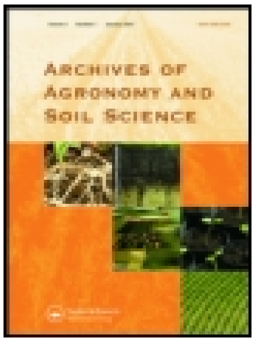

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Eduardo de Sa Pereira, Juan Alberto Galantini & Matias Ezequiel Duval

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SHORT COMMUNICATION

Use of a three-compartment model to evaluate the dynamics of cover crop residues

Eduardo de Sa Pereira[a], Juan Alberto Galantini [b] and Matias Ezequiel Duval [c]

[a]Agencia Extensión Rural INTA Coronel Suárez (EEA Bordenave), Coronel Suarez, Argentina; [b]Comisión Investigaciones Científicas (Bs.As.) CERZOS-Dpto. Agronomía UNS, Bahía Blanca, Argentina; [c]CONICET CERZOS-Dpto. Agronomía UNS, Bahía Blanca, Argentina

ABSTRACT

Cover crop (CC) residues protect the soil from erosion and their permanence on the surface is largely influenced by their biochemical constituents. In this study, the dynamics of CC residue decomposition by applying mathematical models was described. The kinetics of decomposition of residues was obtained from a laboratory incubation experiment. Three CC shoot residues were applied on the soil surface and incubated for 362 days (with eight sampling times). Oats and vetch residues decomposed the most than clover, where *k* values were 3.6×10^{-3}, 3.7×10^{-3} and 5.3×10^{-3} day^{-1}, respectively. The three-compartment model (nonstructural carbohydrates, cellulose–hemicellulose and lignin) to simulate residue decomposition presented a close fit between simulated and measured data. The decomposition rate constant (*k*) of CC can be used to estimate how long residues will remain in the field and how they could affect soil organic carbon.

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Residue decomposition; oats; vetch; clover

Introduction

The decomposition rate of crop residues determines how long the cover will remain on the soil surface. The kinetics of decomposition of crop residues in soil is largely influenced by the quality of the plant materials (Heal et al. 1997). This dynamics varies with weather conditions, mainly precipitation and temperature, and residue quality. In the last case, nutrient concentration, structural carbohydrates and other components (e.g. lignin and other polyphenols) of plant tissues have been used to characterize the biochemical quality of crop residues (Heal et al. 1997). A more detailed characterization of crop residue quality also included soluble carbohydrates and cellulose (Bending et al. 1998) or C:N and lignin:N ratio (Lupwayi et al. 2004; Partey et al. 2014).

Simulation models have been proposed to evaluate the decomposition of residues in soil. Most of these models have taken into account one or several compartments to describe the organic residues, each decomposing according to first order kinetics. In the simpler models, only one pool is used to describe the residue added (Probert et al. 1998), while in other models, the residues may be represented by three fractions or more (Corbeels et al. 1999). However, multiple effects can affect residues decomposition under field decomposition, and shoot tissues are not subjected to equivalent conditions in soils (soil temperature and moisture, among others) (Rasse et al. 2005). Therefore, the objective of this study was to evaluate the decomposition dynamics of different CC residues under controlled conditions of humidity and temperature through incubation experiment.

CONTACT Matias Ezequiel Duval mduval@criba.edu.ar CONICET CERZOS-Dpto. Agronomía UNS, San Andrés, Bahía Blanca (BA) Argentina

Materials and methods

The experiment was carried out in a greenhouse from 15 November 2007 to 12 November 2008. The soil used in the study was collected from the Southwest of Buenos Aires province (37°23′13″S; 62°11′27″W). The soil was classified as a Typic Argiudoll (clay loam) according to the USDA soil classification (Soil Survey Staff 2010) or Luvic Phaeozem according to the World Reference Base for Soil Resources (FAO nomenclature).

Soil and plant samples were collected from the experimental field plots established with different winter CC: oats (*Avena sativa* L.), vetch (*Vicia sativa* L.) and Persian clover (*Trifolium resupinatum* L.). The experiment was established on 150 m^2 plots in a randomized block design with three treatments and three replications. In each plot, eight undisturbed soil samples (corresponding to eight sampling times) were taken from the top 15 cm on 15 October 2007. A PVC pipe (1570 cm^3) of 20 cm in height was placed inside the sampling and filled with 15 cm of undisturbed soil.

The plant samples (0.5 m^2) were collected at the flowering stage (15 October) from the field where the soil samples were collected. They were cut at ground level and dried until constant weight in a forced-air oven at 60°C to transform fresh weight to dry weight of the sample. Half of the CC shoot material was subjected to the biochemical properties described below, and half was reserved for addition to pots.

Experimental design, soil sampling and analysis

Total 72 samples (pots) were placed at random in a greenhouse under controlled conditions of temperature (25 ± 1°C). The water content in the pots was maintained periodically by weight at 60% of soil water-holding capacity using method of Klute (1986).

The basic treatment design consisted of pots in which CC residue (24 pots for each specie), oven-dried, was covered. The residues of oats, vetch and clover cut into 2–3-cm particles and were added to pots at 5.4, 5.4 and 2.7 g dry matter, respectively, which corresponded to biomass rates of 6, 6 and 3 Mg ha^{-1}, respectively. This rate is equivalent to that observed in field experimental plots.

Residue quality and decomposition

Dry matter of the CC, milled to 40 mesh, was analyzed for carbon (dry combustion, Leco Carbon Analyzer) and total nitrogen using Kjeldahl's method (Bremner 1996). The biochemical composition of this dry matter was evaluated by determining neutral detergent fiber (cellulose + hemicellulose + lignin + others), acid detergent fiber (cellulose + lignin + others), acid detergent lignin (lignin + others) and nonstructural carbohydrates (NSC) using the sequential method, with α-amylase and sodium sulfite according to the procedure described by Van Soest et al. (1991) (Table 1).

Three pots from each treatment were destructively sampled on days 0 (referred to as the initial), 21, 59, 93, 130, 201, 270 and 362. There were three replicates for each treatment, which made a total of 72 pots (three treatments × eight sampling times × three replicates). The superficial residues remaining were carefully removed and, its weight determined on each date for each of

Table 1. Dry matter and quality of cover crop residues used in the experiment.

Cover	Cell	Hemi	Lignin	NSC	N	C	LIG:N	C:N
Crops			g kg^{-1}					
Vetch	215a	657b	61a	67a	42b	397a	3.7a	9.4a
Oats	209a	497a	93ab	201c	21a	424a	2.9a	20.1b
Clover	194a	571a	135b	100b	32a	425a	4.1a	13.4a

Cell: Cellulose; Hemi: hemicelluloses; NSC: nonstructural carbohydrates; N: nitrogen; LIG:N: lignin:nitrogen ratio; C: carbon; C:N: carbon:nitrogen ratio. In each column, different letters indicate significant differences among cover crops residues ($p < 0.05$).

the three pots extracted. To minimize the effect of soil contamination, the residual residue weight was calculated on an ash-free weight basis by determining the ash content (550°C) on a 1-g subsample from each pot. This procedure was done to avoid overestimation caused by soil particles attached to the material, which increased as residual matter decreased. The percent of dry matter remaining at each sampling time was calculated as: dry matter remaining (%) = (amount of residue in each sampling time/amount of residue at the start) × 100.

Decomposition model and statistical analysis

The basic structure of the model applied corresponds to the PAPRAN model of Seligman and Van Keulen (1981) described in detail by Godwin and Jones (1991). The model signifies a simple description of the processes of mineralization and immobilization of the N resulting from soil organic matter decomposition. In order to simulate the changes in the quantity of the remaining residue, the equations of PAPRAN were used as a basis from a spreadsheet. In short, the model considered that 'fresh organic matter' was made up of three components: NSC, cellulose and hemicellulose (C + H) and lignin. Each of these components has a different rate of decomposition. The *k* values proposed by Seligman and Van Keulen (1981) were used. These values correspond to 0.80, 0.05 and 9.5×10^{-3} day^{-1} for NSC, C + H and lignin, respectively. The time unit used in the model was 1 day. These *k* values indicate that NSC will be rapidly degraded, that C + H will decay more slowly and, eventually, the only residual component will be lignin.

Each time unit is calculated on the basis of the residual matter from the previous time unit and the potential decomposition. The factors (values being between 0 and 1) that reduce the potential rate are calculated according to N-availability and the C:N ratio of the material. Each of these factors was calculated with Godwin and Jones (1991).

A one-way analysis of variance (ANOVA) was used to test the differences in quality of cover crop (CC) residues. Mean test values were compared using the least significant difference with a significance level of 0.05 to get significant difference. All data were analyzed using Infostat statistical software (Di Rienzo et al. 2013).

Results

CC quality and decomposition

Residue quality (hemicelluloses, lignin, NSC and nitrogen) differed substantially with respect to C:N ratios while cellulose and carbon concentrations and LIG:N ratio were similar among oats and legumes (vetch and clover) (Table 1). The C:N ratios of the dry matter were 20:1, 9:4 and 13:4 for oats, vetch and clover, respectively. The contents of NSC, C + H and lignin were 201, 706 and 93 g kg^{-1} for oats; 67, 872 and 61 g kg^{-1} for vetch and 100, 765 and 135 g kg^{-1} for clover, respectively (Table 1). The dynamics of oats, vetch and clover residues in pots throughout the study period (Figure 1) was best described by an equation of negative exponential type. Loss differences among oats, vetch and clover residues varied with time. The residual matter of oats, vetch and clover was 73%, 59% and 78% after 21 days; it decreased after 100 days (48%, 39% and 61% of their initial biomass, respectively) and the amounts of residues remaining on the surface after 362 days were 21%, 12% and 16%, with a decomposition rate constant (*k*) of 3.6×10^{-3}, 3.7×10^{-3} and 5.3×10^{-3} day^{-1} for oats, vetch and clover, respectively (Figure 2).

The results from the application of the three-compartment model (LIG, C + H and NSC, with their decomposition rate constants) for simulating decomposition of different CC residues showed a better fit with the real data (Figure 2) than the estimation from the negative exponential equation. These decomposition patterns show rapid initial decomposition, during which easily decomposable plant constituents are broken down by soil microorganisms. For example, in vetch, residues were observed a large drop in dry matter remaining in the initial stage (Figure 2) due to the greater N-content and the lower C:N ratio than other CC species (Table 1).

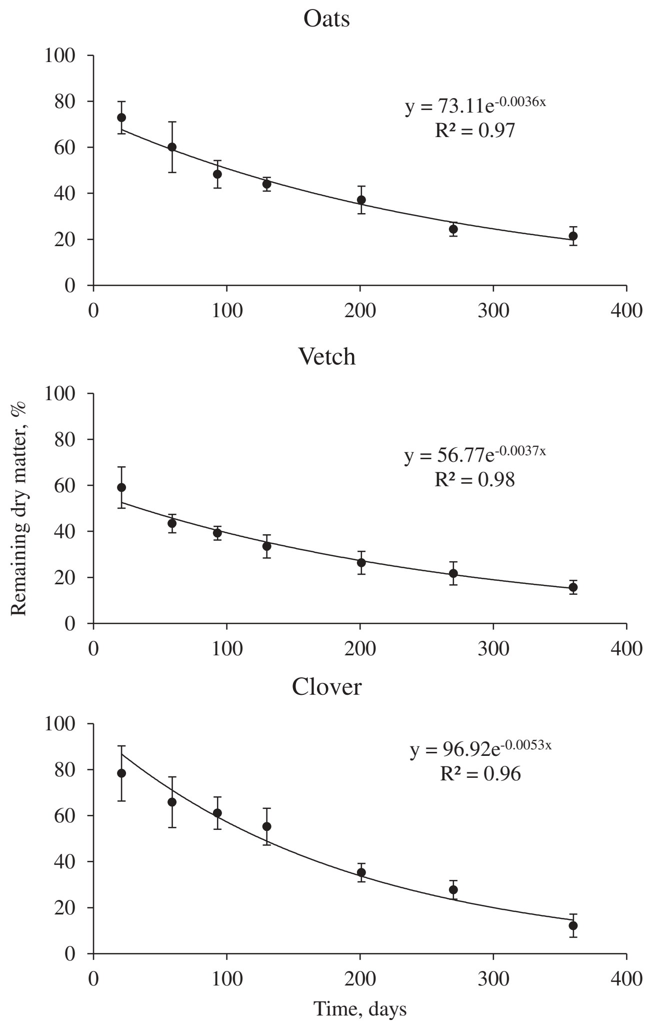

Figure 1. Decomposition dynamics of organic matter over 362 days of the different cover crops. The vertical bars represent ±one standard deviation (n = 3).

Discussion

Residue decomposition

The dynamics of oats, vetch and clover residues in pots throughout the study period (Figure 1) coincided with reports from the literature reviews (Gilmour et al. 1998; Parton et al. 2007), where the best description is that of the negative exponential type. The suitability of this model of residual matter dynamics will help determine the best management practices to be applied and thus protect the soil from erosion (Moraes Sá & Lal 2009).

Loss differences among oats, vetch and clover residues varied with time. They were higher at the beginning of the experiment and tended to decrease with time (Figure 1). There are two key instances in the analysis: the first one corresponds to the first sampling period (0–21 days), when decomposition is clearly faster for vetch than for oats and clover. The initial decomposition of vetch residue was faster than oats and clover residues due to its lower lignin content and higher nitrogen content and, consequently, lower C:N ratios (Table 1). In the case of clover, its lower quality due to larger proportion of stems with high content of lignified tissue at the time of removal would cause a slower initial decomposition

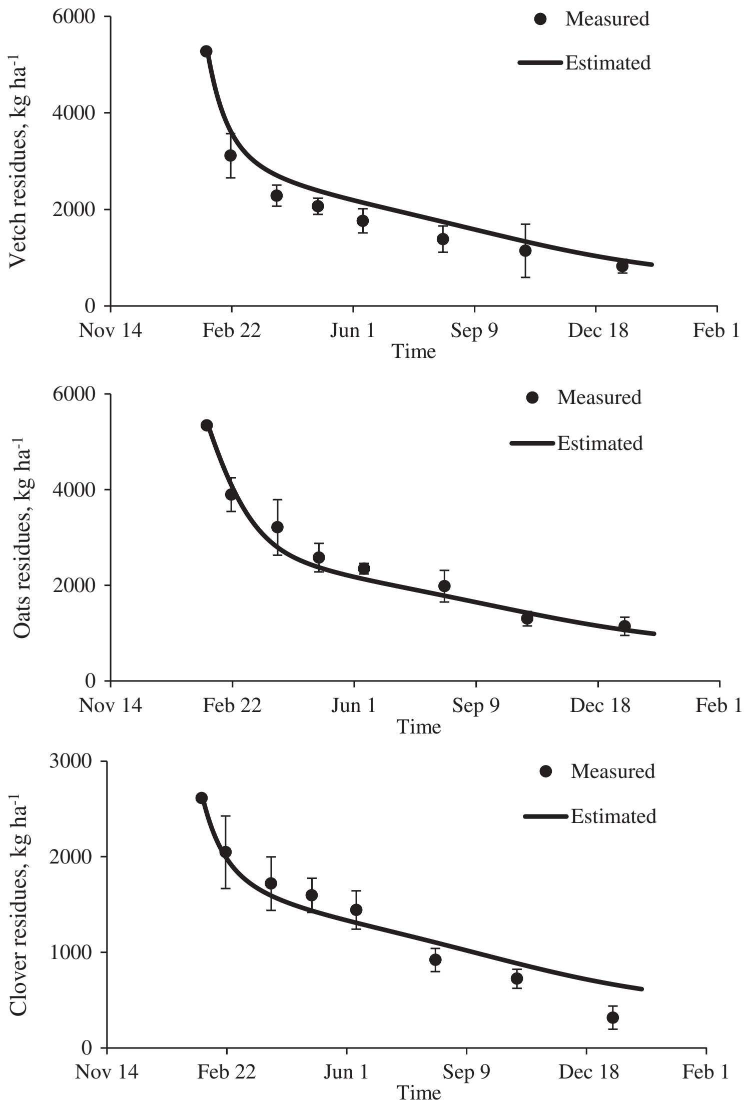

Figure 2. Observed (circle) and simulated (line) residue dry matter in the pots for surface residues of vetch, oats and clover. The vertical bars represent ±one standard deviation (n = 3).

(Table 1, Figure 1). This result points to a physical protection of the easily decomposable carbon by high lignin concentration in agreement with Ambus and Jensen (1997). The second instance is in the 130–201-day period, when the average decomposition rate is fast both for oats and clover, and tends to equal that of vetch. Rapid decomposition rates of oats residues in the field were also observed by Moraes Sá and Lal (2009) in a 107–133-day period. Although residual dry matter decreased exponentially and showed changes among residues during the experiment, the final values ranged from 12% to 21% of the original residue input.

The results show that even though it was possible to obtain an equation with a better adjustment in the long term, there is a certain mismatch between the observed and predicted data at the initial stage of decomposition. The higher rate loss of material readily available by microorganisms is likely to account for these differences. This particular dynamics explains why it is more difficult to obtain a perfect fit when applying a one-compartment (residues) model while considering several residue components such as lignin, cellulose and soluble compounds. In this way, the mathematical models tend to consider the residue characteristics involved in the decay process, like the quality of the different plant constituents.

Application of the model

The better fit of the three-compartment model (LIG, C + H and NSC, with their decomposition rates) with the real data can be associated to a faster decomposition of labile materials (NSC) than predictions of a single-compartment model (Figure 2). Different patterns were observed in decomposition dynamics when the results were analyzed for each type of residue, mainly in the initial stage of decay, where high-quality residues (e.g. vetch) favored a faster decomposition rate (Table 1, Figure 1).

Throughout the 362-day experiment, vetch residues always showed a faster decomposition rate, with a 40% decrease in dry matter 30 days after residue incorporation into the pots. Oats residues showed greater persistence, as even after 130 days, there was still 45% of initial residue input; this stresses the idea that a lower N-content and a higher C:N ratio must have hindered degradation (Table 1, Figure 1). Acosta (2009) worked with decomposition bags of oats and vetch residues in the field; he found that 50% decomposition occurred only after 164 and 49 days, respectively. Clover residues showed intermediate decomposition rates when compared with oats and vetch residues, with intermediate values of N and the C:N ratio (Table 1). The chemical compositions of the crop residues are important in determining their decomposition patterns. Lupwayi et al. (2004) found a close positive and negative relationship between decomposed dry matter and its nitrogen content and C:N ratio, respectively.

The N released from residue decomposition was estimated through the model by using the C:N ratio. When it is higher than 20, the N-content in the residues is retained by microbial biomass. However, when the C:N ratio is lower, residue-N is released at the rate at which organic matter is lost. The difference in residue input influenced the mineralization process and the immobilization of N in terms of the C:N ratio for each CC. These results are in agreement with observed in field conditions, where vetch residues released up to 32% of the N accumulated in the residues during the first 30 days, causing soil available N-levels to vary from 35 to 130 kg ha^{-1} (Sá Pereira et al. 2014). These characteristics of vetch residues could replace up to 50% of nitrogen fertilizers and promote a grain yield increase by as much as 100% (Sá Pereira et al. 2014). An initial immobilization was observed for oats residues, which became stronger as the residue input was raised. According to the model, partial remineralization of the soil occurred 60 days after residue incorporation into the pots. Rates of N-mineralization of up to 50% in the first 30 days were obtained by Acosta (2009) when measuring the quantity of vetch residues placed in the decomposition bags.

If the dynamics of residue decomposition in the field is assumed to be similar to the value obtained in the pots, we may understand why fertilization of maize at V4–V6 responded better when preceded by oats than by vetch crop residues (Sá Pereira et al. 2014). The results obtained in pots would indicate that N-availability in the soil was directly related to the dynamics of residue decomposition, to residue quality and to fluctuations in humidity and temperature. Leguminous residues, hence, release larger N-quantities and the following crop may certainly be required a lower complementary N-rate. On the other hand, N-input should be increased to manage maize after oats CC because N-availability is reduced as a result of a higher residue C:N ratio and a slower decay rate, thus favoring the immobilization process.

Conclusions

Vetch residues initially showed a fast decomposition rate. They lost over 40% in the first 21 days after being placed in incubation pots, which allowed high N-availability in the soil.

Oats residues decomposed more slowly and caused temporary N-immobilization in the soil, with a late partial release between 3 and 4 months after the residues were placed in the pots.

Decomposition rates for oats, vetch and clover residues were different, whereas the processes of mineralization and immobilization were enhanced by the C:N ratio of each CC. The decomposition dynamics of the CC can be described by a simple equation in the medium term, or else a three-compartment model can be used for more accurate descriptions in the short term.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Juan Alberto Galantini http://orcid.org/0000-0002-4536-8605
Matias Ezequiel Duval http://orcid.org/0000-0002-8731-9107

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