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Estimating soil carbon dynamics in intercrop and sole crop agroecosystems using the Century model

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Abstract

Using process-based models to predict changes in carbon (C) stocks enhances our knowledge on the long-term dynamics of soil organic carbon (SOC) in various land management systems. The objective of this study was to apply the Century model to evaluate temporal SOC dynamics in two temperate intercrop systems [1:2 (one row of maize and two rows of soybeans); 2:3 intercrop (two rows of maize and three rows of soybean)] and in a maize and soybean sole crop. Upon initiation of intercropping, SOC increased by 47% after ≈ 100 years, whereas SOC in the maize sole crop increased by 21% and 2% in the soybean sole crop. The quantity of crop residue input was sufficient to increase the active (turnover time of months to years) SOC fraction in the intercrops and the maize sole crop, but not in the soybean sole crop. The slow fraction, with a turnover time of 20 to 50 years, increased in all crop systems and was the major driver of SOC accumulation. A 3 to 15% loss of SOC from the passive fraction, with a turnover time of 400 to 2000 years, in all crop systems showed the long-term impact of land-use conversion from historically undisturbed native grasslands to intensive agricultural production systems. This study provided an example of the potential of process-based models like Century to illustrate possible effects of cereal–legume intercropping on SOC dynamics and that the model was able to predict SOC stocks within –7 to +4% of measured values. We conclude, however that further fine-tuning of the model for application to cereal–legume intercrop systems is required in order to strengthen the relationship between measured and simulated values.

Key words: carbon sequestration / soil organic matter / soil organic carbon fractions / temperate agroecosystems

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1 Introduction

The conversion of forests or grasslands to agricultural production systems has decreased global soil organic carbon (SOC) stocks up to 75% (*Smith* et al., 2016). In agroecosystems, SOC accumulation is a dynamic equilibrium between carbon (C) inputs from crop residues or external amendments such as manure and its loss *via* mineralization and erosion (*Jensen* et al., 2012). Therefore, SOC accumulation is strongly influenced by the quantity and quality of organic residue input, agroecosystem management practices, climate, and soil structure and texture (*Six* et al., 2002; *Campbell*, 2007). However, modern agricultural practices have decreased SOC stocks, also affecting soil biodiversity and fertility (*Verhulst* et al., 2010).

The unfavorable effects on soil due to modern agriculture can be addressed by conservation agriculture (*Delgado*, 2010) and the adoption of complex agroecosystems including cereal–legume intercrops. These land management practices can help maintain or increase SOC stocks, in addition to providing other agronomic and environmental benefits (*Powlson* et al., 2014). Intercropping is defined as the simultaneous growth of more than one species in the same field, where one of the crop species is a legume (*Vandermeer*, 1992). The concept of legume-based intercropping is not new in tropical agroecosystems and it is re-gaining recognition in temperate biomes. This is because legume-based intercrops address some of the major problems associated with conventional agroecosystem management practices (*Brooker* et al., 2015). For example, *Li* et al. (2001) found that legume-based intercrops have a lower environmental impact compared to sole crops. *Regehr* et al. (2015) found that intercrops were a more sustainable land management option compared to sole cropping since intercrops contributed to the long-term immobilization of nitrogen (N), with the potential to reduce nitrification and nitrate leaching. Reduced soil nitrification rates also moderate nitrous oxide losses, causing intercrops to abate the overall contribution of this greenhouse gas to global climate change

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(*Regehr* et al., 2015). *Dyer* et al. (2012) noted that intercrops are more resilient to climate change due to a greater structural complexity, where a higher landscape-level complexity plays an important ecological role in maintaining microbial activity and diversity. In high-input intercrops, the quantity of nitrogen (N) fertilizer is reduced because of dynamic soil–plant interactions, where crops use N in a complementary way (*Pelzer* et al., 2012). The mixed crop arrangement captures resources from different parts of the soil and/or uses resources at different times and/or in different forms (*Echarte* et al., 2011). Input from mixed residue sources also create complex interactions that influence the magnitude of C and N cycled through the intercrop compared to the sole crop (*Flavel* and *Murphy*, 2006). For example, legumes contributed up to 15% of the N to the intercropped cereal (*Li* et al., 2009). Additionally, mixing residues with high and low C/N ratio increases microbial activity and diversity and nutrient translocation, improving the synchrony between N supply and crop demand (*Redin* et al., 2014).

To date, most research on temperate cereal–legume intercrops focused on biomass production (*Chapagain* and *Riseman*, 2014), fertilizer requirement, erosion control, and nutrient leaching (*Pappa* et al., 2011). Although research on the potential of cereal–legume intercrop systems to sequester C (*Oelbermann* et al., 2015) or their role in mitigating greenhouse gas (GHG) emissions (*Pappa* et al., 2011; *Dyer* et al., 2012) was addressed through a limited number of field studies and some researchers noted that temperate cereal–legume intercrops remain an under-recognized option as a potential climate change abatement strategy (*Brooker* et al., 2015). Knowledge on long-term C accumulation and changes in active, slow and passive SOC fractions in cereal–legume intercrop systems compared to sole crop systems is limited. Due to the extended time frame needed to assess changes in SOC stocks, process-based models provide an opportunity to identify factors leading to C accumulation or loss. Previously, the Century model was successfully applied to evaluate long-term changes in SOC under different temperate agroecosystem management practices (*Oelbermann* and *Voroney*, 2011; *Jing* et al., 2016). However, application of Century to cereal–legume intercrops in temperate environments is lacking. This is because the model can only handle the production of one crop at a time and therefore simulating SOC changes in intercrop systems with Century remains a challenge. The objective of this study was to use the Century model to evaluate long-term changes in cereal–legume intercrops and sole crops on SOC stocks and slow, active and passive C fractions.

2 Material and methods

2.1 Study site description and management

The research site was located in the southern Argentine Pampa, near the city of Balcarce (37°45'S, 58°18'W). The climate in this area is temperate and classified as mesothermal subhumid–humid (Thornthwaite classification). Mean annual rainfall, potential evapotranspiration and the annual mean daily air temperature (1980–2012) were 860 mm y^{-1}, 856 mm y^{-1}, and 14.3°C (maximum 24.2°C and minimum 7.6°C), respectively (Unidad Integrada Balcarce Weather Station; 130 m asl.). The soil was classified as a Typic Agriudoll (U.S. Soil Taxonomy) or Luvic Phaeozem (FAO Soil Taxonomy) with a loam soil texture consisting of 41.1% sand, 35.8% silt, and 23.1% clay (*INTA*, 1979). In 2007, the soil (0–20 cm) was moderately acidic (pH = 5.78) with a soil organic C (SOC) content of 34.2 g kg^{-1} (*Oelbermann* et al., 2015). The soil has a low available phosphorus (P) of 7.87 mg kg^{-1} (Bray-extractable P) and the slope of the site was < 2%, suggesting little to no potential for water erosion (Videla, 2014; pers. comm.).

Experimental intercrop and sole crop plots were established in 2007 (*Regehr* et al., 2015; for further details on the experimental site and its management). The study was a randomized complete block design with four treatments, herein referred to as crop systems: 1:2 intercrop [one row of maize (*Zea mays* L.) and two rows of soybeans (*Glycine max* (L.) Merr.)], 2:3 intercrop (two rows of maize and three rows of soybeans), maize sole crop, and soybean sole crop. Each crop system was replicated three times. All crop systems were under minimal tillage using a disk harrow followed by a spike harrow. Tillage occurred before crop seeding. All crop systems received P fertilizer (35 kg P ha^{-1}), and maize in the sole crop and in the intercrops was fertilized with 150 kg N ha^{-1}. Crop residues were left on the field and not removed. Under field conditions, the maize and soybean sole crops were rotated annually to minimize crop disease. For example, treatment plots referred to as maize sole crop were under maize production in 2008/09, 2010/11, 2012/13 and under soybean production in 2007/08, 2009/10. Treatment plots referred to as soybean sole crop were under soybean production in 2008/09, 2010/11, 2012/13 and under maize production in 2007/08 and 2009/10. The intercrops were continuous (not rotated) and soybean and maize were planted in the same rows in successive years (*Regehr* et al., 2015).

Aboveground biomass was sampled from each crop system replicate at crop harvest over a total of six crop seasons. Biomass samples were oven dried at 65°C for 72 h, ground to 2 mm, and analyzed for C using an elemental analyzer (Costech 4010, Cernusco, Italy). Crop residue C was determined by multiplying C concentration (%) by the amount of residue produced and expressed as g m^{-2} y^{-1}. Three soil samples were extracted randomly from each crop system replicate per year over a total of six crop seasons, except for the 1:2 intercrop and the soybean sole crop, which was sampled over five crop seasons. Soil was sampled to a 20 cm depth after each crop harvest using a soil corer with a 7 cm inner diameter and air dried. A 20 g subsample was oven-dried at 105°C for 48 h to determine oven dry weight. Bulk density was calculated using the inner diameter of the core sampler and the oven dry weight of the soil. Bulk density was not adjusted for rock volume (mineral particles $\geq$ 2 mm diameter) since these soils had no rock content. All air-dried soil samples were passed through a 2-mm sieve to remove the coarse mineral fraction and large plant residue fractions, ground in a ball mill (Retsch® ZM1, Haan, Germany), and analyzed for SOC using an elemental analyzer. Soil organic C stock was determined by multiplying SOC concentration (%) by the amount of soil per m^2, using soil bulk density.

2.2 The Century model and its parameterization

Century is a site-specific model based on soil–plant-climate interactions and therefore parameterizing Century can be achieved through modifying soil biophysical characteristics, climate and management practices. The plant production sub-model in Century simulates above- and belowground biomass production of crops, grasslands, savannas or forests (*Parton* et al., 1988). The SOM sub-model predicts changes in the soil active, slow and passive fractions based on microbial decomposition of plant residues and resulting microbial products, which are the basis for humus formation (*Parton* et al., 1988). Approximately 2 to 4% of the total SOM pool is composed of the active fraction and includes soil microbes and microbial products with a turnover time of a few months to a few years (*Metherell* et al., 1993). The slow fraction comprises 45 to 65% of the total SOM pool with a turnover time of 20 to 50 years, depending on climate, and includes resistant plant material derived from structural plant material and stabilized soil microbial products (*Metherell* et al., 1993). The passive SOM fraction comprises 30 to 40% of the total SOM pool with a turnover time of 400 to 2000 years and includes physically and chemically stabilized SOM that is highly resistant to decomposition (*Metherell* et al., 1993). The extent to which the decomposed compounds are stabilized is a function of soil texture (*Parton* et al., 1988). Century was initially developed to simulate changes in SOC stocks in grasslands (*Parton* et al., 1988), but the model is also able to simulate agroecosystems (*Ouyang* et al., 2014; *Brandani* et al., 2015), forest ecosystems (*Hashimoto* et al., 2012), and agroforestry systems (*Oelbermann* and *Voroney*, 2011) in temperate and tropical environments. Century, therefore, has become one of the most widely used models due to its broad applicability.

In our study, the Century model (version 4.0) was used to simulate temporal changes in SOC stocks to a 20 cm depth in temperate maize–soybean intercrop systems with a 1:2 and 2:3 configuration and maize and soybean sole crops. To initiate the model prior to simulating various agricultural management practices, Century was run for ≈ 10,000 years under grassland, which is native to this region of Argentina, to estimate equilibrium SOC levels and plant productivity (Tab. 1).

Table 1: Scheduling of agricultural management practices in Century based on actual historical events at the Instituto Nacional Tecnología Agropecuaria (INTA), Balcarce, Argentina.

Date	Management Practices
–10,000 to 1880	*Grassland* ● Grassland: 50% warm & 50% cool season grass (G50) from October to April; grass senescence in May ● ≈10,000 years of simulation to estimate equilibrium soil organic carbon levels and plant productivity
1881 to 1950	*Pasture for livestock production* ● Pasture: grass pasture with 25% legumes (GLC) with high intensity grazing (GH) from October to April; grass senescence in May
1951 to 1999	*Monocrop maize* ● Cultivation: plough (P) in September ● Crop Seeding and production: medium yielding corn (CMD) from October to April ● Fertilizer: typical rate for this region (15 g N m^{-2} y^{-1}, 3.5 g P m^{-2} y^{-1}); applied in November ● Crop Harvest: grain only (G) in April
2000 to 2006	*Sunflower* ● Based on the high yielding corn (CHI)[a] file with a biomass production of 479 g C m^{-2} y^{-1}, and a lignin value of 0.09 ● Cultivation: cultivator (C) in September ● Crop Seeding and production: sunflower (SUNFL) from October to April ● Fertilizer: typical rate for this region (15 g N m^{-2} y^{-1}, 3.5 g P m^{-2} y^{-1}); applied in November ● Crop Harvest: grain only (G) in April
2007 to 2120	*Sole crops and intercrops* ● Cultivation: cultivator (C) in September ● Crop Seeding and production: – Maize sole crop: high yielding corn (CHI) sown in October, harvested in April – Soybean sole crop: soybean (SYBN) sown in November, harvested in May – Intercrops: soybean (SYBN) sown in October, harvested in May ● Fertilizer: – Maize sole crop and intercrops: typical rate for this region (15 g N m^{-2} y^{-1}, 3.5 g P m^{-2} y^{-1}); applied in November – Soybean sole crop: typical rate for this region (3.5 g P m^{-2} y^{-1}); applied in December ● Crop Harvest: grain only (G) in April (maize) and May (soybean) ● Organic matter addition (OMAD) in intercrops from maize residues in May[b]: – 1:2 intercrop[†]: 599 g C m^{-2} y^{-1} – 2:3 intercrop [†]: 643 g C m^{-2} y^{-1} [†]based on six-year mean of maize production at this site in the intercrops

[a] Sunflower is not an available default crop option in Century 4.0. Therefore, sunflower was simulated as maize (high harvest) with modified patterns of residue incorporation, as suggested by *Tittonell* et al. (2006).

[b] based on organic matter input from maize residues in May at the time when maize would typically be harvested.

Table 3: Soil physical and chemical characteristics (0–20 cm) upon initiation of intercropping in Balcarce, Argentina, in 2007.

	1:2 Intercrop	2:3 Intercrop	Maize Sole Crop	Soybean Sole Crop
Sand (g kg^{-1})[a]	41.1	41.1	41.1	41.1
Silt (g kg^{-1})[a]	35.8	35.8	35.8	35.8
Clay (g kg^{-1})[a]	23.1	23.1	23.1	23.1
pH (water)[b]	5.9	5.7	5.9	5.6
Bulk density (g cm^{-3})[b]	1.18	1.14	1.23	1.18
Soil organic carbon (g C m^{-2})[b]	5413	5309	6191	5863
C/N[b]	17.4	17.3	16.7	16.7

[a]adapted from *Studdert* and *Echeverría* (2000);
[b]adapted from *Oelbermann* et al. (2015).

The initialization of SOC equilibrium was used to bring the model to its first year of simulation which began in 1881 with pasture for livestock production (Tab. 1). Monthly average maximum and minimum temperature and monthly total precipitation data (36-year mean) were obtained from a nearby meteorological station housed at the Unidad Integrada Balcarce, Argentina (Tab. 2). Following the initialization of SOC levels, the model was scheduled using historical events based on different agricultural land management practices prior to the initiation of intercropping and sole cropping in 2007 (Tab. 1). Initial site-specific parameters (Tab. 3), including soil texture, SOC, bulk density, and soil pH were obtained from previous studies (*Studdert* and *Echeverría*, 2000; *Oelbermann* et al., 2015). The proportion of SOM initial values for the active, slow and passive fractions were 3%, 65% and 32%, respectively (*Metherell* et al., 1993; *Yiridoe* et al., 1997; *Oelbermann* and *Voroney*, 2011). Values for the maximum decomposition rate of SOM with active, slow and passive turnover were 4, 0.0013, and 0.05, respectively (*Yiridoe* et al., 1997; *Oelbermann* and *Voroney*, 2011).

Table 2: Climate data used for the Century simulation in Balcarce, Argentina based on a 36-year mean monthly temperature and precipitation at the Unidad Integrada Balcarce Weather Station, Argentina.

	Temperature (°C)		Precipitation (cm)
	Minimum	Maximum	
January	13.3	27.2	9.8
February	13.0	26.1	7.0
March	11.8	24.1	8.7
April	8.7	19.9	5.8
May	6.1	16.4	4.9
June	3.6	12.7	4.6
July	3.1	12.2	4.6
August	3.6	14.3	3.9
September	4.6	16,3	5.2
October	7.1	19.0	8.9
November	9.2	22.2	6.3
December	11.8	25.3	9.0

Since Century can only handle the production of one crop at a time, therefore simulating changes in SOC and its associated fractions in intercrop systems is challenging. We addressed this limitation by growing soybeans with grain harvest only and added organic matter from maize residues at the time of soybean harvest (Tab. 1). This was achieved by creating a OMAD.100 file, where maize residue return was based on actual field data collected over six crop seasons in both intercrop configurations (Tab. 4). The assigned lignin value for the maize crop residue was 0.12 and a C/N ratio of 64. A separate FERT.100 file was created for the soybean sole crop that received P fertilizer only. An additional file in FERT.100 was created for fertilizer addition in the intercrops and the maize sole crop (Tab. 1). Crop parameters for maize and soybeans were modified to accommodate regional crop production values (Tab. 6). Sunflower is not an available default crop option in Century 4.0. Therefore, sunflower was simulated as maize (high harvest) with modified patterns of residue incorporation, as suggested by *Tittonell* et al. (2006). Default values set by the Century model were used for atmospheric N deposition and N_2-fixation rates. All other parameters used in this simulation were provided by the Century model, and modified parameters are listed in Tab. 6 (*Keough*, 2008; pers. comm.). Century simulates changes in SOC stocks on a yearly or monthly time-step. In this study we used the monthly time-step in order to align simulated values to their corresponding month when field soil sampling took place.

The measured field data were compared with the simulated data using the regression function in SPSS (*SPSS Science Inc.*, 1989). The following metrics were used: correlation coefficient (r), coefficient of determination (r^2), adjusted r^2, root mean square error (RMSE) representing the size of a typical error, the mean difference (M) between simulated and measured levels of SOC, the coefficient of residual mass (CRM)

Table 4: Aboveground crop residue biomass carbon (C) input over six cropping seasons from the years 2007/08 to 2012/13 from soybean and maize residues in 1:2 and 2:3 intercrops and maize and soybean sole crops, Balcarce, Argentina. Standard errors are given in parentheses.

		Cropping Year						
	Treatment	**2007/08**	**2008/09**	**2009/10**	**2010/11**	**2011/12**	**2012/13**	**Mean (years)**
C input from maize residue (g C m^{-2} y^{-1})	1:2 Intercrop	685 (21)	551 (14)	557 (54)	579 (26)	450 (18)	769 (54)	599 (46)
	2:3 Intercrop	644 (28)	631 (25)	601 (23)	605 (16)	471 (23)	907 (23)	643 (58)
	Maize	1068 (39)	923 (27)	1015 (113)	1030 (34)	490 (88)	1283 (59)	968 (107)
	Soybean	–	–	–	–	–	–	–
C input from soybean residue (g C m^{-2} y^{-1})	1:2 Intercrop	192 (22)	76 (18)	159 (19)	176 (28)	72 (11)	60 (7)	123 (24)
	2:3 Intercrop	208 (36)	79 (8)	160 (7)	176 (8)	78 (3)	100 (3)	134 (23)
	Maize	–	–	–	–	–	–	–
	Soybean	494 (66)	305 (34)	255 (32)	532 (33)	329 (10)	155 (7)	345 (59)

which is a measure of the tendency of the model to over- or underestimate the measurements, and modeling efficiency (EF) which compares simulated values to the average value of the measurements (*Steel* et al., 1997). The threshold probability level for determining goodness of fit was $p < 0.05$.

3 Results

The initiation of pasture for livestock production in 1881 decreased the SOC stock by 2030 g m^{-2} (15.7%). Soil organic C continued to decline when sole crop maize production began in 1951 and did not start to recover until 2010 in all crop systems (Fig. 1). There was a sharp decline in SOC stocks between 2000 and 2005, after which there was a steady increase with recovery beginning in 2010 in all crop systems. However, 113 years after the initiation of intercropping, none of the crop systems were able to reach pre-1881 SOC levels. The model predicted a greater SOC stock, by the year 2120, in the intercrops compared to the sole crops. For example, SOC increased by 46.7% (1:2 intercrop) and 45.2% (2:3 intercrop) between 2007 and 2120. Comparatively, the soybean sole crop increased by 1.7% and the maize sole crop by 20.5% during this time.

Carbon in the active fraction in the soybean sole crop decreased by 34% from 2007 onwards to the end of the simulation in 2120, whereas the slow fraction increased by 20% during this time (Fig. 2). The active fraction increased by 61% in the intercrops and 53% in the maize sole crop between 2007 and 2120. During this time, the slow fraction also increased by 35% in the intercrops and 29% in the maize sole crop. The passive fraction decreased in all crop systems, with the greatest loss in the soybean sole crop (15%) followed by the maize sole crop (4.0%) and the intercrops (3%).

Model performance was good, with a significant relationship (*P*-values ranging from 0.01 to 0.04) between measured field data and simulated values of SOC in the intercrops and maize sole crop (Tab. 5; Fig. 3). However, model performance in the

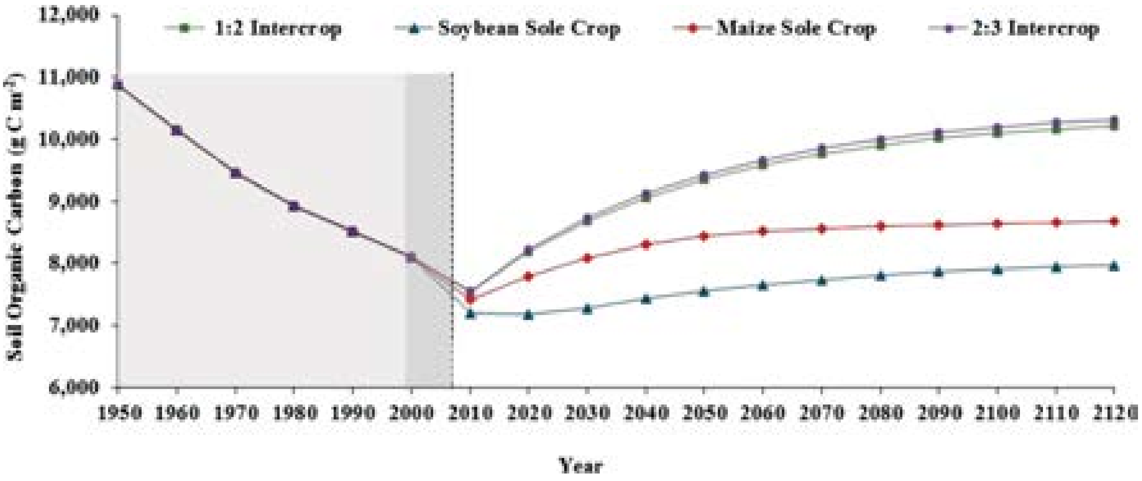

Figure 1: Soil organic carbon simulated by Century in sole crops and two differently configured cereal–legume intercrops in a temperate climate of the Argentine Pampa. The light grey shaded area indicates maize monocrop, the dark grey area indicates sunflower production and the dashed line indicates the year intercropping was initiated.

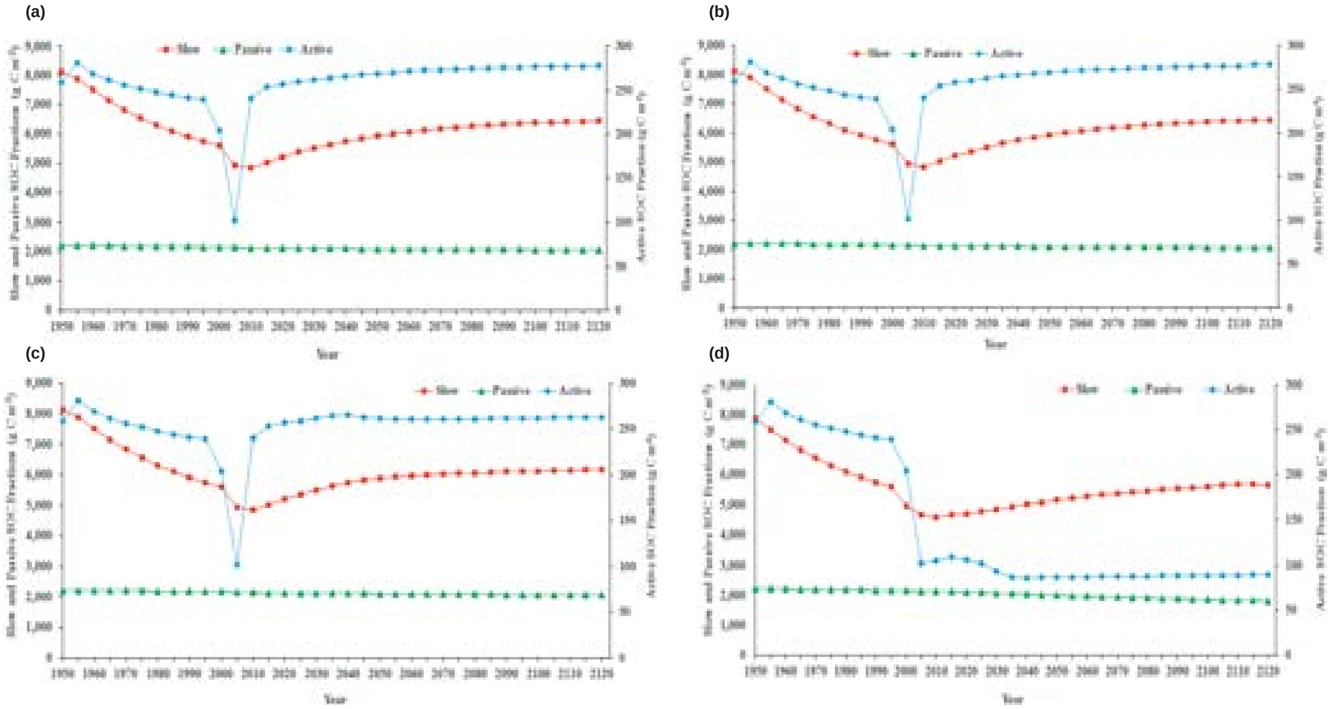

Figure 2: Soil organic carbon fractions simulated by Century in a 1:2 intercrop (a), 2:3 intercrop (b), maize sole crop (c) and soybean sole crop (d) in a temperate climate of the Argentine Pampa.

soybean sole crop was poor and did not show a significant relationship ($P = 0.08$) between measured field data and simulated values. The coefficient of residual mass (CRM) was close to zero for all crop systems, indicating a lack of bias in the distribution of simulated values with respect to measured values. Century underestimated SOC stocks in the 1:2 intercrop (–1%), the maize sole crop (–2%), and the soybean sole crop (–7%), but overestimated in the 2:3 intercrop (+4%). Overall model performance was good, as indicated by EF values close to 1.0. EF values close to 1.0 indicate a near perfect fit, while EF values less than zero (EF < 0) are indicative of a poor fit.

4 Discussion

Although the Argentine Pampa is recognized as a region with potential for increased agricultural production, initiation of row cropping and intensive tillage practices significantly reduced SOC stocks over the past 40 years (*Alvarez*, 2001). Recognizing that intensive tillage practices are not suited to the soils of the Argentine Pampa, a rapid growth in the adoption of minimum tillage practices occurred (*FAO*, 2004). Currently 95% of the agricultural community in this region of Argentina have adopted minimum tillage (Wilton, 2012; data on file). Parallel to this, our simulation results showed a steep decline in SOC upon initiation of row cropping with conventional tillage (maize monocrop) beginning in 1951 and under sunflower production with minimum tillage. Despite minimum tillage, the loss of SOC under sunflower production was due to

Table 5: Statistical tests applied for agreement between simulated (Century model) and measured values of soil organic carbon in maize and soybean sole crops, and 1:2 and 2:3 cereal–legume intercrops at the Instituto Nacional Tecnología Agropecuaria (INTA), Balcarce, Argentina.[a]

	1:2 Intercrop	2:3 Intercrop	Maize Sole Crop	Soybean Sole Crop
n	5	6	6	5
r	0.97	0.89	0.83	0.83
r^2	0.93	0.89	0.68	0.69
Adjusted r^2	0.91	0.74	0.60	0.59
P	0.01	0.02	0.04	0.08
RMSE (g C m^{-2})	217	389	220	363
CRM (g C m^{-2})	0.01	–0.04	0.02	0.07
M (g C m^{-2})	–261	–1546	848	2617
EF	0.99	0.99	0.99	0.99

[a] n, number of samples (crop seasons); r, correlation coefficient; r^2, coefficient of determination; RMSE, root mean square error or standard error of the estimate; CRM, coefficient of residual mass $[(\Sigma_{\text{measured}} - \Sigma_{\text{simulated}})/\Sigma_{\text{measured}}]$; M mean difference between simulated and measured values of SOC; EF, model efficiency $[1-(\Sigma_{\text{simulated}} - \Sigma_{\text{measured}})^2/(\Sigma_{\text{measured}} - \bar{x}_{\text{measured}})^2$. Positive CRM, values indicate an underestimation of simulated results, whereas negative M values indicate an underestimation of simulated results.

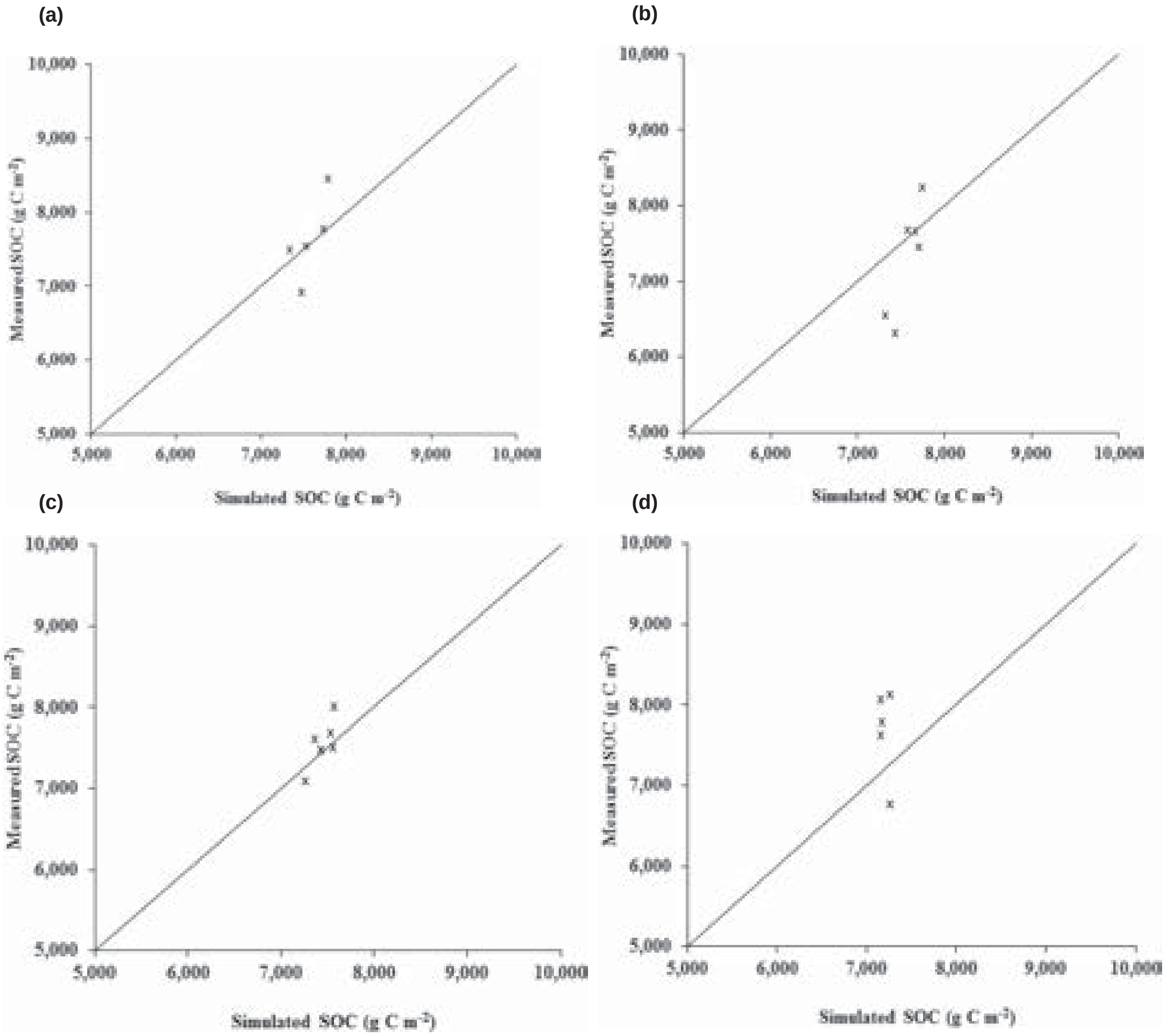

Figure 3: Relationship between observed (field measurements) and predicted (simulated) values of soil organic carbon in the (a) 1:2 intercrop, (b) 2:3 intercrop, (c) maize sole crop and (d) soybean sole crop. Observed data are adapted from *Vachon* (2008), *Dyer* (2010), *Regehr* (2013) and data currently on file.

the small quantity of C (479 g C m^{-2} y^{-1}) input from crop residues (*Andrade*, 1995). Similarly, we expected a continued SOC decline under the soybean sole crop (2007 onwards) due to the low quantity (345 g C m^{-2} y^{-1}) of residue returned from this crop. Instead, the soybean sole crop had an 1.7% increase in SOC between years 2007 and 2120. *Studdert* and *Echeverría* (2000) have studied the soils of the Argentine Pampa extensively and suggested that N fertilization, in this case through N_2-fixation, augments SOC stocks due to an increase in the quantity of crop residue production. Therefore, integrating minimum tillage and legume-based agriculture increases SOC storage relative to conventional tillage in non-legume-based agricultural systems (*Paustian* et al., 1997). Additionally, in legume-based agriculture, the accumulation of recently fixed C or reduced decomposition of older soil C occurs (*Resh* et al., 2002) due to a priming effect (*Qiao* et al., 2016), contributing to the accumulation of SOC (*Stockmann* et al., 2013).

In agroecosystems, the loss of SOC is due to a drastic reduction of organic matter returned to the soil (*Brandani* et al., 2015). For example, *Li* et al. (2003) found that a 25% reduction in crop residue input decreased SOC by 1.6%. Based on this information, we expected the maize sole crop to show the greatest recovery in SOC because it had the greatest C input (968 g C m^{-2} y^{-1}). Despite a lower C input from crop residues in the 2:3 intercrop (777 g C m^{-2} y^{-1}) and 1:2 intercrop (722 g C m^{-2} y^{-1}), SOC stocks were ≈ 18% greater in these crop systems compared to the maize sole crop after 113 years. The synchronous input of residues from cereal and legume plants in intercrops causes interspecific interactions in the soil–plant continuum that stimulates a more active microbial community and affects soil C and N transformations and decomposition differently compared to sole crops (*Redin* et al., 2014). These interspecific interactions are governed by temporal and spatial complementarity through the acquisition of N, the accumulation of recently fixed C or a reduction in the decomposition of older C sources (*Stockmann* et al., 2013).

Table 6: Century parameters measured or modified during model calibration for the 1:2 intercrop (1:2INT), 2:3 intercrop (2:3INT), maize sole crop (MSC) and soybean sole crop (SSC).

Parameter	Description	Code	Value
SITE.100 File	Number of soil layers	nlayer	8
	Number of soil layers in the top level	nlaypg	5
	Fraction of excess water lost by drainage	drain	0.5
	Soil pH	pH	5.78
	Bulk density	bulkd	1.18
	Initial value for unlabeled C in soil organic matter with fast turnover	som1ci(2,1)	3%
	Initial value for unlabeled C in soil organic matter with slow turnover	som2ci(1)	65%
	Initial value for unlabeled C in soil organic matter with passive turnover	som3ci(1)	32%
FIX.100 File	Maximum decomposition rate of soil organic matter with active turnover	dec3(2)	4
	Maximum decomposition rate of soil organic matter with slow turnover	dec4	0.0013
	Maximum decomposition rate of soil organic matter with passive turnover	dec5	0.05
	Maximum C/N ratio for material entering the slow pool	varat2(1,1)	20
	Maximum C/N ratio for material entering the passive pool	varat3(1,1)	8
	Fraction per month of gross mineralization which is volatilized	vlossg	0.01
OMAD.100 File	Grams of C added with the addition of organic matter (g m^{-2})	astgc	599 (1:2INT)643 (2: INT)
	Lignin fraction of organic matter	astlig	0.12
	C/N ratio of added organic matter	astrec(1)	64
CROP.100 File	Potential aboveground monthly production for crops (g m^{-2})	Pdrx(1)	2200 (MSC)360 (SSC)
	Planting month reduction factor to limit seedling growth	pltmrf	1 (MSC)0.5 (SSC)
	Value of aglivic at full canopy cover	fulcan	50 (MSC)150 (SSC)
	Initial fraction of C allocated to roots	frtc(1)	0.5
	Final fraction of C allocated to roots	frtc(2)	0.1

Additionally, N derived from the soil and crop residues from previous cropping seasons (legacy N) also influences C dynamics differently in intercrops than in sole crops (*Regehr* et al., 2015). Although the quantity of residue returned to the soil is the main factor that influences levels of SOC, *Studdert* and *Echeverría* (2000) noted that this is also influenced by other factors including crop combination. For example, *Bichel* et al. (2016) found that microbes in intercrops utilize new C sources more efficiently thereby minimizing the decomposition of native C causing an increase in SOC stocks. *Bichel* (2012) also found that the C sources metabolized in cereal–legume intercrops were distinctly different compared to sole crops.

After ≈ 113 years of sole cropping and intercropping under minimum tillage, SOC stocks remained below native grassland (pre-1880) levels. Other studies, using Century, also found that SOC stocks were below native levels 150 years after the initiation of conservation agriculture in tropical and subtropical agroecossytems (*Tornquist* et al., 2009) and in temperate and tropical agroforestry systems (*Oelbermann* and *Voroney*, 2011). Due to a greater root density and root exudation rates and limited soil aeration, native grasslands have a greater SOC stock than arable lands (*Nieder* and *Benbi*, 2008). Therefore, SOC levels similar to those under native grasslands cannot be expected to be reached with cereal–legume intercrops or sole crops, despite minimum tillage, due to lower above- and belowground inputs compared to grasslands.

Although all SOC fractions decreased upon initiation of agricultural activities, the slow fraction increased in all crop systems, and the active fraction increased in the maize sole crop and intercrops when minimum tillage and/or intercropping began. This is because the different C fractions were controlled by land-use change and management, which affected primary production, quantity and quality of residue returned to the soil and soil nutrient status, contributing toward the accumulation of SOC (*Schwendemann* et al., 2007). Therefore, C stabilization into different soil fractions is controlled by the quality of the crop residue entering the soil ecosystem in addition to physicochemical and biological influences from the surrounding environment (*Schmidt* et al., 2011; *Mazzilli* et al., 2014). However, in intercrops the synchronous input of residues from cereal and legume plants causes interspecific interactions in the soil–plant system that stimulates a more active microbial community and affects soil C transformations differently compared to sole crops (*Redin* et al., 2014). Therefore, the active fraction in the intercrops may have a greater resilience to disturbance (*e.g*., tillage) and that this C fraction could be maintained by input from mixed residue sources (*Ouyang* et al., 2014).

Simulation results showed that C associated with the slow fraction was the key driver in SOC accumulation in all crop systems. The slow fraction resisted the impact of disturbance (*e.g*., tillage) and was maintained by input from crop residues regardless of crop system. This is because C accumulation in the slow fraction is strongly related to the quantity of C and nutrient input from fertilizers and/or crop residues (*Carvalho Leite* et al., 2004). For example, *Cong* et al. (2014) found that long-term fertilizer application caused an accumulation of C in the slow fraction, whereas it decreased C in the passive fraction. Because of its more chemically complex structure and through physical protection, the slow C fraction was more resistant to decomposition than the active fraction (*Parton* et al., 1987). However, the loss of C from the passive fraction in all crop systems indicated the long-term impact on SOC as a result of converting native grasslands to intensely managed row crop agricultural production systems (*Ouyang* et al., 2014).

Variation between measured and simulated values ranged from –7 to +4%. These deviations were similar to those observed by *Alvarez* (2001), who found SOC values within +5 to –15% of the measured SOC values in the Argentine Pampa. *Bricklemyer* et al. (2007) found a 10% deviation between measured and simulated values in temperate soils and *Galdos* et al. (2009) reported a 2 to 8% deviation in a tropical soil from Brazil. Discrepancy between measured and simulated values were due to Century's inability to simulate accumulated impacts of SOC, which are important in the stabilization of humic substances, the microbial biomass and plant residues (*Paul* et al., 1995). For example, SOC concentration increases continually as a single factor, neglecting the integrated impacts of other factors (*Ouyang* et al., 2014). Additionally, a priming effect has not been incorporated into the Century model but could impact simulation outcomes in cereal and legume-based crops with respect to C accumulation in mineral associated soil fractions and the influence of environmental factors on its decomposition rate (*Mazzilli* et al., 2014). Century assumes bulk density as a constant parameter throughout the simulation period (*Pennock* and *Frick*, 2001). However, due to the accumulated impact of SOC, bulk density will decrease with time and therefore influence the distribution and overall quantity of C sequestered over the long-term (*Oelbermann* and *Voroney*, 2011). Century was not able to account for pH effects on SOC turnover (*Jastrow* et al., 2007). The pH lowering effect of fertilizers can reduce decomposition rates and prevent the incorporation of surface litter into SOC or fertilizers can enhance the availability of labile N and promote microbial mineralization of C substrates (*Kelly* et al., 1997). The meager performance between measured and simulated results in the soybean sole crop is likely due to field management practices. Under field conditions, soybean and maize sole crops were rotated annually in order to minimize crop disease. However, crop rotation in the sole crops was not applied in the Century simulation, causing the model to underestimate SOC stocks. The Century model can simulate the production of only one crop at a time. This limits its application to land management practices such as agroforestry and intercropping. However, *Oelbermann* and *Voroney* (2011) created files in OMAD.100 to account for additional organic matter input from litterfall or tree prunings in temperate and tropical agroforestry alley cropping systems. We used a similar approach in this study to address the one crop-only limitation by creating OMAD.100 files to compensate for the additional crop residue input in the intercrops.

5 Conclusions

Since Century can simulate the production of only one crop at a time, it has limited application in complex agroecosystems such as cereal–legume intercrops. This study was the first to configure the model for its application to maize–soybean intercrops. Although residue C input was 20 to 25% lower in the intercrops compared to the maize sole crop, input from cereal and legume sources simultaneously caused complex interactions at the soil-residue scale that influenced soil C transformations differently compared to the sole crops, allowing for the accumulation of SOC. Carbon associated with the slow fraction was the key driver in SOC accumulation in all crop systems. Although the model was capable of predicting SOC stocks within ±7% of measured values, we recommend that fine-tuning of the model for application to cereal–legume intercrop systems is required to strengthen the relationship between measured and simulated values.

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