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Decomposition and Nutrient Release Dynamics of Shoot Phytomass of Cover Crops in the Recôncavo Baiano

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ABSTRACT: Evaluating the decomposition dynamics of vegetative residues from cover crops can provide a better understanding of nutrient release, which is fundamental when choosing a species that is adapted to local conditions. The objective of this study was to evaluate the decomposition rates and nutrient release dynamics of the shoot phytomass of different cover crops that have potential for agricultural use in the Recôncavo Baiano, Brazil. Crop residues of the following species were analyzed: sunn hemp (*Crotalaria juncea* L.) - CROT; velvet bean (*Mucuna aterrima* L.) - MUC; lab lab (*Dolichos lab lab* L.) - LAB; jack bean (*Canavalia ensiformis* [L.] DC.) - JB; white lupin (*Lupinus albus* L.) - WLUP; and Guinea grass (*Urochloa maxima* (Jacq.) R. Webster) - GRAS. The experiment was conducted in a randomized block design with four replications. The decomposition and nutrient release dynamics were evaluated using litter bags, and the remaining dry matter and the nutrient content of litter from each cover crop were quantified. The accumulation of macronutrients in the phytomass was in the following order: N > K > Ca > Mg > P > S. The highest decomposition rates of the phytomass occurred in the species JB, with half-life ($t_{1/2}$) of 36 days, and GRAS, with $t_{1/2}$ of 41 days. K was the element with the shortest $t_{1/2}$, suggesting a rapid transfer rate to the soil. Organic residues from the CROT and WLUP cover crops had lower decomposition rates and are, therefore, recommended for protecting soil in the region. Sunn hemp, unlike WLUP, also had residue of high chemical quality and, thus, it is an excellent nutrient recycler. Jack bean released nutrients into the soil the fastest due to its rapid decomposition rate; therefore, it is not recommended for ground cover.

Keywords: decomposition constant, lignin/N, half-life.

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INTRODUCTION

The Recôncavo Baiano is one the oldest occupied areas of Brazil, where cultivating sugarcane dominated agricultural production of the colony (Araújo, 2010). Presently, farming in the region is very diverse (tobacco, fruit, root, tuber, and vegetable production) but it has undergone a long period of decline in yield levels. Major reasons for this low agricultural productivity include lack of financial capital and lack of technologies for sustainable use of natural resources, such as soil (Silva and Costa, 2012). Family agriculture is predominant in the Recôncavo Baiano, where farms of less than 10 ha make up 57 % of the gross production value in the region (IBGE, 2006).

Designing more sustainable agricultural systems in the Recôncavo Baiano region should consider adopting technologies that maximize biological processes and nutrient recycling. Thus, the use of cover crops, also commonly called green manures (Correia and Durigan, 2008; Balota and Auler, 2011; Xavier et al., 2013), and nutrient recycling (Giacomini et al., 2003) should be considered as strategies to increase the productive capacity of soils, which would benefit crops of economic interest in the region. Among the most-used species of cover crops are legumes because of their ability to biologically fix N in association with diazotrophic bacteria (Mangaravite et al., 2014; Mendonça et al., 2017). Furthermore, some grasses and other non-leguminous plants have proven to be effective in keeping soil covered and recycling nutrients other than N (Gama-Rodrigues et al., 2007; Pacheco et al., 2011; Torres et al., 2015).

The choice of a particular cover crop should be based on the main function to be performed in the agricultural system. For example, to cover/protect soil, cover crops that have shoots with high phytomass and low decomposition rates should be used; to improve the chemical fertility of soil, species that decompose and release nutrients more quickly should be cultivated; and to improve the physical quality of soil, species that have more robust root systems should be considered. According to Souza et al. (2013), cover crops have to be regionally adapted so that they are easy to manage, are not invasive, are easy to plant and remove when needed, cover soil, and successfully compete with weeds for a certain time and at a low cost.

Understanding the pattern of decomposition and nutrient release is fundamental when selecting cover crops, because this allows adequate planning and more efficient use of the benefits of the technology, such as synchronization between the nutrient demand of a crop of economic interest and the nutrient release from residues (Aita and Giacomini, 2006; Gama-Rodrigues et al., 2007). The decomposition process is governed by the quality of the organic substrate, which is related to the organic constituents (e.g., cellulose, hemicellulose, polyphenols, and lignin), nutrient content, environmental climate conditions, and the microbial community that decomposes the deposited organic material and adapts to its quality (Mafongoya et al., 1998).

In Brazil, several studies have evaluated the decomposition and nutrient release potential of cover crops for different regions and purposes, for example, in no-tillage systems in the South and Southeast (Torres et al., 2015; Ziech et al., 2015; Souza et al., 2016; Pavinato et al., 2017), and cover crop mixtures in the semiarid region (Giongo et al., 2011). However, there are no scientific studies on this subject published in recognized journals that have been conducted in the region of the Recôncavo Baiano.

We tested the hypothesis that nutrients release of cover crops occur at different rates depend on residues quality, so that influences the management of such species for a specific agricultural systems in the region of Recôncavo Baiano. Hence, the objective of this study was to evaluate the decomposition rates and nutrient release dynamics of shoot phytomass of different cover crops that have potential agricultural use in the Recôncavo Baiano.

MATERIALS AND METHODS

The study was conducted in an experimental field at the Universidade Federal do Recôncavo da Bahia in the municipality of Cruz das Almas (12° 40′ 19″ S, 39° 06′ 22″ W, 220 m elevation) in a *Latossolo Amarelo Coeso* (Embrapa, 2006), a Haplic Ferralsol (Clayic, Amphidensic, Dystric), according to the FAO classification (IUSS Working Group WRB, 2015). The local climate is tropical hot and humid, with a dry season in the summer, type As in the Köppen classification system. The region has average annual rainfall of 1,131 mm, average annual temperature of 22.4 °C, and mean relative air humidity of 80 % (Almeida, 1991). The average rainfall and average temperatures during the study period are shown in figure 1.

Before starting the experiment, the soil layer from 0.0-0.20 m was characterized as follows: pH(H_2O) 5.2; 15 mg dm^{-3} of P (Mehlich-1); 0.15, 1.7, 0.8, and 2.0 $cmol_c\ dm^{-3}$ of K, Ca, Mg, and H+Al, respectively; 6.0 g kg^{-1} of organic matter; 57 % base saturation; and 785, 42, and 173 g kg^{-1} of sand, silt, and clay, respectively.

The history of use and management of the experimental site is presented in figure 2.

The cover crops were sown in June, 2013, in 18 m^2 (6 × 3 m) experimental plots arranged in a randomized complete block design with four replicates. The following seed densities were used: 25 kg ha^{-1} (sunn hemp); 80 kg ha^{-1} (velvet bean); 50 kg ha^{-1} (lab lab); 100 kg ha^{-1} (jack bean); 50 kg ha^{-1} (white lupin); and 15 kg ha^{-1} (Guinea grass).

The following cover crops residues were evaluated: sunn hemp (*Crotalaria juncea* L.) - CROT; velvet bean (*Mucuna aterrima* L.) - MUC; lab lab (*Dolichos lab lab* L.) - LAB; jack bean (*Canavalia ensiformis* [L.] DC.) - JB; white lupin (*Lupinus albus* L.) - WLUP; and Guinea grass (*Urochloa maxima* [Jacq.] R. Webster) - GRAS.

The cover crops were planted in furrows, 0.7 m apart, using a seeder adapted to a no-tillage system. To help initial plant growth, approximately 260 kg ha^{-1} of the phosphate Top-Phos 118 (N = 1 %; P_2O_5 = 18 %; Ca = 18 %; S = 11 %) was applied to the plots.

Shoot phytomass production was evaluated 93 days after sowing. A chronological period was used because the species have different phenologies and it was not possible to make their flowering times coincide. To quantify the shoot phytomass, a 0.5 × 0.5 m (0.25 m^2) square was randomly thrown in the center of the plot. The fresh phytomass in the square was collected, weighed, and then oven dried at 60 °C until constant weight

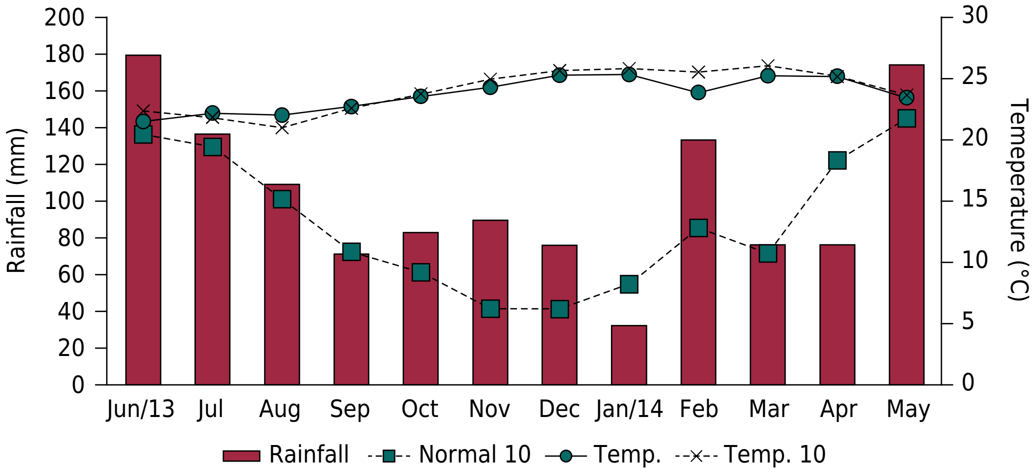

Figure 1. Climatic data throughout the growth period of cover crops (from June 2013 to May 2014) in Cruz das Almas, BA, Brazil. Vertical bars and horizontal line with circles correspond to monthly average of rainfall and temperature, respectively, measured over the period of the experiment. Normal 10 and Temp.10 lines represent the historical series of average monthly rainfall and temperature, respectively, in the last 10 years.

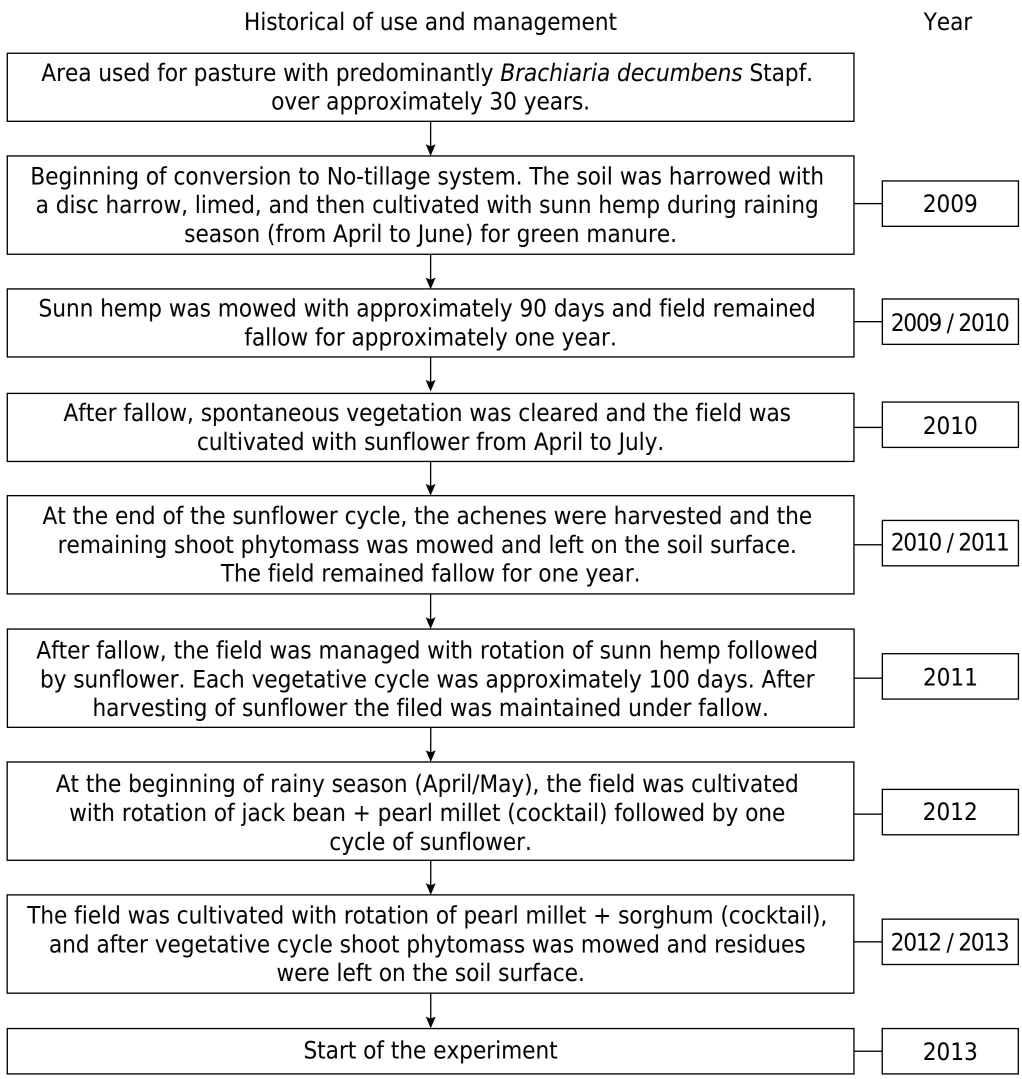

Figure 2. Historical of use and management of the experimental site.

to quantify the dry matter content. After quantifying the phytomass, the plants in the plot were mowed using a string trimmer. Part of the plant residue was separated to analyze the decomposition dynamic and the rest was maintained on the soil surface to decompose naturally.

The decomposition dynamic was evaluated from October 2013 to February 2014 using the litter bag method. The litter bags were 0.20 × 0.25 m, and made of 5-mm mesh nylon. The bags were filled with 100 g of fresh phytomass from each plant species and distributed in the field in direct contact with the soil. Three replications per treatment per collection time were used. The remaining dry matter was calculated by subtracting the initial moisture content of each sample. Litter bags were collected on days 8, 23, 53, 83, 113, and 143 after the bags were placed in the field. After each collection, the litter bags containing the remaining decomposed material were taken to the laboratory; and soil particles, insects, and other natural material (free or adhered) were separated from the initial plant material. The remaining material was placed in paper bags, oven-dried at 60 °C until constant weight, and ground.

The initial plant material (time zero) was analyzed for C, N, P, K, Ca, Mg, S, B, Cu, Mn, Zn, Fe, cellulose, hemicellulose, and lignin content, and the remaining material at each collection time was analyzed for N, P, K, Ca, Mg, S, B, Cu, Mn, Zn and Fe content. The C content was obtained by dry combustion using an elemental analyzer (Vario TOC Cube, Germany). The N content was quantified using sulfur digestion, followed by Kjeldahl distillation (Tedesco et al., 1995). Nitric-perchloric digestion was used to determine the P, K, Ca, and Mg concentrations according to the method described by Bataglia et al. (1983). The P content was quantified using colorimetry with formation of the blue color of the molybdenum phosphate complex in the presence of ascorbic acid, and K was measured using flame photometry. Ca and Mg were quantified using atomic absorption spectroscopy. Chemical analyses of the micronutrients were based on Malavolta et al. (1997) using atomic absorption spectroscopy. Cellulose, hemicellulose, and lignin content were determined using the neutral detergent fiber and acid detergent fiber method, according to Van Soest et al. (1991).

The remaining dry matter as a function of time was calculated by the difference between the original and final weight for each decomposition period. With these data, the decomposition and nutrient release rates were estimated using the simple exponential model described by Rezende et al. (1999), $x = x_0\ e^{-kt}$, where X represents the quantity of dry matter or nutrients remaining after the time period t (in days), X_0 is the quantity of initial dry matter or nutrients, and *k* is the decomposition or nutrient release constant. Based on the fitted model, considering the *k* value, it was possible to measure the half-life ($t_{1/2}$) of decomposition or of nutrient release as $t_{1/2} = \ln(2)/k$, where ln(2) is the neperian logarithm of the number 2, which is a constant value, and *k* is the decomposition constant obtained in the fitted model. The $t_{1/2}$ expresses the time period needed for half the residue to decompose or for half the nutrients in the residue to be released.

The phytomass production and nutrient accumulation data were subjected to analysis of variance, applying the F-test at 5 % significance. When significant, the means were compared using the Scott-Knott test at 5 % probability. Pearson's correlation test and simple linear regression analysis were applied to the data that involved the decomposition test. Data were analyzed with the aid of the ASSISTAT 7.7 program (Silva and Azevedo, 2006).

RESULTS AND DISCUSSION

Dry matter production and nutrient accumulation in the phytomass

The dry matter production of the shoot phytomass of the plants ranged from 6.4 to 16.5 Mg ha^{-1} (Figure 3). The legume CROT, followed by GRAS, showed the greatest phytomass production. MUC and LAB produced the least dry matter, and JB and WLUP presented intermediate values among the species evaluated. The accumulation of C in the phytomass ranged from 2.6 to 6.8 Mg ha^{-1} and showed similar trend in relation to dry matter storage. In general, the accumulation of C in the phytomass was around 40 % of the dry matter. CROT had the highest potential for storing C in the phytomass, exceeding the average of the other legumes by approximately 58 %.

The high phytomass production of the legume CROT in a short period of time indicates that this species has potential for the conditions in the Recôncavo da Bahia, as reported by Carvalho et al. (2004). The other species produced more than 6.0 Mg ha^{-1} of dry matter, which according to Darolt (1998) is the minimum value considered adequate for a cover crop to be incorporated into a crop rotation system. However, selecting a cover crop is based on more than phytomass production. Its function in a selected agriculture system also needs to be considered (for soil cover, nutrient cycling, or increasing organic C in the soil).

Among the species evaluated, WLUP produced 8.46 Mg ha^{-1} of phytomass but it did not adequately covered the soil, which could be perceived by bare patches in the plots. The cover crops that had the lowest dry matter content (MUC and LAB) are vines and exhibit high amounts of soil cover during their vegetative phase and deposit large amounts of senescent material on the soil. Similar results were found by Teodoro et al. (2011), who evaluated agronomic aspects of legumes in the Cerrado in the Jequitinhonha Valley. Herbaceous species with intermediate growth and a vine habit, such as MUC and

LAB, exert more pressure on spontaneous plant species (Dorn et al., 2015) and quickly protect the soil from erosion (Durán Zuazo and Rodríguez Pleguezuelo, 2008).

Chemical characterization of the phytomass of the different cover crop species is presented in table 1. The average overall C content in the plant tissue was 400 g kg^{-1}. The N content ranged from 17 to 30 g kg^{-1} and was highest in the species JB, MUC, and LAB. The P content was similar among the different materials, showing average of 2.8 g kg^{-1}. The GRAS and MUC cover crops had the highest K content and CROT had the lowest K content among the species evaluated. The highest Ca content was observed in the species LAB and JB, which had an average value of 14 g kg^{-1}, approximately 161 % more than the averages of the other species. These results demonstrate the greater potential of Ca recycling by these legumes. The Mg and S content varied little among the different plant residues evaluated.

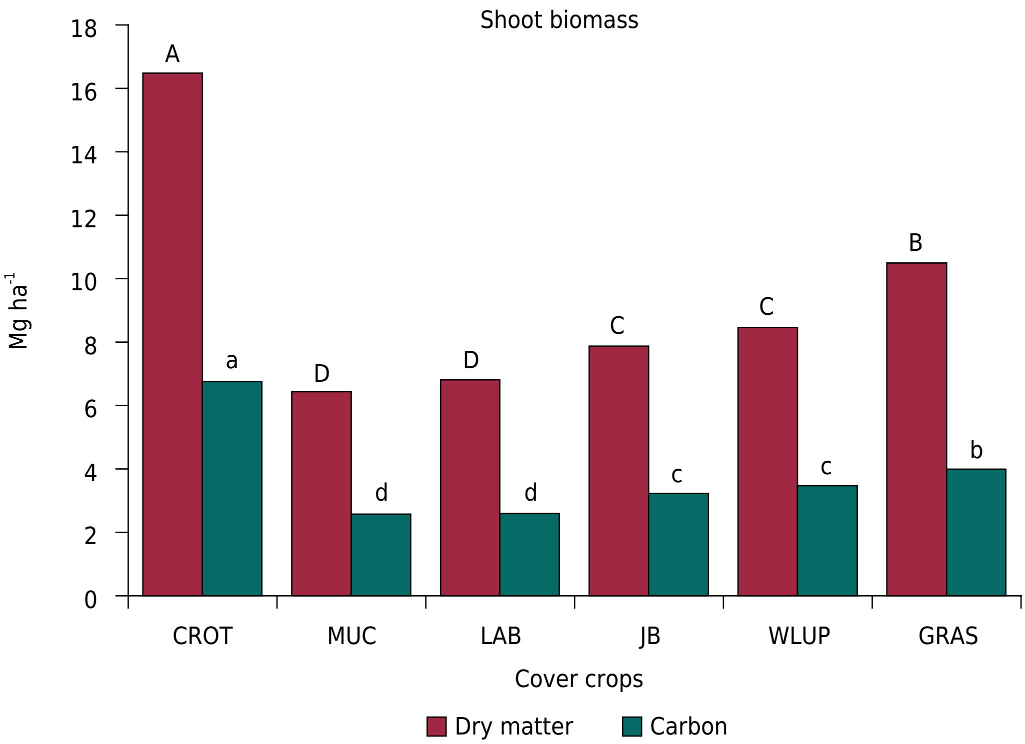

Figure 3. Dry matter production and carbon stock of the shoot biomass of different cover crops at 93 days after planting. CROT: *Crotalaria juncea* (sunn hemp); MUC: *Mucuna aterrima* (velvet bean); LAB: *Dolichos lablab* (lablab bean); JB: *Canavalia ensiformis* (Jack bean); WLUP: *Lupinus albus* (white lupine); GRAS: *Urochloa maxima* (Guinea grass). Different letters, upper case for dry matter production and lower case for carbon stocks, indicate significant differences between cover crops by the Scott-Knott test at p<0.05.

Table 1. Nutrients, cellulose (Cel), hemicellulose (Hem), and lignin (Lig) contents and C/N, Lig/N, C/P, and Lig/P ratios of shoot phytomass from different cover crops at 93 days after planting

Cover crop	C	N	P	K	Ca	Mg	S	Cel	Hem	Lig	C/N	Lig/N	C/P	Lig/P
	g kg^{-1} of dry matter													
CROT	410	18.08	2.11	9.21	5.61	3.41	0.94	419	114	86	23	4.8	194	40.8
MUC	401	22.72	2.28	24.51	7.79	2.02	1.51	363	135	134	18	5.9	176	58.8
LAB	380	20.40	3.76	19.71	14.69	4.80	2.25	318	126	94	19	4.6	101	25.0
JB	415	30.07	3.25	19.41	14.07	3.37	1.44	239	160	69	14	2.3	128	21.2
WLUP	408	18.08	2.34	14.91	4.54	2.37	1.48	335	139	75	23	4.1	174	32.1
GRAS	383	17.31	3.27	29.31	3.78	4.00	1.08	377	297	30	22	1.7	117	9.2

CROT: sunn hemp; MUC: velvet bean; LAB: field bean (lab lab); JB: jack bean; WLUP: white lupin; GRAS: Guinea grass.

The data on chemical composition of the different materials indicated that cellulose was the most abundant, followed by hemicellulose and lignin (Table 1). Cellulose and hemicellulose are the main constituents of cell walls and constitute 30 to 70 % of the plant C, while lignin protects the cellulose in the cell walls and is more resistant to decomposition (Mafongoya et al., 1998). In general, there was not a lot of variation in the cellulose and hemicellulose content among the cover crop species, except for more hemicellulose in the GRAS. In contrast, lignin content varied considerably among the materials. The MUC legume had the highest amount of lignin and GRAS had the lowest amount (Table 1).

Micronutrient accumulation in the dry phytomass of the cover crops (Table 2) was in the following order: N > K > Ca > Mg > P > S.

In general, macronutrient accumulation differed among the species. The legumes, except for WLUP, had a significantly higher average accumulation of N (19 %) than GRAS. Among the legumes, CROT accumulated the most N in the phytomass, followed by JB. The high capacity of N cycling by legumes via biological fixation is important information for determining management strategies for use of these plants as agricultural soil conditioners, which is discussed by Mendonça et al. (2017).

The P stocks in the phytomass of the cover crops ranged from 20 to 35 kg ha^{-1} (Table 2), and had a lower range of variation than N. The species CROT and GRAS had the highest P accumulation capacity, and MUC and WLUP had the lowest. Most P in plant tissues occurs in the cell vacuole as a mineral, which is very water soluble (Marschner, 1995). Thus, to be released from the residue, the vacuole has to be broken.

Potassium was the second most abundant element in the shoot phytomass of the different cover crops (Table 2). The species GRAS accumulated the most K, with an average of 52 % more than the other species. The lowest K accumulation potential was observed in the species WLUP, which did not significantly differ from the legume LAB. Cover crops that are more efficient at storing K represents a suitable strategy in a program of crop rotation to return this nutrient for the next crop. Since K is a fundamental element in activating specific enzymes related to starch synthesis (Hawker et al., 1974; Quadros et al., 2009), green manures that provide a higher quantity of K are an efficient alterative for species that demand K, such as tuberous species that accumulate starch (e.g., yams and manioc), that have high economic value in the Recôncavo da Bahia.

The potential for Ca accumulation in the shoot phytomass varied substantially among the materials (Table 2). The legumes, except for WLUP, showed a higher capacity for recycling Ca than GRAS. The average Ca stock in the legumes was 55 % more than the

Table 2. Macronutrient storage in the shoot phytomass from different cover crops at 93 days after planting

Cover crop	N	P	K	Ca	Mg	S
	kg ha^{-1}					
CROT	298 a	35 a	152 c	92 c	56 a	16 a
MUC	157 e	20 c	169 b	54 d	14 f	11 c
LAB	194 c	26 b	137 d	102 b	33 c	16 a
JB	245 b	26 b	153 c	110 a	27 d	10 c
WLUP	153 e	20 c	126 d	38 e	20 e	12 b
GRAS	182 d	34 a	308 a	40 e	42 b	12 b
Average	206	26	169	73	32	12

CROT: sunn hemp; MUC: velvet bean; LAB: field bean (lab lab); JB: jack bean; WLUP: white lupin; GRAS: Guinea grass. Different letters in the same column indicate significant differences between cover crops by the Scott-Knott test at p<0.05.

average obtained for the grass. Among the legume species, JB and LAB have a greater capacity to accumulate Ca than WLUP and MUC.

Sulfur was the least abundant element in the shoot phytomass (Table 2). The accumulation of this nutrient in the plant tissue varied little among the cover crops. The highest S stocks were observed in the species CROT and LAB. Although significant, the difference in the accumulated S values between the species that had the most and least S was small and, therefore, this was of little value from an agronomic point of view.

Decomposition and nutrient release dynamics

The decomposition dynamic of the plant residues had an initial rapid phase until the 23rd day (Figure 4). According to Mafongoya et al. (1998), in this phase the residues have greater bioavailability of nutrients and soluble C, which attracts microorganisms that rapidly colonize the organic substrate and accelerate the decomposition process.

The highest rates of phytomass decomposition occurred in the species JB and GRAS, which had a $t_{1/2}$ of 36 and 41 days, respectively (Figure 5). The species CROT and WLUP had the highest $t_{1/2}$ (99 days), suggesting greater resistance to decomposition. Intermediate $t_{1/2}$ values were observed in the legumes LAB and MUC.

Regarding nutrient release dynamics (Figure 5), macronutrient release was generally faster than micronutrient. Except for the species CROT and MUC, the release of N, Ca, and Mg occurred at a similar rate, with an average $t_{1/2}$ of 45 days. The nutrients P and S had an average $t_{1/2}$ of 28 days, indicating that they were released more quickly than N, Ca, and Mg. The element K had the highest rate of release for all of the species evaluated, with an average $t_{1/2}$ of six days. This result shows how easily this element is released during the decomposition process. Rapid release of K from plant tissues during the decomposition process is well known (Giacomini et al., 2003; Cattanio et al., 2008; Teixeira et al., 2011). Among the micronutrients, in general, Mn, Zn, and Fe had the highest average $t_{1/2}$, suggesting lower release rates than B and Cu.

Despite of the general behavior of nutrients release as previously related, each species showed a particular pattern of nutrient mineralization (Figure 5). For example, the legume

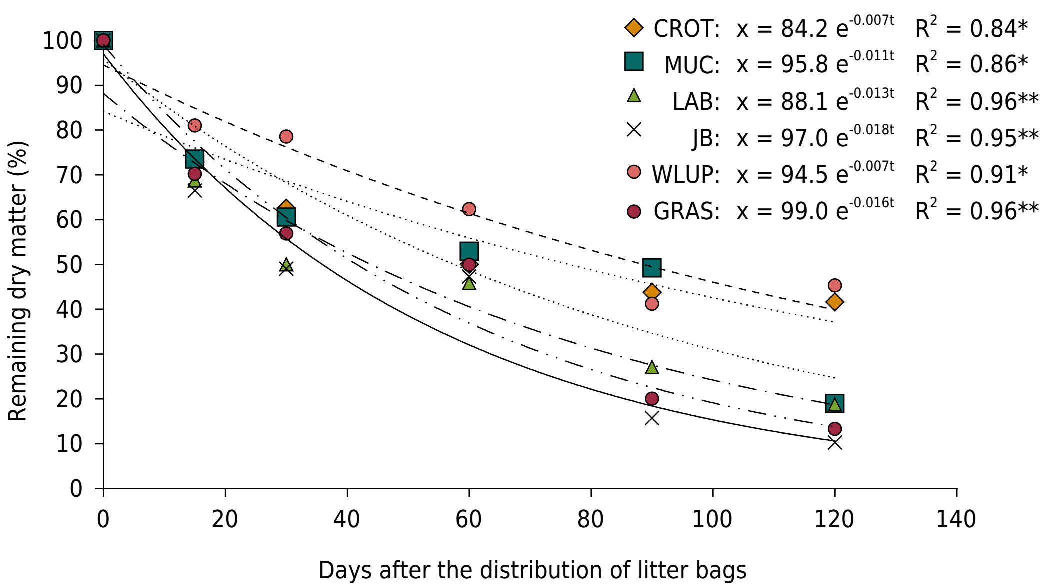

Figure 4. Dry matter remaining in litter bags filled with different litter from cover crops incubated for 120 days on the soil surface. Values represent means of three replicates. Curves fitted in the exponential model: $x = x_0\ e^{-kt}$. CROT: *Crotalaria juncea* (sunn hemp); MUC: *Mucuna aterrima* (velvet bean); LAB: *Dolichos lablab* (lablab bean); JB: *Canavalia ensiformis* (Jack bean); WLUP: *Lupinus albus* (white lupine); GRAS: *Urochloa maxima* (Guinea grass).

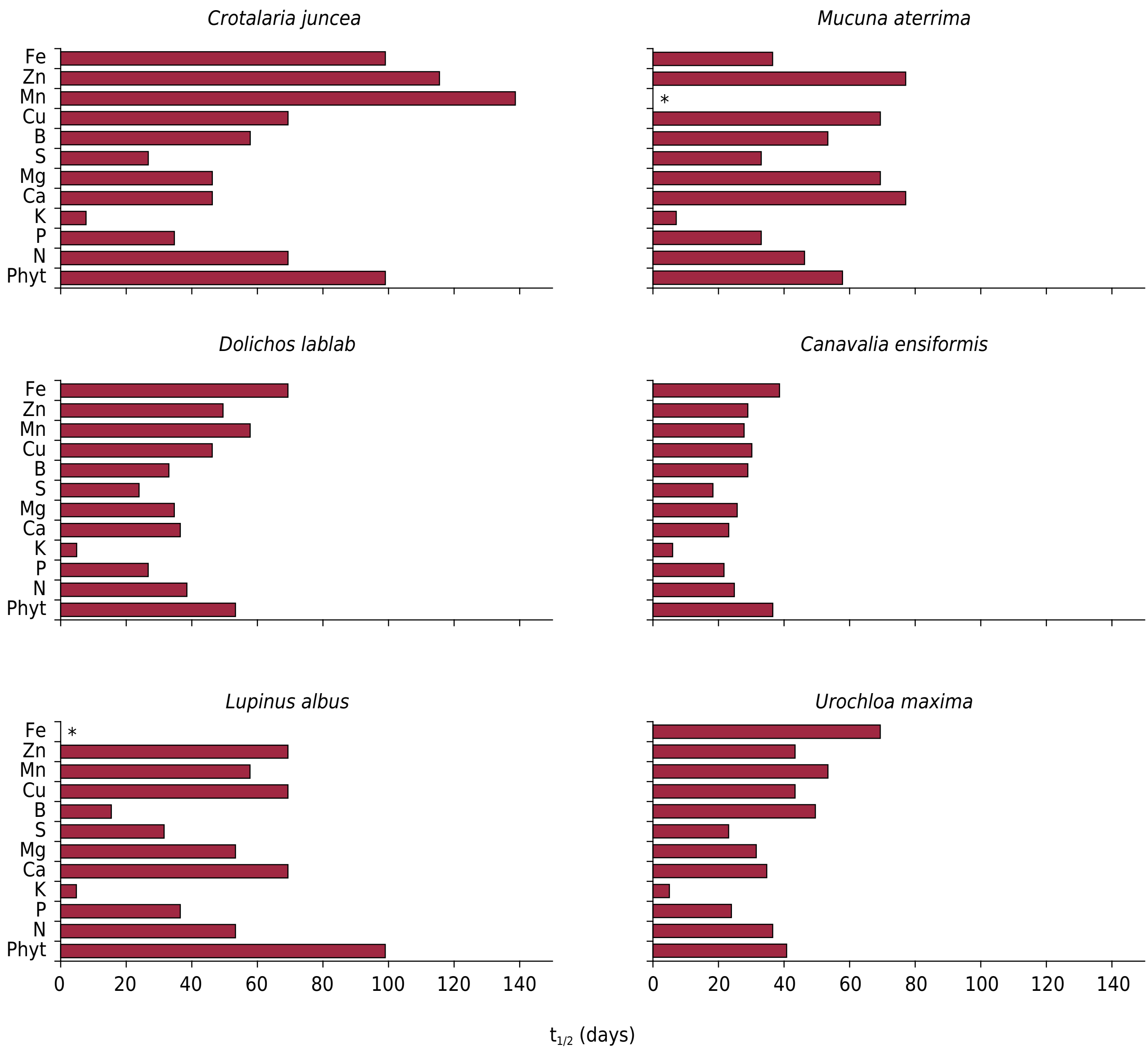

Figure 5. Half-lives ($t_{1/2}$) of phytomass (Phyt) and nutrients of litter from different cover crops. *: not measured.

JB released all nutrients at the highest rate. For JB the release dynamics showed a similar $t_{1/2}$ pattern for all of the nutrients, except for K and Fe, indicating that, on average, 50 % of the nutrients in the phytomass were released in 27 days. The species LAB and GRAS showed very similar nutrient release patterns (Figure 5), however with lower mineralization rate in relation to JB. The legumes CROT and MUC tended to release nutrients slower than the materials of the other species.

Among the legumes, CROT had the lowest release rate of N, followed by WLUP. The residues of LAB and MUC had intermediate $t_{1/2}$ values for N. The species CROT and JB showed the greatest capacity for accumulating N in the phytomass (Table 2); however, their decomposition dynamics showed practically opposite patterns in release of this element. While CROT released 149 kg ha^{-1} of N in 69 days, JB released 122 kg ha^{-1} of N in 25 days. Although the species WLUP had the lowest N storage capacity (Table 2), its release rate of this element was slower than the other taxa (Figure 5). These results demonstrate that selecting a species depends on the function to be performed in a management plan. In this study, the residues of CROT and WLUP had the lowest phytomass decomposition and N release rates, suggesting they are more adequate medium - to long-term options for covering soil and recycling N. The species JB has low potential for soil cover; however, it rapidly releases nutrients, which may be important for short-term conditioning of the chemical fertility of a soil.

The lowest P release rates were recorded for the species WLUP, CROT, and MUC (Figure 5). Although MUC and WLUP have lower P accumulation potential in the phytomass than CROT, the three species have a very similar $t_{1/2}$ for P. Among the macronutrients, P was one of the elements stored in lowest amounts in the plant tissue and had an intermediate release rate ($t_{1/2}$ = 29 days) compared to the others. The lower P release rates in the species are associated with higher C/P ratio values (Table 1), suggesting that this index has the ability to predict P release. The higher the C/P ratio of the plant material, the lower the transfer of this element to the soil during decomposition.

In general, although the species accumulated different amounts of K (Table 2), the K release rates were very similar among the species (Figure 5). Regardless of the species evaluated, K is a rapidly released element, with an average $t_{1/2}$ of six days. Studies suggest that the rapid release of K is directly associated with leaching as a transfer mechanism of this nutrient to the soil. This is because K is not a structural component of any plant compound (Lupwayi et al., 2006; Gama-Rodrigues et al., 2007) and most of this element in plant tissue (up to 70 %) is in a water soluble form (Giacomini et al., 2003). The mineralization of K depends on the concentrations of C and phenolic compounds during the incubation period (Cattanio et al., 2008). Considering the storage potential of K (Table 2) and the average $t_{1/2}$ observed for this element (Figure 5), in only six days, the K content released by the species would be the following: GRAS (154 kg ha^{-1}) > MUC (84 kg ha^{-1}) > CROT = JB (76 kg ha^{-1}) > LAB = WLUP (65 kg ha^{-1}).

The release pattern of Ca and Mg was practically the same for all the species evaluated, except for WLUP, which had a lower release rate of Ca than Mg (Figure 5). The lowest Ca and Mg release rates were recorded for the species MUC and WLUP, followed by CROT. The legume WLUP had the lowest potential to accumulate Ca and Mg (Table 2), but the release dynamics indicated that this species can release these elements more slowly than the others. The slow release of Ca is linked to the fact it is a constituent of the middle lamella of the cell wall (Taiz and Zeiger, 1991), forming one of the most recalcitrant components of plant tissues.

The release dynamic of S was very similar to the release of P (Figure 5). MUC, WLUP, and CROT had lower release rates of S, with an average $t_{1/2}$ of 30 days. S was the element least taken up by the plant tissues (Table 1), and the accumulation potential of this nutrient by the different species was very similar (Table 2). On average, except for JB, the residues had the potential to release around 6 kg ha^{-1} of S in 28 days.

Plant material that had higher amounts of lignin, such as MUC and LAB (Table 1), did not necessarily have lower decomposition rates, suggesting that lignin content was not a determining factor in the decomposition process. As alternatives to analysis of lignin content, several quality indices have been proposed as good predictors of the decomposition and nutrient release rates. Among these, the following ratios stand out: C/N, C/P, lignin/N, polyphenol/N, and polyphenol + lignin/N (Mafongoya et al., 1998; Giacomini et al., 2003; Gama-Rodrigues et al., 2007). In general, elevated values for any of these indices result in low decomposition and nutrient release. According to Mafongoya et al. (1998), the main objective of using these indices is to establish robust parameters that have good predictive ability of decomposition and nutrient release dynamics, which means detailed studies regarding different locations and plants would not be needed. In the present study, however, the predictive ability of these indices was low. Despite high correlation coefficients, only few showed significant relationship (Table 3). Among these, were notable: negative correlation

Table 3. Pearson's correlation coefficient between decomposition or nutrient release constant (*k*) and carbon/nitrogen (C/N), lignin/nitrogen (Lig/N), carbon/phosphorus (C/P), and lignin/phosphorus (Lig/P) ratios of the shoot phytomass from different cover crops

	Phytomass	N	P	K	Ca	Mg	S
C/N	-0.715	-0.847*	-0.659	0.156	-0.651	-0.534	-0.644
Lig/N	-0.681	-0.650	-0.777	-0.433	-0.733	-0.825*	-0.739
C/P	-0.748	-0.688	-0.804	-0.634	-0.647	-0.746	-0.640
Lig/P	-0.559	-0.533	-0.718	-0.662	-0.684	-0.820*	-0.689

*: significant correlation at 5 %.

between release of N and both C/N and lignin/N ratios; and release of Mg and both lignin/N and lignin/P ratios.

There is a lot of variation in the predictive potential of these indices in the literature, suggesting that the use of them as parameters to better understand the dynamics of decomposition and nutrient release is limited, and depends on the type of plant material and local soil and climate conditions. Gama-Rodrigues et al. (2007) suggested that the predictive models involved in the relationship of these indices with nutrient release rates are, in general, applicable to specific locations, and are restricted by soil and climatic requirements, type of production system, associated species, and management.

The distinct decomposition and nutrient release rates of the species evaluated in the present study show the need to associate management of these species to specific agroecosystem functions in the region of the Recôncavo Baiano. Functions such as soil cover, for example, can be improved by using residues with a longer $t_{1/2}$, such as the legumes CROT and WLUP. Other species, for example, JB, are better if the objective is to rapidly transfer nutrients to the soil.

For annual crops, such as corn, beans, peanuts, and some fruits, pre-planting cover crops that demand less water and rapidly decompose (e.g., velvet bean and jack bean) is recommended because they release nutrients faster. In areas that will be fallow or where the soil needs to be restored, cover crops should be used to improve the physical, chemical, and biological characteristics of the soil. For that reason, combining grass and legume species (a mix of cover crops) during the rainy season is the best strategy. For perennial crops, such as the citrus orchards that are common in the region, it is possible to plant legumes (which biologically fix N) and grasses (which increase the organic C in the soil) between the crops during the rainy season (Oliveira et al., 2016).

Nutrient release adjustment by mixing cover crop residues with different chemical quality is a very promising technique, as indicated by Ziech et al. (2015). Combining residues that decompose slowly and release nutrients quickly could be a good strategy for most of the crops grown in the region.

Another challenge, based on information about the decomposition and nutrient release rates obtained in the present study, is synchronizing the phase of greatest nutritional demand of the associated crops with the nutrients supplied by the cover crops. Moreover, this study evaluated the chemical quality of the shoot phytomass of different cover crops. However, to help choose the most adequate species for the region, new studies are necessary to investigate the role that roots play in the physical fertility of the soil, as conducted by Cunha et al. (2011). It is possible that a species considered low in quality from a chemical point of view could be extremely efficient at improving the physical quality of a soil because of its root system. In addition to the soil factor, new studies should focus on phytosanitary aspects to evaluate the attractiveness of these plants to insect pests or natural enemies.

CONCLUSIONS

The patterns of decomposition and nutrient release varied according to the species of cover crop. Jack bean released the nutrients into the soil the fastest due to its rapid rate of decomposition, and thus its use for the specific function of ground cover is not suggested, whereas sunn hemp and white lupin are recommended for covering and/or protecting soil in the Recôncavo Baiano.

Sunn hemp had residues of high chemical quality, and is thus an excellent nutrient recycler.

Among the macronutrients, N, Ca, and Mg were released later than P and S, and K was released the fastest among all of the cover crops evaluated.

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REFERENCES

Aita C, Giacomini SJ. Plantas de cobertura de solo em sistemas agrícolas. In: Alves BJR, Urquiaga S, Aita C, Boddey RM, Jantalia CP, Camargo FAO, editores. Manejo de sistemas agrícolas: impacto no sequestro de C e nas emissões de gases de efeito estufa. Porto Alegre: Genesis; 2006. p.59-79.

Almeida OA. Informações meteorológicas do CNP - Mandioca e Fruticultura Tropical. Cruz das Almas: Embrapa - CNPMF; 1991. (Documentos, 34).

Araújo AO. Dinâmica territorial do Recôncavo baiano: espacialidade e Temporalidade. In: Anais do 16º Encontro Nacional de Geógrafos; 2010; Porto Alegre. Porto Alegre: Associação do Geógrafos Brasileiros; 2010. Não paginado.

Balota EL, Auler PAM. Soil microbial biomass under different management and tillage systems of permanent intercropped cover species in an orange orchard. Rev Bras Cienc Solo. 2011;35:1873-83. https://doi.org/10.1590/S0100-06832011000600004

Bataglia OC, Furlani AMC, Teixeira JPF, Furlani PR, Gallo JR. Métodos de análise química de plantas. Campinas: Instituto Agronômico de Campinas; 1983. (Boletim Técnico, 78).

Carvalho SRL, Rezende JO, Fernandes JC, Pereira AP. Avaliação da resistência à penetração mecânica do solo cultivado com leguminosas e gramíneas em solo coeso dos tabuleiros costeiro do Recôncavo Baiano (etapa I). Salvador: EBDA; 2004. (Documentos, 20).

Cattanio JH, Kuehne R, Vlek PLG. Organic material decomposition and nutrient dynamics in a mulch system enriched with leguminous trees in the Amazon. Rev Bras Cienc Solo. 2008;32:1073-86. https://doi.org/10.1590/S0100-06832008000300016

Correia NM, Durigan JC. Culturas de cobertura e sua influência na fertilidade do solo sob sistema de plantio direto (SPD). Biosci J. 2008;24:20-31.

Cunha EQ, Stone LF, Moreira JAA, Ferreira EPB, Didonet AD, Leandro WM. Sistemas de preparo do solo e culturas de cobertura na produção orgânica de feijão e milho. I - Atributos físicos do solo. Rev Bras Cienc Solo. 2011;35:589-602. https://doi.org/10.1590/S0100-06832011000200028

Darolt MR. Princípios para manutenção e implantação do sistema. In: Darolt MR, editor. Plantio direto: pequena propriedade sustentável. Curitiba: IAPAR; 1998. (Circular, 101).

Dorn B, Jossi W, Van Der Heijden MGA. Weed suppression by cover crops: comparative on-farm experiments under integrated and organic conservation tillage. Weed Res. 2015;55:586-97. https://doi.org/10.1111/wre.12175

Durán Zuazo VH, Rodríguez Pleguezuelo CR. Soil-erosion and runoff prevention by plant covers. A review. Agron Sustain Dev. 2008;28:65-86. https://doi.org/10.1051/agro:2007062

Gama-Rodrigues AC, Gama-Rodrigues EF, Brito EC. Decomposição e liberação de nutrientes de resíduos culturais de plantas de cobertura em Argissolo Vermelho-Amarelo na região noroeste fluminense (RJ). Rev Bras Cienc Solo. 2007;31:1421-8. https://doi.org/10.1590/S0100-06832007000600019

Giacomini SJ, Aita C, Hübner AP, Lunkes A, Guidini E, Amaral EB. Liberação de fósforo e potássio durante a decomposição de resíduos culturais em plantio direto. Pesq Agropec Bras. 2003;38:1097-104. https://doi.org/10.1590/S0100-204X2003000900011

Giongo V, Mendes AMS, Cunha TJF, Galvão SRS. Decomposição e liberação de nutrientes de coquetéis vegetais para utilização no semiárido brasileiro. Rev Cienc Agron. 2011;42:611-8. https://doi.org/10.1590/S1806-66902011000300006

Hawker JS, Marschner H, Downton WJS. Effects of sodium and potassium on starch synthesis in leaves. Funct. Plant Biol. 1974;1:491-501. https://doi.org/10.1071/PP9740491

Instituto Brasileiro de Geografia e Estatística - IBGE. Censo agropecuário 2006 - Brasil, grandes regiões e unidades da federação. Rio de Janeiro: Ministério do Planejamento, Orçamento e Gestão; 2006.

IUSS Working Group WRB. World Reference Base for Soil Resources 2014, International soil classification system for naming soils and creating legends for soil maps. update 2015. Rome: FAO; 2015. (World Soil Resources Reports, 106).

Lupwayi NZ, Clayton GW, O'Donovan JT, Harker KN, Turkington TK, Soon YK. Potassium release during decomposition of crop residues under conventional and zero tillage. Can J Soil Sci. 2006;86:473-81. https://doi.org/10.4141/S05-049

Mafongoya PL, Giller KE, Palm CA. Decomposition and nitrogen release patterns of tree prunings and litter. Agrofor Syst. 1998;38:77-97. https://doi.org/10.1023/A:1005978101429

Malavolta E, Vitti GC, Oliveira SA. Avaliação do estado nutricional das plantas: princípios e aplicações. 2a ed. Piracicaba: Potafós; 1997.

Mangaravite JCS, Passos RR, Andrade FV, Burak DL, Mendonça ES. Phytomass production and nutrient accumulation by green manure species. Rev Ceres. 2014;61:732-9. https://doi.org/10.1590/0034-737X201461050017

Marschner H. Functions of mineral nutrients: macro-nutrients. In: Mineral nutrition of higher plants. 2nd ed. San Diego: Academic; 1995. p. 229-312.

Mendonça ES, Lima PC, Guimarães GP, Moura WM, Andrade FV. Biological nitrogen fixation by legumes and N uptake by coffee plants. Rev Bras Cienc Solo. 2017;41:e0160178. https://doi.org/10.1590/18069657rbcs20160178

Oliveira FER, Oliveira JM, Xavier FAS. Changes in soil organic carbon fractions in response to cover crops in an orange orchard. Rev Bras Cienc Solo. 2016;40:e0150105. https://doi.org/10.1590/18069657rbcs20150105

Pacheco LP, Leandro WM, Machado PLOA, Assis RL, Cobucci T, Madari BE, Petter FA. Produção de fitomassa e acúmulo e liberação de nutrientes por plantas de cobertura na safrinha. Pesq Agropec Bras. 2011;46:17-25. https://doi.org/10.1590/S0100-204X2011000100003

Pavinato PS, Rodrigues M, Soltangheisi A, Sartor LR, Withers PJA. Effects of cover crops and phosphorus sources on maize yield, phosphorus uptake, and phosphorus use efficiency. Agron J. 2017;109:1039-47. https://doi.org/10.2134/agronj2016.06.0323

Quadros DA, Iung MC, Ferreira SMR, Freitas RJS. Composição química de tubérculos de batata para processamento, cultivados sob diferentes doses e fontes de potássio. Ciênc Tecnol Aliment. 2009;29:316-23. https://doi.org/10.1590/S0101-20612009000200013

Rezende CP, Cantarutti RB, Braga JM, Gomide JA, Pereira JM, Ferreira E, Tarré R, Macedo R, Alves BJR, Urquiaga S, Cadisch G, Giller KE, Boddey RM. Litter deposition and disappearance in *Brachiaria* pastures in the Atlantic Forest region of the South of Bahia, Brazil. Nutr Cycl Agroecosys. 1999;54:99-112. https://doi.org/10.1023/A:1009797419216

Silva BCD, Costa AED. Diagnóstico sócio-produtivo dos agricultores familiares cooperados à cooperativa da agricultura familiar do território do recôncavo da Bahia - COOAFATRE. Magistra. 2012;24:151-9.

Silva FAS, Azevedo CAV. A new version of the Assistat - statistical assistance software. In: 4th World Congress on Computers in Agriculture; 2006; Orlando. Orlando: American Society of Agricultural and Biological Engineers. 2006. p.393-6.

Souza GP, Figueiredo CC, Souza DMG. Soil organic matter as affected by management systems, phosphate fertilization, and cover crops. Pesq agropec bras. 2016;51:1668-76. https://doi.org/10.1590/S0100-204X2016000900067

Souza LD, Santos CV, Souza LS, Pereira BLS. Resistência à penetração em Latossolo Amarelo dos Tabuleiros Costeiros, sob cobertura vegetal com leguminosas. Cruz das Almas: Embrapa Mandioca e Fruticultura; 2013. (Boletim de pesquisa e desenvolvimento, 58).

Taiz L, Zeiger E. Plant physiology. Redwood City: Benjamin/Cummings Publishing Company; 1991.

Tedesco MJ, Gianello C, Bissani CA, Bohnen H, Volkweiss SJ. Análises de solo, plantas e outros materiais. 2a ed rev ampl. Porto Alegre: Universidade Federal do Rio Grande do Sul; 1995. (Boletim técnico, 5).

Teixeira CM, Carvalho GJ, Silva CA, Andrade MJB, Pereira JM. Liberação de macronutrientes das palhadas de milheto solteiro e consorciado com feijão-de-porco sob cultivo de feijão. Rev Bras Cienc Solo. 2010;34:497-505. https://doi.org/10.1590/S0100-06832010000200023

Teixeira MB, Loss A, Pereira MG, Pimentel C. Decomposição e liberação de nutrientes da parte aérea de plantas de milheto e sorgo. Rev Bras Cienc Solo. 2011;35:867-76. https://doi.org/10.1590/S0100-06832011000300021

Teodoro RB, Oliveira FL, Silva DMN, Fávero C, Quaresma MAL. Aspectos agronômicos de leguminosas para adubação verde no cerrado do alto do Vale do Jequitinhonha. Rev Bras Cienc Solo. 2011;35:635-43. https://doi.org/10.1590/S0100-06832011000200032

Torres JLR, Pereira MG, Rodrigues Junior DJ, Loss A. Production, decomposition of residues and yield of maize and soybeans grown on cover crops. Rev Cienc Agron. 2015;46:451-9. https://doi.org/10.5935/1806-6690.20150026

Van Soest PJ, Robertson JB, Lewis BA. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J Dairy Sci 1991;74:3583-97. https://doi.org/10.3168/jds.S0022-0302(91)78551-2

Xavier FAS, Maia SMF, Ribeiro KA, Mendonça ES, Oliveira TS. Effect of cover plants on soil C and N dynamics in different soil management systems in dwarf cashew culture. Agric Ecosyst Environ. 2013;165:173-83. https://doi.org/10.1016/j.agee.2012.12.003

Ziech ARD, Conceição PC, Luchese AV, Balin NM, Candiotto G, Garmus TG. Proteção do solo por plantas de cobertura de ciclo hibernal na região Sul do Brasil. Pesq Agropec Bras. 2015;50:374-82. https://doi.org/10.1590/S0100-204X2015000500004