Revista Brasileira de Ciência do Solo

Division - Soil Processes and Properties | Commission – Soil Biology

Summer Cover Crops Shoot Decomposition and Nitrogen Release in a No-Tilled Sandy Soil

Douglas Adams Weiler[(1)], **Sandro José Giacomini**[(2)*], **Celso Aita**[(2)], **Raquel Schmatz**[(3)], **Getúlio Elias Pilecco**[(3)], **Bruno Chaves**[(3)] **and Leonardo Mendes Bastos**[(4)]

[(1)] Universidade Federal de Santa Catarina, Coordenadoria Especial de Ciências Biológicas e Agronômicas, Curitibanos, Santa Catarina, Brasil.
[(2)] Universidade Federal de Santa Maria, Departamento de Solos, Santa Maria, Rio Grande do Sul, Brasil.
[(3)] Universidade Federal de Santa Maria, Programa de Pós-Graduação em Ciência do Solo, Santa Maria, Rio Grande do Sul, Brasil.
[(4)] Kansas State University, Department of Agronomy, Manhattan, United States.

*** Corresponding author:**
E-mail: sjgiacomini@ufsm.br

Received: February 20, 2019

Approved: September 11, 2019

How to cite: Weiler DA, Giacomini SJ, Aita C, Schmatz R, Pilecco GE, Chaves B, Bastos LM. Summer cover crops shoot decomposition and nitrogen release in a no-tilled sandy soil. Rev Bras Cienc Solo. 2019;43:e0190027.
https://doi.org/10.1590/18069657rbcs20190027

ABSTRACT: Cover crops have numerous benefits when used in a no-till system. Understanding the processes of decomposition and N release of summer cover crops (SCC) may help select species and management to be used in cropping systems. This study aimed to evaluate C and N loss of SCC shoots. Six SCCs were evaluated: velvet bean (*Mucuna aterrima*), pearl millet (*Pennisetum americanum*), dwarf pigeon pea (*Cajanus cajan*), sunn hemp (*Crotalaria juncea*), showy rattlebox (*Crotalaria spectabilis*), and jack bean (*Canavalia ensiformis*). The experiment was conducted for two years under no-till in soil classified as Typic Hapludalf (*Argissolo*). The C and N remaining of crop shoots were evaluated for 140 days using litter bags and the results were fitted with a simple nonlinear regression model. Elevated air temperature and rainfall volume accelerated C and N loss in the first year. Carbon and N loss was characterized by a rapid initial phase followed by a slower one. Jack bean had the highest C loss rates, while the lowest rates were found in pearl millet. Velvet bean and pearl millet had the lowest N loss rates in the first year, together with showy rattlebox in the second year. The rates of C (kC) and N (kN) loss were positively correlated with total N and water-soluble C and N in crop shoots. During the 35 days after cover crop termination, SCCs released 35 to 137 kg ha^{-1} N in 2010 and 5 to 66 kg ha^{-1} N in 2011. Velvet bean and showy rattlebox showed more gradual N release, which may favor the synchronization between N release and N uptake by the succeeding crop. The sunn hemp was the legume species that combined higher remaining residues on the soil surface, releasing less N but preventing soil erosion.

Keywords: chemical composition, legumes, cropping system, crop residue, nutrient cycling.

INTRODUCTION

No-till is widespread throughout Brazil, but some challenges such as adequate crop rotation and high biomass input into the soil are still not fully addressed by the traditional cropping systems. An alternative to reach these conditions is the inclusion of soil cover crops in cropping systems. Soil cover crops have numerous benefits mainly under no-till system, such as preventing soil erosion, increasing soil C stocks (Amado et al., 2006; Bayer et al., 2009), nutrient cycling (Tiecher et al., 2017), and adding nitrogen (N) to soil by biological N fixation combined with low nitrous oxide emissions (Bayer et al., 2015; Weiler et al., 2018).

Summer cover crops (SCC) produce high biomass (Aita and Giacomini, 2006; Weiler et al., 2018), but their use is limited because they are grown in the same period as summer cash crops (e.g., soybean and corn), which are typically main sources of income. Several studies have shown the long-term effects of including SCCs in cropping systems, which are generally intercropped with cash crops, mainly corn (Spagnollo et al., 2002; Bayer et al., 2003; Amado et al., 2006; Bayer et al., 2009). Alternatively, SCC can be grown summer/autumn, between the harvesting of a summer cash crop and the sowing of a winter cash crop, promoting sustainable intensification of the production system. The potential of biomass production of these species may be even higher when grown alone, even in a relatively short period (Weiler et al., 2018), due to vigorous growth and high capacity of legumes to fix N_2 in symbiosis with diazotrophic bacteria (Aita and Giacomini, 2006). However, little is known about the use of SCCs in cropping systems, especially in relation to crop residue decomposition and N release. Some studies have evaluated the dynamics of SCC decomposition in production systems in tropical climates (Carvalho et al., 2008; Soratto et al., 2012; Xavier et al., 2017), but the climatic conditions where these studies were conducted differ from those found in southern Brazil. Under the same environmental conditions, crop residues differ in decomposition and N release basically due to chemical composition (Trinsoutrot et al., 2000; Redin et al., 2014), generically called quality. In general, high quality crop residues (e.g., high N content and soluble fraction) are decomposed and release N faster than low-quality residues.

Understanding decomposition dynamics and N release of crop shoots may help farmers manage cover crops between cash crops with the aim of protecting soil from erosion and saving on synthetic N fertilizers. Thus, this study aimed to: i) evaluate the rates of C and N loss of SCC shoots; ii) evaluate the relationship between chemical composition of SCC residues and constants of C and N loss and; iii) suggest species that combine soil protection and gradual N release during decomposition on the soil surface.

MATERIALS AND METHODS

Site and soil

The study was conducted from April to August of 2010 and 2011 at the experimental area of the Soil Science Department of the Universidade Federal de Santa Maria (29° 42′ S, 53° 48′ W, about 90 m altitude). The regional climate is humid subtropical (Cfa2), according to the Köppen classification system. The mean annual temperature is 19.3 °C and annual rainfall is 1,769 mm. The soil is classified as *Argissolo Vermelho Distrófico arênico* (Santos et al., 2013), which corresponds to Typic Hapludalf (Soil Survey Staff, 2014). The soil was sampled prior to the start of the experiment at a layer of 0.00-0.10 m and it presented 600 g kg^{-1} of sand, 300 g kg^{-1} of silt, 100 g kg^{-1} of clay, and 7.5 g kg^{-1} of carbon. One year and a half prior to cover crop sowing, the area was amended with limestone, then plowed and seeded with black oats (*Avena strigosa*). Climate data were collected from an automatic weather station located 1.7 km from the experiment.

Experimental design and crop management

The experiment followed a randomized complete block design with four replicates. The following SCCs were evaluated: velvet bean (*Mucuna aterrima*), pearl millet (*Pennisetum americanum*), dwarf pigeon pea (*Cajanus cajan*), sunn hemp (*Crotalaria juncea*), showy rattlebox (*Crotalaria spectabilis*), and jack bean (*Canavalia ensiformis*). Summer cover crops were grown between January and April, after harvesting of the summer cash crop and before the sowing of the winter crop. The SCCs were grown in 45-cm spaced rows. Velvet bean and jack bean were seeded in pits spaced 0.25 m apart with density of two plants per pit. Pearl millet, sunn hemp, showy rattlebox, and dwarf pigeon pea were sowed at a density of 12, 30, 30, and 50 kg ha^{-1}, respectively. The SCCs were managed with a knife roller at flowering. During SCC decomposition (April to August), the plots were grown with oats (*Avena sativa*) in 2010 and black oats in 2011. Oats were grown under no-till, sown at a density of 80 kg ha^{-1} and fertilized with 80 kg ha^{-1} of P_2O_5 and 80 kg ha^{-1} of K_2O.

Cover crop shoot characterization

The chemical composition of the SCCs was determined in shoots collected the day before cover crop management. The shoots were dried at 40 °C and finely ground for chemical analysis following the method of Van Soest (1963). A subsample of the shoots was dried at 65 °C to determine C and N contents in the elemental analyzer (FlashEA 1112, Thermo Electron Corporation, Milan, Italy). Water-soluble C (Csw) and N (Nsw) contents were determined after stirring 0.5 g of shoot residue in 60 mL of distilled water for 30 min (Redin et al., 2014). The mixture was filtered (Whatman #2) and water-soluble C was determined according to Nelson and Sommers (1982), and water-soluble N was determined following Bremner and Mulvaney (1982) methodology.

Litter bags

Shoots of summer cover crop were collected at flowering, dried in a forced-air oven (40 °C), and chopped into pieces of approximately 0.19 m. Shoots were placed into litter bags with dimensions of 0.2 × 0.2 m and mesh size of 0.005 m. The amounts of dry matter added to the litter bags were as follows for 2010 and 2011, respectively: velvet bean, 4.5 and 4.4 Mg ha^{-1}; pearl millet, 12.8 and 10.1 Mg ha^{-1}; dwarf pigeon pea, 5.8 and 6.0 Mg ha^{-1}; sun hemp, 8.2 and 8.9 Mg ha^{-1}; showy rattlebox, 7.5 and 5.0 Mg ha^{-1}; jack bean, 6.1 and 5.7 Mg ha^{-1}. Litter bags were arranged in each respective plot shortly after cover crop management. The chemical composition of the SCC shoots on the two-year evaluation period is shown in table 1. Further details about chemical composition of SCCs were previously discussed by Weiler et al. (2018).

The remaining amounts of C and N in crop shoots were evaluated by periodic collections of the litter bags at 0, 7, 14, 21, 35, 70, 105, and 140 days after litter bags were disposed on soil surface. At each sampling date, a litter bag from each block was collected and dried in an oven at 65 °C to determine remaining dry matter (DM). Carbon and N contents in the finely ground shoots were determined via dry combustion as described above. Ash was determined by incinerating 1 g of this material in a muffle furnace at 550 °C, and the remaining C and N were expressed free from contamination with soil.

Fitting and parameters of nonlinear regression model

The rates of C (*k*C) and N (*k*N) loss and residue C and N pools (A) were calculated based on the single compartment regression model fitted to the observed values (Jenny et al., 1949). The model has the following equation:

$$C \text{ and } N = A^{-kt}$$

Table 1. Chemical composition of summer cover crops

Cover crop residue	C	N	Csw	Nsw	CEL	HEM	LIG
	g kg^{-1}						
Year 2010							
Velvet bean	438.1	20.6	99.8	7.5	372.6	69.6	80.8
Pearl millet	431.6	9.6	50.0	4.1	374.3	260.3	42.6
Dwarf pigeon pea	451.3	24.1	57.3	4.8	348.5	156.6	90.8
Sunn hemp	436.1	16.5	59.4	7.0	424.2	169.4	86.1
Showy rattlebox	424.1	22.0	86.3	8.0	318.5	95.4	84.6
Jack bean	417.7	36.3	123.7	20.1	254.6	84.8	56.5
Year 2011							
Velvet bean	447.3	20.0	62.0	6.8	371.5	128.7	96.0
Pearl millet	449.8	6.0	44.3	2.9	361.8	294.1	70.8
Dwarf pigeon pea	469.6	18.8	51.3	6.9	384.9	173.1	101.3
Sunn hemp	462.2	16.5	45.2	6.4	454.9	156.4	114.8
Showy rattlebox	438.3	22.6	60.8	8.3	334.6	124.1	83.2
Jack bean	447.2	26.5	82.2	12.4	260.9	146.8	67.9

C: carbon; N: nitrogen; Csw: soluble water carbon; Nsw: soluble water nitrogen; CEL: cellulose; HEM: hemicellulose; LIG: lignin. C and N determined by combustion in a elemental analyser; Csw and Nsw were extracted with water and determined by oxidation and titration (Nelson and Sommers, 1982) and destilation and titration (Bremner and Mulvaney, 1982), respectively; CEL, HEM, and LIG were determined by Van Soest methodology (Van Soest, 1963).

in which: C and N are the amounts of remaining C and N (% of C and N added); A represents the residue C and N pools (%); *k* is the loss rate of C or N (day^{-1}); and *t* is time (day). The half-life of fraction A corresponds to the number of days required to release half of the amount of C and N in the crop residue. It was obtained from the following equation:

$$C_{1/2} \text{ and } N_{1/2} = \frac{ln2}{k}$$

Cumulative N release in each treatment was obtained from the sum of the amounts of N released from SCC shoots in the periods between each collection of the litter bags.

Statistical analyses

The remaining amounts of C and N in crop shoots at each collection date were submitted to analysis of variance (ANOVA), and the difference between means of treatments evaluated by the LSD test (α<0.05). The model parameters fit for the remaining C and N in SCC shoots were tested by two-way ANOVA: crop shoots × year; followed by the LSD test (α<0.05). The relationship between chemical composition and *k*C and *k*N rates of the crop shoots was evaluated using Principal Component Analysis (PCA). In PCA, *k*C and *k*N rates were used as supplementary variables. The correlation coefficients between chemical composition of the SCCs and *k*C and *k*N rates were considered significant if ≥0.5.

RESULTS

Weather conditions

Rainfall distribution and volume and average air temperature were different between the two years of the study (Figure 1). In 2010, there was no rainfall in the first seven

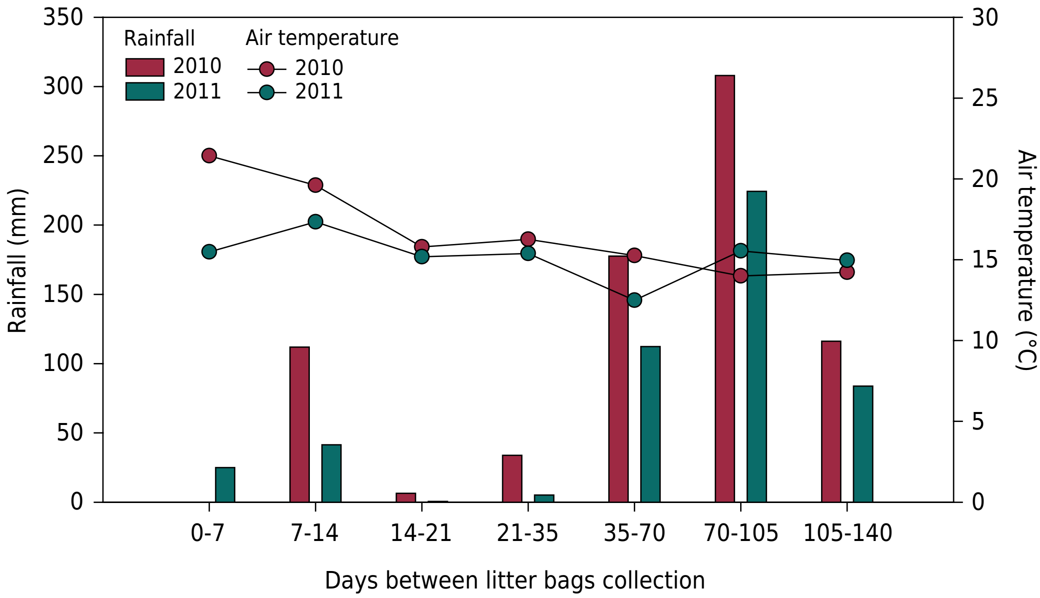

Figure 1. Average air temperature and accumulated rainfall in the intervals between each litter bag collection.

days of SCC decomposition, but there was a high amount of rainfall (120 mm) from day 7 to day 14. In 2011, rainfall volume was similar in the first two collection intervals, and average air temperature was slightly lower than in 2010. Total rainfall during the evaluation period was 84 % higher in 2010 than in 2011.

Crop shoot decomposition

The loss of C of the shoots was different between the SCCs, with significant interaction between year and treatment, except at 140 days of evaluation. The loss of C had a rapid initial phase, followed by a slower one (Figures 2a and 2b). In the first 35 days after cover crop management in 2010, remaining C in crop shoots varied from 51 % in jack bean to 76 % in showy rattlebox. In the same period of 2011, remaining C ranged from 59 % in jack bean to 81 % in pearl millet. At the end of 140 days, remaining C in jack bean was 16 % in 2010 and 30 % in 2011, while in pearl millet 53 % was remaining in 2010 and 65 % in 2011.

The *k*C and half-life of C of the SCCs were higher in 2010 than in 2011, except for velvet bean. Jack bean showed the highest rates of C loss while the lowest rates were found in pearl millet. The half-life of remaining C in pearl millet in 2010 did not differ from velvet bean and showy rattlebox, but it was higher than that of the other species in 2011 (Table 2).

Crop shoot N release

The kinetics of N loss followed the same trend observed in the C loss of crop shoots (Figures 2c and 2d), with significant interaction between treatment and year at all the evaluation dates. During the first 35 days of 2010, remaining N in crop shoots was around 36 % for jack bean and dwarf pigeon pea. Remaining N in crop shoots at 140 days was 54 % in 2010 and 76 % in 2011 in pearl millet, while only 7 and 20 % in jack bean, respectively. The *k*N rates were higher in 2010 than in 2011 for all cover crop species, except velvet bean (Table 2). In 2010, jack bean and dwarf pigeon pea shoots showed the highest values of *k*N. In 2011, *k*N rates did not differ between jack bean and sunn hemp. The half-life of N in crop shoots did not differ among the SCCS in 2010, but it was the highest in pearl millet in 2011.

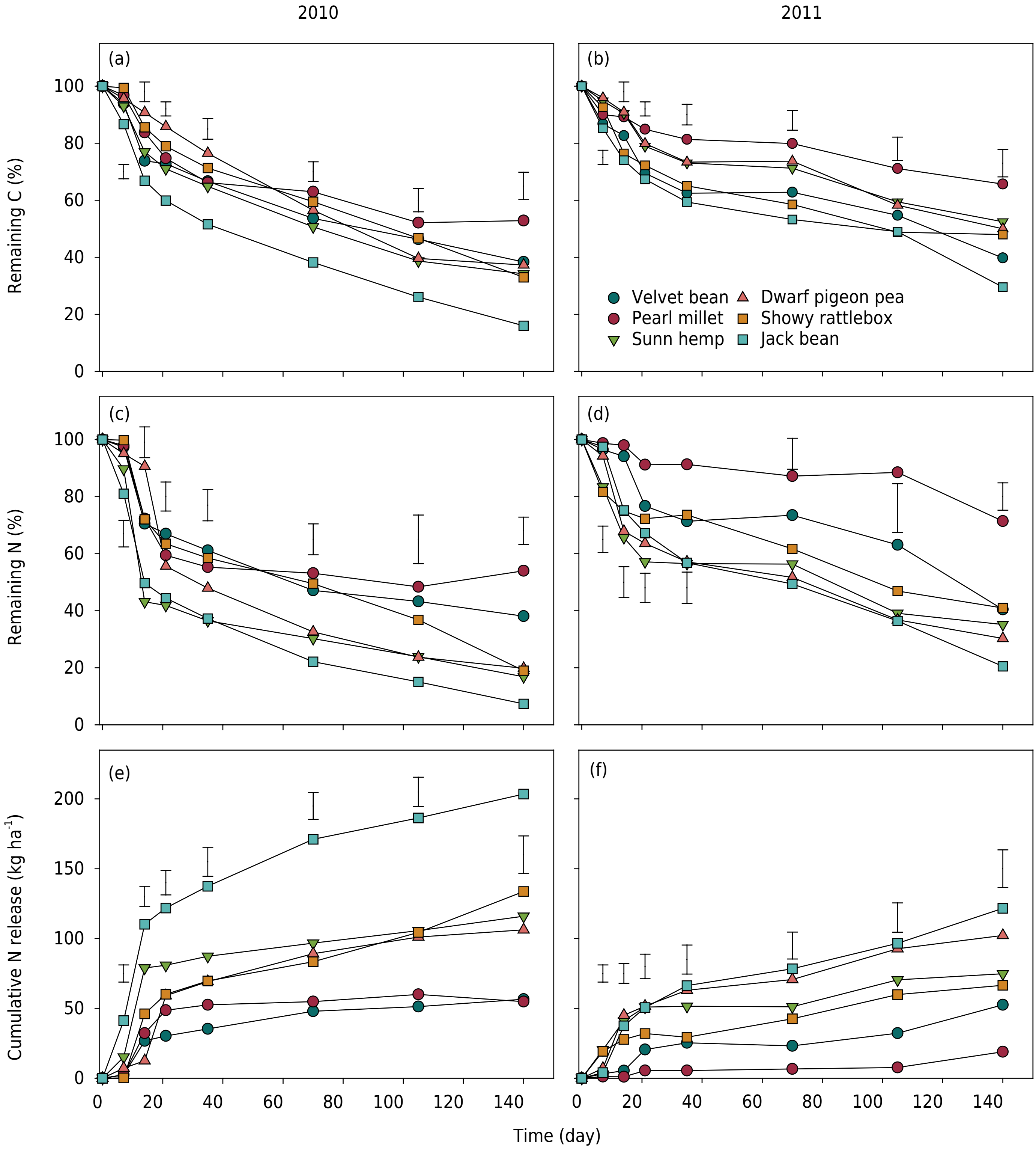

Figure 2. Remaining carbon (a, b) and nitrogen (c, d) in summer cover crop shoots and cumulative nitrogen release (e, f) in 2010 and 2011. Vertical bars indicate significant differences between treatments according to the LSD test (α<0.05).

Cumulative N release was significant in the first 35 days of decomposition of the SCCs, period in which legume species released between 27 and 65 % of N accumulated in biomass (Figures 2e and 2f). Cumulative amounts of N released by the legumes up to 35 days ranged from 35 kg ha^{-1} in velvet bean to 137 kg ha^{-1} in jack bean in 2010 and 25 kg ha^{-1} in velvet bean to 66 kg ha^{-1} in jack bean in 2011. Between 35 and 140 days of decomposition, N release varied from 20 and 36 % (21 and 66 kg ha^{-1} of N) of the total N accumulated in shoot biomass.

Table 2. Model parameters fit to the measured values of remaining C and N, half-life, and R^2 in each treatment

Treatment	Remaining C				Remaining N			
	A	kC	$t_{1/2}$	R^2	A	kN	$t_{1/2}$	R^2
	%	day^{-1}	day		%	day^{-1}	day	
2010								
Velvet bean	91.5 b	0.0071 c	97 ab	0.87	90.5 bc*	0.0081 cd	87	0.78
Pearl millet	92.2 b	0.0052 d*	134 a*	0.77	85.6 c*	0.0057 d*	130*	0.47
Dwarf pigeon pea	93.0 b	0.0085 b*	85 bc*	0.92	93.4 b*	0.0258 a*	51	0.71
Sunn hemp	98.7 a	0.0080 bc*	87 bc*	0.97	98.8 a*	0.0163 b*	43	0.89
Showy rattlebox	98.4 a*	0.0077 bc*	90 abc*	0.95	94.7 ab*	0.0110 c*	63	0.86
Jack bean	91.2 b	0.0140 a*	50 c*	0.94	93.2 b	0.0281 a*	25	0.91
2011								
Velvet bean	89.3 b	0.0058 b	122 bc	0.83	96.7 a	0.0053 c	133 b	0.80
Pearl millet	93.3 ab	0.0026 d	271 a	0.88	99.3 a	0.0015 d	665 a	0.39
Dwarf pigeon pea	94.7 a	0.0046 c	153 b	0.90	83.3 d	0.0074 bc	94 b	0.69
Sunn hemp	95.7 a	0.0048 bc	146 b	0.91	89.8 bc	0.0092 ab	76 b	0.80
Showy rattlebox	89.7 b	0.0058 b	144 b	0.82	88.6 c	0.0059 c	127 b	0.70
Jack bean	88.0 b	0.0075 a	94 c	0.86	95.1 ab	0.0109 a	64 b	0.90

Means followed by the same letter are not statistically different within each year according to the LSD test ($\alpha<0.05$). *: indicates that differences between years are statistically significant according to the LSD test ($\alpha<0.05$).

Relationship between C and N loss rates and chemical composition of the SCCs

The PCA analysis indicated that the two main components explained 87 and 84 % of the total data variance for the first and second year, respectively (Figure 3). In 2010 and 2011, *k*C rates were positively correlated with N content (0.93; 0.76), Csw (0.73; 0.68), and Nsw (0.91; 0.77) and negatively correlated with hemicellulose content (-0.54; -0.62), respectively. In both years, *k*C rates were not significantly correlated with lignin content of the cover crops.

The *k*N rates were positively correlated with Nsw (0.55; 0.76) and N content (0.77; 0.75) in 2010 and 2011, respectively, and with Csw (0.54) in 2011. The *k*N rates were inversely related to cellulose content (-0.49) in 2010 and to hemicellulose content (-0.57) in 2011.

DISCUSSION

Summer cover crops are rustic species, undemanding high soil fertility (Aita and Giacomini, 2006) and with high growth rates, which allows significant biomass production even in a short period of time (Weiler et al., 2018). Thus, the use of these cover species between cash crops (from January to April) is an interesting alternative to increase the input of C and N to the soil. Also, growing cover crops provides soil protection from erosion (Lanzanova et al., 2013; Ziech et al., 2015), reducing runoff and increasing soil water infiltration.

Carbon and N loss of the SCCs were characterized by a rapid initial phase, followed by a slower one. Several studies have shown the same pattern of decomposition and C and N loss of crop residues, which is attributed to the presence of organic fractions with different degrees of lability (Trinsoutrot et al., 2000; Aita and Giacomini, 2003; Redin et al., 2014). As indicated by PCA analysis, the constants *k*C and *k*N were positively related to the soluble compounds of crop shoots. In addition to the fraction readily available to soil

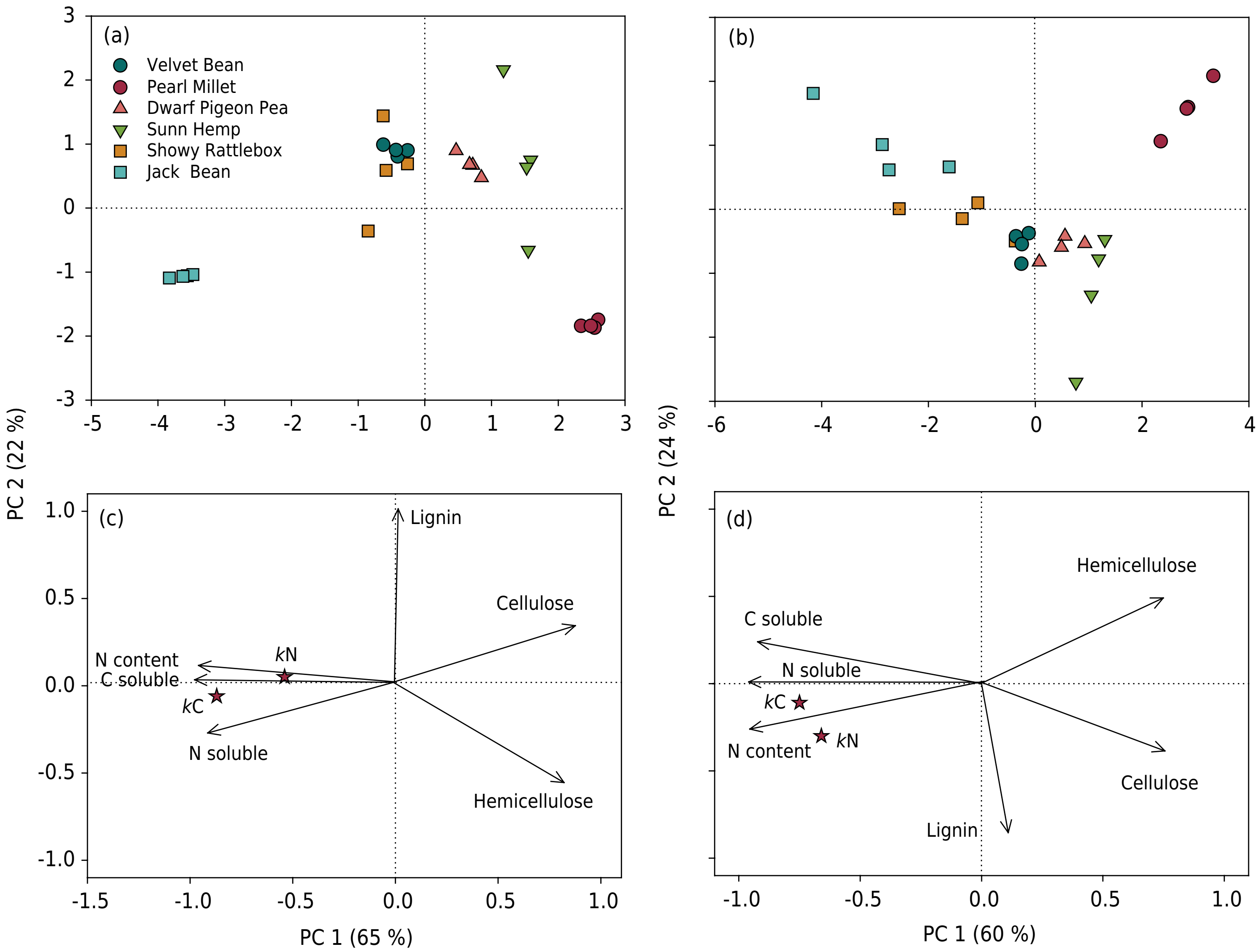

Figure 3. Principal component analysis for chemical composition of summer cover crop shoots and rates of C (*k*C) and N (*k*N) in 2010 (a, c) and 2011 (b, d). The top plots (a, b) are showing the PC scores, whereas the bottom plots (c, d) are showing the eigenvectors.

microbial population, climatic conditions were also a determining factor in decomposition and N release dynamics of the summer cover crops. The higher average air temperature and rainfall volume, especially during the first 35 days, promoted higher C and N loss rate of the crop shoots in the first year. Varela et al. (2017) suggest that the combination of climatic conditions (e.g., humidity) and initial chemical composition of crop shoots should regulate decomposition and nutrient release in no-till. Some water-soluble components such as sugars, low molecular weight phenols, and several nutrients are easily dissolved and leached from crop shoots and easily assimilated by the soil heterotrophic microbial population (Berg and McClaugherty, 2014). Thus, the greater the proportion of soluble components in cover crop shoots, the faster will be the release of nutrients in the period after termination. Also, it is possible to infer that increased rainfall volume after cover crop termination and higher temperatures accelerated crop shoot decomposition and N loss, as these conditions favor microbial population growth. Although the soluble fraction of the SCC shoots is rapidly released, the inclusion of these soil cover crops in cropping systems may be beneficial to increase soil C stabilization. Labile constituents of crop residues are used more efficiently by the soil microbial population, generating microbial products responsible for soil aggregation and stabilization of SOM through strong connections with the soil mineral matrix (Cotrufo et al., 2013).

Initial rapid decomposition was also favored by the low C:N ratio of the cover crops, except for pearl millet. The C:N ratio is one of the main characteristics to control the rates of decomposition and N loss of crop residues (Trinsoutrot et al., 2000; Redin et al., 2014). Mixing crops of distinct families has been tested by research, especially winter cover crops. This strategy could result in intermediate C:N ratio and combine N input and soil protection (Heinrichs et al., 2001; Doneda et al., 2012). Mixing of summer species also deserves further evaluation to optimize the use of these cover crops in cropping systems (Soratto et al., 2012).

As the decomposition process of crop shoots progresses, the concentration of structural polymers such as lignin increases in plant tissue, which reduces decomposition rates (Trinsoutrot et al., 2000; Jahanzad et al., 2016). The presence of structural polymers (i.e., lignin, cellulose, and hemicellulose) in plant tissue protects the cellular constituents from microbial attack (Cobo et al., 2002). Thus, there is an inverse relationship between the fibrous fraction of the plant tissue and the decomposition and N release of the crop residues (Aita and Giacomini, 2003; Redin et al., 2014). The PCA analysis showed our data generally support these assertions, but there were some inconsistencies (e.g., sunn hemp). Other components of crop shoots such as polyphenol content and its relationship to N content of the crop shoots should be considered in estimating decomposition (Puttaso et al., 2011). Among the summer legume species evaluated in this study, velvet bean and showy rattlebox released N more gradually. Carvalho et al. (2009) showed that although some legumes have a low C:N ratio, high percentage of aromatic compounds and consequently increased aromaticity and hydrophobicity of some species (e.g. velvet bean) confer lower rates of decomposition to these crop shoots.

Depending on the amounts and N release dynamics of the SCC shoots, they may substitute N fertilization at the sowing of subsequent winter crops. For instance, the recommended N fertilization of wheat or winter pastures varies from 15 to 30 kg ha^{-1}. These amounts could be fully met by N release of summer legumes under the conditions of our study. On the other hand, it is not possible to state that the SCCs could also substitute topdressing nitrogen fertilization because of the smaller amounts of N released from 35 to 140 days of decomposition. However, the benefits of using SCCs are not limited to N input for the subsequent crop. The use of summer cover crops is also an important alternative to promote long-term improvement in soil quality (Bayer et al., 2009; Tiecher et al., 2017). In addition, SCCs are characterized by large inputs of C and N to the soil associated with low nitrous oxide emissions during decomposition, which should also be a criterion for choosing the species that will compose the cropping systems (Weiler et al., 2018). Xavier et al. (2017) suggest that the selection of species depends on the purpose of the cover crops in the production system. Plants with slower decomposition rates may be important in the long term, while plants with rapid decomposition and nutrient release may be important in the short term when there is a high demand for nutrients, especially N.

Among the legumes evaluated in our study, sunn hemp stood out as a species of high biomass production (average of 8.5 Mg ha^{-1}) and intermediate C and N loss rates. At 140 days after SCC management, the amount of sunn hemp residues at the soil surface was 3.65 Mg ha^{-1}. This indicates that this species combines benefits of soil protection and nutrient input to the succeeding crop. Sunn hemp is also one of the SCC with the best trade-off between C and N inputs to the soil and N_2O emissions (Weiler et al., 2018). In the Cerrado region, Carvalho et al. (2004) also confirmed the potential of sunn hemp to provide N to the succeeding crop when grown in the spring, increasing corn yields by an additional 18 % compared to maintaining the soil fallow.

The growth period of the SCCs should also be considered, as it depends on the harvest time of the summer cash crops included in the cropping system. Harvesting of cash crops in January or February followed by the sowing of the SCCs allowed a longer growth period and, consequently, higher amounts of biomass and N to the soil. Therefore, it is important to choose short-cycle cash crops (e.g., corn and soybean) for the cultivation of SCCs in succession. Furthermore, root production by cover crops (Redin et al., 2018) and effective input to soil C and N should be evaluated in future studies.

CONCLUSIONS

Carbon and nitrogen loss rates of the summer cover crops are directly related to the contents of N and water-soluble C and N in crop shoots.

Nitrogen release of crop shoots is intense in the first 30 days, which requires the sowing of the winter species immediately after managing the cover crops.

Velvet bean and showy rattlebox were the legume species with more gradual N release, which can improve N use by succeeding crops, while sunn hemp was the species that combined higher remaining residues on the soil surface, preventing soil erosion and N release.

ACKNOWLEDGEMENTS

This work was supported by the Brazilian government through the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes).

AUTHOR CONTRIBUTIONS

Conceptualization: Douglas Adams Weiler (equal) and Sandro José Giacomini (equal).

Methodology: Douglas Adams Weiler (lead), Raquel Schmatz (equal), Getúlio Elias Pilecco (equal), Bruno Chaves (equal), and Leonardo Mendes Bastos (supporting).

Formal analysis: Douglas Adams Weiler (lead).

Investigation: Douglas Adams Weiler (equal) and Sandro José Giacomini (equal).

Data curation: Douglas Adams Weiler (lead).

Writing – original draft: Douglas Adams Weiler (lead).

Writing – review & editing: Douglas Adams Weiler (lead), Sandro José Giacomini (equal), and Celso Aita (supporting).

Visualization: Douglas Adams Weiler (lead) and Sandro José Giacomini (supporting).

Supervision: Sandro José Giacomini (lead).

Project administration: Sandro José Giacomini (lead).

Funding acquisition: Sandro José Giacomini (lead).

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