0-5 and 5-20 cm layers, resulting better under NT (Fig. **3**). The classical POC superficial stratification and mixing effect of the crop



*p< 0.01. Figure a: black squares indicate intensified crop sequences (maize-double cropped wheat/soybean, double cropped wheat/soybean-maize and double cropped wheat/soybean) and white squares indicate soybean and maize monocultures. Figure b: black and white squares indicate sequences with or without maize, respectively. NT: no tillage. CP: chisel plow.

Fig. (3). Relationships between active carbon (*Ca*) and particulate organic carbon (POC) under NT (a) and CP (b) for the 0-5 and 5-20 cm layers.



*p< 0.01; NT: no tillage; CP: chisel plow; MWS: maize-double cropped wheat/soybean. WSM: double cropped wheat/soybean-maize. WS: double cropped wheat/soybean. M: maize monoculture. S: soybean monoculture. U: unstable. MS: moderately stable. S: stable.

Fig. (4). Relationship between modeled soil organic carbon (*SOCm*) and structural stability index (SSI) in five crop sequences under NT (a) and CP (b) for the 0-5 cm layer.

residues were observed under NT and CP, respectively. On the other hand, under NT, the POC contents in WSM, MWS and WS tended to be higher than in monocultures, while in CP the highest POC contents were associated with the presence of maize in the crop sequence, for the 0-5 cm layer. The size of POC was 58% smaller than that of *Ca* and showed no differences between tillage systems.

The relationship between *SOCm* and SSI was significant for the two tillage systems in the 0-5 cm layer. SSI varied from unstable to moderately stable under CP, and from unstable to stable under NT, showing the effect of the presence of maize on the crop sequence in SSI for both tillage systems. Only WSM and MWS under NT showed a stable pore system (Fig. **4**).

Table 4. Projection of SOC reserves in 2032 for the agronomic scenarios analyzed.

Land use and Management		SOCm	ΔSOC	Ca	m	k	k1	SOCm	ΔSOC	Ca	Ceq
		2012						2032			
2012	2012-2032	Mg ha^{-1}			Mg ha^{-1} yr^{-1}	yr^{-1}		Mg ha^{-1}			
MWS NT	S NT	45.9	32.6	13.3	3.00	0.079	0.17	40.5	-5.43	7.9	39.1
MWS NT	MWS NT	45.9	32.6	13.3	5.83	0.070	0.14	44.5	-1.36	11.9	44.1
MWS NT	MWS opt.	45.9	32.6	13.3	7.00	0.070	0.14	46.3	0.38	13.7	46.4
MWS NT	MWS NT R	45.9	32.6	13.3	5.34	0.070	0.14	43.8	-2.09	11.2	43.1
MWS NT	MWS opt. R	45.9	32.6	13.3	6.41	0.070	0.14	45.4	-0.50	12.8	45.2
S NT	S NT	38.7	29.8	8.9	3.00	0.079	0.17	36.9	-1.78	7.2	36.5
S NT	S ST	38.7	29.8	8.9	3.00	0.105	0.20	36.1	-2.62	6.3	35.7
S NT	3S NT : 1S ST	38.7	29.8	8.9	3.00	0.086	0.18	36.7	-2.02	6.9	36.2
S NT	MWS NT	38.7	29.8	8.9	5.83	0.070	0.14	40.6	1.92	10.9	41.2
S NT	*Miscanthus x giganteus*	38.7	29.8	8.9	7.52	0.070	0.13	42.2	3.46	12.4	43.3

MWS: maize-double cropped wheat/soybean. S: soybean monoculture. MWS opt: maize-double cropped wheat/soybean with high crop yields. NT: no tillage. ST: shallow tillage. R: removal of 30% of maize residue for bioenergy production. 3 S NT : 1 S ST: 3 years of soybean under no tillage and 1 year of soybean under shallow tillage. *C0*: initial soil organic carbon reserve. *Cs*: stable soil organic carbon pool. *Ca*: active soil organic carbon pool. *m*: mass of annual C input. *k1*: humification coefficient (unitless). *k*: mineralization coefficient of the active pool (Mg ha^{-1}). *SOCm*: modeled soil organic carbon. *ΔSOCm*: percentage variation between *C0* and *SOCm* in 2032. *Ceq*: soil organic carbon reserve at equilibrium.

Simulation of SOC Reserves Under Different Agronomic Scenarios

In rich SOC soils (Table **4**), the passage from MWS NT to S NT caused a significant SOC loss as a consequence of the reduction in *m*. The maintenance of MWS NT or the passage to MWS opt. caused no changes in SOC reserves for the time horizon considered. Maize residue removal in MWS NT reduced SOC reserves but maintained them in MWS opt.

In poor SOC soils (Table **4**), the monoculture continuity kept the current SOC reserves under NT but the continuously or periodically inclusion of ST decreased them. The transformation of S to MWS NT caused no changes in SOC reserves; however, the *Ceq* showed that SOC reserves increased beyond 2032. Finally, the introduction of *Miscanthus x giganteus* significantly improved the SOC reserves.

All simulated scenarios reached equilibrium in 2032 (Table **4**).

DISCUSSION

Model Validation

The quality of fit of the AMG model was very good, probably because the model was validated with a data set generated from long-term experiments, in which the sources of variation were controlled. The availability of the *C0* values and the annual yields of each crop (from which *m* was calculated) reduced the uncertainty about these two parameters, which are the most sensitive of this model [56]. The quality of fit obtained agrees with that reported by Milesi Delaye et al. [1] for the same study region and by Saffih-Hdadi & Mary [36] for different edaphoclimatic and land management conditions, using the same model. In turn, other researchers have reported similar results using other models in different regions [32, 57-59].

The average size of *Cs* for all crop sequences and tillage systems was close to that reported previously for the same edaphoclimatic conditions [1]. The difference in the size of the *Cs* pool among tillage systems would be indicating the existence of a pool with intermediate turnover time that would be part of the active-slow-passive SOM continuum not taken into account by the AMG model.

At equilibrium, the proportion of *Ca* in relation to *SOCm* differed between crop sequences but not between tillage systems, showing the positive effect of intensified crop sequences [20, 60]. In this study, *Ca* represented approximately 26% of *Ceq* for WSM, MWS and WS, 21% for M and 17% for S.

Relationships Between Modeled Pools and Soil Properties in 2008

The relationship between *Ca* and POC was successful under the two tillage systems and the five crop sequences analyzed. POC values are often used as direct estimates of *Ca* [21, 61]. Cambardella & Elliot [28] suggested that the POC fraction may provide an accurate estimate of the slow pool. By applying the natural ^{13}C abundance technique, we have previously found that the mean residence time of *Ca* was 9 years for CT and 14 years for NT [1]. Although POC represented an important portion of *Ca*, other active fractions that were not measured by the physical fractionation method used may exist.

POC was higher near the soil surface (0-5 cm) than at lower depth (5-20 cm) because of the dominant inputs from crop residues. In accordance with Franzluebbers [62], the retention of surface residues under NT led to higher POC near the soil surface than at lower depth, particularly in intensified crop sequences due to higher *m* than in monocultures. However, under CP, POC was higher when crop sequences included maize due to the nature and morphology of its residue, which offers a contact surface with the soil of about half of wheat stubble [63] and thus leads to a low rate of mineralization [64]. In contrast, in WS, besides the high contact of the wheat residue with the soil, the fall of soybean leaves of second sowing (rich in N) accelerates the decomposition of wheat straw, leading to the incorporation of very processed fractions and relatively slower SOM turnover times into the soil, not measured as POC [31].

The SSI of the soil surface was higher under NT than under CP. Reported data suggest that macroaggregates under NT have a slower turnover time than those under reduced tillage systems, like CP [65, 66], because physical perturbation is lower. The type and quantity of the crop residue input to the soil are among possible stabilization factors [67]. In support of this idea, we have previously found higher SSI in M than in S under NT [68] and the same tendency for MWS compared with WS [31]. The latter would indicate different mechanisms of stabilization between rotations with or without maize: a very important physical protection of macroaggregates around organic matter of recent incorporation and around POM [69, 70]. However, Alvarez & Steinbach [71] found no relationship between the crop sequence and SSI for the assembly of the Pampa soils, probably due to the high soil texture variability.

Changes in SOC Reserves Following the Implementation of Different Agronomic Scenarios

The future of the SOC reserves in the Rolling Pampa is uncertain and depends on the interaction between the different driving forces in the region [72]. Indeed, the current difference in SOC reserves between rich and poor SOC soils is ~7 Mg ha^{-1} and considering the results of the projections to 2032, the difference could increase to 10 Mg ha^{-1}.

If S under NT continues its expansion over lands where crop rotation is currently practiced, SOC reserves of rich SOC soils will decrease significantly (~7 Mg ha^{-1}), negatively impacting soil fertility. The same result was achieved when S was cultivated under ST. In poor SOC soils, the continuous or periodical use of ST will cause SOC losses while if this monoculture continues under NT, SOC losses will occur beyond the projection horizon.

If the demand of maize increases, in rich SOC soils, the maintenance of the MWS sequence under NT with the current or greater level of yields (greater *m*) will preserve SOC reserves, whereas in poor SOC soils, the change from S to MWS NT will increase SOC reserves beyond 2032. Although this scenario had a positive impact on soil fertility, if the de-linking of livestock production from the land leads to increases in feed crop production based on inadequate use of irrigation, synthetic fertilizer application, and waste treatment, the positive impact of crop rotation could be offset by water pollution, and greater greenhouse gas emissions [12].

Concerns are being raised about whether the bioenergy produced from crop residues is effective to improve the C balance [19]. The use of dedicated crop for energy production will be useful and acceptable if it provides a real environmental benefit in comparison with fossil fuels [73]. Significant SOC losses due to the maize residue export have been reported [74, 75]. In this study, removing 30% of maize residues under crop rotation caused a decrease of 8.4% in *m*, which resulted in a loss of SOC of ~2.1 Mg ha^{-1}, only in MWS NT R. This showed that the practice is not sustainable with the current production level of the rich SOC soils in the Rolling Pampa, even only considering the crop with the greatest biomass production of the sequence and a typical rate residue removal of 30%. This practice could be sustainable with an average sustained increase of 20% in the grain crop yield, likely derived from other inputs such as fertilizers and water. However, additional environmental stress to supporting and surrounding ecosystems can be generated unless input use efficiency improves dramatically [76]. Besides, care should be taken in predicting, since in a small range of *C0* (40-43 Mg SOC ha^{-1}) this practice may be carried out with easily achievable C organic additions (4-5 Mg C ha^{-1} $years^{-1}$) in MWS under NT in rainfed conditions.

The introduction of *Miscanthus x giganteus* in poor SOC soils is established as the only practice able to sequester SOC among those tested for the projection horizon considered. The main cause of this effect is that *m* is comparable to the MWS opt. sequence, which currently cannot be obtained in poor SOC soils under rainfed conditions. The production levels of *Miscanthus x giganteus* used correspond to average production values normally obtained in humid temperate climates [17]. The estimated annual carbon input coincides with that modeled by Agostini et al. [77] using the Roth-C model. Although there are no long-term experiments in the Rolling Pampa, it is well known that because *Miscanthus x giganteus* is a native plant of tropical and subtropical areas of Southeast Asia [78], its naturalization in temperate climates with water availability is feasible. Therefore, it is expected that the biomass yield used (20 Mg dry matter ha^{-1} yr^{-1}) could be achievable under the edaphoclimatic conditions of the region. Once the prediction is fulfilled, this scenario represents a win-win system, that is, SOC is sequestered, improving soil fertility and functions, reducing inputs and greenhouse gas emissions while biofuel is obtained for oil substitution.

The simplified model that tends to soybean monoculture poses a serious threat to the sustainability in both rich and poor SOC soils. By contrast, the current level of intensification of the crop sequence (MWS) in rich SOC soils is the minimum to maintain soil fertility. An increased level of intensification through the implementation of cover crops of autumn-winter cycle and/or temporal pastures in this sequence is needed for the sustainability of the region [79]. The most promising alternative in poor SOC soils is the production of *Miscanthus x giganteus* as feedstock for the production of second generation biofuels. This practice could be extended to agricultural areas in which urbanization is progressing and to transition zones of mid-hill slope.

In this study, the effect of climate change on crop production and on SOC reserves was not considered. We have previously found that climate change was a driving force of great potential impact on the productivity of agricultural production systems and on SOC evolution under similar scenarios in the same region [79]. Undoubtedly, many of the assumptions included during the modeling process will not happen in the medium term in case of climatic variations of high magnitude.

CONCLUSION

The approach used to reduce uncertainties associated with the future of SOC reserves and of soil fertility, due to the effect of possible changes in land use and management in the Rolling Pampa soils, proved satisfactory. However, improving the linkage between modeled and measured fractions continues to be a challenge for SOC research.

Among the main transitions faced by the global systems of food production, the perennial grass *Miscanthus x giganteus* has shown SOC sequestration and beneficial effects on soil fertility in degraded soils. Intensified crop sequences without maize residue removal are necessary to maintain SOC reserves in rich SOC soils, whereas soybean monoculture causes soil fertility degradation in any situation.

CONFLICT OF INTERESTS

The authors confirm that this article content has no conflicts of interest.

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