Environmental Earth Sciences (2018) 77:428
https://doi.org/10.1007/s12665-018-7606-0

ORIGINAL ARTICLE

Cover crops in the Southeastern region of Buenos Aires, Argentina: effects on organic matter physical fractions and nutrient availability

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Received: 11 January 2018 / Accepted: 14 June 2018
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Abstract

In the Southeastern region of Buenos Aires province, soybean monoculture has led to a decline in soil organic matter (SOM) levels in soil, mostly the labile fractions. The reduction of SOM has a negative impact on the soil environment. Cover crops (CC) constitute an alternative to maintain or improve SOM levels. The aim of this study was to determine the effect of oat as CC on (a) the SOM dynamics and (b) the availability of macro- and micronutrients in a representative soil of the Southeastern region of Buenos Aires province. Total organic carbon (TOC) and nitrogen (TON), as well as their labile and mineral-associated fractions, and macro- and micronutrient availability were determined. The treatments were soybean monoculture with and without oat as cover crop. The increases in SOC and TON were 22.7% and 11%, respectively, when CC was included to the soybean monoculture. These increases were observed mostly in the labile fractions, with increases of 61.3 and 38.7% for the particulate coarse organic carbon (PCOf) and particulate fine organic carbon (PCOf), respectively, and 79.2% for the particulate coarse organic nitrogen (NOPg). Regarding the nutrients, an increase of 47.6% was observed in manganese (Mn) in the first 5 cm of soil depth, and a decrease in phosphorous (P) availability in the same soil layer due to its consumption and retention by CC. It can be conclude that CC presented a surface soil effect on the dynamic of SOM, increasing C, N, and available Mn contents, but decreasing soil P availability.

Keywords Oat · Soybean monoculture · Particulate organic carbon and nitrogen

Introduction

In the last decades, there has been a severe soil degradation in the Pampas region as a consequence of a long agricultural history (Taboada et al. 1998). Use of high-yield crops, and low nutrient placement by fertilization, erosion, and reduction in the soil organic matter content (SOM) increase this problem (Lavado and Taboada 2009). SOM is the most important nutrient reservoir (Rani Sarker et al. 2018), and it has effects on the physical and chemical properties of the soil; therefore, SOM reduction affects directly the soil quality and productivity. In the southeast of Buenos Aires province, the agriculture intensification process has reduced the SOM content, mainly the labile fractions (Sainz Rozas et al. 2011). The SOM balance of soil depends on the carbon (C) balance, based on the inputs and outputs of this element. Under soybean monoculture, the low contribution of harvest residues, and consequently, C inputs decrease the SOM contents compared with rotations containing gramineous species (Mazzilli et al. 2014). An alternative to increase residue contribution is the incorporation of cover crops (CC), which are sown among the productive crops and their residues are not removed from the soil. Cover crops could be gramineous species, leguminous species, or different mixtures of plants. The most labile fractions of C are more sensitive to changes produced by soil and crop management practices (Yang et al. 2012; Muñoz-Romero et al. 2017), and CC, especially the gramineous one increased SOM contents, mainly the labile fractions (Restovich et al. 2011).

The method proposed by Cambardella and Elliott (1992) is traditionally used to determine the labile fraction of C. This method is based on the physical separation of the SOM using a sieve of 53 micron mesh. The most labile fraction is

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composed mostly by organic residues that have not totally been processed by microorganisms; this fraction is known as particulate organic carbon (POC). In addition, for better understanding of the C flux, Galantini and Rosell (1997) have proposed a more intensive fractionation separating the POC into coarse POC (POCc) and fine POC (POCf). The POCc represents the most active fraction of the SOM (Duval et al. 2014), and consists in microbial biomass and partially humified OM with a turnover rate of 1–5 years (Anderson and Ingram 1989). The POCf corresponds to the most stable fraction in the POC, with a turnover rate of 10–20 years (Galantini and Suñer 2008). Finally, the organic fraction lower than 53 microns is the most stable fraction of the OM, and is associated with clays and metallic complex. The humic and fulvic acid and the humina are contained in this associated fraction (Galantini and Suñer 2008).

Apart from increasing C levels, cover crops could increase C stratification due to a greater C accumulation in the first layer of soil caused by a deposition of CC tissues, compared to deeper horizons. This stratification can be measured by a stratification index. Highest values of this index represent a higher stability of soils systems, because greater C levels on the surface reduce erosion processes (Duval et al. 2016).

Regard to nutrient availability, inclusion of CC in rotations could lead into modifications of nutrient recycling at soil. The increase in POC could affect availability of nutrients associated with C cycle, such as nitrogen (N) and sulfur (S) (Sainju et al. 2007). In this sense, some authors reported that particulate organic matter is positively related to N and S release (Cambardella and Elliott 1994; Dominguez et al. 2016; Galantini et al. 2004). Moreover, the absorption of nutrients by CC reduces losses of mobile nutrients as nitrates (NO_3) and sulfates (SO_4) by lixiviation process (Salmerónet al. 2011). In addition, the presence of cover crops improves soil microbial activity, affecting the availability of some nutrients (Kunze et al. 2011). On the other hand, CC could increase nutrient concentration at the soil surface, particularly the low-mobile ones, due to the absorption of its nutrients from deeper layers and their reincorporation to surface once the CC are dried and their tissues are decomposed. In the case of phosphorous (P) and potassium (K), a high stratification of their concentrations due to the use of CC has been determined by Tiecher et al. (2012). The same process has been observed for calcium (Ca) and magnesium (Mg) (Calegari et al. 2013). In the case of P, CC also improve the enzymatic activity of soil, which can increase its availability by phosphorus solubilizers (Horst et al. 2001). Micronutrient soil contents and its availability could also be affected by crops. Kopittke et al. (2017) reported that the availability of zinc (Zn), iron (Fe), copper (Cu), and manganese (Mn) was reduced at long term due to their absorption and exportation to grain in different crop sequences. Wei et al. (2006) also observed a decrease in the amount of Zn overtime due to its consumption by crops. According to Havlin (2005), soluble organic compounds, which are associated with the particulate fraction of the SOM, could increase Zn availability. Wei et al. (2006) also observed a direct and positive relationship between SOM and Zn availability. These authors also pointed out that the radicular activity of some crops can increase their availability through the release of organic acids that reduce the pH of the ryzosphere. In the north of the Pampean region, Beltrán et al. (2016) observed a trend in the increase in Zn and Mn availability in the first centimeters of soil caused by the use of wheat as CC in a Typic Argiudoll soil.

Several studies have shown how CC increase C and N organic levels, but the effect of CC on macro and micronutrient availability and its relationship with different fractions of C is less known. The purpose of this research was to evaluate the effect of oat (Avena sativa) as a cover crop on (a) the organic matter dynamics and (b) the macro- and micronutrient availability associated with granulometric fractions with different lability.

Materials and methods

Study site and experimental design

The experiment was located at INTA (National Institute of Agricultural Technology), Balcarce Research Station (37°45′00″S 58°15′00″O, 138 m above sea level), Argentina, on a Typic Argiudoll (USDA Taxonomy), deep, well-drained, with a silt loam texture in the surface horizons, with more than 25 years of agricultural history. The climate is tempered humid–subhumid with a dry season, with mean annual temperature of 13.3 °C and mean rainfall of 800 mm. Rainfall occurs mainly in fall and spring, while the summer usually present deficits of varying intensities in the agro-climatic balance.

A long-term experiment was designed in 2006 to evaluate crop sequence with different intensities of soybean participation under no till system. The experiment among other crop sequence included soybean–soybean (S–S) or soybean combined with oat (Avena sativa) as cover crop in winter with (S–CCf) or without nitrogen fertilization (S–CC). All treatments were arranged in a randomized complete block design with three replicates. Each experimental unit was 12 × 5 m.

In the year of the soil sampling (2014), soybean (Don Mario 3810) was sown on November 19 (25 plants per m^2), inoculated with Bradyrhizobium sp., and fertilized with 24 and 16 kg ha^{-1} of phosphorus and sulfur, respectively. Oat (Calen INTA) was sown on April 15 (300 plants per m^2) and fertilized with 100 kg ha^{-1} of nitrogen for the S–CCf treatment. The CC was dry with 3 L ha^{-1} of glyphosate on October 10.

Soil sampling and measurements

Soil samples were taken at 0–5, 5–10, and 10–20 cm depth with a stainless steel soil sampling collector tool in 2014 cropping season (October), and replicated three times in each experimental unit. Subsamples were mixed and homogenized, air-dried, and sieved through a 2-mm-diameter mesh.

Total soil organic carbon (TOC) content was quantified using the wet oxidation method (Nelson and Sommers 1996). Total nitrogen (TN) was determined using the Kjeldhal method (Bremmer and Mulvaney 1982). C and N stock was calculated for 0–20-cm depth, affecting each concentration value with the bulk density. The stratification index was calculated according to the method described by Franzluebbers and Stuedemann (2002) (%COT 0–5 cm/%COT 5–20 cm). Soil particle size fractionation was performed by wet sieving (Cambardella and Elliott 1992). Briefly, 50 g of soil previously air-dried and sieved (2 mm) was dispersed and mixed with 100 mL of distilled water. Then samples were subjected to mechanical dispersion through a rotary shaker for 16 h at 40 rpm to disintegrate the aggregates. The sieving was done with sieves of 53 and 105 µm of diameter mesh, until the water coming out through the sieve was clear to the naked eye. Three fractions were obtained: coarse fraction (105–2000 µm) containing coarse particulate organic fraction and fine-to-coarse sands (Pcf); medium fraction (53–105 µm) which included fine particulate organic fraction and very fine sand (Pff); and the fine fraction (< 53 µm) containing mineral-associated organic fraction (Maf) and silt and clay minerals. The material retained in each sieve was transferred to aluminum pots and oven-dried at 105 °C for 24 h for later weighing. Total C and N concentration of the different size fractions was analyzed following the procedures described above.

The content of extractable phosphorous was determined following the method described by Bray and Kurtz (1945). The method of ammonium acetate pH 7 (Simard 1993) was used for the extraction of calcium (Ca), magnesium (Mg), and potassium (K). Cupper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) were extracted with DTPA (pentaacetatediethylenetriamine) pH: 7,3 (Lindsay and Norvell 1978). Concentrations of macro- and micronutrients were determined using a Varian 2005 atomic absorption spectrophotometer.

Statistical analyses

Homogeneity of variance was performed for each analyzed variable. Results were analyzed by analyses of variance (ANOVA) with a significance level of 0.05, using a mixed linear model (Littell et al. 2006), where CC, depth, and their interaction were fixed factors and block the random factor. Simple linear regression was carried out to determine relationships between C input and SOC, and between pH and micronutrients. Correlation analyses were performed between the different SOM fractions and macro- and micronutrient availability.

Results and discussion

Total and particulate soil carbon and nitrogen

Soybean monoculture has an annual average contribution of 1.1 Mg of C and the use of oat as cover crops increase significantly this value. Treatment with CC had an addition of 2.2 and 3.4 Mg of C with and without N fertilization, due of its dry matter production. This means that the use of CC improves the C input to soil in a 100 and a 209%, respectively, compared with soybean monoculture (Table 1).

After 8 years of experiment, the C input was positively related with high significance ($r^2 = 0.817$, $p = 0.0008$) to the increase of total soil C in the first 5-cm depth (Fig. 1). The 0–20 cm depth showed minor relationships among C input and C soil, indicating that, in the period of time evaluated, the effect was of oat was shallow. Duval et al. (2016) found similar values of C input in the Pampas Region because of the use of oat and a similar effect over de soil total C.

There were no significant differences among treatments in the stock of C and N in the first 20 cm (Table 2). However, the analysis of C and N concentration according to depths showed an increase in both elements in the first 5 cm, with

Table 1 Average carbon contribution (C) in Mg ha^{-1} of the aerial and radicular biomass of oat and soybean crops per year and total accumulated during the 8-year experiment

Treatment	C (Mg) oat			C (Mg) soybean			Av. C	Total C
	Aerial	Radicular	Total	Aerial	Radicular	Total		
S–S	0.0	0.0	0.0	0.8	0.3	1.1	1.1c	8.4c
S–CC	1.5	0.7	2.2	0.7	0.3	1.0	3.2b	25.7b
S–CCf	2.3	1.1	3.4	0.8	0.3	1.1	4.5a	35.7a

Different letters indicate significant differences ($p < 0.01$) among treatments

S–S, soybean monoculture; S–CC, soybean with cover crop; S–CCf, soybean with fertilized cover crop. Av. C, average carbon per year; total C, total carbon after 8 year experiment

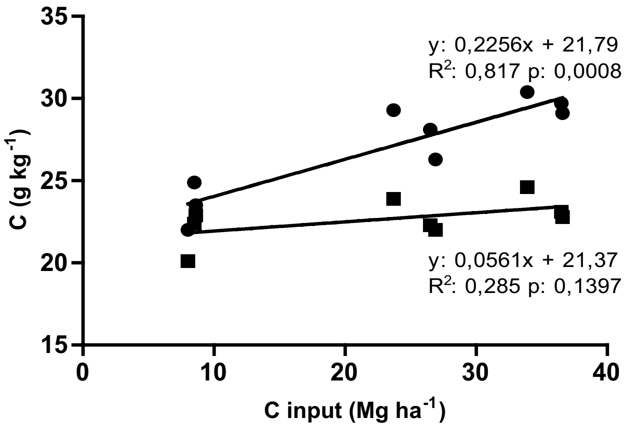

Fig. 1 Relationship between total C contribution by crops and the level of total C of all treatments after 8-year experiment for 0–5-cm (circles) and 0–20-cm (squares) depths

no significant differences at 5–10 and 10–20 cm. On average, oat as cover crops increased 22.7% the soil C compared with soybean monoculture at 0–5 cm, with no differences between S–CC and S–CCf treatments. Alvarez et al. (2017) also reported that treatments with cover crops showed a tendency to higher concentrations of TOC in the first cm soil depth. For the same soil depth, TON showed an increase of 11% due to the use of cover crops, with no differences between fertilized or unfertilized cover crop. Therefore, oat as cover crop increased C more than N; probably due to the fact that gramineous species, such as oat, have higher C/N ratio in their tissues, and, therefore, they have a greater impact on C as observed in our experiment. Although C and N increases were different, C/N ratio in the first soil depth was not significantly modified compared with soybean monoculture (10.68 vs 11.77 for S–S and treatments with CC, respectively).

The increase in the TOC levels in the first 5 cm could be associated with the increment of the labile fractions, COPg, and COPf (Fig. 2). This results are in agreement with those of Martinez et al. (2014) in the same experiment 4 years after the present study. Similar results were reported by Duval et al. (2013) and Diovisalvi et al. (2008) who concluded that the particulate fraction best reveals changes depending on soil management. There was a significant increase of 61.3% in the COPg fraction attributed to CC use. On average, treatments with cover crop presented 5.0 g kg^{-1} of COPg, with no differences due to fertilization, while soybean monoculture showed a value of 3.1 g kg^{-1}. The COPf significantly increased (38.7%) in response to CC use, with no differences between fertilized or unfertilized cover crops. On average, COPf for soybean monoculture and treatments with cover crops was 3.1 and 4.3 g kg^{-1}, respectively. Increments in COPg and COPf would be caused by residues supplied by crops, which are closely related to changes in the OM content (Studdert and Echeverria 2000). Therefore, COPg was more sensitive than COPf to CC inclusion; this is due to the fact that this fraction is more labile and dynamic than the COPf. Finally, the carbon in the mineral-associated fraction was not statistically modified due to CC use, since, probably, this is the most stable fraction of the OM (Galantini and Suñer 2008). Part of the COPg can be lost in the form of CO_2 when used by soil microorganisms (Colozzi-Filho et al. 2001) and another part of the COPg can be transformed into the fine particulate fraction. This process partly depends on the quality of the crop residues. Residues of leguminosas tend to degrade more rapidly, while those of gramineous species degrade slower due to their greater C/N ratio (Xu et al. 2017), and thus, the humification process is favored. Soil texture also affects recycled C, since coarse textures favor OM mineralization, because leads C substrates more exposed to microbial activity; conversely, fine textured soils favor humification, since they produce a physical protection of the OM that is retained in micropores where microorganisms cannot access (Buschiazzo et al. 1991).

The increase in the C concentration in the 0–5 cm produced a greater stratification compared to that naturally observed under no tillage; this agrees with Spargo et al.

Table 2 Average values of total organic C and N concentrations for each soil depth and treatment, and average values of carbon and nitrogen stock at 0–20 cm

Soil depth (cm)	C (g kg^{-1})			N (g kg^{-1})		
	S–S	S–CC	S–CCf	S–S	S–CC	S–CCf
0–5	23.5b	27.9a	29.8a	2.2b	2.4a	2.5a
5–10	22.3a	22.9a	24.2a	2.1a	2.2a	2.1a
10–20	20.7a	20.1a	20.0a	2.0a	2.0a	2.1a
Soil depth (cm)	C (Mg ha^{-1})			N (Mg ha^{-1})		
0–20	53.9a	56.1a	58.0a	5.0a	5.3a	5.3a

Different letters indicate significant differences ($p < 0.05$) among treatments

C, carbon; N, Nitrogen; S–S, soybean monoculture; S–CC, soybean with cover crop; S–CCf, soybean with fertilized cover crop

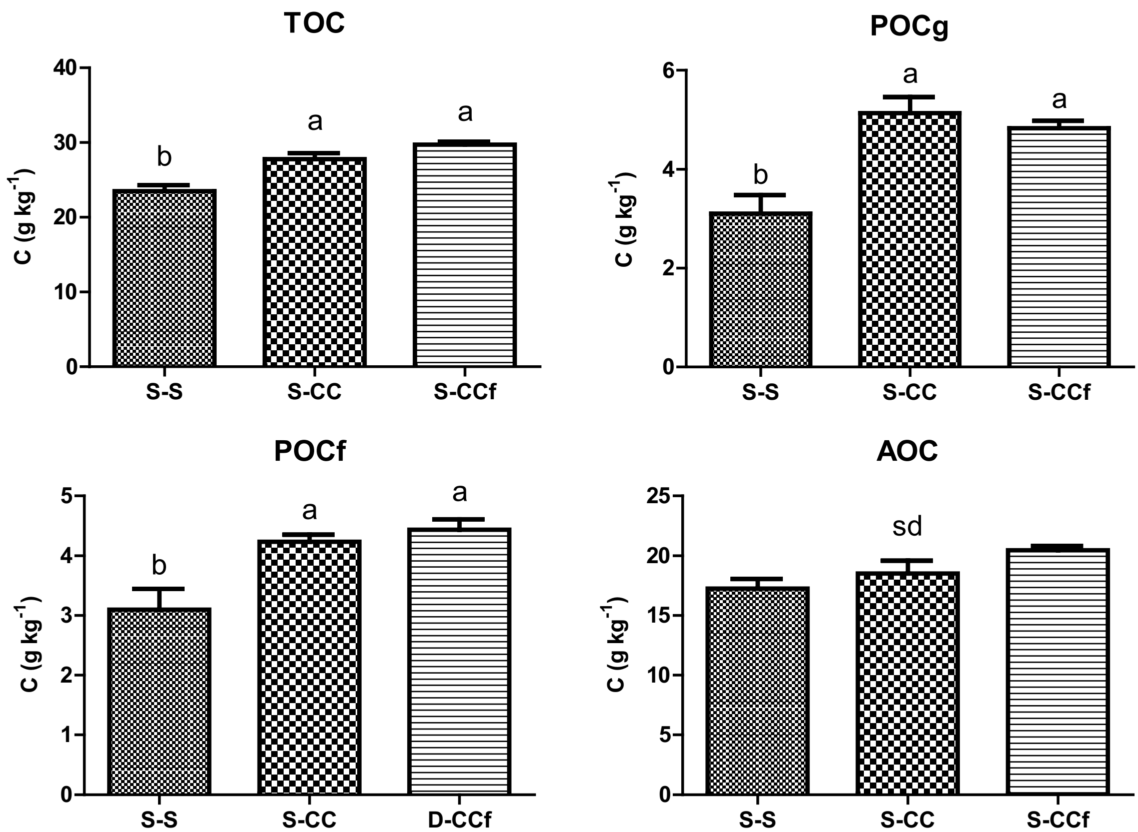

Fig. 2 Concentration of total organic carbon (TOC), coarse particulate organic carbon (POCg), fine particulate organic carbon (POCf), and associate organic carbon (AOC) for the top 0–5 cm of soil. Different letters indicate significant differences ($p<0.05$) among treatments. S–S, soybean monoculture; S–CC, soybean with cover crop; S–CCf, soybean with fertilized cover crop

(2008) who reported that extra supplies of C increased stratification of TOC. This phenomenon is observed when analyzing the stratification index (IE) that relates C concentrations in the top layer with the subsurface layer (Fig. 3). Higher IE values are related to soil systems with higher stability attributed to higher C concentration that reduces erosion. For the case under study, the IE for the soybean monoculture was 1.15, while that, on average, for the treatment with CC was 1.36, being this value statistically higher (18%) than the first one. Duval et al. (2016) also found increases in the IE due to the increment of gramineous species in rotation with soybean. This result suggests that the CC favored stability and sustainability of the productive system, since higher values of IE determine soil sustainability Franzluebbers and Stuedemann (2002).

Regarding N, the effect of CC was similar to that of C, probably due to the close relationship in their cycles in the soil (Fabrizzi et al. 2003; Álvarez and Álvarez 2000). TON increase in the first 5 cm of the soil was attributed to the increase of the labile fraction of N (Fig. 4). However, in this case, only the coarse particulate organic nitrogen (NOPg) increased and no differences were detected in the fine particulate fraction and mineral-associated fraction. There was a significant increase of 79.2% in NOPg when CC was included to soybean monoculture. NOPg was 0.24 g kg^{-1} for soybean monoculture and increase to 0.43 g kg^{-1} on average for treatments with CC, with no differences due to fertilization. Therefore, the NOPg was the only fraction that revealed changes due to the use of cover crops. Increases

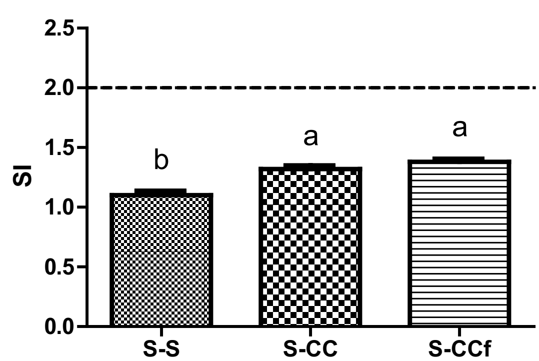

Fig. 3 Stratification index (SI) per treatment. Different letters indicate significant differences ($p<0.05$) among treatments. S–S, soybean monoculture; S–CC, soybean with cover crop; S–CCf, soybean with fertilized cover crop

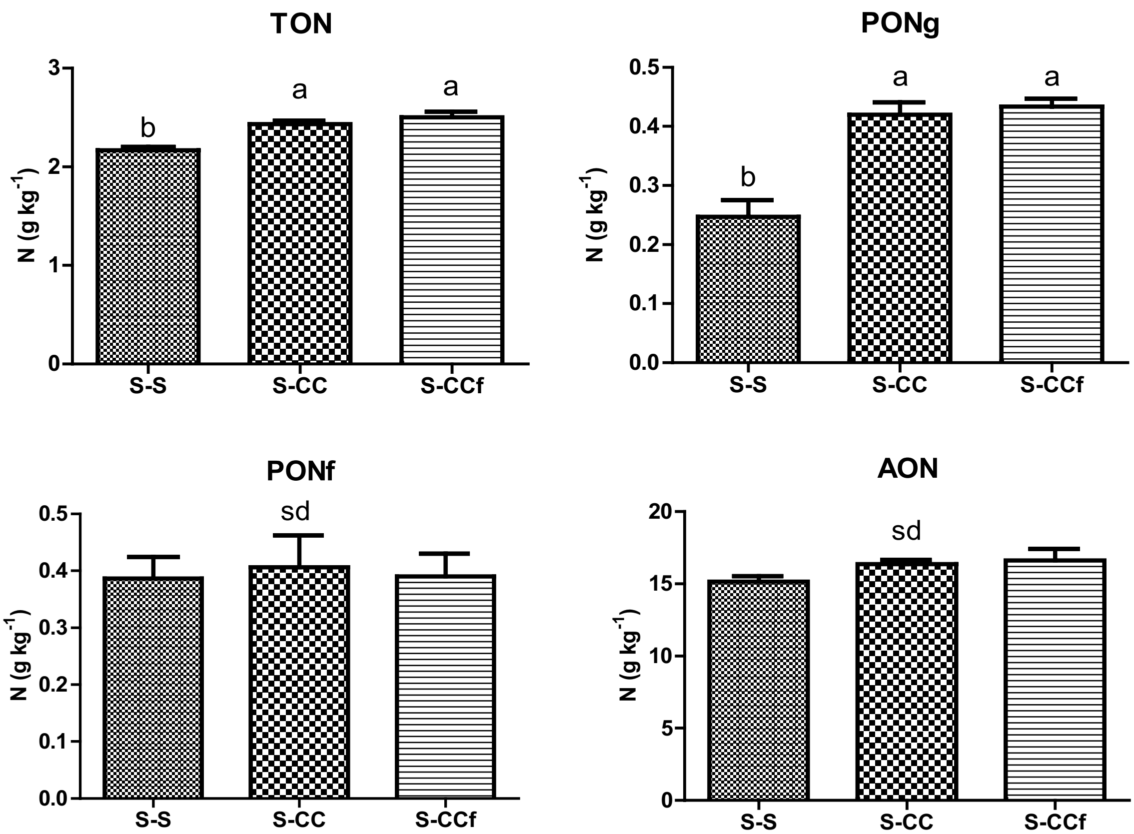

Fig. 4 Concentration of total organic nitrogen (TON), coarse particulate organic nitrogen (PONg), fine particulate organic nitrogen (PONf), and associate organic nitrogen (AON) for 0–5 cm depth. Different letters indicate significant differences ($p < 0.05$) among treatments. $p < 0.05$. S–S, soybean monoculture; S–CC, soybean with cover crop; S–CCf, soybean with fertilized cover crop

in the organic N in the first 5 cm of soil caused by the use of cover crops were also reported by Villamil et al. (2006). Because oat used as a CC does not supply extra N to the system as legume-based cover crops, the increases of N in the labile organic fraction could be explained, because, during the winter season, the plant absorbs inorganic N from soil solution as NO_3, then transforms it into the organic form, and, finally, releases then to soil when the cover crops tissues are degraded.

The total C/N ratio did not vary significantly among treatments, with values of 11.3, 11.0, and 10.4 for 0–5, 5–10, and 10–20-cm depths, respectively. Moreover, due to the fact that oat improves the C and N soil concentration among the different analyzed fractions with similarity, no significant differences were observed in the C/N ratio in any fraction either.

Availability of macro- and micronutrients

Analysis of availability of main macronutrients and their distribution in the soil profile up to 20 cm revealed that P exhibited the greatest stratification in depth followed by K (Table 3).

Higher phosphorus availability in soil was detected in the treatment without CC. Thus, CC reduced P availability in soil probably due to the fact that CC during the winter absorbed and retained P in its tissues. Moreover, the CC fertilized was the treatment with the lower value of P in soil (Table 3), due to the greater production of dry matter (Table 1) and, therefore, higher absorption of P. Despite this reduction in the availability in the first 5 cm, treatments with CC and CCf P availability at 20 cm were 27 and 23 mg kg^{-1}, respectively, far over the response threshold to the addition of P as fertilizer for soybean crop (13 mg kg^{-1}) (Echeverría and García 1998). Therefore, no negative effect would be expected in P nutrition for the leguminous species. The reduction in P availability was detected due to soil sampling which was conducted immediately after the drying process of the CC. This would not constitute P losses in the system, since this element could be released again during the residue degradation without further affecting soybean crop. It should be highlighted that cover crops did not significantly affect soybean crop yields (Table 4).

Table 3 Average values of concentration of available phosphorous (P), calcium (Ca), magnesium (Mg), and potassium (K) interchangeable per depth and stratification index (SI) for each treatment

Soil depth (cm)	S–S	S–CC	S–CCf
P (mg kg^{-1})			
0–5	66.40c	58.33b	50.67a
5–10	20.43a	26.90a	19.73a
10–20	12.57a	11.53a	10.90a
SI	5.29a	5.28a	4.66a
Ca (cmol$_c$ kg^{-1})			
0–5	11.20a	12.87a	11.37a
5–10	10.57a	10.30a	10.80a
10–20	11.07a	11.03a	10.83a
SI	1.02a	1.17a	1.05a
Mg (cmolc kg^{-1})			
0–5	2.23a	2.50a	2.00a
5–10	1.87a	2.00a	1.90a
10–20	1.83a	1.90a	1.90a
SI	1.21a	1.30a	1.05a
K (cmol$_c$ kg^{-1})			
0–5	1.87a	2.00a	1.77a
5–10	1.60a	1.53a	1.73a
10–20	1.37a	1.30a	1.30a
SI	1.36a	1.54a	1.36a

Different letters indicate significant differences ($p < 0.05$) among treatments for concentration and stratification index (SI)

S–S, soybean monoculture; S–CC, soybean with oat used as a CC; S–CCf, soybean with fertilized oat as CC

Cations (Ca, Mg, and K) availability is associated with the capacity of cationic exchange in the soil (CEC), which could be affected by changes in the concentration of humic and fulvic acids. These organic acids contributed to generate bonds between cations and the soil organic matter which could increment cations availability (Donisa et al. 2003; Peel et al. 2017; Zhang et al. 2013). The fact that these acids are found in the associated carbon fraction (Galantini and Suñer 2008); its concentration was not affected by the use of CC; thus, the concentration of Ca, Mg, and K was not be affected either. The SI of this cations was not affected by the CC and their values were within the normal range of the Pampas Region (Sainz Rozas et al. 2013).

Regarding micronutrients, availability of Fe and Cu had a significant and negative correlation with the pH (Table 5), without being affected by the presence of CC (Fig. 5). These results are in accordance with reports by Shukla et al. (2016) who found a high negative relationship between pH and Fe and Cu availability. Moreover, Wu et al. (2010) also found that Cu concentration increased with decreasing pH, and Lindsay (1978) observed that Fe availability was the most sensitive of the micronutrients extractable with DTPA to pH fluctuations, reducing their values with increments in the soil pH.

Mn availability was significantly affected by cover crops (Table 6) with an increase of 47.6% in the first 5 cm when oat as CC was included to the soybean monoculture.

Mn and Cu were the only two micronutrients whose stratification in the soil was affected significantly by the CC. Analyzing the stratification indexes (SI) for each element, we observed that the indexes raised by 35.5 and 28.2% for Mn and Cu, respectively (Table 6). According to Barber (1978), copper distribution in the profile positively correlates with the SOM.

Mn presented a high and significant positive correlation with all the carbon fractions (Table 7). Wei et al. (2006) observed increases in the concentration of Mn in the long term attributed to continuous cultivation of legumes, hypothesizing that this increase was related to the decrease of pH and supply of organic matter (OM) by leguminous species. Other authors, such as Mandal and Mitra (1982) and Guimaraes Moreira et al. (2016), also

Table 5 pH values per treatment and depth.

Soil depth (cm)	S–S	S–CC	S–CCf
pH			
0–5	5.83a	5.97a	5.70A
5–10	5.47a	5.73a	5.67A
10–20	5.50a	5.70a	5.60A

Different letters indicate significant differences ($p < 0.05$) among treatments

S–S, soybean monoculture; S–CC, soybean with oat as CC; S–CCf, soybean with oat used as a fertilized CC

Table 4 Soybean crop yield (kg ha^{-1}) per treatment per research trips and average of the total number of research trips

Treatment	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14	Average
S–S	2982	3866	979	3754	2691	2689	3370	3191	2940a
S–CC	2873	3657	1086	3899	2783	2585	2996	2380	2782a
S–CCf	2881	3970	1024	4332	2371	3128	3232	3320	3032a

Different letters indicate significant differences ($p < 0.05$) among treatments

S–S, soybean monoculture; S–CC, soybean with oat used as a CC; S–CCf, soybean with oat used as a fertilized CC

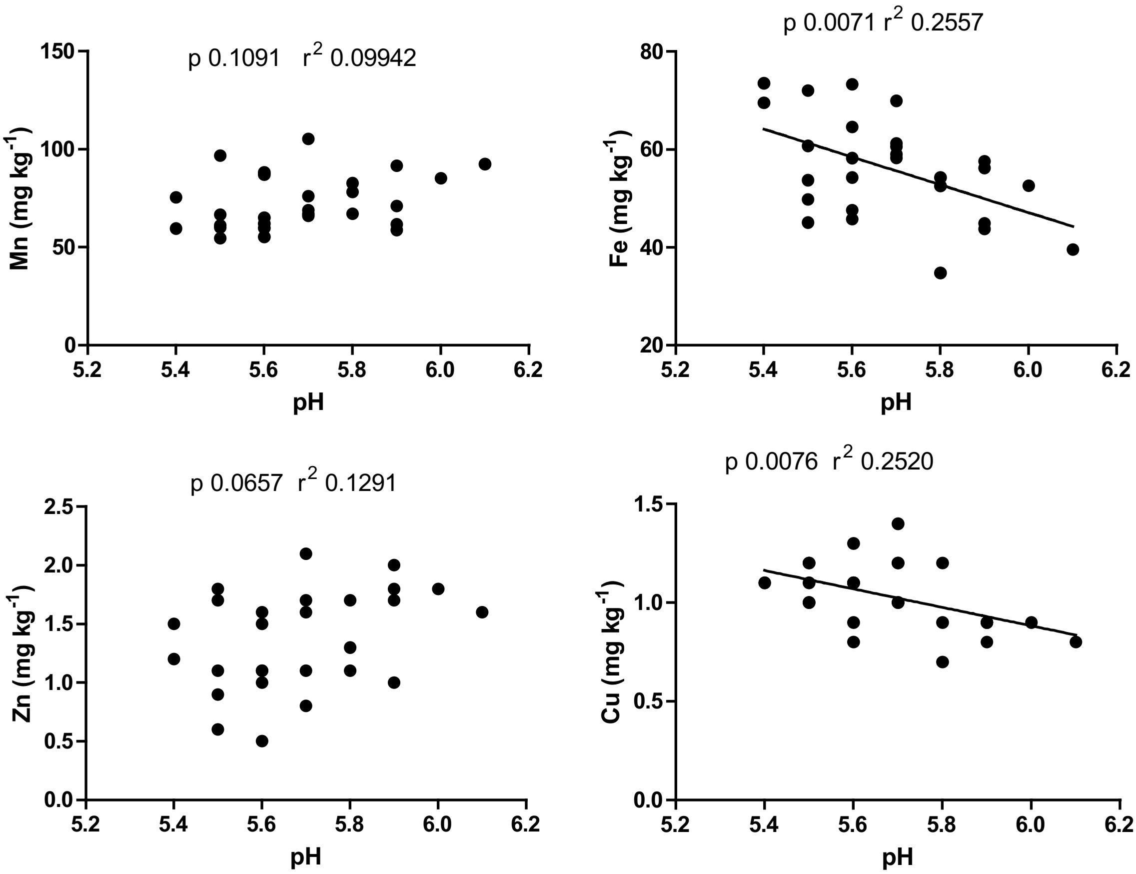

Fig. 5 Relationship between micronutrient concentration (extractable with DTPA) and pH

found a positive relationship between the OM and the concentration of interchangeable and soluble Mn. This is in accordance with observations by Beltrán et al. (2016) who found an increase in Mn availability due to the effect of wheat as a CC, and related to this increase positively with increases in the labile fractions of the OM, with no changes in the pH of the soil. Moreover, as CC did not significantly affect soybean yields (Table 4), extraction of Mn by leguminous species was similar for all the treatments, being the differences in extractable Mn due to effects of CC directly into the soil. The first effect could be the increase in Mn availability due to the CC absorption from lower layers and redistribution in the surface stratum as DTPA extractable forms of Mn. The second effect could be as Shuman and Anderson (1988) reported that OM decomposition can increase soluble Mn levels due to reductive effects in the soil (decline in the redox potential), which could mobilize Mn from the oxide fraction to the organic and interchangeable fraction.

Finally, it should be highlighted that availability of the nutrients studied was within the normal range referred to the literature for the Pampas Region (Sainz Rozas et al. 2013).

Conclusions

Although oat used as a CC did not increase carbon stock in the first 20-cm soil depth, it did increase its concentration in the top layer of the soil (0–5 cm) and its stratification in the soil profile favoring the system stability. Carbon increase was observed in the labile fractions, particularly in the coarse particulate fraction.

Regarding nitrogen, cover crops increase its concentration in the first 5 cm of the soil, especially in the coarse particulate fraction.

The cover crop reduced the P availability due to its absorption, but without reaching detrimental values for further soybean cultivation.

Among micronutrients, an increase in Mn availability in the first 5 cm was observed when CC was included to soybean monoculture.

Table 6 Average values of manganese (Mn), Iron (Fe), zinc (Zn) and copper (Cu) for depth, and stratification index (SI)

Soil depth (cm)	S–S	S–CC	S–CCf
Mn (mg kg^{-1})			
0–5	62.50a	86.77b	97.87b
5–10	67.37a	68.33a	84.50a
10–20	58.70a	64.27a	64.17a
SI	1.07a	1.35b	1.54b
Fe (mg kg^{-1})			
0–5	53.37a	48.83a	56.20a
5–10	59.77a	56.00a	63.47a
10–20	66.57a	46.30a	53.97a
SI	0.8a	1.08a	1.05a
Zn (mg kg^{-1})			
0–5	1.80a	1.70a	1.87a
5–10	1.30a	1.37a	1.33a
10–20	1.13a	1.07a	0.73a
SI	1.57a	1.62a	2.79a
Cu (mg kg^{-1})			
0–5	0.90a	0.87a	1.03a
5–10	1.10a	1.13a	1.20a
10–20	1.13a	0.87a	1.03a
SI	0.78a	1.01b	0.99b

Different letters indicate significant differences ($p < 0.05$) among treatments

S–S, soybean monoculture; S–CC, soybean with oat as CC; S–CCf, soybean with oat used as a fertilized CC

Table 7 Correlation between the different carbon fractions and the availability of macronutrients

	POCg		POCf		AOC		TOC	
	p	*R*	*p*	*R*	*p*	*R*	*p*	*R*
Mn	0.0008	0.90	0.0022	0.87	0.0249	0.73	0.0004	0.92
Zn	0.7866	0.08	0.7678	−0.12	0.4626	0.28	0.7746	0.11
Fe	0.8331	−0.11	0.7675	−0.12	0.7704	−0.11	0.7283	−0.14
Cu	0.32	0.38	0.7056	0.15	0.4917	0.26	0.5369	0.24

POCg, coarse particulate organic carbon; POCf, fine particulate organic carbon, AOC, associate organic carbon; TOC, total organic carbon. *R* correlation coefficient

Acknowledgements This study was conducted through the specific Project "Status and Dynamics of nutrients in soil" of the National Soil Program of INTA, Argentina (PN 1134024).

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