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Changes in soil characteristics after six seasons of cereal–legume intercropping in the Southern Pampa

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ABSTRACT

The Argentine Pampa is one of the most productive agricultural regions in the world, but sole crop management practices have led to soil degradation and losses of soil organic matter. The objective of this study was to evaluate soil organic carbon (SOC) and nitrogen (N) dynamics in 2007 and in 2012 in two intercrop systems [1:2 intercrop (one row of maize (*Zea mays* L.) and two rows of soybeans (*Glycine max* L. Merr.)) and 2:3 intercrop (two rows of maize and three rows of soybean)], and in a maize and soybean sole crop. Results showed that C and N input from crop residues was significantly greater ($P < 0.05$) in the maize sole crop, followed by the intercrops and the soybean sole crop. The land equivalent ratio (LER), based on crop biomass, was significantly greater ($P < 0.05$) in the 2:3 intercrop. Soil physical and chemical characteristics (bulk density, pH, SOC and N, C/N ratio) were not significantly ($P < 0.05$) different among treatments and were significantly greater in 2012, except for pH, at all depths. Gross SOC turnover time was significantly longer ($P < 0.05$) in 2012 compared to 2007 for all treatments and depths, except in the maize sole crop. Soil microbial biomass (SMB) C and N were significantly greater ($P < 0.05$) in the 2:3 intercrop in both years. To a 40 cm depth, SMB-C turnover time (SMB-C_T) was significantly greater ($P < 0.05$) in the soybean sole crop followed by the intercrops and the maize sole crop in 2007, whereas in 2012, SMB-C_T was significantly greater ($P < 0.05$) in the intercrops followed by the soybean and the maize sole crops. The soil light fraction N (LF-N) was significantly greater ($P < 0.05$) in the maize sole crop in both years. There was no significant difference ($P < 0.05$) for LF-C. Our results demonstrated that cereal–legume intercropping is a more sustainable agroecosystem land management practice in the Argentine Pampa, with respect to soil C and N transformations, compared to sole cropping.

1. Introduction

The rapid depletion of soil organic carbon (SOC) coincides with the adoption of sole crop agroecosystem management practices in temperate biomes (Stavi and Lal, 2012). This has resulted in a 30 to 50% loss of SOC in the top 30 cm (Berhongaray et al., 2013). In temperate regions like the Pampa, the most productive agricultural land in Argentina, 90% of the land has been converted from natural grasslands to livestock and to sole crop production systems (Medan et al., 2011). These activities have reduced SOC stocks in the Argentine Pampa by 35%, to a 15 cm depth, over the past four decades (Álvarez, 2001).

Implementing agroeocsystem management practices that maintain or increase SOC stocks, while mitigating climate change via carbon (C) sequestration, and providing sufficient quantities of food, fiber and fuel for a growing population remains an agronomic challenge. Complex agroecosystems such as intercrops, where more than one crop is grown on the same land area at the same time, are currently re-gaining recognition in temperate biomes (Oelbermann and Echarte, 2011). This is because intercrops have a lower environmental impact compared to sole crops, and are more resilient to climate change due to their greater structural complexity.

Intercrops use their resources more efficiently since the mixed arrangement of crops captures resources from different parts of the soil, and/or uses resources at different times, and/or in different forms [e.g., atmospheric nitrogen (N) versus reduced forms of N] (Echarte et al., 2011). Additionally, the mixing of residues from cereal and legume crops causes complex interactions that influence the magnitude of N cycled through the intercrops compared to sole crops (Flavel and Murphy, 2006). From an agronomic perspective, the classic criterion to evaluate whether or not an intercrop is more effective than its associated sole crop is the concept of land equivalent ratio (LER) (Mead and Willey, 1980). LER, based on crop biomass or grain yield, represents the biological efficiency of growing two crops together (Mead and Willey, 1980). When LER is greater than 1, resources are used more effectively in the intercrop compared to the sole crop (Barker and Dennett, 2013).

To date, most research in temperate intercropping systems has focused on grain yield and quality, crop competition, pest management, weed and erosion control, nutrient-use efficiency, nutrient leaching, and LER (Hauggaard-Nielsen et al., 2001; Prasad and Brook, 2005;

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Waddington et al., 2007; Echarte et al., 2011; Pappa et al., 2011; Klimek-Kopyra et al., 2013). Only a few studies have investigated soil C and N dynamics, including residue decomposition (Vachon and Oelbermann, 2011) and gross N mineralization (Regehr, 2013), greenhouse gas emissions (Pappa et al., 2011; Dyer et al., 2012), and baseline changes in soil characteristics (Oelbermann and Echarte, 2011). To date no studies have investigated the short-term (2–5 years) effect of cereal–legume intercropping on SOC and N in temperate regions. Therefore, the objective of this study was to evaluate the short-term influence of intercropping on SOC and N dynamics in the Argentine Pampa. This research advances our knowledge on identifying the most effective intercrop configuration(s) to help maintain agricultural productivity, improve soil characteristics, enhance agroecosystem resilience to climate change, and encourage C sequestration.

2. Materials and methods

2.1. Experimental site

The research site was located in the southern Pampa, near the city of Balcarce (37°45′ S, 58°18′ W), Argentina. The 32-year mean annual precipitation was 860 mm, the mean annual temperature was 14.3 °C, and the site was located 130 m above sea level. The soil was classified as a Typic Agridudoll (US Soil Taxonomy) or Luvic Phaeozem (FAO Soil Taxonomy) and was part of the *Mar del Plata* series (Studdert and Echeverria, 2000). The soil texture was loam, consisting of 41.1% sand, 35.8% silt and 23.1% clay (Domínguez et al., 2009). The soil was moderately acid, had a low available phosphorus (P), and a high soil organic C (SOC) content (Fabrizzi et al., 2003). The slope was 2%, indicating little to no erosion (Domínguez et al., 2009).

The study site was established in 2007 on land previously under experimental use of alternating crop and pastures, where the most recent crop was two years of sunflower (*Helianthus annuus* L.) production, cultivated using a disk harrow followed by a spike harrow. The current study design was a randomized complete block design (RCBD) with four treatments: maize sole crop, soybean sole crop, 1:2 intercrop (one row of maize and two rows of soybeans) and 2:3 intercrop (two rows of maize and three rows of soybeans). Each treatment was replicated three times, and each treatment plot size was 8.8 × 12 m. The maize and soybean sole crops were rotated annually. For example treatment plots referred to as maize sole crop were under maize production in 2008–09, 2010–11 and 2012–13, and under soybean production in 2007–08 and 2009–10. Treatment plots referred to as soybean sole were under soybean production in 2008–09, 2010–11 and 2012–13, and under maize production in 2007–08 and 2009–10. However, the intercrops were continuous (not rotated) and soybean and maize were planted in the same rows in successive years. Plant density (plants m^{-2}) was 4.3 (1:2 intercrop), 5.3 (2:3 intercrop), 8.0 (maize sole crop) and 29 (soybean sole crop), with a 0.52 m distance between crop rows in all treatments. The site was disk harrowed three times and spike harrowed before planting. Weeds were controlled by N-phosphonomethyl glycine (Glyphosate). All crops received P fertilizer (35 kg P ha^{-1}). Maize in the sole crop and in the intercrops received N fertilizer (150 kg N ha^{-1}) in the form of urea. In the intercrops, the fertilizer was applied by hand at the bottom of the maize stems at the 6th leaf stage. Soybeans were inoculated with *Bradyrhizobium japonicum*. Maize was typically seeded in late October or early November and harvested in April; soybeans were seeded in November and harvested in May. All agronomic practices, including soil cultivation, fertilizer application rates, and intercrop configurations, were typical of those under study in this region.

2.2. Crop residues and land equivalent ratio

Aboveground biomass from crop residues was sampled at harvest, over a total of six cropping seasons from 2007–08 to 2012–13, using three randomly located areas, 1 m^2 in size, within each treatment replicate. Samples were oven dried at 65 °C for 72 h, ground to 2 mm and analyzed for C and N using an elemental analyzer (Costech 4010, Cernusco, Italy). Crop residue C and N input was determined by multiplying C and N (%) by the amount of residue produced, and expressed as g m^{-2} y^{-1}.

Land equivalent ratio (LER), on a biomass basis, was quantified according to Mead and Willey (1980):

$$\mathrm{LER} = (\mathrm{MR_I}/\mathrm{MR_{SC}}) + (\mathrm{SR_I}/\ \mathrm{SR_{SC}}) \tag{1}$$

where $\mathrm{MR_I}$ is the quantity (g m^{-2} y^{-1}) of maize crop residue produced under intercropping, $\mathrm{MR_{SC}}$ is the quantity of maize crop residue produced under maize sole cropping, $\mathrm{SR_I}$ is the quantity of soybean crop residue produced under intercropping, and $\mathrm{SR_{SC}}$ is the quantity of soybean crop residue produced under soybean sole cropping.

2.3. Soil physical and chemical characteristics

Soil was sampled after the soybean harvest at 0–20 and 20–40 cm depths using a soil corer with a 7 cm inner diameter. Soil was sampled in the 2007–08 (referred to as 2007) cropping season, and again in the 2012–13 (referred to as 2012) cropping season. Three random samples per treatment replicate were extracted and composited, corresponding to depth, into one sample 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 ≥ 2 mm) because these soils had minimal 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. Soil pH was quantified using a 20 g subsample in a 1:1 soil:water suspension (BioKit AB 15B, Houston, TX, USA). Soil carbonates were removed by adding 150 ml of 0.5 M HCl to 2 g of air-dried and sieved soil. The mixture was stirred 3 times over 24 h, and subsequently washed by pipetting the HCl from the settled soil and adding ultrapure water to the soil. This washing procedure was repeated daily for 4 days after which the soil was dried in an oven at 40 °C for 2 days (Midwood and Boutton, 1998). The acid treated soil was ground in a ball mill (Retsch® ZM1, Haan, Germany) and analyzed for SOC and total N. Soil organic C and total N stocks were determined by multiplying SOC and total N (%) by the amount of soil per m^2, using soil bulk density and the corresponding soil depth. Gross SOC turnover time ($\mathrm{SOC_T}$), defined as the amount of C in a soil system at equilibrium divided by the annual input of C into that system (Jenkinson and Rayner, 1977) was determined to a 20 and 40 cm depth.

2.4. Soil microbial biomass and soil light fraction

Chloroform fumigation extraction (CFE) was used on sieved soil at 0–10, 10–20 and 20–40 cm depths to evaluate soil microbial biomass C (SMB-C) and N (SMB-N) (Voroney et al., 2008). Prior to CFE, the soil was pre-incubated for 7 days at 25 °C and 45% water holding capacity. The extracted samples were freeze-dried, ground and analyzed for C and N, and quantified as the difference between fumigated and non-fumigated samples using a conversion factor of 0.35 for C and 0.5 for N (Voroney et al., 2008). Soil microbial biomass C turnover time ($\mathrm{SMB\text{-}C_T}$) was quantified by:

$$\mathrm{SMB\text{-}C_T} = \mathrm{SMB\text{-}C}/(\mathrm{R_i} + \mathrm{MY_{cf}}) \tag{2}$$

where SMB-C is the soil microbial biomass C pool (g m^{-2}), $\mathrm{R_i}$ is the annual amount of C input from crop residues (g m^{-2} y^{-1}), and $\mathrm{MY_{cf}} = 0.4$ is the microbial yield coefficient for biomass production (R.P. Voroney, personal communication, 2009).

The soil light fraction (LF) was quantified using 25 g of air dried and sieved (2 mm) soil at a 0–20 cm depth. The LF was quantified only in the top 20 cm because the site was managed using disk and spike harrowing, which resulted in the homogenization and mixing of soil in the plow layer (Tan et al., 2007). The soil was shaken with 50 ml of NaI solution with a specific gravity of 1.7 and left to settle. After 48 h, the LF was removed from the surface of the NaI and rinsed with 0.01 M $CaCl_2$ and 75 ml of distilled water to remove the NaI. The recovered LF was dried at 60 °C for 48 h, ground in a ball mill and analyzed for C and N (Gregorich and Beare, 2008). The LF-C and LF-N as a proportion of total soil organic C and soil total N was quantified according to Oelbermann and Echarte (2011):

$$\text{LF-C/SOC}\ (\%) = \left(\text{LF-C g kg}^{-1}\right)/\left(\text{SOC g kg}^{-1}\right) \times 100 \tag{3}$$

$$\text{LF—N/soil total N}\ (\%) = \left(\text{LF-N g kg}^{-1}\right)/\left(\text{Soil total N g kg}^{-1}\right) \times 100. \tag{4}$$

2.5. Statistical analysis

Data were examined for homogeneity of variance and were normally distributed (Steel et al., 1997). All data were tested using the univariate general linear model (ANOVA) in SPSS (SPSS Science Inc., 1989). Significantly different main effects were tested using the Tukey's multiple comparison test for factors with three or more levels; and differences for factors with two levels were derived from the F-statistic (Steel et al., 1997). Significant simple effects were tested with the estimated marginal means function using the least significant difference (LSD) test in SPSS. A linear regression model was used to evaluate the relationship between SMB-C and SOC, and SMB-N and soil total N. The threshold probability level for determining significant differences was $P < 0.05$ for all statistical analyses.

3. Results

3.1. Crop residues and land equivalent ratio

The interaction effects of treatment-by-year [F(15, 72) = 6.492, P = 0.001] and residue type-by-year [F(5, 72) = 13.783, P = 0.001] were significant for C input from crop residues (Table 1). Interaction effects of treatment-by-year [F(15, 72) = 7.439, P = 0.001] and residue type-by-year [F(5, 72) = 12.336, P = 0.001] were significant for N input from crop residues (Table 1). Simple effects showed that C and N input from maize residue was significantly greater in the maize sole crop whereas C and N input from soybean residues was significantly greater in the soybean sole crop compared to the intercrops (Table 2). There were no significant differences in C and N input from maize or soybean residues between the intercrop configurations. Carbon and N input from crop residues varied significantly among years. The mean C and N input over six seasons was highest in the maize sole crop followed by the 2:3 intercrop, 1:2 intercrop and soybean sole crop (Table 2). In both intercrop configurations, 83% of crop residue C was derived from maize.

Interaction effects for LER were not significant. Main effects showed significant differences in LER between intercrop configurations (Table 3). Over six cropping seasons, the mean LER was significantly greater in the 2:3 intercrop compared to the 1:2 intercrop. In both intercrop configurations, 1:2 and 2:3, the LER was significantly different among years (Table 3).

3.2. Soil physical and chemical characteristics

Interaction effects for soil physical and chemical characteristics were not significant. Main effects showed no significant differences among treatments for all soil physical and chemical characteristics (Table 4). However, soil physical and chemical characteristics were significantly different in 2007 compared to 2012, except for soil pH. Soil bulk density was significantly greater at both sampling depths in 2012 with a relative increase ranging from 9% to 20% at 0–20 cm, and ranging from 15% to 31% at 20–40 cm. Soil organic C concentration (%) and C and N stocks (g m^{-2}), and C/N ratio were significantly greater in 2012 for all treatments and at both depths except for the C/N ratio in the soybean sole crop at the 20–40 cm depth. Soil organic C concentration showed a relative increase by 2012, ranging from 27% to 37% at 0–20 cm and from 38% to 53% at 20–40 cm. Soil total N concentration (%) increased between by 2012, but was significantly greater only in the soybean sole crop at both depths and in the 1:2 intercrop at 20–40 cm. For example, soil total N concentration had a relative increase that ranged from 5% to 20% at 0–20 cm and from 13% to 33% at 20–40 cm. Soil bulk density, SOC, soil total N, and C/N ratio were significantly lower at the 20–40 cm depth, whereas soil pH was significantly greater at 20–40 cm.

Interaction effects of treatment-by-year [F(3, 32) = 317.359, P = 0.001], treatment-by-soil depth [F(3, 32) = 37.820, P = 0.001], year-by-soil depth [F(1, 32) = 61.368, P = 0.001], and treatment-by-soil depth-by-year [F(3, 32) = 23.557, P = 0.001] were significant for SOC_T (Table 1). Simple effects showed that SOC_T was significantly longer in the soybean sole crop to a 20 and 40 cm depth in 2007 and 2012 (Table 4). Gross SOC_T was significantly longer in 2012 compared to 2007 for all treatments and depths, except for the maize sole crop. SOC_T had a relative increase, ranging from 13% to 376% at 0–20 cm and from 1% to 393% at 20–40 cm, between 2007 and 2012. Gross SOC turnover time was significantly longer to a 40 cm depth compared to a 20 cm depth.

3.3. Soil microbial biomass and soil light fraction

Interaction effects of treatment-by-year [F(3, 48) = 13.066, P = 0.001] were significant for SMB-C (Table 1). Simple effects showed

Table 1
P-values of analysis of variance (ANOVA) and interactions for carbon (C) and nitrogen (N) input from maize and soybean residues, and for soil characteristics in maize and soybean sole crops and 1:2 and 2:3 intercrops, Balcarce, Argentina.

Factors	C Input	N Input	SOC_T	N_T	SMB-C	SMB-N	SMB-C/N	SMB-C_T
Treatment (T_R)	0.001	0.001	0.001	0.001	0.001	0.042	n.s.	0.001
Residue type (R_T)	0.001	0.001						
Year (Y_R)	0.001	0.001						
$T_R \times R_T$	n.s.	n.s.						
$R_T \times Y_R$	0.001	0.001						
$T_R \times R_T \times Y_R$	n.s.	n.s.						
Soil depth (S_D)			0.001	0.001	0.001	0.028	n.s.	0.001
Year (Y_R)			0.001	0.001	0.001	0.033	0.009	0.001
$T_R \times S_D$			0.001	0.001	n.s.	n.s.	n.s.	0.001
$T_R \times Y_R$	0.001	0.001	0.001	0.001	0.001	n.s.	n.s.	0.001
$S_D \times Y_R$			0.001	n.s.	n.s.	n.s.	n.s.	0.001
$T_R \times S_D \times Y_R$			0.001	0.001	n.s.	n.s.	n.s.	0.001

Table 2
Aboveground crop residue biomass carbon (C) and nitrogen (N) input over six cropping seasons from the years 2007–08 to 2012–13 from soybean and maize residues in sole crops and in 1:2 and 2:3 intercrops, Balcarce, Argentina.

		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})	Maize	$1068^{A,b}$	$923^{A,bc}$	$1015^{A,b}$	$1030^{A,b}$	$490^{A,c}$	$1283^{A,a}$	968^{A}
	Soybean	–	–	–	–	–	–	–
	1:2 intercrop	$685^{B,b}$	$551^{B,c}$	$557^{B,c}$	$579^{B,c}$	$450^{B,d}$	$769^{B,a}$	599^{B}
	2:3 intercrop	$644^{B,b}$	$631^{B,b}$	$601^{B,b}$	$605^{B,b}$	$471^{B,c}$	$907^{B,a}$	643^{B}
C input from soybean residue (g C m^{-2} y^{-1})	Maize	–	–	–	–	–	–	–
	Soybean	$494^{A,a}$	$305^{A,bc}$	$255^{A,c}$	$532^{A,a}$	$329^{A,b}$	$155^{A,d}$	345^{A}
	1:2 intercrop	$192^{B,a}$	$76^{B,b}$	$159^{B,a}$	$176^{B,a}$	$72^{B,b}$	$60^{B,b}$	123^{B}
	2:3 intercrop	$208^{B,a}$	$79^{B,d}$	$160^{B,b}$	$176^{B,b}$	$78^{B,d}$	$100^{B,c}$	134^{B}
N input from maize residue (g N m^{-2} y^{-1})	Maize	$17^{A,b}$	$14^{A,c}$	$16^{A,b}$	$16^{A,b}$	$8^{A,d}$	$20^{A,a}$	15^{A}
	Soybean	–	–	–	–	–	–	–
	1:2 intercrop	$11^{B,a}$	$9^{B,b}$	$9^{B,b}$	$9^{B,b}$	$7^{A,b}$	$12^{C,a}$	9^{B}
	2:3 intercrop	$10^{B,b}$	$10^{B,b}$	$9^{B,b}$	$9^{B,b}$	$7^{A,b}$	$14^{B,a}$	10^{B}
N input from soybean residue (g N m^{-2} y^{-1})	Maize	–	–	–	–	–	–	–
	Soybean	$15^{A,a}$	$10^{A,b}$	$8^{A,b}$	$17^{A,a}$	$10^{A,b}$	$5^{A,c}$	11^{A}
	1:2 intercrop	$6^{B,a}$	$2^{B,b}$	$5^{B,a}$	$6^{B,a}$	$2^{B,b}$	$2^{B,b}$	4^{B}
	2:3 intercrop	$7^{B,a}$	$2^{B,c}$	$5^{B,ab}$	$6^{B,a}$	$2^{B,c}$	$3^{B,c}$	4^{B}

Values followed by the same upper case letters, comparing differences among treatments within years, are not significantly different at $P < 0.05$ according to LSD. Values followed by the same lower case letters, comparing differences among years within treatments, are not significantly different at $P < 0.05$ according to LSD.

that SMB-C was significantly different among treatments in 2007 and 2012. The greatest SMB-C occurred in the 2:3 intercrop in both years and at all depths (Table 5). Soil microbial biomass C was significantly greater in 2012 in all treatments and at all depths. SMB-C showed a relative increase between 2007 and 2012, which ranged from 26% to 46% at 0–10 cm and from 14% to 67% at 10–20 cm. There was a significant decrease in SMB-C with depth in both years. SMB-C was positively correlated with SOC concentration in all treatments with R^2-values ranging from 0.97 in the sole crops, to 0.82 (1:2 intercrop) and 0.96 (2:3 intercrop) in 2007; and from 0.89 in the sole crops, 0.93 (2:3 intercrop) to 0.99 (1:2 intercrop) in 2012.

Interaction effects for SMB-N, and SMB-C/N ratio were not significant. Main effects showed that SMB-N was significantly different among treatments and depths, but not between years (Table 5). In 2007, SMB-N was significantly greater in the 2:3 intercrop at all depths. In 2012, SMB-N was significantly greater in the 2:3 intercrop at 0–10 and 10–20 cm depths. However, at 20–40 cm, SMB-N was significantly greater in the soybean sole crop followed by the 2:3 intercrop and was lowest in the 1:2 intercrop and maize sole crop. The SMB-N was positively correlated with soil total N content in all treatments where R^2-values ranged from 0.80 (1:2 intercrop), 0.91 (2:3 intercrop), 0.92 (soybean sole crop) to 0.97 (maize sole crop) in 2007; and from 0.76 (1:2 intercrop), 0.84 (maize sole crop), 0.94 (2:3 intercrop) to 0.95 (soybean sole crop) in 2012. SMB-C/N ratio was not significantly different among treatments in 2007 and in 2012; and was not significantly different among depths and between years (Table 5).

Table 3
Land equivalent ratio (LER) of two differently configured intercrops (1:2 and 2:3) from the years 2007–08 to 2012–13, and the mean LER over six cropping seasons in Balcarce, Argentina. Standard errors are given in parentheses.

Year	1:2 Intercrop	2:3 Intercrop
2007–08	$1.04\ (0.04)^{A,b}$	$1.04\ (0.11)^{A,b}$
2008–09	$0.85\ (0.07)^{A,b}$	$0.95\ (0.03)^{A,b}$
2009–10	$1.18\ (0.02)^{B,a}$	$1.25\ (0.03)^{A,a}$
2010–11	$0.90\ (0.07)^{A,b}$	$0.92\ (0.04)^{A,b}$
2011–12	$1.20\ (0.17)^{A,a}$	$1.27\ (0.20)^{A,a}$
2012–13	$0.99\ (0.07)^{B,b}$	$1.35\ (0.02)^{A,a}$
Mean	$1.03\ (0.04)^{A}$	$1.13\ (0.05)^{B}$

Values followed by the same upper case letters, comparing differences between intercrop configurations within years, are not significantly different at $P < 0.05$ according the F-statistic. Values followed by the same lower case letters, comparing differences among years within intercrop configurations, are not significantly different at $P < 0.05$ according to Tukey's multiple comparison test.

Interaction effects of treatment-by-year [F(3, 48) = 101.602, P = 0.001], treatment-by-soil depth [F(6, 48) = 9.985, P = 0.001], year-by-soil depth [F(2, 48) = 30.646, P = 0.001], and treatment-by-soil depth-by-year [F(6, 48) = 9.209, P = 0.001] were significant for SMB-C_T (Table 1). Simple effects showed that SMB-C_T was significantly different among treatments at all soil depths and both years (Table 5). To a 40 cm depth, SMB-C_T was significantly greater in the soybean sole crop followed by the intercrops and the maize sole crop in 2007, whereas in 2012, SMB-C_T was significantly greater in the intercrops followed by the soybean sole crop and the maize sole crop.

Interaction effects for the soil LF were not significant. Main effects showed no significant differences among treatments for LF-C concentration (%) in 2007 and in 2012 (Table 6). When comparing differences between years, the LF-C concentration was significantly greater in all treatments in 2012, and showed a relative increase that ranged from 31% to 47%. LF-N concentration was significantly different among treatments in 2007, with the greatest concentration in the maize sole crop, followed by the soybean sole crop, the 1:2 intercrop and 2:3 intercrop. In 2012, the 2:3 intercrop had a significantly lower LF-N concentration compared to the remaining treatments. The soil LF-N showed a relative increase between 2007 and 2012 in all treatments that ranged from 25% to 34%. The LF-C/N ratio was not significantly different among treatments in either year but was significantly higher in 2012 compared to 2007. Soil LF-C and N stocks were not significantly different among treatments in 2007, however in 2012 it was significantly greater in the soybean sole crop compared to the other treatments. The LF-C stock showed a relative increase between 2007 and 2012, which ranged from 50% to 103%, and was greater than 400% in all treatments for LF-N stock. The LF organic C as a proportion of total SOC was not significantly different among treatments and between years. However, the LF-N as a proportion of soil total N was significantly different among treatments in 2012 with the greatest value occurring in the soybean sole crop. The LF-N as a proportion of soil total N was also significantly greater in 2012 for all treatments.

4. Discussion

4.1. Crop residues and land equivalent ratio

Maize was the dominant component contributing 83% of the C input from crop residues in the intercrops. Similarly, Martin et al. (1998) also found that 74% of the crop residue input in a Canadian maize–soybean intercrop was derived from maize. However, N input from crop residues was more evenly distributed among sole crop and intercrop treatments.

Table 4
Soil characteristics (0–20 and 20–40 cm) in maize and soybean sole crops and in 1:2 and 2:3 intercrops in 2007 and in 2012, Balcarce, Argentina. Standard errors are given in parentheses.

Soil characteristics	Depth (cm)	Maize sole crop		Soybean sole crop		1:2 intercrop		2:3 intercrop	
		2007	2012	2007	2012	2007	2012	2007	2012
BD (g cm^{-3})[b]	0–20	1.23 (0.02)^{A,b}	1.34 (0.04)^{A,a}	1.18 (0.07)^{A,b}	1.42 (0.05)^{A,a}	1.18 (0.03)^{A,b}	1.38 (0.05)^{A,a}	1.14 (0.04)^{A,b}	1.30 (0.05)^{A,a}
	20–40	1.25 (0.15)^{A,b}	1.44 (0.02)^{A,a}	1.23 (0.08)^{A,b}	1.48 (0.02)^{A,a}	1.16 (0.07)^{A,b}	1.52 (0.02)^{A,a}	1.24 (0.11)^{A,b}	1.53 (0.02)^{A,a}
pH[a]	0–20	5.9 (0.1)^{A,a}	5.7 (0.1)^{A,a}	5.6 (0.7)^{A,a}	5.4 (0.1)^{A,a}	5.9 (0.7)^{A,a}	5.6 (0.2)^{A,a}	5.7 (0.3)^{A,a}	5.7 (0.1)^{A,a}
	20–40	6.1 (0.2)^{A,a}	5.9 (0.2)^{A,a}	5.9 (0.3)^{A,a}	5.8 (0.2)^{A,a}	6.1 (0.1)^{A,a}	5.8 (0.1)^{A,a}	6.0 (0.2)^{A,a}	5.8 (0.1)^{A,a}
SOC (%)[b]	0–20	3.57 (0.18)^{A,b}	4.52 (0.17)^{A,a}	3.36 (0.19)^{A,b}	4.61 (0.12)^{A,a}	3.35 (0.02)^{A,b}	4.48 (0.27)^{A,a}	3.41 (0.18)^{A,b}	4.58 (0.18)^{A,a}
	20–40	1.74 (0.19)^{A,b}	2.44 (0.28)^{A,a}	2.07 (0.01)^{A,b}	2.86 (0.28)^{A,a}	1.79 (0.13)^{A,b}	2.69 (0.26)^{A,a}	1.94 (0.22)^{A,b}	2.87 (0.34)^{A,a}
N (%)[b]	0–20	0.21 (0.01)^{A,a}	0.22 (0.01)^{A,a}	0.20 (0.01)^{A,b}	0.24 (0.02)^{A,a}	0.20 (0.01)^{A,a}	0.23 (0.02)^{A,a}	0.20 (0.01)^{A,a}	0.21 (0.04)^{A,a}
	20–40	0.15 (0.02)^{A,a}	0.18 (0.03)^{A,a}	0.16 (0.02)^{A,b}	0.21 (0.01)^{A,a}	0.15 (0.01)^{A,b}	0.20 (0.02)^{A,a}	0.15 (0.01)^{A,a}	0.17 (0.06)^{A,a}
C/N[a]	0–20	16.7 (1.0) ^{A,b}	20.3 (0.4) ^{A,a}	16.7 (0.6) ^{A,b}	19.2 (0.7) ^{A,a}	17.4 (0.7) ^{A,b}	19.7 (0.3) ^{A,a}	17.3 (0.7) ^{A,b}	24.0 (0.9) ^{A,a}
	20–40	12.0 (0.1)^{A,b}	13.6 (0.2)^{A,a}	13.1 (1.3)^{A,a}	13.9 (0.8)^{A,a}	12.0 (0.1)^{A,b}	13.5 (0.4)^{A,a}	12.9 (0.8)^{A,b}	21.0 (1.2)^{A,a}
SOC stock (g m^{-2})[b]	0–20	6191 (189) ^{A,b}	8065 (312) ^{A,a}	5863 (507) ^{A,b}	8759 (314) ^{A,a}	5413 (312) ^{A,b}	8432 (416) ^{A,a}	5309 (243) ^{A,b}	7576 (552) ^{A,a}
	20–40	4453 (1031)^{A,a}	3531 (350)^{A,b}	3990 (956)^{A,b}	4903 (250)^{A,a}	4172 (276)^{A,a}	3824 (276)^{A,b}	4475 (546)^{A,a}	4087 (290)^{A,b}
N Stock (g m^{-2})[b]	0–20	525 (13)^{A,b}	607 (28)^{A,a}	470 (31)^{A,b}	681 (23)^{A,a}	457 (24)^{A,b}	634 (24)^{A,a}	450 (23)^{A,b}	616 (48)^{A,a}
	20–40	371 (89)^{A,a}	260 (29)^{A,b}	410 (56)^{A,a}	304 (22)^{A,b}	347 (45)^{A,a}	285 (17)^{A,b}	373 (49)^{A,a}	306 (20)^{A,b}
SOC$_T$ (years)[c]	0–20	5.9^{B,a}	6.3^{C,a}	11.9^{A,b}	56.6^{A,a}	6.2^{B,b}	10.2^{B,a}	6.2^{B,b}	7.5^{C,a}
	0–40	10.0^{B,a}	9.0^{C,a}	17.9^{A,b}	88.3^{A,a}	10.9^{B,b}	14.8^{B,a}	11.5^{B,a}	11.6^{B,a}

Values followed by the same upper case letters, comparing differences among treatments within years and depth, are not significantly different at $P < 0.05$ according to Tukey's multiple comparison test. Values followed by the same lower case letters, comparing differences between years within treatments and depth, are not significantly different at $P < 0.5$ according to the F-statistic.

[a] Values are significantly greater at the 20–40 cm depth for all treatments and years.

[b] Values are significantly lower at the 20–40 cm depth for all treatments and years.

[c] Values are significantly different between depths for all treatments and years. Values followed by the same upper case letters, comparing differences among treatments within years and depth for SOC$_T$, are not significantly different at $P < 0.05$ according to LSD. Values followed by the same lower case letters, comparing differences between years within treatments and depth for SOC$_T$, are not significantly different at $P < 0.05$ according LSD.

This was due to the incorporation of leguminous soybeans in the intercrops and the addition of N fertilizer to the maize plants in the intercrops and maize sole crop, which resulted in an input of maize residues with a higher N concentration. Similar results were also observed by Hauggaard-Nielsen et al. (2001) in a barley (*Hordeum vulgare* L.) and field pea (*Pisum sativum* L.) sole crop and intercrop in Denmark; and by Chang and Shibles (1985) in a maize and cowpea (*Virginia ungiclata* L. Walp.) sole crop and intercrop in Costa Rica. This is due to a change in soil dynamics and crop growing conditions when maize is combined with a legume, leading to a greater efficiency in the utilization of nutrient resources (Vachon and Oelbermann, 2011).

Variation in LER among years (Table 3) was due to seasonal weather differences that affected crop biomass productivity (Echarte et al., 2011). Over a mean of six growing seasons, both intercrop configurations had an LER value greater than 1.0 however the production advantage was more robust in the 2:3 intercrop (Chen et al., 2004). For example, the 2:3 intercrop had an LER value of 1.13, suggesting that 13% more land area would be required for the sole crop to produce the same crop biomass as the 2:3 intercrop. Chen et al. (2004) reported LER values ranging from 1.05 to 1.26, based on crop biomass, in a pea-barley (*Horedum vulgare* L.) intercrop in Montana, USA. They attributed differences in LER values to interspecies competition and availability of N rather than differences in intercrop row configurations. In Argentina, Echarte et al. (2011) reported an LER value, based on grain yield, of 1.03 over two growing seasons in a maize–soybean intercrop. They found that LER values increased when plant density of the maize decreased, and suggested that this was associated with the agronomic performance of the dominant crop.

4.2. Soil physical and chemical characteristics

Soil physical and chemical characteristics were similar to those reported by others from the same region of the Argentine Pampa (Studdert and Echeverria, 2000; Aparicio and Costa, 2007; Domínguez et al., 2009). Dyer et al. (2012) found a lower bulk density (0–10 cm) in 2009 and 2010 at the same site compared to our study in 2012; and they also found a significantly lower bulk density in the intercrops compared to the sole crops. The observed increase in bulk density in all treatments after six cropping

Table 5
Soil microbial biomass carbon (SMB-C) and nitrogen (SMB-N), SMB-C/N ratio and SMB turnover time (SMB-C$_T$) at 0–10, 0–20 and 0–40 cm depths in 2007 and in 2012 in maize and soybean sole crops and in 1:2 and 2:3 intercrops, Balcarce, Argentina.

Soil characteristics	Depth (cm)	Maize sole crop		Soybean sole crop		1:2 intercrop		2:3 intercrop	
		2007	2012	2007	2012	2007	2012	2007	2012
SMB-C	0–10	243.8^{C,b}	308.0^{C,a}	294.5^{B,b}	377.5^{B,a}	259.8^{C,b}	380.3^{B,a}	341.0^{A,b}	493.9 ^{A,a}
(μg C$_{mic}$ g^{-1})[a]	10–20	249.1^{A,a}	214.4^{C,b}	270.8^{A,b}	334.9^{B,a}	182.1^{B,b}	303.7^{B,a}	277.2^{A,b}	408.0^{A,a}
	20–40	138.5^{A,b}	172.7^{B,a}	177.9^{A,b}	213.6^{B,a}	178.6^{A,b}	197.9^{B,a}	130.8^{A,b}	306.7^{A,a}
SMB-N	0–10	41.4^{B,a}	31.7^{C,a}	55.1^{B,a}	62.6^{B,a}	37.8^{B,a}	60.0^{B,a}	69.2^{A,a}	75.1^{A,a}
(μg N$_{mic}$ g^{-1})[a]	10–20	41.3^{B,a}	27.1^{C,a}	41.1^{B,a}	51.5^{B,a}	31.4^{B,a}	28.0^{C,a}	75.7^{A,a}	74.6^{A,a}
	20–40	53.7^{A,a}	24.3^{C,a}	46.7^{B,a}	49.0^{A,a}	23.4^{C,a}	20.3^{C,a}	37.5^{C,a}	39.8^{B,a}
SMB-C/N ratio[a]	0–10	5.9 ^{A,a}	9.7 ^{A,a}	5.3 ^{A,a}	6.0 ^{A,a}	6.9 ^{A,a}	6.3 ^{A,a}	4.9 ^{A,a}	6.6 ^{A,a}
	10–20	6.0 ^{A,a}	7.9 ^{A,a}	6.6 ^{A,a}	6.5 ^{A,a}	5.8 ^{A,a}	10.8 ^{A,a}	3.7 ^{A,a}	9.3^{A,a}
	20–40	2.6 ^{A,a}	7.1 ^{A,a}	3.8 ^{A,a}	4.4 ^{A,a}	7.6 ^{A,a}	9.7 ^{A,a}	3.5 ^{A,a}	7.7^{A,a}
SMB-C$_T$ (years)[a]	0–10	0.81^{C,a}	0.54^{C,b}	1.62^{B,a}	1.69^{B,a}	1.81^{A,b}	2.99^{A,a}	1.0^{C,b}	2.95^{A,a}
	0–20	0.85^{C,b}	1.55^{B,a}	1.70^{A,a}	1.48^{B,a}	1.47^{B,b}	5.24^{A,a}	0.68^{C,b}	5.05^{A,a}
	0–40	0.94^{C,a}	1.12^{B,a}	2.29^{A,a}	1.22^{B,b}	1.36^{B,b}	3.62^{A,a}	1.44 ^{B,b}	5.35^{A,a}

Values followed by the same upper case letters, comparing differences among treatments within years and depth, are not significantly different at $P < 0.05$ according to LSD. Values followed by the same lower case letters, comparing differences between years within treatments and depth, are not significantly different at $P < 0.05$ according LSD.

[a] Values are significantly different among depths for all treatments and years.

Table 6
Soil light fraction carbon (LF-C) and nitrogen (LF-N) to a 20 cm depth in 2007 and in 2012 in maize and soybean sole crops and in 1:2 and 2:3 intercrops in Balcarce, Argentina. Standard errors are given in parentheses.

Soil characteristics	Maize sole crop		Soybean sole crop		1:2 intercrop		2:3 intercrop	
	2007	2012	2007	2012	2007	2012	2007	2012
LF-C (%)	17.1 (0.8)^{A,b}	25.1 (1.7)^{A,a}	16.7 (0.5)^{A,b}	24.7 (1.3)^{A,a}	16.7 (1.1)^{A,b}	23.9 (0.2)^{A,a}	17.4 (1.1)^{A,b}	22.7 (0.6)^{A,a}
LF-N (%)	1.13 (0.02)^{A,b}	1.41 (0.13)^{A,a}	1.06 (0.01)^{B,b}	1.38 (0.06)^{A,a}	0.99 (0.02)^{C,b}	1.33 (0.02)^{A,a}	0.97 (0.02)^{D,b}	1.25 (0.03)^{B,a}
LF-C/N ratio	15.2 (0.6)^{A,b}	17.8 (0.5)^{A,a}	15.7 (0.3)^{A,b}	17.9 (0.2)^{A,a}	16.9 (1.0)^{A,a}	17.9 (0.2)^{A,a}	17.9 (1.1)^{A,a}	18.2 (0.6)^{A,a}
LF-C stock (g C m^{-2})	182.9 (8.7)^{A,b}	273.4 (57.9)^{A,a}	155.8 (14.7)^{A,b}	315.9 (21.1)^{AB,a}	143.3 (22.1)^{A,b}	242.9 (23.8)^{A,a}	143.6 (16.1)^{A,b}	233.6 (18.0)^{A,a}
LF-N stock (g N m^{-2})	12.12 (1.09)^{A,b}	61.65 (14.04)^{A,a}	9.91 (0.98)^{A,b}	70.03 (4.10)^{AB,a}	8.46 (1.07)^{A,b}	53.77 (5.61)^{A,a}	8.04 (0.84)^{A,b}	51.45 (5.84)^{A,a}
LF-C/SOC (%)	29.6 (1.7)^{A,a}	34.7 (7.9)^{A,a}	28.3 (2.1)^{A,a}	34.5 (1.7)^{A,a}	26.2 (2.5)^{A,a}	29.3 (3.3)^{A,a}	26.9 (2.5)^{A,a}	29.2 (4.9)^{A,a}
LF-N/soil N (%)	2.3 (0.2)^{A,b}	10.5 (2.6)^{A,a}	2.1 (0.2)^{A,b}	10.3 (0.5)^{AB,a}	1.8 (0.1)^{A,b}	8.6 (0.9)^{A,a}	1.8 (0.2)^{A,b}	8.6 (1.7)^{A,a}

Values followed by the same upper case letters, comparing differences among treatments within years, are not significantly different at $P < 0.05$ according to Tukey's multiple comparison test. Values followed by the same lower case letters, comparing differences between years within treatments and depth, are not significantly different at $P < 0.05$ according to the F-statistic.

seasons was due to the periodic disruption of the soil's structure as a result of disk and spike harrowing, leading to soil compaction over time and with depth. In the eastern rolling Pampa, Tolon-Becerra et al. (2011) also observed greater compaction in soil under tillage compared to no-till. They suggested that this was due to a greater number of machinery passes in the cultivated soil, during the growing season, compared to no-till soil.

The significant increase in SOC and soil total N between 2007 and 2012 was due to a greater biomass input from crop residues in all treatments compared to that of sunflower, which was produced at this site prior to the establishment of our study. Andrade (1995) reported that aboveground residue input from sunflower in Balcarce, Argentina was 958 g m^{-2}. Comparatively, crop residue input (mean over six growing seasons) from maize was 2295 g m^{-2}, 771 g m^{-2} from soybeans, 1693 g m^{-2} from the 1:2 intercrop, and 1824 g m^{-2} from the 2:3 intercrop. This overall greater input of organic matter from crop residues in all treatments in our study led to the observed increase in SOC and soil total N between 2007 and 2012.

This study showed little influence of intercropping on SOC and soil total N, and as such no significant differences among treatments were observed in 2007 or in 2012. This was due to the short-term nature of the study and the inherently high levels of SOC of these soils. Measureable differences in SOC in the Argentine Pampa were only detected after more than 5 years (Alvarez et al., 1998), or 11 years (Studdert and Echeverria, 2000). Soil with an inherently high SOC content, such as that in the Canadian Prairies or the Argentine Pampa, does not allow for readily observable increases in SOC and N over the short-term (Malhi et al., 2008).

The length of time organic matter remains in the soil depends on a variety of site-specific parameters. Of these parameters, soil moisture and temperature, and substrate quality are the most influential (Davidson et al., 2006). As such, SOC_T can be longer than 20 years in temperate biomes (Stout et al., 1981). In our study, SOC_T was similar to that reported by Zach et al. (2006) from the Argentine Pampa. The addition of N fertilizer influenced SOC_T causing faster turnover times in the maize sole crop and intercrops compared to the soybean sole crop. In England, Jenkinson and Rayner (1977) observed that treatments with N fertilizer had a faster SOC_T (16 years) compared to unfertilized treatments (22 years). Between 2007 and 2012, SOC_T (0–20 cm) had a relative increase of 21% in the 2:3 intercrop and 65% in the 1:2 intercrop, compared to 12% in the maize sole crop. This was due to the greater biomass input from crop residues (Oelbermann et al., 2006) as a result of changing from sunflower to intercropping or maize–soybean sole crop rotation. Additionally, the mixing of crop residues caused changes in the chemical and physical attributes of SOM, which in turn lead to different dynamics of C and N mineralization in the intercrops, and therefore longer turnover rates, compared to the maize sole crop (Salvo et al., 2013).

4.3. Soil microbial biomass and soil light fraction

Values of SMB-C and N were similar to those reported previously from the Argentine Pampa (Tessier et al., 1998). Our results indicated that in 2007 and in 2012, SMB-C and N were influenced by land management practices rather than by the amount of C and N input from crop residues. Tu et al. (2006) also observed an increase in SMB-C and N in a system under transition from conventional agriculture to an organic production system. Song et al. (2007) found a greater SMB-C and N in intercrops [wheat (*Triticum aestivum* L.)–bean (*Vicia faba* L.), wheat–maize and maize–bean] compared to sole crops. Differences in microbiological properties of the rhizosphere in the intercrops led to a greater SMB (Song et al., 2007); resulting in a more diverse and active microbial community able to effectively decompose a greater variety of C compounds (Anderson and Domsch, 1989). This is because microbes in the intercrops evolved in a system with a more species-rich input of organic matter compared to the sole crops, which enhanced the interaction and simultaneous assimilation of C and N by heterotrophic soil organisms (Sall et al., 2007; Chen et al., 2008).

Our results showed that sufficient N was available to microorganisms for residue decay due to the relatively low SMB-C/N ratio (Joergensen and Emmerling, 2006). An overall increase in the SMC-C/N ratio between 2007 and 2012 to a 40 cm depth in the sole crops and intercrops suggested that C input from crop residues and decaying roots exceeded N input and availability for residue decay (Jannoura et al., 2014). A greater relative increase in the SMB-C/N ratio, to a 20 cm depth, in the intercrops (66%) compared to the sole crops (27%) showed that mixing of crop residues reduced the release and use of N from the soybean residue, which is of higher quality than the maize residue (Vachon and Oelbermann, 2011).

The faster SMB-C_T in the 2:3 intercrop and maize sole crop in 2007 suggested that the availability of N from crop residues and fertilizers in these treatments was greater compared to that in the 1:2 intercrop and the soybean sole crop. However, the significantly slower SMB-C_T in 2012 in the intercrops suggested that the dynamics of the SMB evolved differently over time compared to the sole crops. A slower SMB-C_T resulted in the accumulation and storage of nutrients in a biologically active form not available for plant uptake, whereas a fast SMB-C_T may indicated a release of nutrients to the growing plants (Kouno et al., 2002). Therefore in 2012, a substantial amount of nutrients were cycled through the SMB in the sole crops.

The soil LF is an active pool of soil organic matter (SOM), and it responds readily to changes in land management, and also plays a role in governing soil N mineralization (Bending and Turner, 2009). Liang et al. (1998) reported a change in the soil LF three years after a change in soil management practices, whereas Janzen et al. (1992) observed changes after 6 years. However, results from our study showed that intercropping did not strongly influence the soil LF-C and N concentration in 2007 and in 2012 among treatments. This was because six seasons of intercropping were insufficient to detect changes in the LF. In addition, the similar quantity of crop residue input among treatments in our study also contributed to similar values of the soil LF among treatments (Bending et al., 2004). The amount of crop residue input accumulating as LF depends on its quality, where residues high in lignocellulose content and low in N favor the formation of the LF because of its greater recalcitrance to microbial attack (Bending et al., 1998; Fließbach and Mäder, 2000). This explains the slightly greater accumulation of LF in the maize sole crop in 2012 because it is a low quality cereal residue high in lignocellulose (Bending et al., 2004). As such, the incorporation of mixed crop residues and differences in the fertilizer regime compared to the maize sole crop resulted in a lower LF accumulation in the intercrops, allowing the decomposer community to use it as a substrate (Fließbach and Mäder, 2000).

The greater values of LF-C and N stocks in 2012, compared to 2007, were due to the recent increase in C and N additions from above- and below-ground crop residues, which was consistent with the significant increases in SOC and N in all treatments (Bending and Turner, 2009). Similarly, Nelson et al. (2008) observed an increase in soil LF-C associated with grassland restoration in south-central Saskatchewan, Canada as a result of greater C inputs. The greater C/N ratio of the LF in the intercrops in 2007 (and the 2:3 intercrop in 2012) showed that the LF was not readily mineralized compared to the sole crops. This was an indication of short-term N immobilization causing the transfer of C and N from the LF to the more stable humified fraction (Compton and Boone, 2000), which occurred in response to changes in soil management in the intercrops compared to the sole crops.

5. Conclusions

Results from this study provide a quantitative analysis of crop residue biomass C and N input, LER, and soil chemical and biological characteristics after six cropping seasons with cereal–legume intercrops compared to sole crops. Our results demonstrate that cereal–legume intercropping is a more sustainable agroecosystem land management practice in the Argentine Pampa, with respect to soil C and N transformations, compared to sole cropping.

This was especially evident for the quantified changes of SOC_T, SMB-C, SMB-N, and LF-N. We expect that over the long-term further changes in SMB, LF, SOC and soil total N will be quantifiable among sole crop and intercrop treatments. Our study also showed similarities in crop residue C and N input and soil physical and chemical characteristics between the two intercrop configurations, suggesting that neither affected the soil negatively over six cropping seasons. However, indicators sensitive to changes in land management practices over the short-term, such as SMB and LF, suggest that the 2:3 intercrop is a more optimal configuration for the long-term transformation of C and N in the soil. Based on the LER, our results also show that the 2:3 intercrop is a more effective land management practice than the 1:2 intercrop. It is recommended that further intercropping trials be established in the Argentine Pampa using cereal and legume crops including maize and soybean as well as other crops commonly produced in this region. This will help to bridge our current knowledge gap on soil C and N dynamics, including greenhouse gas emissions, C sequestration and resilience to climate change, in temperate intercropping systems in general and specifically in the Argentine Pampa.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.geodrs.2015.01.002. These data include Google maps of the most important areas described in this article.

References

Álvarez, R., 2001. Estimation of carbon losses by cultivation from soils of the Argentine Pampas using the Century Model. Soil Use Manag. 17, 62–66.

Alvarez, R., Russo, M.E., Prystupa, P., Scheiner, J.D., Lotta, L., 1998. Soil carbon pools under conventional and no-tillage systems in the Argentine Rolling Pampa. Agron. J. 90, 138–143.

Anderson, T.H., Domsch, K.H., 1989. Ratios of microbial biomass carbon to total organic carbon in arable soils. Soil Biol. Biochem. 21, 471–479.

Andrade, F.H., 1995. Analysis of growth and yield of maize, sunflower and soybean growth at Balcarce, Argentina. Field Crop Res. 41, 1–12.

Aparicio, V., Costa, J.L., 2007. Soil quality indicators under continuous cropping systems in the Argentinean Pampa. Soil Tillage Res. 96, 155–165.

Barker, S., Dennett, M.D., 2013. Effect of density, cultivar and irrigation on spring sown monocrops and intercrops of wheat (*Triticum aestivum* L.) and faba beans (*Vicia faba* L.). Eur. J. Agron. 5, 108–116.

Bending, G.D., Turner, M.K., 2009. Incorporation of nitrogen from crop residues into light-fraction organic matter in soils with contrasting management histories. Biol. Fertil. Soils 45, 281–287.

Bending, G.D., Turner, M.K., Burns, I.G., 1998. Fate of nitrogen from crop residues as affected by biochemical quality and the microbial biomass. Soil Biol. Biochem. 30, 2055–2065.

Bending, G.D., Turner, M.K., Rayns, F., Marx, M.C., Wood, M., 2004. Microbial and biochemical soil quality indicators and their potential for differentiating areas under contrasting agricultural management regimes. Soil Biol. Biochem. 35, 1785–1792.

Berhongaray, G., Alvarez, R., de Paepe, J., Caride, C., Cantet, R., 2013. Land use effects on soil carbon in the Argentine Pampas. Geoderma 192, 97–110.

Chang, J.F., Shibles, R.M., 1985. An analysis of competition between intercropped cowpea and maize II. The effect of fertilization and population density. Field Crop Res. 12, 145–152.

Chen, C., Westcott, M., Neill, K., Wichman, D., Knox, M., 2004. Row configuration and nitrogen application for barley-pea intercropping in Montana. Agron. J. 96, 1730–1738.

Chen, M., Chen, B., Marschner, P., 2008. Plant growth and soil microbial community structure of legumes and grasses grown in monoculture or mixture. J. Environ. Sci. 20, 1231–1237.

Compton, J.E., Boone, R.D., 2000. Long-term impacts of agriculture on soil carbon and nitrogen in New England forests. Ecology 81, 2314–2330.

Davidson, E.A., Janssens, I.A., Luo, Y., 2006. On the variability of respiration in terrestrial ecosystems: moving beyond Q10. Glob. Chang. Biol. 12, 154–164.

Domínguez, G.F., Diovisalvi, N.V., Studdert, G.A., Monterubbianesi, M.G., 2009. Soil organic C and N fraction under continuous cropping with contrasting tillage systems on Mollisols of the southeastern Pampa. Soil Tillage Res. 102, 93–100.

Dyer, L., Oelbermann, M., Echarte, L., 2012. Soil carbon dioxide and nitrous oxide emissions during the growing season from temperate maize–soybean intercrops. J. Plant Nutr. Soil Sci. 175, 394–400.

Echarte, L., Della Maggiora, A., Cerrudo, D., Gonzalez, V.H., Abbate, P., Cerrudo, A., Sadra, V.O., Calviño, P., 2011. Yield response to plant density of maize and sunflower intercropped with soybean. Field Crop Res. 121, 423–429.

Fabrizzi, K.P., Moron, A., Garcia, F.O., 2003. Soil carbon and nitrogen organic fractions in degraded vs. non-degraded Mollisols in Argentina. Soil Sci. Soc. Am. J. 67, 1831–1841.

Flavel, T.C., Murphy, D.V., 2006. Carbon and nitrogen mineralization rates after application of organic amendments to soil. J. Environ. Qual. 35, 183–193.

Fließbach, A., Mäder, P., 2000. Microbial biomass and size-density fraction differ between soils of organic and conventional agricultural systems. Soil Biol. Biochem. 32, 757–768.

Gregorich, E.G., Beare, M.H., 2008. Physically uncomplexed organic matter. In: Carter, M.R., Gregorich, E.G. (Eds.), Soil Sampling and Methods of Analysis. CRC Press, Boca Raton, pp. 607–616.

Hauggaard-Nielsen, H., Ambus, P., Jensen, E.S., 2001. Interspecific competition, N use and interference with weeds in pea–barley intercropping. Field Crop Res. 70, 101–109.

Jannoura, R., Joergensen, R.G., Bruns, C., 2014. Organic fertilizer effects on growth, crop yield, and soil microbial biomass indices in sole and intercropped peas and oats under organic farming conditions. Eur. J. Agron. 53, 250–270.

Janzen, H.H., Campbell, C.A., Brandt, S.A., Lafond, G.P., Townley-Smith, L., 1992. Light fraction organic matter in soils from long term crop sequences. Soil Sci. Soc. Am. J. 56, 1799–1806.

Jenkinson, D.S., Rayner, J.H., 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Sci. 123, 298–305.

Joergensen, R.G., Emmerling, C., 2006. Methods for evaluating human impact on soil microorganisms based on their activity, biomass, and diversity in agricultural soils. J. Plant Nutr. Soil Sci. 169, 295–309.

Klimek-Kopyra, A., Zajac, T., Rebilas, K., 2013. A mathematical model for the evaluation of cooperation and competition effects in intercrops. Eur. J. Agron. 51, 9–17.

Kouno, K., Wu, J., Brooke, P.C., 2002. Turnover and biomass C and P in soil following incorporation of glucose or ryegrass. Soil Biol. Biochem. 34, 617–622.

Liang, B.C., MacKenzie, A.F., Schnitzer, M., Monreal, C.M., Voroney, R.P., Beyaert, R.P., 1998. Management-induced change in labile soil organic matter under continuous corn in eastern Canada. Biol. Fertil. Soils 26, 88–94.

Malhi, S.S., Moulin, A.P., Johnston, A.M., Kutcher, H.R., 2008. Short-term and long-term effects of tillage and crop rotation on soil physical properties, organic C and N in a black Chernozem in northeastern Saskatchewan. Can. J. Soil Sci. 88, 273–282.

Martin, R.C., Astatkie, T., Cooper, J.M., 1998. The effect of soybean variety on corn–soybean intercrop biomass and protein yields. Can. J. Plant Sci. 78, 289–294.

Mead, R., Willey, R.W., 1980. The concept of a 'Land Equivalent Ratio' and advantages in yields from intercropping. Exp. Agric. 16, 217–228.

Medan, D., Torretta, J.P., Hodara, K., de la Fuente, E.B., Montaldo, N.H., 2011. Effects of agriculture expansion and intensification on the vertebrate and invertebrate diversity in the Pampas of Argentina. Biodivers. Conserv. 20, 3077–3100.

Midwood, A.J., Boutton, T.W., 1998. Soil carbonate decomposition by acid has little effect on delta ^{13}C of organic matter. Soil Biol. Biochem. 30, 1301–1307.

Nelson, J.D.J., Schoenau, J.J., Malhi, S.S., 2008. Soil organic carbon changes and distribution in cultiaved and restored grassland soils in Saskatchewan. Nutr. Cycl. Agroecosyst. 82, 137–148.

Oelbermann, M., Echarte, L., 2011. Evaluating soil carbon and nitrogen dynamics in recently established maize–soyabean inter-cropping systems. Eur. J. Soil Sci. 62, 35–41.

Oelbermann, M., Voroney, R.P., Thevathasan, N.V., Gordon, A.M., Kass, D.C.L., Schlönvoigt, A.M., 2006. Soil carbon dynamics and residue stabilization in a Costa Rican and southern Canadian alley cropping system. Agrofor. Syst. 68, 27–36.

Pappa, V.A., Rees, R.M., Walker, R.L., Baddeley, J.A., Watson, C.A., 2011. Nitrous oxide emissions and nitrate leaching in an arable rotation resulting from the presence of an intercrop. Agric. Ecosyst. Environ. 141, 152–161.

Prasad, R.B., Brook, R.M., 2005. Effect of varying maize densities on intercropped maize and soybean in Nepal. Exp. Agric. 41, 365–382.

Regehr, A., 2013. Evaluation of maize and soybean intercropping on soil quality and nitrogen transformations in the Argentine Pampa. Master of Environmental Studies Thesis. University of Waterloo, Waterloo, ON, Canada, p. 104.

Sall, S., Bertrand, I., Chotte, J.L., Becous, S., 2007. Separate effects of the biochemical quality and N content of crop residues on C and N dynamics in soil. Biol. Fertil. Soils 48, 797–804.

Salvo, L., Hernandez, J., Ernst, O., 2013. Soil organic carbon dynamics under different tillage systems in rotation with perennial pastures. Soil Tillage Res. 135, 41–48.

Song, Y.N., Zhang, F.S., Marschner, P., Fan, F.L., Gao, H.M., Baro, X.G., 2007. Effect of intercropping on crop yield and chemical and microbiological properties in rhizosphere of wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and faba bean (*Vicia faba* L.). Biol. Fertil. Soils 43, 565–574.

Stavi, I., Lal, R., 2012. Agroforestry and biochar to offset climate change: a review. Agron. Sustain. Dev. 33, 81–96.

Steel, G.C., Torrie, J.H., Dikey, D.A., 1997. Principles and Procedures of Statistics: A Biometrical Approach. McGraw-Hill, New York.

Stout, J.D., Goh, K.M., Rafter, T.A., 1981. Chemistry and turnover of naturally occurring resistant organic compounds in soil. In: Paul, E.A., Ladd, J.N. (Eds.), Soil Biochemistry. Marcel Dekker, New York, pp. 9–24.

Studdert, G.A., Echeverria, H., 2000. Crop rotations and nitrogen fertilization to manage soil organic carbon dynamics. Soil Sci. Soc. Am. J. 64, 1496–1503.

Tan, Z., Lal, R., Owens, L., Izaurralde, R.C., 2007. Distribution of light and heavy fractions of soil organic carbon as related to land use and tillage practice. Soil Tillage Res. 92, 53–59.

Tessier, L., Gregorich, E.G., Tropp, E., 1998. Spatial variability of soil microbial biomass measured by the fumigation-extraction method, and KEC as affected by depth and manure application. Soil Biol. Biochem. 30, 1369–1379.

Tolon-Becerra, A., Tourn, M., Botta, G.F., Lastra-Bravo, X., 2011. Effects of different tillage regimes on soil compaction, maize (*Zea mays* L.) seedling emergence and yields in the eastern Argentinean Pampas region. Soil Tillage Res. 117, 184–190.

Tu, C., Louws, F.J., Creamer, N.G., Mueller, J.P., Brownie, C., Fager, K., 2006. Responses of soil microbial biomass and N availability to transition strategies from conventional to organic farming systems. Agric. Ecosyst. Environ. 113, 206–215.

Vachon, K.E., Oelbermann, M., 2011. Crop residue input and decomposition in a temperate maize–soybean intercrop system. Soil Sci. 176, 157–163.

Voroney, R.P., Brookes, P.C., Beyaert, R.P., 2008. Soil microbial biomass C, N, P, and S. In: Carter, M.E., Gregorich, E.G. (Eds.), Soil Sampling and Methods of Analysis. CRC Press, Boca Raton, pp. 637–651.

Waddington, S.R., Mekuria, M., Siziba, S., Karigwindi, J., 2007. Long-term yield sustainability and financial returns from grain legume–maize intercrops on a sandy soil in subhumid north central Zimbabwe. Exp. Agric. 43, 489–503.

Zach, A., Tiessen, H., Nollemeyer, E., 2006. Carbon turnover and carbon-13 natural abundance under land use change in semiarid savanna soils of La Pampa, Argentina. Soil Sci. Soc. Am. J. 70, 1541–1546.