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Cover crop effects on soybean residue decomposition and P release in no-tillage systems of Argentina

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ABSTRACT

Cover crops (CC) provide many benefits to soils but their effect on decomposition of previous crop residues and release of nutrients in continuous no-tillage soybean [*Glycine max* (L.) Merr.] production are little known. Our objective was to quantify CC effects on decomposition and phosphorus (P) release from soybean residue using litterbags. Three CC species (oat, *Avena sativa* L.; rye, *Secale cereal* L.; and rye grass, *Lolium multiflorum* L.) and a no CC control were evaluated. Temperature, moisture content, microbial biomass and microbial activity were measured in the surface 2 cm of soil and residues. Cover crops increased soybean residue decomposition slightly both years (8.2 and 6.4%). Phosphorus release from soybean residue did not show any significant differences. Cover crops increased microbial biomass quantity and activity in both soil and residue samples ($p < 0.001$, $p = 0.049$ for soil and residue microbial biomass; $p = 0.060$, $p = 0.003$ for soil and residue microbial activity, respectively). Increased residue decomposition with CC was associated with higher soil and residue microbial biomass and activity, higher near-surface (0–2 cm) moisture content (due to shading) and soil organic carbon enrichment by CC. Even though CC increased soybean residue decomposition (233 kg ha^{-1}), this effect was compensated for by the annual addition of approximately 6500 kg ha^{-1} of CC biomass. This study demonstrated another role for CC when calibrating models that simulate the decomposition of residues in no-tillage systems.

1. Introduction

Crop residues contribute to improved soil quality by storing and recycling nutrients, enhancing water retention, improving soil physical conditions and increasing microbial activity (Lal, 2005; Blanco-Canqui, 2013). These benefits are magnified with no-tillage, because plant residues remain largely undisturbed at the soil surface as mulch. Sustaining a high percentage of soil cover provides additional benefits including reduced soil erosion and soil organic carbon mineralization (Lal et al., 2007; Blanco-Canqui, 2013).

Residue input can be improved by including cover crops (CC) in rotations. This is especially true for non-leguminous CC which provide longer-lasting biomass (Erenstein, 2003). In the Argentinean Pampas, CC have therefore been recommended for cropping systems like monoculture soybean that produce insufficient residue to provide adequate soil protection and cover (Novelli et al., 2011; Varela et al., 2011).

The rate of residue decomposition in soil is regulated by the physico-chemical characteristics of the decomposing material, the soil-residue contact and environmental factors including temperature, water content and nutrient availability (Parr and Papendick, 1978). Soil management practices, including tillage and crop rotation, can also affect residue decomposition. Due to higher decomposer activity in the bulk soil and closer contact between residues and the soil matrix, residue decomposition is faster for incorporated residues than those at the soil surface (e.g. Douglas et al., 1980; Curtin and Francis, 2008).

Most residue decomposition studies have been conducted on buried residues, but with no-tillage, crop rotation will determine if the residues will be lying on the soil surface between crops or will

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decompose under the influence of a subsequent crop. Published reports show that growing plants can increase (Bottner et al., 1999; Paré et al., 2000), decrease (Reid and Goss, 1982; Christensen, 1985; Janzen and Radder, 1989; Nicolardot et al., 1995; Muhammad et al., 2007) or have no effect (Haider et al., 1989) on residue decomposition rates. Enhanced residue decomposition by growing plants has been associated with greater microbial activity due to exudation of root organic compounds (Bottner et al., 1999). In contrast, decreased decomposition rates were attributed to modified environmental conditions, including lower soil temperature and moisture content (Christensen, 1985; Muhammad et al., 2007) and/or competition between plants and microorganism for available nutrients (mainly N) (Nicolardot et al., 1995; Jannoura et al., 2012). Most of these studies have been performed under controlled conditions, using soil and residue incubation or greenhouse experiments (Haider et al., 1989; Nicolardot et al., 1995; Muhammad et al., 2007; Jannoura et al., 2012). To our knowledge, there are no published field studies quantifying effects of growing plants on crop residue decomposition in no-tillage systems.

The incorporation of CC between continuous cash crops represents a situation where growing plants may affect decomposition of previous crop residue. Cover crops may modify decomposition rates through changes in the near-surface (0–5 cm) soil environment. In addition, other soil properties like pH and organic matter content may also change after growing CC for many years (e.g., Villamil et al., 2006). If cash crop residue decomposition rates were increased under CC, it may be possible to actually decrease soil cover under no-tillage. In contrast, if the rates were decreased in the presence of CC, the enhanced soil cover provided by the CC could be further increased.

Factors affecting crop residue decomposition may also affect nutrient release from them. For grain crops, most nitrogen (N) and phosphorus (P) taken up by plants are exported with the harvested product (e.g., Ciampitti et al., 2011). Potassium and the remaining plant nutrients are returned to the soil in variable proportions of directly available or less labile forms (Bhupinderpal-Singh et al., 2006; Noack et al., 2012). In the case of P, the release from crop residues may constitute an important source of the nutrient for subsequent crops (Jalali and Ranjbar, 2009; Noack et al., 2012). Considering that crop residues provide soil coverage and simultaneously constitute a source of nutrients for the following crop, there is a possible trade-off between rapid nutrient turnover and a slow decomposition rate needed to maintain surface residues. Some reports have focused on the effects of growing plants on N dynamics during residue decomposition (Nicolardot et al., 1995; Paré et al., 2000; Jannoura et al., 2012), but it is not known whether growing plants also affect P release, which globally is the second most limiting nutrient in no-tillage systems. Therefore, our objective was to evaluate CC effects on decomposition and P release from soybean residues in a no-tillage system.

2. Materials and methods

2.1. Study site and experimental design

The experiment was conducted on a Thapto-Argic Hapludoll which has a topsoil (0–20 cm) with 133, 450, and 471 g kg^{-1} of clay, silt and sand, respectively, an average annual precipitation of 906 mm, and is located at the General Villegas Experimental Station of the National Agricultural Technology Institute (INTA) (Buenos Aires, Argentina; 34° 52′ 27.47″ S, 62°45′ 31.95″ W). A randomized complete block with four replicates per treatment has been used, since 2005, to quantify the effects of different winter CC within a continuous no-tillage soybean cropping system. This study focused on soybean residue decomposition with four treatments: no CC (control, soybean monoculture), oat, rye and ryegrass. Measurements were made during 2009, 2010 and 2011. Each plot had an area of 250 m^2 (50 m × 5 m). Soybean grain yield was recorded each year and residue input was estimated using a harvest index of 0.43 (grain dry matter/aboveground biomass dry matter) (Alvarez et al., 2011). Cover crops were sown on April17th in 2009, May 4th in 2010 and May 4th in 2011 and killed with herbicide (glyphosate, N-phosphonomethyl glycine) at the end of October. Daily precipitation and mean air temperature 1.5 m above the soil surface were recorded using a data-logger (weather station, Siap, Argentine). Degree days were calculated using 0 °C as the base temperature. Soil pH and soil organic carbon content at the beginning of the decomposition experiments are shown in Table 1.

Table 1
Soil properties (0–5 cm) at the beginning of the experiments of soybean residue decomposition, after 5 consecutive years of growing soybean as the main crop without and with different winter cover crops (oat, rye and ryegrass). Different letters in each row indicate significant difference at the 5% level (n = 4). Standard error between parentheses.

Soil properties	Treatments			
	No CC	Oat	Rye	Ryegrass
Total organic carbon (%)	1.42 (0.09) c	1.61 (0.06) a	1.51 (0.11) b	1.46 (0.04) bc
pH	5.84 (0.13)	5.75 (0.10)	5.75 (0.08)	5.68 (0.10)

2.2. Initial quality of soybean residue

Standing soybean residue was collected from the field and air dried in the laboratory. The residues were separated into three components which averaged 11% leaves, 85% stems and 4% pods. Three composite soybean residue subsamples were taken each year to determine their initial chemical quality. Samples representing the average proportion of each component mentioned above were oven-dried at 60 °C for 48 h and grounded to pass a 0.5 mm sieve. Total carbon (C) and N concentration were determined with an automatic analyzer (LECO CN Analyzer St. Joseph, Michigan). Lignin and cellulose were determined by proximate analysis (Goering and Van Soest, 1970). Total P was determined on dry ashed residues (550 °C) that were re-suspended in HCl (0.28 N). Inorganic soluble P was extracted after shaking 1 g of the residue material with 20 ml of cold deionized water for 1 h (200 rpm) and then filtered. Total and inorganic P content were quantified spectrophotometrically (Murphy and Riley, 1962).

2.3. Soybean residue decomposition and P release

Soybean residue decomposition was evaluated in 2009 and 2010 within fallow (no CC) and beneath the three CC treatments using a litterbag technique (e.g., Lupwayi et al., 2007; Verhoef, 1995). The litterbags were 0.15 m × 0.20 m and had a mesh size of 2 mm. Twelve grams of soybean residue cut into 5 cm lengths were placed in each litterbag. The proportions of leaves, stems and pods were as described above. Eight litterbags (two per sampling date) were randomly assigned to each plot of the four treatments and placed on the soil surface on April 29th in 2009 and on May 19th in 2010. Gravimetric moisture and ash contents were determined on additional litterbags to calculate an initial dry weight for each litterbag. The bags were collected at 30, 105, 161 and 192 and 41, 67, 123 and 165 days after placement on the soil in 2009 and 2010, respectively. Once collected, litterbags were stored at 5 °C until laboratory analysis. The residues were removed from the litterbag, shaken gently over a sieve (1 mm) to remove the soil and then dried at 60 °C for 48 h to determine dry weight biomass. Samples were ground to pass a 0.5 mm sieve and subsamples (0.1 g) were

ashed in a muffle furnace at 550 °C for 16 h. The ash content was used to adjust the sample dry weights to an ash-free dry weight basis. This accounted for variable quantities of contaminating soil. Total P content of each litterbag was determined as described for initial residue assessments.

2.4. Soil and residue temperature, moisture content and microbial activity and biomass

Temperature, moisture content, and microbial biomass and activity were measured in the topsoil (0–2 cm) and surface residues on July 9th, August 19th and November 1st 2011. Soil temperature was measured *in situ* 1 cm below the soil surface to the nearest 0.1 °C during the morning (10:00 am–11:00 am) using a digital thermometer with a stainless steel piercing probe. Residue temperature was measured just beneath the mulch. Measurements of soil and residue temperature were repeated four times in each plot.

Soil and residue moisture content, microbial biomass and microbial activity were measured in soil (0–2 cm depth) and residue samples taken individually using a 10 cm × 10 cm quadrant (one composite sample consisted of four quadrants per plot). Residue samples were shaken gently over a sieve (1 mm) to remove most of the soil and two subsamples of each composite sample was dried at 60 °C for 48 h to determine gravimetric moisture content. The residue samples were grounded to pass an 8 mm sieve. Soil samples were sieved through a 1 mm screen, and two subsamples of each composite sample were dried at 105 °C for 48 h to determine gravimetric soil moisture. Metabolically active microbial biomass in soil and residue were quantified using the substrate-induced respiration (SIR) technique (Anderson and Domsch, 1978; Beare et al., 2002), while microbial activity was quantified using the fluorescein diacetate (FDA) hydrolysis technique (Schnürer and Rosswall, 1982; Adams and Duncan, 2001). Both residue and soil microbial biomass and activity were measured in triplicate.

2.5. Data and statistical analysis

Biomass decomposition was analyzed using decomposition days as a temporal scale (Stroo et al., 1989; Steiner et al., 1999; Ruffo and Bollero, 2003). Decomposition days are a way to normalize time based on weather conditions, assuming the primary environmental factors regulating residue decomposition are temperature and moisture. The decomposition day equation included two coefficients: a temperature coefficient, based on daily average air temperature and a moisture coefficient based on daily precipitation. Both coefficients range from 0 (no decomposition) to 1 (maximum decomposition). For a given day, the lower of the two coefficients was used to represent the fractional decomposition relative to a day at optimum conditions. The fractional decomposition days were accumulated as "decomposition days" to normalize the time scale for environmental conditions.

The temperature coefficient (TC) was calculated as:

$$\mathrm{TC} = \frac{(2 \times T_{\mathrm{mean}}^2 \times T_{\mathrm{opt}}^2 - T_{\mathrm{mean}}^4)}{T_{\mathrm{opt}}^4},$$

where T_{mean} is the daily average air temperature (recorded by a data-logger) and T_{opt} is the optimum air temperature for residue decomposition (32 °C).

The moisture coefficient was calculated assuming that 4 mm of rain is enough to moisten a layer of residues (Steiner et al., 1999). Thus, the moisture coefficient is set to 1 when precipitation was equal or higher than 4 mm; if precipitation was less than 4 mm, the coefficient is equal to precipitation divided by 4. Without precipitation, the moisture coefficient decreased by a factor of 0.5 each day after the last precipitation.

Experimental data of remaining biomass or remaining P vs. decomposition days were expressed as percentage of initial biomass or P and fitted to a first order exponential decay model for each treatment and year:

$$\text{remaining biomass (or remaining P)} = (100 - b) + b\exp^{-kx}$$

where b was biomass decomposed at this time period (%), k was relative decomposition rate (decomposition days^{-1}) and x was decomposition days. In those cases where no initial decomposition occurred, an initial plateau followed by a decay exponential function was fitted.

The parameters describing the initial quality of residues were compared between years using a t test. Exponential decay models fitted to decomposition data (for both remaining biomass and P) were compared between treatments using an F test (Mead et al., 1993). In those cases where no significant difference between treatments occurred, a single exponential decay function was jointly fitted for these treatments. Soil and plant residue temperature, gravimetric moisture content, microbial biomass and activity were analyzed by split plot analysis of variance. As each variable was measured in three different sampling times, a repeated measures analysis was performed. Treatment was considered as main plot factor and decomposition days as subplot factor (Schaberger and Pierce, 2002). When the interaction "Treatment × decomposition days" was not significant, and the main effects were significant, means of each level were compared using the least significant difference LSD test ($p < 0.05$).

3. Results

3.1. Weather conditions and initial quality of soybean residues

Soybean residue decomposition was analyzed between harvest and planting of the following soybean crop. This period lasted 165 days in 2009 and 192 days in 2010. Small differences in temperature were detected between years, as reflected by the roughly parallel curves of cumulative degree days (Fig. 1A). However, the temporal accumulation of decomposition days (which involves both daily temperature and precipitation) varied (Fig. 1B), primarily due to the distribution and intensity of precipitation events. Total decomposition days were similar for both years: 12.0 and 12.4 days in 2009 and 2010, respectively. However, the rate of accumulation was more rapid in 2009, since there were 27 fewer days between harvest and planting. The 2011 decomposition period had intermediate weather conditions compared to the previous years.

The initial quality of soybean residues differed between 2009 and 2010 (Table 2). A lower total C, total P, lignin and inorganic soluble P contents, but higher C:N and C:P ratios were observed in 2009 in comparison with 2010. The initial P concentration of soybean residues was 0.50 g kg^{-1} in 2009 and 0.88 g kg^{-1} in 2010 (Table 2), representing an input of 1.3 kg P ha^{-1} in 2009 and 3.5 kg P ha^{-1} in 2010. Water soluble inorganic P was 0.2 kg P ha^{-1} in 2009 and 1.0 kg P ha^{-1} in 2010.

3.2. Soybean residue decomposition and P release

The estimated input (aboveground dry matter) of soybean residues to the soil was 2558 kg ha^{-1} in 2009 and 4021 kg ha^{-1} in 2010. On average, 12% and 29% of these residues were broken down (in terms of dry biomass) during the fallow (or CC growing

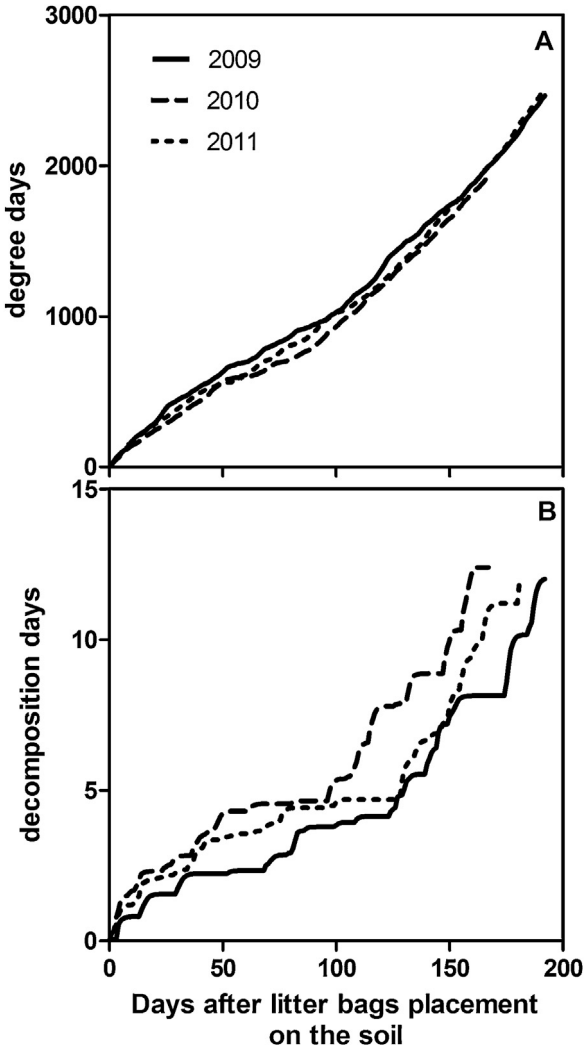

Fig. 1. Cumulative degree days (A) and decomposition days (B) for 2009, 2010 and 2011 after litterbag placement on the soil. Since no decomposition experiments were done in 2011, the starting date for this year was taken as the midpoint of the 2009 and 2010 experiments. Degree days were calculated using 0 °C as base temperature. Decomposition days were calculated using the equations developed by Stroo et al. (1989) and Steiner et al. (1999), which consider both daily precipitation and temperature.

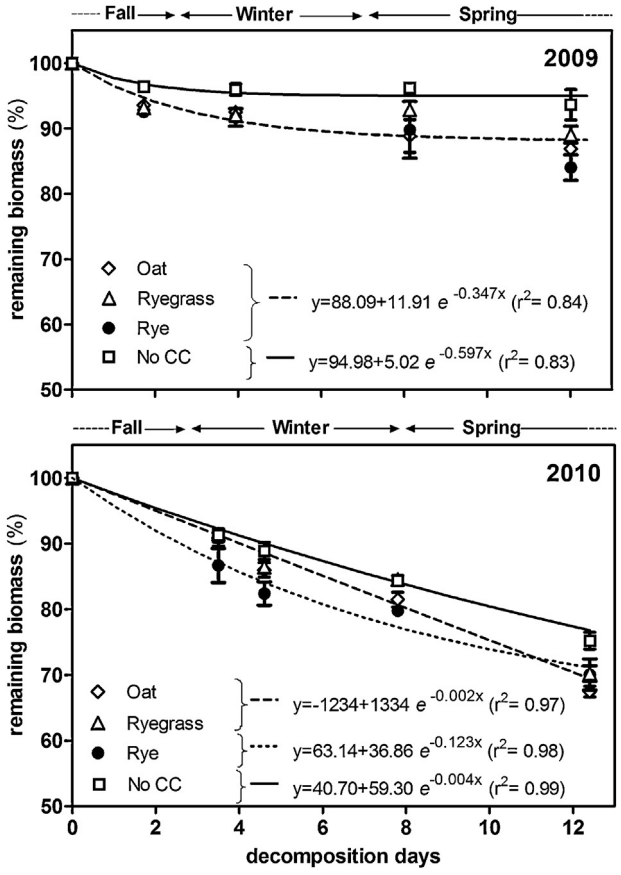

Fig. 2. Remaining biomass (% of initial ash free dry weight) of soybean residues plotted against decomposition days, for the two experimental periods. Treatments compared no cover crops (no CC) and cover crops (CC: oat, rye and ryegrass). Data points represent the average of four replicates. Bars represent standard error of the mean. Lines show decay exponential model fitted for treatments that had significant differences: no CC ($p = 0.032$) and rye, oat and ryegrass (pooled, $p < 0.001$) for 2009; and no CC ($p < 0.001$), rye ($p = 0.001$) and oat and ryegrass (pooled, $p < 0.001$) for 2010. Scale of real seasons (fall, winter and spring) is also provided.

period) in 2009 and the rainier 2010, respectively. This means that 2251 kg ha^{-1} and 2855 kg ha^{-1} of soybean residues remained on the soil surface when the following soybean crop was sown.

Cover crops promoted decomposition of soybean residues (Fig. 2), such that the difference between no CC and the average for the three CC treatments were 8.2 ($p = 0.018$) and 6.4 percent ($p = 0.004$) in 2009 and 2010, respectively. The no CC exponential decay curves differed significantly from those fitted to CC treatments both years ($p = 0.006$ in 2009 and $p = 0.029$ in 2010). Differences in soybean residue decomposition between CC species were observed only during the second year (species, $p = 0.023$), when soybean decomposition in the rye treatment was faster than in oat or ryegrass.

Phosphorus release from residues showed no differences between treatments but differed between years (Fig. 3). In 2009, there was rapid P release at the beginning of the decomposition period, but subsequent P release was almost negligible (Fig. 3). The result was that following the decomposition period, an average of 80.3% of the initial total P remained in the soybean residue. In 2010, P release showed an initial plateau followed by an exponential decay function (Fig. 3). With this decomposition pattern, soybean residue retained an average of 67.1% of the initial total P following the decomposition period. Based on these measurements, the absolute amount of P released from soybean residue to the soil averaged 0.25 and 1.16 kg P ha^{-1} in 2009 and 2010, respectively.

Table 2
Initial chemical properties of soybean residues in 2009 and 2010. Different letters in each row indicate significant difference at the 5% level ($n = 3$).

Residue property	2009	2010
Total C, g C kg^{-1} residue	453 b	473 a
Lignin, g kg^{-1}residue	73 b	104 a
Cellulose, g kg^{-1} residue	512	492
Total N, g N kg^{-1}residue	7.56 b	9.96 a
C/N ratio	60.0 a	47.7 b
Total P, g P kg^{-1} residue	0.50 b	0.88 a
Water extractable inorganic P, % of total residue P	19 b	27 a
C/P ratio	838a	562 b

3.3. Soil and residue temperature, moisture content, microbial biomass and activity

Surface soil and residues temperatures under no CC and ryegrass treatments were higher than those under rye and oat

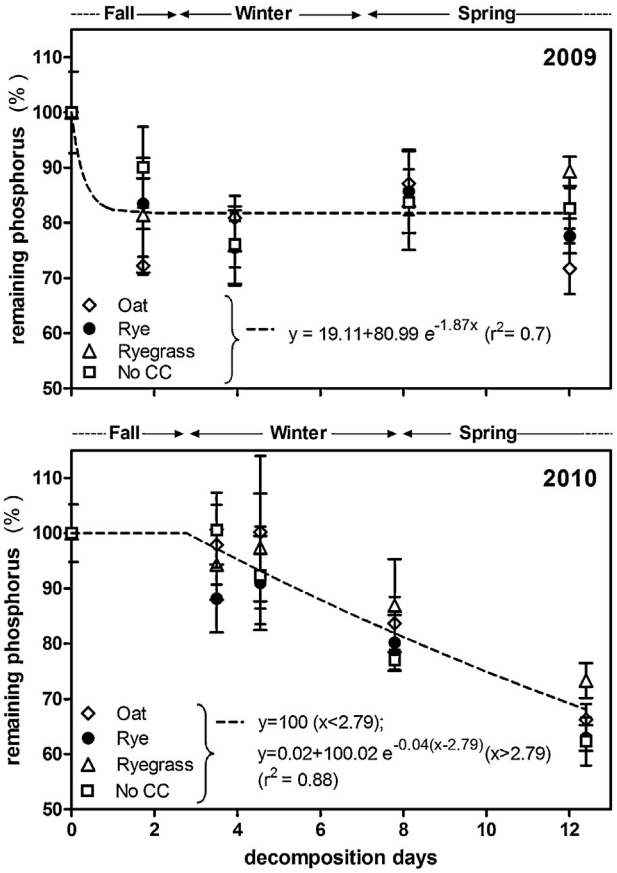

Fig. 3. Remaining P (% of initial total P content) of soybean residue plotted against decomposition days, for the two experimental periods. Treatments compared were control without cover crops (no CC) and cover crops (oat, rye and ryegrass). Data points represent the average of four replicates. Bars represent standard error of the mean. Lines show the function fitted for all treatments (no significant difference between treatments was found). Decay exponential function was fitted for 2009 ($p < 0.001$) and plateau followed by decay exponential function for 2010 ($p < 0.001$). Scale of real seasons (fall, winter and spring) is also provided.

(Fig. 4A and B and Table 3). Soil and residue moisture contents showed a significant interaction between treatments and decomposition days ($p < 0.001$ and $p = 0.001$ respectively) (Fig. 4C and D, Table 3). In general, both soil and residue moisture content decreased throughout the decomposition period (Fig. 4C and D). Initially, soil and residue moisture contents were higher in rye and oat CC than in ryegrass and no CC treatments (Table 3). At the end of the measurement period, soil moisture content was higher under no CC than under all CC treatments and residue moisture content did not show any significant differences between treatments (Table 3).

Soil microbial biomass was always higher under the three CC treatments than under the control (Fig. 4E and Table 3). Soil microbial activity showed a tendency ($p = 0.060$) for higher values in the plots with CC (Fig. 4G). Residue microbial biomass in rye CC (average across sampling dates 825 mg $C–CO_2\ h^{-1}\ g^{-1}$) was significantly higher than in the no CC treatment (average 642 mg $C–CO_2\ h^{-1}\ g^{-1}$) (Fig. 4F and Table 3), although in general, residue microbial activity was higher under all CC treatments (Fig. 4H and Table 3). Both soil microbial biomass and activity were higher in CC treatments by the end of the experimental periods (Fig. 4E and G and Table 3), but the temporal variation for residue microbial parameters did not follow a clear pattern (Fig. 4F and H and Table 3).

4. Discussion

In our field experiments, we observed that decomposition of soybean residues was promoted by the presence of CC (Fig. 2) and that plots with CC had higher soil and residue microbial biomass and activity than the no CC counterparts (Fig. 4E, F, G and H). The higher soil and residue moisture content (Fig. 4C and D) in the plots with CC and the higher soil C content (Table 1), promoted by five successive years of CC cultivation, arise as key factors to explain the observed increased activity of decomposers in the CC treatments.

To our knowledge, this is the first report on the effects of the presence of plants on crop residue decomposition under no-tillage systems. All previous studies have been carried out with buried residues in conventional tillage systems (Haider et al., 1989; Nicolardot et al., 1995; Muhammad et al., 2007; Jannoura et al., 2012). Extrapolation from results of the two tillage systems is not straightforward, because the environmental conditions that ultimately regulate residue decomposition are very different in subsoil and topsoil. We explore these differences to discuss and understand our results on residue decomposition at the soil surface.

Some studies have found a higher decomposition of buried residues under the presence of growing plants (Bottner et al., 1999; Paré et al., 2000). The authors attributed these effects to the stimulatory effect of carbon-rich root exudates on soil microbial activity. Root exudates might have a minor role (if any) on the accelerated decomposition found in our experiments because they are diluted at the soil surface. In our experiment, soil organic carbon appeared to promote soybean residue decomposition and microbial activity observed in the plots with CC. In fact, a statistically significant 13.3% ($p = 0.006$, Table 1) increase in the total organic carbon content was found in the surface 5 cm of plots that were maintained under CC for five consecutive years compared to plots without CC.

On the other hand, some studies found that the presence of plants reduced the soil and residue microbial activity and the decomposition rate of buried residues (Christensen, 1985; Nicolardot et al., 1995; Muhammad et al., 2007; Jannoura et al., 2012). These results were attributed to a decreased N availability, soil temperature and soil water content (Muhammad et al., 2007). If topsoil is considered instead of bulk soil, these arguments may not apply. Regarding soil temperature, our results showed that CC treatments with oat and rye (the highest yields species, data not shown) decreased average soil and residue temperature by 3.6 and 1.7 °C, respectively (Fig. 4A and B). Therefore, temperature did not explain the enhanced effect of CC on soybean decomposition. Moisture content, in contrast, could have contributed to the increase in the microbial activity found in the treatments involving CC since they remained wetter than the control treatment (Fig. 4C and D). Cover crops consume water, but they also shade and cover the soil surface, reducing evaporation from the soil surface.

Many models have been developed to simulate decomposition of crop residues in soils (reviewed by Guérif et al., 2001). Some have specifically simulated residue decomposition on the soil surface (mulch) (*i.e.*, APSIM–Residue, Thorburn et al., 2001; $PASTIS_{mulch}$ model, Findeling et al., 2007; Coppens et al., 2007). Most of these models consider residue C:N ratio, temperature, moisture, residue–soil contact, N availability and microbial biomass to be the primary regulating factors. Growing plants are rarely taken into account. One exception is the model developed by Douglas and Rickman (1992). They simulated the decomposition of crop residues in a wheat – pea rotation using an exponential decay function that included air temperature and soil moisture content. Obtained simulations indicated that decomposition was faster for bare fallow (non-CC treatments) than in the presence of growing plants due to higher soil water content. Those

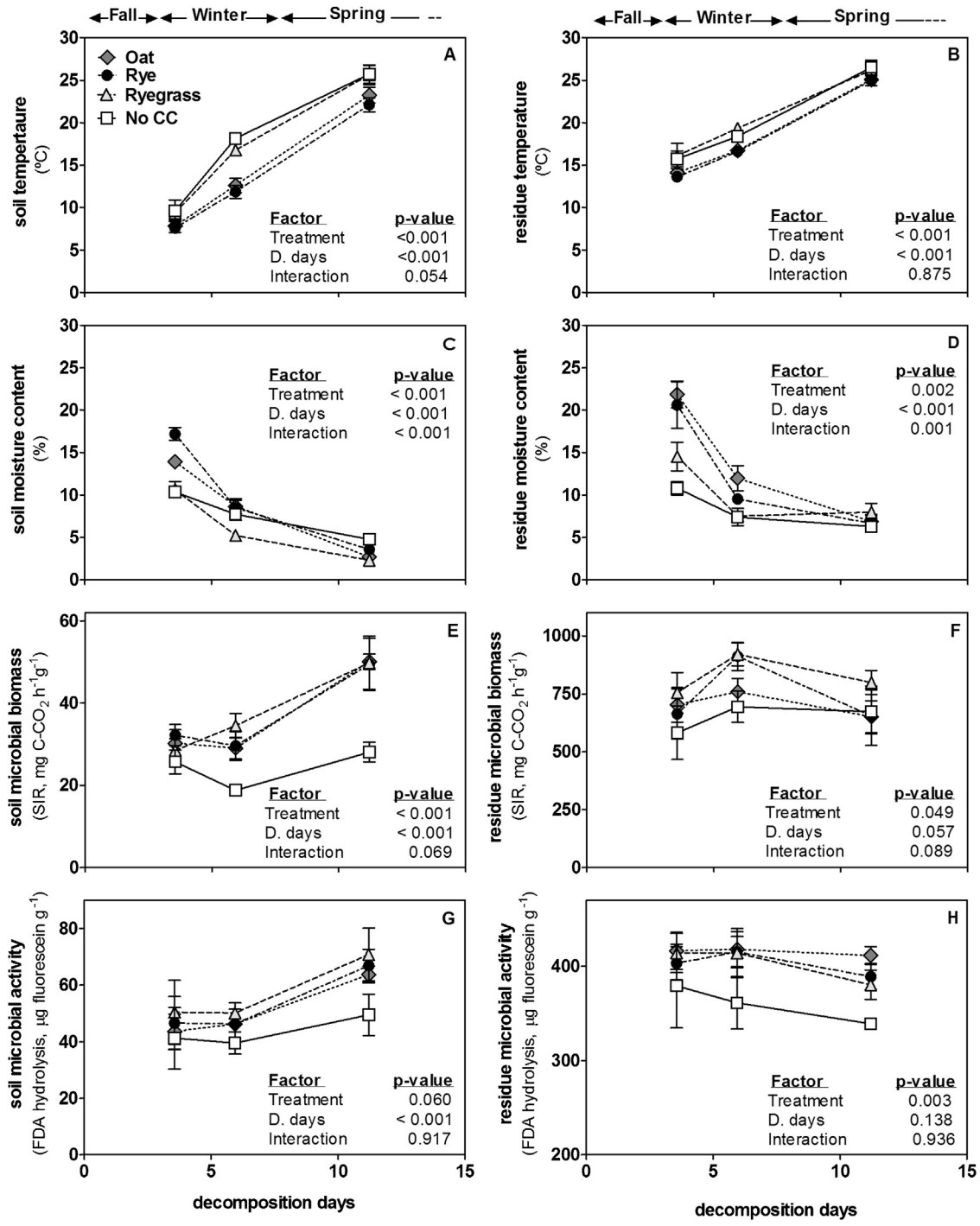

Fig. 4. Soil and residue temperature (A and B), gravimetric soil and residue moisture content (C and D), microbial biomass (E and F) and microbial activity (G and H) in soil and residues plotted against decomposition days during soybean residue decomposition. Treatments compared were control without cover crops (no CC) and cover crops (oat, rye and ryegrass). Data points represent the average of four replicates. Bars represent standard error of the mean. Split plot ANOVA table is shown for each variable within graph. Treatment (no CC, oat, rye and ryegrass) was main plot and decomposition days (D. days) were subplot. Scale of real seasons (fall, winter and spring) is also provided.

predictions do not agree with our no-tillage field measurements of moisture content and residue decomposition rates. Our results suggest that the presence of growing plants may be an important variable that should be taken into account to calibrate models that attempt to simulate the decomposition of residues in no-tillage systems. It should also be noted that the climatic conditions for which the model by Douglas and Rickman (1992) was developed may have been quite different from those encountered in the Argentinean Pampas.

In addition to studying the effect of cover crops on biomass decomposition, this study examined the effect of CC on P release from soybean residues. Our results show that the dynamics of P release from residues differed from those associated with biomass decomposition. The release of P was 9.2% and 6.4% higher than biomass decomposition during the first and second year, respectively (Figs. 2 and 3). Besides the factors that drive the decomposition of residues, P release from them also depends on the total P content, the proportion of inorganic P and the C:P ratio

Table 3
Mean comparison (LSD, $\alpha = 0.05$) for variables with significant mean effect (Treatment and/or decomposition days) at ANOVA. Treatments compared were control without cover crops (no CC) and cover crops (oat, rye and ryegrass). For cases without interaction "treatment × decomposition days" mean comparison were performed to each main factor. For cases with significant interaction "treatment × decomposition days", treatments effect within each time was analyzed. Different letters horizontally indicate significant differences between treatment or decomposition days.

	Treatment				Decomposition days		
	No CC	Rye	Oat	Ryegrass	3.6	5.9	11.2
Variables without significant interaction "treatment × decomposition days"							
Soil temperature	a	b	b	a	c	b	a
Soil microbial biomass	b	a	a	a	b	b	a
Soil microbial activity	b	b	a				
Residue temperature	a	b	b	a	c	b	a
Residue microbial biomass	b	a	ab	b			
Residu microbial activity	b	a	a	a			
Variables with significant interaction "treatment × decomposition days"							
Soil moisture content							
3.6 decomposition days	c	a	b	c			
5.9 decomposition days	a	a	a	b			
11.2 decomposition days	a	b	c	c			
Residue moisture content							
3.6 decomposition days	b	a	a	b			
5.9 decomposition days	b	ab	a	b			
11.2 decomposition days	a	a	a	a			

of the residue (Jones and Bromfields, 1969; Noack et al., 2012). It is generally assumed that plant residue P concentrations below 2 g kg^{-1}or C:P ratios greater than 300 determine P immobilization whereas residue P concentrations greater than 2–3 g kg^{-1} or C:P ratios below 100–200 determine P mineralization (Fuller et al., 1956; Singh and Jones, 1976; White and Ayoub, 1983; Iyamuremye and Dick, 1996; Kwabiah et al., 2003). Phosphorus concentrations (0.50 and 0.88 g kg^{-1}, Table 2) and C:P ratios (838 and 562, Table 2) of soybean residues suggest that a net P immobilization should be expected (Iyamuremye and Dick, 1996; Kwabiah et al., 2003). However, P release from residues followed an exponential decay function or a plateau followed by an exponential decay function in 2009 and 2010, respectively (Fig. 3). It suggests that factors such as the commonly accepted residue P concentrations and C:P ratio thresholds were determined from incubated and buried plant residues (Singh and Jones, 1976; Kwabiah et al., 2003; White and Ayoub, 1983) and may have contributed to these differences. The external conditions that originated those threshold values may differ from our field study with residues laid on the soil surface. Accordingly, some studies under no-tillage conditions have shown net P mineralization from crop residues with C:P ratios higher than 300 or P concentrations below 2 mg P kg^{-1} (Yadvinder-Singh et al., 2010; Lupwayi et al., 2007; Soon and Arshad, 2002; Schomberg and Steiner, 1999). Moreover, a fast release of water extractable inorganic PP from residues during the initial stages of decomposition (diminishing the residue P content) may be the responsible for the exponential decay observed in our experiment. The quantity of P released from soybean residues during the fallow period was modest (0.25 and 1.2 kg P ha^{-1}) compared to the CC or cash crop P requirements (Fernández et al., 2009). Other works also found small amounts of P supplied from cash crop residues to subsequent crops (Lupwayi et al., 2007; Nachimuthu et al., 2009).

Interestingly, and in contrast to what we observed for residue biomass decomposition (Fig. 2A and B), the presence of CC did not affect the release of P from soybean residues (Fig. 3A and B). We are not aware of antecedents on the P release from residues under the effect of CC in no-tillage systems. Under conventional tillage, Friesen and Blair (1988) evaluated the rates of transfer of P from plant residues to various soil P pools in the presence and absence of growing plants and concluded that cropping had no effect on the rates of release of P from crop residues. In general terms, the effect of growing plants on nutrient release from residues has been studied for N in systems with buried residues (Nicolardot et al., 1995; Paré et al., 2000; Jannoura et al., 2012). These studies showed either no effect (Nicolardot et al., 1995), an increase (Paré et al., 2000) or a decrease (Jannoura et al., 2012) of N mineralization from residues. Our results suggest that the environmental and biological soil and residue alterations verified after the introduction of CC were not great enough to produce changes in the release of residue P. The lack of parallelism between C and P mineralization suggests that both processes are regulated by different controls in no-tillage systems.

5. Conclusions

The inclusion of CC in agricultural rotations involves a direct effect on soil coverage through the input of residues but also an indirect effect over the decomposition of pre-existing crop residues. Our results indicate that introduction of CC increased decomposition of soybean residues. However, the magnitude of this effect was largely compensated for by the amount of residue provided by the CC, which led to an overall increase in soil coverage. The presence of CC increased decomposition of soybean residues by 233 kg ha^{-1}. However, after the CC were killed, the input of biomass was about 6500 kg ha^{-1}(average between CC species and years).

Our results were consistent between years, despite differences in weather conditions and quality of soybean residue. However, our results might not be applicable to all no-tillage systems. No-tillage systems are spread on more than 110 million ha worldwide, covering several climates, soils and cropping conditions (Derpsch et al., 2010). Different results may be expected in drier regions, where no-tillage systems are applied to save water or in rainier regions, where no-tillage systems are applied to prevent soil erosion. Both crop residue input and decomposition rates determine the soil organic carbon balance in no tillage systems, and should be taken into account to select a crop rotation that maintains soil cover and promote soil conservation.

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