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The Open Agriculture Journal, 2013, *7*, (Suppl 1-M3) 11-21

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Decomposition and Carbon Dynamics of Crop Residue Mixtures in a Semiarid Long Term No-Till System: Effects on Soil Organic Carbon

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Abstract: Plant residues decomposition transfers organic matter and nutrients to soil, and plays a decisive role in carbon (C) cycling. The aims of our study were to analyze under realistic field conditions the annual decomposition and C dynamics of crop residues mixtures under long-term no-till management and their effect on soil organic carbon (SOC). Three treatments were evaluated: soybean monoculture, soybean rotation (maize as preceding crop), and maize rotation (soybean as preceding crop). In each treatment soil samples and crop residue samples were collected. In crop residues samples we determined: total residue mixture biomass, soybean residue biomass, maize residue biomass, non identifiable residue biomass, total C, soluble C, insoluble fiber. In soil samples, SOC were analyzed. Decomposition rates were calculated for residues mixture, soybean and maize residue before and after deposition of fresh residue. Decomposition rates of all residues analyzed showed a high variability between treatments. Total C, soluble C and insoluble fiber concentrations of the residues mixtures showed a great similarity among treatments. Contrarily, their annual dynamics differed between sampling dates in all treatments. We concluded that decomposition and C dynamics of crop residues mixtures in long-term no-till systems in the semiarid central Argentina are strongly influenced by: the interaction of the chemical quality of the residues, the proportion of the residues from different crops and/or with different decomposition degree,and the seasonal effect. The greater C amount in residues mixture of rotation was not reflected in SOC contents, and further studies are recommended.

Keywords: Soybean, maize, decomposition rates, soluble C, insoluble fibers.

INTRODUCTION

Plant residues decomposition transfers organic matter and nutrients to soil, and plays a decisive role in carbon (C) cycling in terrestrial ecosystems. Soil organic matter (SOM) content in ecosystems is strongly influenced by the rates of addition and decomposition of organic residues, and by soil erosion processes. Consequently, SOM content in agroecosystems would be highly dependent on farmers' practices, particularly crop rotations, crop residue management and tillage system. Knowledge about the dynamics of crop residues decomposition becomes essential for a sustainable management of agricultural ecosystems.

In the semiarid region of Argentina, no-till system (NT) has been widely adopted in order to prevent soil erosion during bare fallow periods, and other benefits were associated with this management system, including increases in SOM [1, 2]. The importance of SOM in maintaining soil chemical, physical and biological fertility is well known, and its potential to reduce greenhouse gases and improve the sustainability of agroecosystems is also recognized [3].

Residue decomposition and nutrient release are affected by residue quality [4-6], environmental conditions, like humidity and temperature [4, 7], and decomposer community composition and diversity [8]. The vast majority of studies define the quality of plant residues as their relative ease of mineralization by decomposer microorganisms [9], and evaluate the initial biochemical composition of plant material because of its major influence on decomposition and nutrient release patterns [10, 6]. In this sense, the C/N ratio has been accepted as a general index of quality of crop residues [11, 12], assuming that mineralization rates decrease with increasing C/N ratio [13]. Additionally, different studies found that other biochemical characteristics, (e.g. soluble C, cellulose, hemicellulose, lignin, etc.) are also useful residue quality indicators [14, 15].

From a decomposition point of view, NT systems have very important similarities with natural ecosystems that must be considered when assessing decomposition process, such as: a) deposition of plant residues on the soil surface, and b) presence of plant residue mixtures. Surface placement of crop residues in NT reduces the residue-soil contact as compared with tillage practices. This consideration affects microclimatic conditions, nutrient availability and microbial community, and subsequently, decomposition dynamics [16, 17]. Secondly, in NT systems, as well as occurs in natural ecosystems, crop residues usually become mixed and decompose simultaneously with other crop residues from different species (depending on the crop sequence, intercropping, etc.) and with different decomposition degree (depending on the time since their deposition in soil surface). In this regard, it has been suggested that plant residue mixtures fre-

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quently produce non-additive effects on decomposition dynamics [8, 18, 19], and that these interactions may vary depending on the residue quality of the component species [20], and residue mixing proportion [21, 22], among others. Consequently, as suggested by Mao and Zeng [22], residue decomposition dynamics in agroecosystems should be assessed on the basis of residue mixtures for a better understanding and management of nutrient dynamics. Despite these considerations, the broad majority of studies in agroecosystems have focused on decomposition and nutrient dynamics of single or _more scarcely_ mixed fresh residues [4, 15, 23-25]. However, information about the decomposition of realistic crop residues mixtures in NT systems (i.e., mixtures of residues with different decomposition degree) or its contribution to crops nutrition and soil fertility is very scarce [2, 26, 27].

The aims of our study were to analyze: a) the decomposition dynamics of crop residue mixtures (based on residue weight), b) the annual changes of residue C compounds, and c) the effect of residue characteristics on SOM content, under realistic field conditions in two typical crop sequences in the central region of Argentina (soybean monoculture and soybean/maize rotation) after long-term NT management. To our knowledge, this would be the first study that evaluates dynamics of decomposition and C mineralization of crop residues mixtures under realistic conditions of long-term NT systems, and despite some methodological limitations, it provides a very valuable information in a still very poorly evaluated area.

MATERIALS AND METHODOLOGY

The study was conducted in Manfredi INTA Experimental Station, located in a semiarid zone of Córdoba, Argentina (31°49' S and 63°46' W), which is characterized by flat to gently undulating relief. The original vegetation corresponds to marginal Chaco Woodland with predominance of xerophytic species of low size and dense shrub stratum and summer grasses. During the sampling period, total annual precipitation in Manfredi was 779.0 mm, concentrated from October to April. This value was higher than the historical average for the area (759.5 mm). Mean annual temperature was 16.9 ºC. Soils are Typical Entic Haplustolls, slightly acid, and with low organic matter content (<2%).

Experimental Design

The experimental units were plots of 35m x 110m, with a completely randomized design with two replications. Two agricultural practices were studied: i) soybean monoculture, and ii) soybean/maize annual rotation, both under NT management since 1992 and weed chemical control in the fallow period (winter bare fallow). The treatments evaluated in this work were: a) soybean monoculture (SbM), b) soybean rotation (maize as preceding crop) (SbR), and c) maize rotation (soybean as preceding crop) (MzR).

Soybean and maize were sowed in November and harvested (maize manually harvested) in April. Soybean treatments (SbM and SbR) were fertilized with 70 kg ha^{-1} of diammonium phosphate (DAP) at sowing. Maize treatment (MzR) was fertilized with 90 kg ha^{-1} of DAP at sowing and 200 kg ha^{-1} of urea-ammonium nitrate (UAN) at 4-5 leaves stage.

Sampling Design

Ten samples of soil (0-20 cm) and 5 samples of surface crop residue (by a square of 40 cm side) were randomly collected in each plot every month during one year (August 2005-July 2006). Samples were pooled to have an unique sample for month and plot. November and April samples were collected after sowing and harvesting, respectively.

Laboratory Analysis

Crop residue samples were weighted to determine residues mixture biomass, and fractionated to determine: a) soybean residue biomass; b) maize residue biomass, and c) non identifiable residue (NIR) biomass. For chemical analysis, residues mixture samples were oven-dried at 60ºC (until constant weight), weighed and milled, to determine: a) moisture by gravimetric method; b) total C by wet digestion method [28], modified for plant material [29], c) soluble C after extraction with water at 80ºC [30], d) insoluble fiber by the gravimetric-enzymatic method [31], and e) total N by Kjeldahl.

Soil samples were air-dried and passed through a 2 mm pore sieve. Total organic carbon (SOC) content in sieved soil samples was determined by the Walkley-Black wet digestion method [28].

Calculations and Statistical Analysis

Age and proportion of the residues components in all treatments were carefully detailed (Fig. **1**) for an accurate comprehension of the residues decomposition process under realistic and un-manipulated conditions.

Two annual periods were separated by the ocurrence of the deposition of fresh residues from the crops. On the basis of residues weight, decomposition rates (k) were calculated: k_B for the period before deposition of fresh residue (BFR period) and k_A for the period after deposition of fresh residue (AFR period). The decomposition rates were calculated for residues mixtures, and soybean and maize components. The continuous and simultaneous inputs and outputs that characterize the dynamics of the NIR biomass did not allow us to calculate its decomposition rate with the methodology used in this study [27]. The decomposition rates were calculated using the negative exponential model of Olson [32]: $x_t/x_0 = e^{-kt}$, where x_0 is the initial (time t_0) residue dry weight and x_t is the residue dry weight at time t.

Data of chemical analysis in residues mixture samples were transformed to net values (kg ha^{-1}) by multiplying measured concentrations with total biomass of residues mixture. Data of SOC concentration were transformated to net values (Mg ha^{-1}) (bulk density = 1.23 Mg m^{-3}).

Differences between sampling dates and treatments were analyzed using ANOVA and Tuckey test for mean comparison ($p \leq 0.05$). The statistical program InfoStat [33] was used for the statistical analysis.

RESULTS

Biomasses and Decomposition Rates of Residues Mixture and its Components

The proportion (%) of different components in residues mixtures was highly variable and depended on treatment and

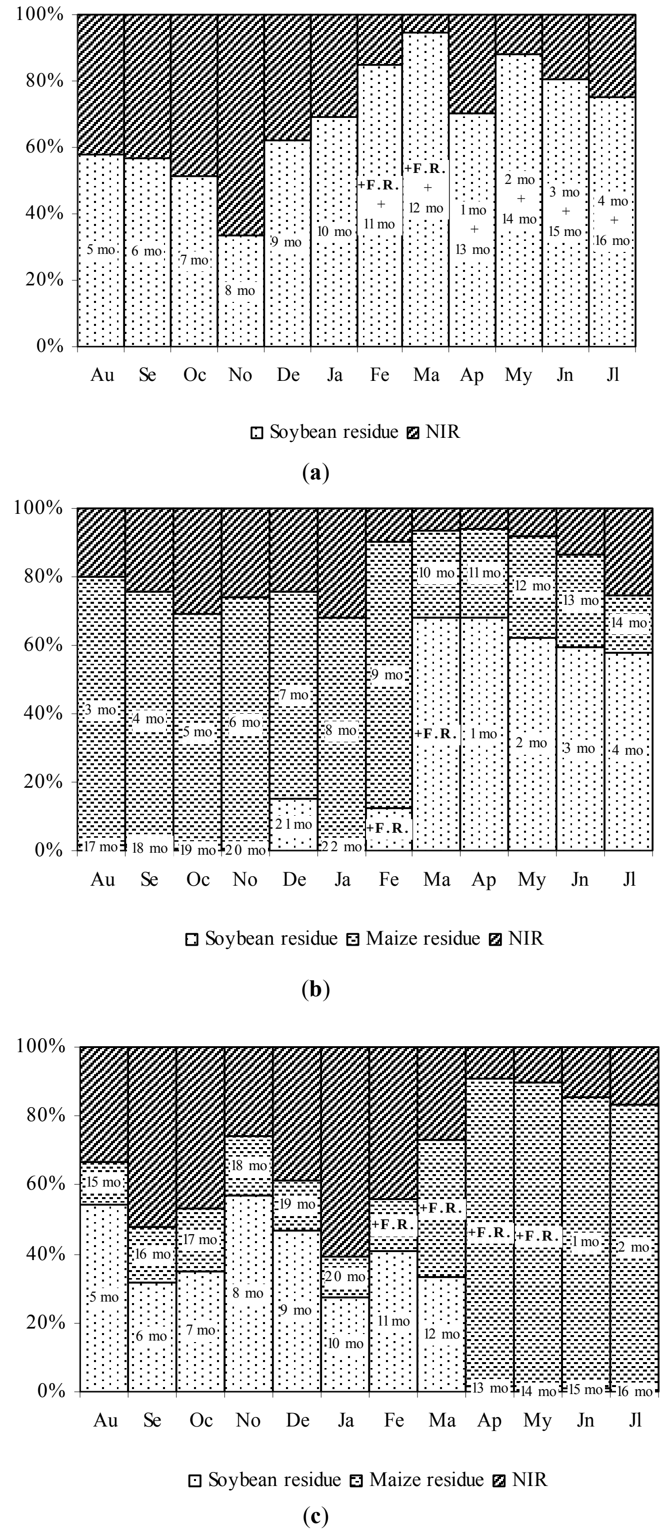
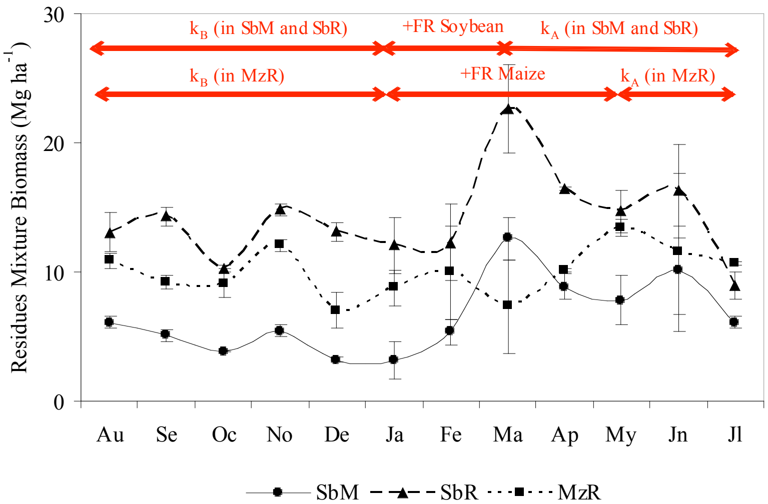
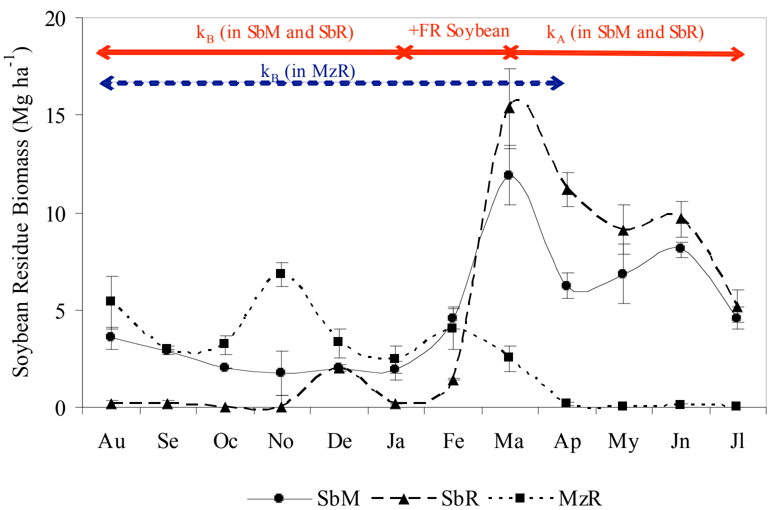


Fig. (1). Age (mo) and proportion in the residues mixture (%) of the residues components corresponding to the different treatments: **a**) soybean monoculture, **b**) soybean rotation (maize as preceding crop) and **c**) maize rotation (soybean as preceding crop). NIR: non identifiable residue. X mo: Age of the residue (time since its deposition on soil) in months (mo). + F.R.: Deposition of fresh residue. Au to Jl: August to July.

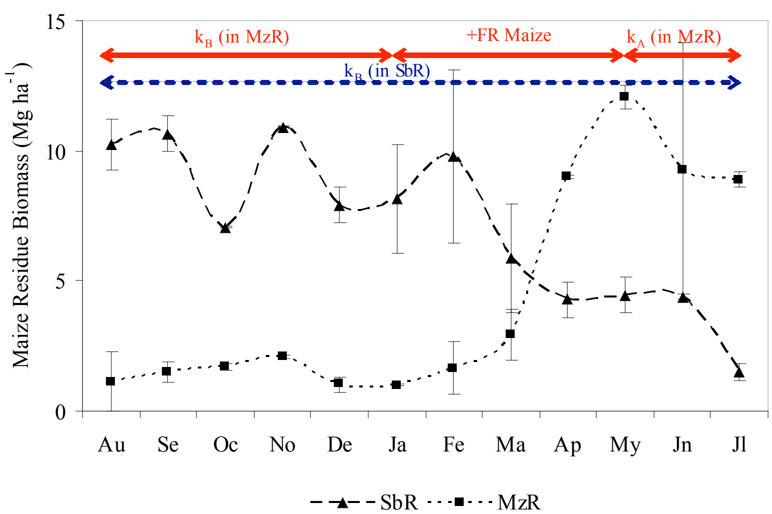
on sampling date (Fig. **1**). Residues mixture biomass and its components (soybean, maize and NIR) differed significantly among sampling dates in all treatments (Fig. **2**). In SbM, the highest biomasses of residues mixture and soybean residue were detected in March, but did not differ of April and June. Similarly, in SbR the greatest biomass of the residues mixture and soybean residue were observed in March, but in the case of the residues mixture only differed of July and October, whereas soybean residue differed of the rest of the sampling dates. In MzR, biomass of the residues mixture showed the highest value in May and maize residue biomass in April-July was higher than in August-March (Fig. **2**).


30
20
10
0
Residues Mixture Biomass (Mg ha^{-1})
k_B (in SbM and SbR)
+FR Soybean
k_A (in SbM and SbR)
k_B (in MzR)
+FR Maize
k_A (in MzR)
Au Se Oc No De Ja Fe Ma Ap My Jn Jl
SbM
SbR
MzR

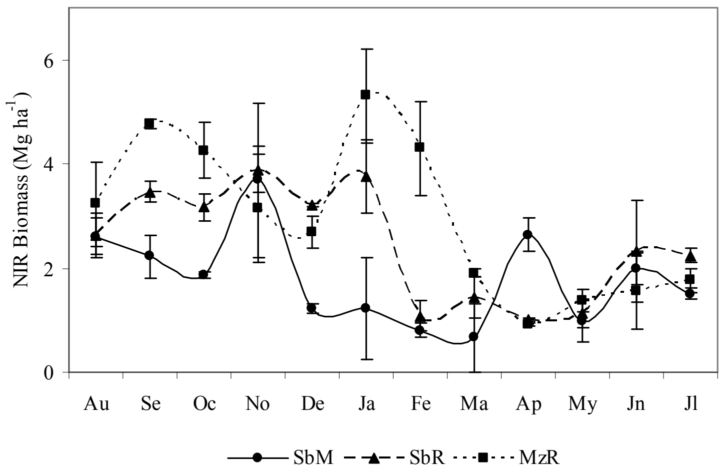
(a)


20
15
10
5
0
Soybean Residue Biomass (Mg ha^{-1})
k_B (in SbM and SbR)
+FR Soybean
k_A (in SbM and SbR)
k_B (in MzR)
Au Se Oc No De Ja Fe Ma Ap My Jn Jl
SbM
SbR
MzR

(b)


15
10
5
0
Maize Residue Biomass (Mg ha^{-1})
k_B (in MzR)
+FR Maize
k_A (in MzR)
k_B (in SbR)
Au Se Oc No De Ja Fe Ma Ap My Jn Jl
SbR
MzR

(c)



(d)

Fig. (2). Annual dynamics of the residues mixture and its components (soybean residue, maize residue and NIR residue) biomasses corresponding to the different treatments. SbM: soybean monoculture, SbR: soybean rotation (maize as preceding crop), MzR: maize rotation (soybean as preceding crop). **a**) Residues mixture biomass, b) soybean residue biomass, **c**) maize residue biomass, and **d**) NIR residues biomass. Error bars correspond to SD (p≤0.05). NIR: non identifiable residue. Au to Jl: August to July. Horizontal arrows indicate decomposition periods: references in Table **1**.

Table 1. Decomposition Rates (k) for Residues Mixture, Soybean Residue and Maize Residue, and Their Characteristics in Two DECOMPOSITION Periods (BFR and AFR) and in All Treatments. NIR: Non Identifiable Residue. X mo: Age of the Residue (Time Since its Deposition on Soil) in Months (mo). Au to Jl: August to July

	BFR Period		**AFR Period**	
	k_B (month^{-1})	Residue Characteristics	k_A (month^{-1})	Residue Characteristics
Residues Mixture				
SbM	0.136	Sb (5-10 mo) + NIR	0.181 a	Sb (1-4 mo) + NIR
SbR	0.016	Mz (4-9 mo) + Sb (17-22 mo) + NIR	0.233 a	Sb (1-4 mo) + Mz (12-15 mo) + NIR
MzR	0.044	Mz (15-20 mo) + Sb (5-10 mo) + NIR	0.100 b	Mz (1-2 mo) + NIR
Soybean Residue				
SbM	0.126 b	Sb (5-10 mo)	0.239 b	Sb (1-4 mo)
SbR	0.034 b	Sb (17-22 mo)	0.271 a	Sb (1-4 mo)
MzR	0.364 a	Sb (5-13 mo)		
Maize Residue				
SbM	-	-	-	-
SbR	0.174 a	Mz (3-14 mo)		
MzR	0.026 b	Mz (15-20 mo)	0.153	Mz (1-2 mo)

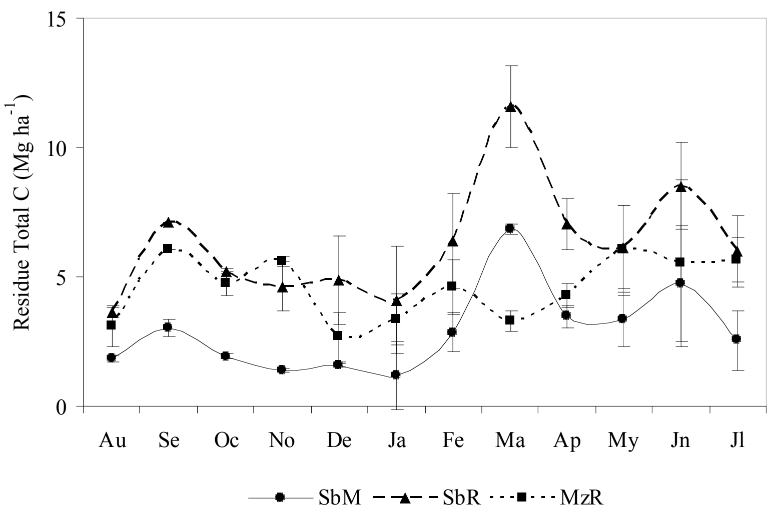
SbM = Soybean monoculture, SbR = Soybean rotation (with maize as preceding crop), MzR = Maize rotation (with soybean as preceding crop).
Sb= Soybean residue, Mz = Maize residue, NIR = Non identifiable residue.
BFR: Decomposition period before the deposition of fresh residue (soybean or maize residue).
AFR: Decomposition period after the deposition of fresh residue (soybean or maize residue)
k_A: Decomposition rate corresponding to the BFR period.
k_B: Decomposition rate corresponding to the AFR period.
Letters within column indicate significant differences among treatments (Tuckey test p≤0.05).

Decomposition rates of the residues analyzed (residues mixture, soybean residue component and maize residue component) showed a great variability between treatments (Table **1**). In BFR period, soybean residue decomposed significantly faster (higher decomposition rate) in MzR than in SbM and SbR, maize residue decomposed faster in SbR than in MzR, and residues mixture did not differ significantly among treatments (Table **1**). In the AFR period, decomposition

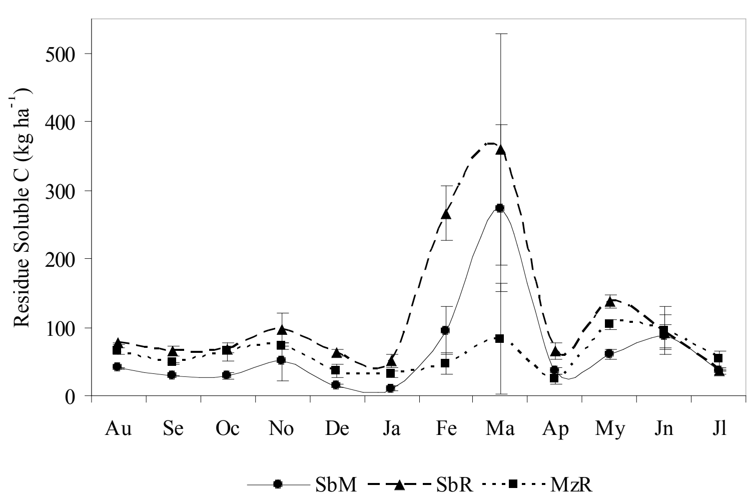
Table 2. Concentration of Quality Parameters (g kg^{-1}) of Residues Mixture Corresponding to the Different Treatments

		Au	Se	Oc	No	De	Ja	Fe	Ma	Ap	My	Jn	Jl
Total C (g kg^{-1})	SbM	301.8	590.1 b	501.5	252.3 b	497.1	376.5	533.5	545.1 a	398.3	421.5	468.0	404.1
	SbR	280.2	497.1 c	510.2	311.1 b	366.3	319.8	513.1	513.1 a	428.8	411.3	526.2	661.4
	MzR	280.3	659.9 a	521.8	463.4 a	377.9	396.8	473.9	452.0 b	423.0	450.6	460.8	530.6
Soluble C (g kg^{-1})	SbM	6.5	5.7 a	7.4	8.9	4.6	3.7	17.3 a	21.7 a	4.2 a	8.0 ab	8.5 ab	6.1
	SbR	6.0	4.5 b	6.6	6.5	4.8	4.3	22.2 a	15.1 ab	4.0 a	9.5 a	5.6 b	4.1
	MzR	6.1	5.2 ab	7.0	6.0	5.1	3.6	4.7 b	11.8 b	2.4 b	7.7 b	9.3 a	5.0
Insoluble fiber (g kg^{-1})	SbM	322.8 b	407.6	572.5	291.3 c	488.2	479.1	603.2	728.0 a	782.4	765.4	713.6	722.7 b
	SbR	646.7 a	443.3	625.9	483.9 b	526.9	409.4	560.2	561.9 ab	829.4	724.0	720.0	760.2 ab
	MzR	363.5 b	545.5	359.7	693.4 a	435.4	305.6	465.1	495.3 b	743.1	794.2	698.0	825.2 a
Total N (g kg^{-1})	SbM	6.2 b	8.7	9.5	7.5	4.8	7.1	5.3	5.7 a	5.7	6.8 b	8.6	7.5 a
	SbR	7.1 b	6.6	8.4	8.4	5.3	4.2	3.8	4.1 b	7.8	13.6 a	9.3	6.0 a
	MzR	10.1 a	8.0	9.9	7.1	4.4	6.5	6.9	4.2 b	4.4	5.0 c	6.0	3.6 b
C/N ratio	SbM	49	71	58	34 b	104	59	102 ab	96 b	69	64 b	55	59 b
	SbR	44	75	65	39 b	90	86	140 a	127 a	68	30 c	63	111 ab
	MzR	29	92	56	66 a	87	65	76 b	111 ab	105	92 a	82	150 a

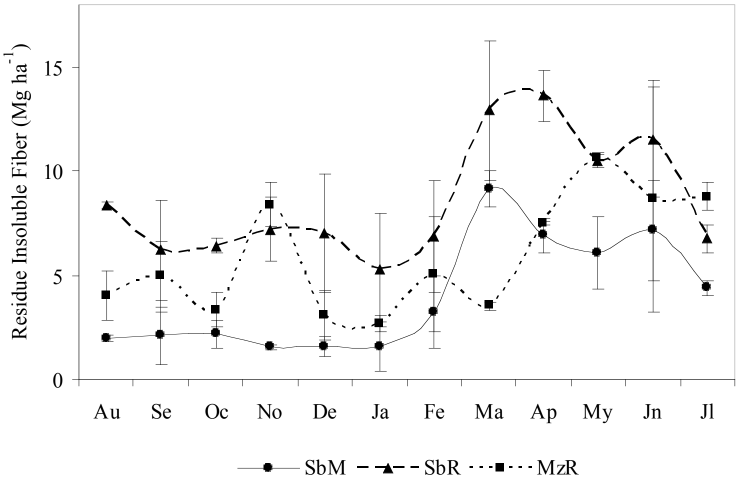
SbM: soybean monoculture, SbR: Soybean rotation (maize as preceding crop), MzR: Maize rotation (soybean as preceding crop).
The letters indicate significant differences among treatments (Tukey test, p≤0.05). Au to Jl: August to July.



(**a**)



(**b**)



(c)

Fig. (3). **A**nnual dynamics of residues mixture C compounds net values corresponding to the different treatments. SbM: soybean monoculture, SbR: soybean rotation (maize as preceding crop), MzR: maize rotation (soybean as preceding crop). **a**) Residue total C, **b**) Residue soluble C, and **c**) Residue insoluble fiber. Error bars correspond to SD (p≤0.05). Au to Jl: August to July.

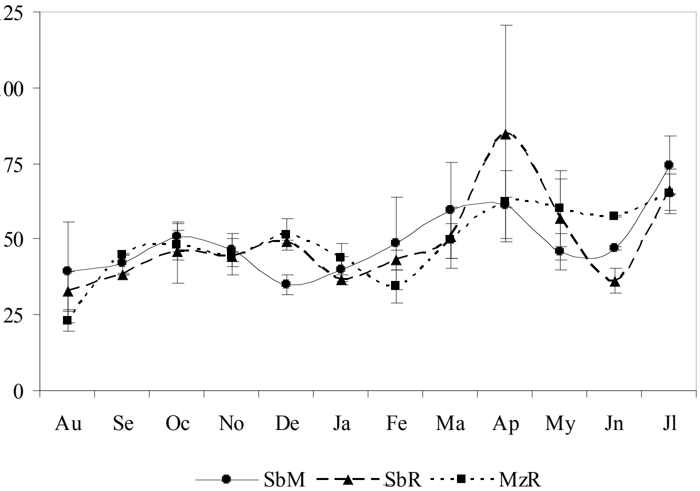


Fig. (4). Annual dynamics of SOC corresponding to the different treatements analyzed. SbM: soybean monoculture, SbR: soybean rotation (maize as preceding crop), MzR: maize rotation (soybean as preceding crop). Error bars correspond to SD (p≤0.05). Au to Jl: August to July.

rate of soybean residue in SbR was significantly higher than in SbM, whereas residues mixture showed higher decomposition rates in SbM and SbR than in MzR (Table **1**).

Residues Mixture C Compounds

The total C, soluble C and insoluble fiber concentrations (g kg^{-1}) of the residues mixtures showed a great similarity among treatments during the evaluation year (Table **2**). Total C concentration differed significantly between treatments only in September and November (highest value in MzR), and in March (highest values in SbM and SbR). Soluble C concentration showed significant differences among treatments in the half of the sampling dates, with the highest values in SbM and SbR during February-May period. Insoluble fiber concentration only differed between treatments in August, November, March and July.

The annual dynamics of the amount of the residues mixture C compounds showed significant variations among sampling dates in all treatments analyzed (Fig. **3**). Thus, in SbM the net amount of total C (Fig. **3a**), soluble C (Fig. **3b**) and insoluble fiber (Fig. **3c**) of the residues mixture showed their highest values in March, although total C and insoluble fiber values did not differ from April, May and June. Similarly, total C (Fig. **3a**) and soluble C (Fig. **3b**) amount in SbR were higher in March, and insoluble fiber (Fig. **3c**) values were higher in August and in March-June period. In MzR, total C amount (Fig. **3a**) differed only between September and May (highest values) and December (lowest value), whereas soluble C amount (Fig. **3b**) showed the greatest value in May and the lowest in April. The greatest amount of insoluble fiber (Fig. **3c**) in MzR residues mixture was observed in April-June period and in November.

Soil Organic Carbon

The amount of total SOC only differed among treatments in September, December and June, with the highest values in MzR (but similar to SbM in September and similar to SbR in December) (Fig. **4**).

Besides, all the treatments evaluated showed variations among sampling dates in the evaluation year, although such variations were not always significant. (Fig. **4**).

DISCUSSION

Biomass Dynamics and Decomposition Patterns

Biomasses of the residues mixture and its components (soybean, maize and NIR) showed an annual dynamic highly influenced by: i) the deposition of fresh residue from the crop cultivated on each plot; ii) the preceding crop in the crop sequence, and iii) the persitence of each residue on the soil surface.

The major increases in the biomass of residues mixture in soybean treatments (SbM and SbR) observed in the pre-harvest sampling (March) reflect the great addition of soybean fresh residue when soybean crop senesces and defoliation occurs. However, the effect of this contribution is only significant in the monoculture, since the presence of large amounts of old maize residue from previous crops in SbR dilutes its relative effect on the residues mixture biomass. In MzR, the manual harvest leaded to a more gradual deposition of maize fresh residue (mainly during April and May) instead of the great contribution that would be expected immediatly after a mechanical harvest, and this is reflected in the great similarity in the annual dynamics of the mixture biomass.

Before the sowing of maize and soybean crops (i.e., October sampling), an amount of 1.69 Mg ha^{-1} of maize residue from two-years ago maize crop persisted in the residues mixture of the MzR treatment, whereas soybean residue from two-years ago soybean crop was barely found in the residues mixture of the SbR. In this regard, it is widely accepted that legume residues decompose faster than grasses residues [6, 34-36]. Nevertheless, the large particle size of maize residue and the high amount of residue biomass from the maize crop would have also impact significantly on the ability of this residue for remaining in soil surface over time [36, 37].

The C/N ratio is usually considered a key factor controlling decomposition and nutrient release and a good predictor of litter decomposition rates in many ecosystems [5, 6]. The greater lability of soybean fresh residue compared with maize residue explains the greater decomposition rates found in residues mixture of soybean treatments (SbM and SbR) during the AFR period, and in agreement with the lower average C/N ratio in soybean treatments compared with maize treatment (SbM = 69 and SbR = 80 *vs.* MzR = 108). Similarly, before the deposition of fresh residue (BFR period), the decomposition rates of residues mixture were similar between treatments, with average C/N ratio highly similar (SbM = 63, SbR = 67, MzR = 66). Our results agree with several studies which stated that plant residues with higher C/N ratios show lower decomposition rates [5, 13, 35].

It is noteworthy that the decomposition rates of soybean residue varied depending on the residues mixed with it. In this regard, although the contributions of fresh residue from soybean crop in SbM and SbR are assumed similar in quantity and quality, and therefore similar decomposition rates would be expected, soybean residue decomposed faster in the rotation treatment than in the monoculture treatment. Thus, the decomposition rate of soybean residue in the first 4 months of decomposition was significantly higher when it was mixtured with remaining maize residue from previous crops than when it was deposited on remaining soybean residue (SbR=0.271 *vs.* SbM=0.239). Moreover, the same pattern was observed from the fifth month of decomposition, by comparing k_B values of soybean residue in MzR and SbM respectively (MzR=0.364 *vs.* SbM=0.126). These results strongly suggest that in NT systems, the presence of remaining residues from previous crops in the soil surface determines, in some way, the rates of decomposition of the different residue fractions that constitute the residues mixture, and agree with those reported by different authors about the existence of interactions that affect the decomposition process when residues with different quality are mixed [8, 18, 20, 38]. Furthermore, and as suggested by Mao and Zeng [22], it is possible that the greater number of plant residues in the rotation treatments would lead to a more efficient nutrient transfer, as well as a greater habitat complexity [8], and this consideration would maintain a greater diversity of the decomposer community, enhancing the decomposition rate by a more efficient use of substrates [39].

In this work, decomposition rates of soybean and maize residues under rotation showed a dynamic pattern different to the expected pattern. It is widely accepted that the decomposition process can be divided in a first rapid phase, controlled by the decomposition of labile fractions, and a second slow phase when decomposition of recalcitrant compounds prevails [40]. Some authors observed that the highest biomass loss in decomposing crop residues occurred at the early months of decomposition and then slows down as time progresses [23, 24]. Contrarily, in our study, soybean residue in rotation with maize decomposed more slowly during the first 4 months of the decomposition process (SbR, k= 0.271) than during the following 9 months of decomposition (MzR, k= 0.345). It is likely that autumm climatic conditions (low temperature and drought) negatively affected microbial activity, whereas the subsequent months coincided with the warm and wet season and this would have promoted the decomposition of crop residues [7]. Similarly, maize residue decomposed more slowly during the first 3 months of decomposition (MzR, k= 0.153) than after 4-15 months of decomposition (SbR, k= 0.174), newly related to environmental conditions. Our results agree with others who stated the impact of a seasonal effect in the decomposition of plant residues, particularly in arid and semiarid zones [15, 7, 5]. Furthermore, Seastadt [41] and Scherer-Lorenzen [38] suggested that nutrient release from rapidly decaying residues may result in a fertilizer effect through nutrient transfer and that would enhance the decomposition of adjacent and more recalcitrant residues. In this connection, the deposition of the labile, soybean fresh residue in the residues mixture of the SbR treatment would have stimulated the decay of the more recalcitrant, old weathered maize residue [8]. Our results agree with Sakala *et al.* [42] who state that decomposition of residues mixtures can not be accurately measured on the basis of the decomposition dynamics of individual species.

The lowest k values corresponding to soybean residues after 17-22 months of decomposition (SbR=0.034) and maize residue after 16-21 months of decomposition (MzR= 0.026) reflect the high recalcitrance of the residues in their last stages of decomposition.

In general, the k values calculated in our work are lower than those obtained by Mao and Zeng [22] for decomposing soybean and maize residues, and more similar to Santanatoglia *et al.* [26] for soybean residues in a rotation with wheat. In this relation, it must be borne in mind that the vast majority of studies in plant residues decomposition evaluate this process through laboratory incubations or mesh bag procedures. These methodologies facilitate the calculations of decomposition rates, since biomass and chemical composition of vegetal residue is known, and enable a greater control of the decomposition process as time goes by. However, generally these procedures use highly manipulated residues (e.g., residues are often chopped, milled, dried, moistened,...) and in highly controlled conditions, for example, decompositon of residues of one specie isolated, residues on phenologial stages previous to harvest maturity or natural senesce, residues mixtures with random residue proportions, mixtures of residues with identical time in decomposition_what would mean that their are deposited exactly at the same time in soil surface_ , controlled conditions of temperature, humidity, availability of nutrients, microbial and fauna activity, etc., that too often are excessively different to the realistic conditions in the agroecosystem. By contrast, despite the lower accuracy of the metholody used here, our work analyzes residues decomposition in realistic conditions of long-term NT systems, i.e., mixtures of different species and/or different decomposition degree which interact one to each other, without any manipulation of the residues and/or environmental conditions that determine the microbial activity. Thus, the comparison among k values obtained by laboratory incubations, mesh bag procedures, etc, and our results would be not adequate.

C Compounds of Residues Mixtures

Here we analyze the concentration of the different C compounds (total C, soluble C, and insoluble fiber) measured in the residues mixture of each treatment analyzed. In this regard, the great similarity among treatments in the concentration of their residues mixture C compounds would be due to: i) the mixture of residues from different species; ii) the initial chemical composition of each residue, and iii) the C-mineralization dynamics in plant residues.

Mixtures of residues from different species have chemical characteristics intermediate to those of their component species alone [23, 25, 38], and this has been specifically observed in grass-legume mixtures [43, 44]. In addition, Andriulo and Cordone [45] and Ernst *et al.* [34] found insoluble fiber concentrations very similar between soybean and maize residues. Both considerations would have greatly contributed to the similarity between treatments in the C composition of their residues mixtures.

Moreover, it is known that the greatest variation in plant residues C concentration occurs in the early stages of decomposition, related to the labile C mineralization, whereas recalcitrant C declines very slowly as decomposition progresses [14, 24]. This could explain both, the higher concentration of soluble C in residues mixtures of soybean treatments in February-May, in coincidence with the deposition of soybean fresh residues (with high contents of soluble compounds), and the huge similarity among treatments in the concentration of all C-compounds during the rest of the year, in coincidence with the more advanced stages of decomposition.

C Compound Dynamics of Residues Mixtures

Total C Dynamics

Annual dynamics of the amount of residues mixture total C is clearly conditioned by the annual dynamics of the mixture total biomass. Besides, we found that when soybean is cultivated in rotation with maize, annual average of total C amount of the surface residues is more than twice the amount in soybean monoculture (6.27 Mg ha^{-1} *vs.* 2.89 Mg ha^{-1}). This would be somehow indicating that agricultural practices that return higher amounts of crop residues to the soil surface (e.g., crops rotation with maize) would promote C sequestration and improve SOM in agricultural soils [46, 47].

Soluble C Dynamics

Our work indicates that annual dynamics of soluble C amount in residues mixtures depends on: i) chemical composition of fresh residues; ii) time since their deposition on soil surface, and iii) climatic conditions.

The deposition of a great amount of pre-harvest soybean fresh residue in January-March leads to a notorious increase in the amount of soluble C in SbM and SbR. Subsequently, microbial activity in the more labile C fractions [48, 49] and losses by leaching [23, 48] due to the important rainfall in April (121mm) would be resposible for the enormous decline (80-90%) of soluble C amount detected in March-April.

In MzR, the stepwise deposition of maize fresh residue, in coincidence with the dry season, and its lower amount of soluble compounds [16, 45] would justify the greater stability detected in the soluble C dynamics.

Insoluble Fibers Dynamics

As observed in the total C amount dynamics, the annual dynamic of the amount of insoluble fiber in residues mixtures is conditioned by the annual dynamic of the mixture biomass, with the highest values in the months of preharvest and postharvest deposition of fresh residues. In coincidence with total C amount, annual average of insoluble fiber amount of the residues mixture when soybean is cultivated in rotation with maize is newly more than twice the amount detected in soybean monoculture (8.57 Mg ha^{-1} *vs.* 3.99 Mg ha^{-1}). Our results indicate the possibility that the inclusion of maize in the crop sequence would lead to a greater accumulation of lignin in soil surface that would promote the formation of SOM in agricultural soils.

It is noteworthy that the significant decay of insoluble fibers in SbM and SbR during March-May period would be in connection with the previously mentioned “fertilizer effect” resulting from mixing residues with different chemical characteristics. Thus, it seems that the great amount of soybean fresh residue deposited in March, with high concentration of soluble compounds and low C/N ratio, together with warm and wet climatic conditions, would have enhanced microbial abundance and activity, and promoted the decomposition of the more recalcitrant residues from preceding crops [8, 38, 41].

Soil Organic Carbon Content

Contrarily to what expected on the basis of our residues analysis, SOC showed a great similarity between treatments. These results are in coincidence with Gal *et al.* [42], who found no differences in SOM between maize monoculture and soybean-maize rotation after 28 years, and others who suggest that residue quantity and rotation sequence would be not a key factor for C retention in agricultural soils [50, 51].

Several studies state that total SOC is not a good indicator for the effects of management practices in the short time compared with the more labile fractions of SOC [50-52]. As observed by Álvarez *et al.* [47] and Sainju *et al.* [53], it is possible that in our work do indeed exist greater differences corresponding to the labile SOC content that are not detected through the total SOC analysis. Despite this, it can be observed a slight tendence to increase SOC after periods of soluble C mineralization from residues, and this could be suggesting increases in the more labile fraction of SOC.

Besides, as suggested by Jia *et al.* [54], it is possible that in our study, nitrogen fertilization applied in maize crop would have leaded to a decrease of soil C/N ratio, with a subsequent SOC decomposition due to a growth of microbial population that would obtain energy from SOC and as a consequence, would reduce the humification process [55]. If we consider that our results indicate that residues mixture from rotation treatments would be provinding to the soil a 45% more C than the soybean monoculture, but this difference is not detected in SOC amount, we might assume that increasing nitrogen fertilization in maize crop would have a significant negative effect on SOC accumulation that should be considered and evaluated in future studies.

CONCLUSION

Based on our results, we concluded that decomposition and C dynamics of crop residues mixtures in long-term NT systems in the semiarid central Argentina are strongly influenced by: i) the interaction of the chemical quality of the residues, particularly soluble C and insoluble fiber, ii) the proportion of the residues from different crops and/or with different decomposition degree, and iii) the seasonal effect.

The inclusion of maize in the crop sequence leads to greater amounts of total C and insoluble fiber in residues mixtures that were not reflected in the rotation SOC values, probably related to the low suitability of SOC as indicator of variations in the short time. However, an evaluation of the effects of increasing nitrogen fertilization on SOC mineralization in recommended for future research.

CONFLICT OF INTEREST

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

ACKNOWLEDGEMENT

Declared none.

REFERENCES

[1] Andriulo A, Sasal C, Rivero M. In: Panigatti J, Buschiazzo D, Marelli H, Eds. Los sistemas de producción conservacionistas como mitigadores de la pérdida de carbono edáfico. Siembra Directa II, INTA, Buenos Aires, 2001; pp. 17-28.

[2] Abril A, Salas P, Lovera E, *et al*. Efecto acumulativo de la siembra directa sobre algunas características del suelo en la región semiárida central de la Argentina. Ciencia del Suelo 2005; 23: 179-88.

[3] Lal R. Soil carbon sequestration to mitigate climate change. Geoderma 2004; 123: 1-11.

[4] Gholz HL, Wedin DA, Smitherman SM, *et al*. Long-term dynamics of pine and hardwood litter in contrasting environments: toward a global model of decomposition. Global Change Biol 2000; 6: 750-65.

[5] Zhang D, Hui D, Luo Y, *et al*. Rates of litter decomposition in terrestrial ecosystems: global patterns and controlling factors. J Plant Ecol 2008; 2: 85-93.

[6] Zeng DH, Mao R, Chang SX, *et al*. Carbon mineralization of tree leaf litter and crop residues from poplar-based agroforestry systems in Northeast China: A laboratory study. Appl Soil Ecol 2010; 44: 133-7.

[7] Noe L, Abril A. Interacción entre calidad de restos vegetales, descomposición y fertilidad del suelo en el desierto del Monte de Argentina. Ecología Austral 2008; 18: 181-93.

[8] Hättenschwiler S, Tiunov AV, Scheu S. Biodiversity and litter decomposition in terrestrial ecosystems. Annu Rev Ecol Evol Syst 2005; 36: 191-218.

[9] Paustian K, Andrén O, Janzen HH, Lal R, *et al.* Agricultural soils and sink to mitigate CO_2 emissions. Soil Use Manage 1997; 13: 230-44.

[10] Mungai NW, Motavalli PP. Litter quality effects on soil carbon and nitrogen dynamics in temperate alley cropping systems. Appl Soil Ecol 2006; 31: 32-42.

[11] Trinsoutrot I, Recous S, Bentz B, *et al*. Biochemical quality of crop residues and carbon and nitrogen mineralization kinetics under nonlimiting nitrogen conditions. Soil Sci Soc Am J. 2000; 64: 918-26.

[12] Nicolardot B, Recous S, Mary B. Simulation of C and N mineralisation during crop residue decomposition: a simple dynamic model based on the C:N ratio of the residues. Plant Soil 2001; 228: 83-103.

[13] Kumar K, Goh M. Crop residues and management practices: effects on soil quality, soil nitrogen dynamics, crop yield and nitrogen recovery. Adv Agron 2000; 68: 197-319.

[14] Jensen LS, Salo T, Palmason F, *et al*. Influence of biochemical quality on C and N mineralisation from a broad variety of plant materials in soil. Plant Soil 2005; 273: 307-26.

[15] Coûteaux MM, Hervè D, Beck S. Descomposición de hojarasca y raíces en un sistema de descanso largo (Altiplano de Bolivia). Ecol Boliv 2006; 41: 85-102.

[16] Henriksen TM, Breland TA. Carbon mineralization, fungal and bacterial growth and enzyme activities as affected by contact between crop residues and soil. Biol Fertil Soils 2002; 35: 41-8.

[17] Giacomini SJ, Recous S, Mary B, Aita C. Simulating the effects on N availatility straw particle size and location in soil on C and mineralization. Plant Soil 2007; 301: 289-301.

[18] Gartner TB, Cardon ZG. Decomposition dynamics in mixed-species leaf litter. Oikos 2004; 104: 230-46.

[19] Gessner MO, Swan CM, Dang CK, *et al*. Diversity meets decomposition. Trends Ecol Evol 2010; 25: 372-80.

[20] Hoorens B, Stroetenga M, Aerts R. Litter mixture interactions at the levels of plant functional types are additive. Ecosystems 2010; 13: 90-8.

[21] Bonanomi G, Incerti G, Antignani V, *et al*. Decomposition and nutrient dynamics in mixed litter of Mediterranean species. Plant Soil 2010; 331: 481-96.

[22] Mao R, Zeng DH. Non-additive effects vary with the number of component residues and their mixing proportions during residue mixture decompositión: a microcosm study. Geoderma 2012; 170: 112-7.

[23] Aita C, Giacomini SJ. Crop residue decomposition and nitrogen release in single and mixed cover crops. R Bras Ci Solo 2003; 27: 601-12.

[24] Bertol I, Leite D, Zoldan WA. Corn crop residue decomposition and related parameters. R Bras Ci Solo 2004; 28: 369-75.

[25] Oyun MB, Akharayi FC, Adetuyi FC. Microbial population in decomposing legume litter of differing quality. Am J Agric Biol 2006; 1: 22-6.

[26] Santanatoglia OJ, Álvarez R, Barbero N, Russo M. Descomposición de la cobertura de rastrojo y evolución de su contenido de nitrógeno en el doble cultivo trigo-soja bajo siembra directa. Ciencia del Suelo 1994; 12: 63-7.

[27] Casado-Murillo N, Abril A. In: Degenovine K, Ed. Crop residue contribution to N fertilization under long term no-till systems in the

central semi-arid region of Argentina. Semi-arid Environments: Agriculture, Water Supply and Vegetation. New York: Nova Science Publishers 2011; pp. 63-82.

[28] Nelson DW, Sommers LE. In: Sparks DL, Pages AL, Helmke PA, Loeppert RH, Soltanpour PN, Tabatabai MA, Johnston CT, Sumner ME, Eds. Total carbon, organic carbon, and organic matter. Methods of Soil Analysis. Madison: Soil Science Society of America 1996: pp. 961-1010.

[29] Torres PA, Abril AB, Bucher EH. Microbial succession in litter decomposition in the semi-arid Chaco woodland. Soil Biol Biochem 2005; 37: 49-54.

[30] Robertson PG, Coleman DC, Bledsoe CS, *et al*. Standard Soil Methods for Long -Term Ecological Research. New York: Oxford University press 1999; p. 462.

[31] Asp N, Claes G, Johansson G, *et al*. Rapid enzymatic assay of insoluble and soluble dietary fiber. J Agric Food Chem 1983; 31: 476-82.

[32] Olson J. Energy storage and the balace of producers and decomposers in ecologycal systems. Ecology 1963; 44: 322-31.

[33] InfoStat. Grupo InfoStat. Universidad Nacional de Córdoba, Facultad de Ciencias Agropecuarias, Córdoba, Argentina 2006.

[34] Ernst O, Betancur O, Borges R. Decomposition of crop residues under no-till management: wheat, corn, soybeans and wheat after corn or soybeans. Agrociencia (Uruguay) 2002; 6: 20-6.

[35] Oliver L, Pérez-Corona ME, Bermúdez de CF. Degradación de la hojarasca en un pastizal oligotrófico mediterráneo del centro de la Península Ibérica. Anales de Biología 2002; 24: 21-32.

[36] Hättenschwiler S, Vitousek PM. The role of polyphenols in terrestrial ecosystem nutrient cycling. Trends Ecol Evol 2000; 15: 238-43.

[37] Romero LM, Smith III TJ, Fourqurean JW. Changes in mass and nutrient content of wood during decomposition in a south Florida mangove forest. J Ecol 2005; 93: 618-31.

[38] Scherer-Lorenzen M. Functional diversity affects decomposition processes in experimental grasslands. Funct Ecol 2008; 22: 547-55.

[39] Swan CM, Gluth MA, Horne CL. Leaf litter species evenness influences nonadditive breakdown in a headwater stream. Ecology 2009; 90: 1650-8.

[40] Vaieretti MV, Pérez HN, Gurvich DE, *et al*. Decomposition dynamics and physico-chemical leaf quality of abundant species in a montane woodland in central Argentina. Plant Soil 2005; 278: 205-21.

[41] Seastadt TR. The role of microarthropods in decomposition and mineralisation processes. Annu Rev Entomol 1984; 25-46.

[42] Sakala WD, Cadisch G, Giller KE. Interactions between residues of maize and pigeonpea and mineral N fertilizers during decomposition and N mineralization. Soil Biol Biochem 2000; 32: 679-88.

[43] Ranells NN, Wagger MG. Nitrogen release grass and legume cover crop monocultures and bicultures. Agron J 1996; 88: 777-82.

[44] Heinrichs R, Aita C, Amado TJC, Fancelli AL. Cultivo consorciado de aveia e ervilhaca: relação C/N da fitomassa e productividade do milho em sucessão. R Bras Ci Solo 2001; 25: 331-40.

[45] Andriulo A, Cordone G. In: Panigatti JL, Marelli H, Gil R, Eds. Impacto de las labranzas y rotaciones sobre la materia orgánica de suelos en la región pampeana húmeda. Siembra Directa, Buenos Aires, Hemisferio Sur 1998; pp. 65-96.

[46] Forján HJ. Balance de nutrientes en sistemas agrícolas. AgroBarrow 2003; 28: 17-9.

[47] Álvarez C, Scianca C, Barraco M, *et al*. Aporte de diferentes volúmenes de rastrojo en rotaciones agrícolas: impacto sobre las propiedades edáficas. Memoria Técnica 2005-2006. EEA INTA General Villegas, pp: 18-20.

[48] Cleveland CC, Reed SC, Townsend AR. Nutrient regulation of organic matter decomposition in a tropical rain forest. Ecology 2006; 87: 492-503.

[49] Gál A, Vyn TJ, Michéli E, *et al*. Soil carbon and nitrogen accumulation with long-term no-till versus moldboard plowing overestimated with tilled-zone sampling depths. Soil Till Res 2007; 96: 42-51.

[50] Roldán AA, Salinas GJR, Alguacil MM, *et al*. Soil sustainability indicators following conservation tillage practices under subtropical maize and bean crops. Soil Till Res 2007; 93: 273-82.

[51] Soon YK, Arshad MA, Haq A, *et al*. The influence of 12 years of tillage and crop rotation on total and labile organic carbon in a sandy loam soil. Soil Till Res 2007; 95: 38-46.

[52] Oorts K, Merckx R, Gréhan E, *et al*. Determinants of annual fluxes of CO2 and N2O in long-term no-tillage and conventional tillage systems in northern France. Soil Till Res 2007; 95: 133-48.

[53] Sainju UM, Whitehead WF, Singh BP, *et al*. Carbon supply and storage in tilled and non-tilled soils as influenced by cover crops and nitrogen fertilization. J Environ Qual 2006; 35: 1507-17.

[54] Jia Y, Li F, Wang XL, Xu J. Dynamics of soil organic carbon and soil fertility affected by alfalfa productivity in a semiarid agroecosystem. Biogeochemistry 2006; 80: 233-43.

[55] Doran J, Elliot E, Paustian K. Soil microbial activity, nitrogen cycling and long-term changes in organic carbon pools as related to fallow tillage. Soil Till Res 1998; 49: 3-18.

Received: August 11, 2012 Revised: November 25, 2012 Accepted: December 03, 2012