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Nutrient cycling of different plant residues and fertilizer doses in broccoli cultivation

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ABSTRACT

The decomposition and release of nutrients from plant residues that precede the cultivation of vegetables can positively affect the morphological parameters and crop productivity. The objective of this study was to evaluate the effects of plant residue decomposition and the cycling of macro and micronutrients of four cover crops preceding the broccoli production (single head Avenger hybrid). A 4x3 factorial scheme was implemented including four cover crops: signal grass (SG), pearl millet (PM), sunn hemp (SH), mixture PM+SH; and three doses of mineral fertilizer: 0, 50 (200 kg ha^{-1} of P_2O_5, 50 kg ha^{-1} of K_2O, 75 kg ha^{-1} of N) and 100% of the recommended fertilizer dose (400 kg ha^{-1} of P_2O_5, 100 kg ha^{-1} of K_2O and 150 kg ha^{-1} of N). Fresh (FB) and dry biomass (DB), residue decomposition, nutrient cycling of cover crops, the number of leaves, head height (HH), stem diameter (SD), head diameter (HD), head fresh-biomass (FB), head dry biomass (DB) and broccoli yield were evaluated. The FB production from PM (25.9 t ha^{-1}), SG (23.3 t ha^{-1}) and mixture PM+SH (23.9 t ha^{-1}) were similar, while the largest production of DB occurred in the SG (11.9 t ha^{-1}). The lowest rate of decomposition and the greatest half-life time of residues occurred where PM was present. The accumulation and nutrient cycling follow the sequence K>N>Ca>Mg>P>S and Mn>Zn>B>Cu for all cover crop treatments evaluated. The highest SD (51.95; 51.44 and 50.67 mm), HD (187.97; 187.41 and 183.48 mm), FB (1.01; 1.00 and 0.97 kg), DB (0.08; 0.07 and 0.07 kg) and broccoli yield (25.3; 24.9 and 24.7 t ha^{-1}) was observed in the 100% dose of mineral fertilizer and on the residues of SH or PM+SH mixture, respectively.

Keywords: *Brassica oleracea* var. *itálica*, *Crotalaria juncea*, *Urochloa brizantha* cv *marandu*, *Pennisetum glaucum*, NPK.

RESUMO

Ciclagem de nutrientes de diferentes resíduos vegetais e doses de fertilizantes no cultivo de brócolis

A decomposição e a liberação de nutrientes dos resíduos das plantas que antecedem o plantio direto das hortaliças podem afetar de forma positiva os parâmetros morfológicos e a produtividade da cultura. O objetivo deste estudo foi avaliar os efeitos da decomposição de resíduos e da ciclagem de macro e micronutrientes de quatro culturas de cobertura em uma área de produção de brócolis (híbrido Avenger, cabeça única). Em delineamento de blocos ao acaso, em esquema fatorial 4x3, foram avaliadas quatro coberturas: braquiária (B), milheto (M), crotalária (C) e a mistura M+C; três doses de fertilizante mineral: 0, 50 (200 kg ha^{-1} de P_2O_5, 50 kg ha^{-1} de K_2O e 75 kg ha^{-1} de N) e 100% da dose de fertilizante recomendado (400 kg ha^{-1} de P_2O_5, 100 kg ha^{-1} de K_2O e 150 kg ha^{-1} de N), com quatro repetições. Foram avaliadas a biomassa fresca (BF) e seca (BS), decomposição de resíduos e ciclagem de nutrientes de plantas de cobertura, número de folhas, altura da cabeça, diâmetro do caule (Dcau), diâmetro de cabeça (Dcab), BF e BS da cabeça e produtividade de brócolis. A maior produção de BF ocorreu no M (25,9 t ha^{-1}), B (23,3 t ha^{-1}) e mistura M + C (23,9 t ha^{-1}) que foram estatisticamente similares, enquanto a maior produção de BS ocorreu na B (11,9 t ha^{-1}). A menor taxa de decomposição e o maior tempo de meia-vida de resíduos ocorreu onde M estava presente. O maior acúmulo e ciclagem de nutrientes nos resíduos das plantas ocorreu na sequência K>N>Ca>Mg>P>S e Mn>Zn>B>Cu em todos os tratamentos avaliados. Os maiores valores de Dcau (51,95; 51,44 e 50,67 mm), Dcab (187,97; 187,41 e 183,48 mm), BF (1,01; 1,00 e 0,97 kg), BS (0,08; 0,07 e 0,07 kg) e produtividade (25,3; 24,9 e 24,7 t ha^{-1}) de brócolis foram observados em 100% da dose de adubo mineral e sobre os resíduos de C ou na mistura M+C, respectivamente.

Palavras-chave: *Brassica oleracea* var. *itálica*, *Crotalaria juncea*, *Urochloa brizantha* cv *marandu*, *Pennisetum glaucum*, NPK.

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Broccoli (*Brassica oleracea* var. *italica*) is a vegetable grown all over the world, mainly in regions with mild temperatures, where broccoli presents better production and qualitative performance. The development of cultivars tolerant to high temperatures would allow the cultivation of broccoli in many hot regions of Brazil (Cecílio Filho *et al*., 2012). Broccoli can be consumed *in natura* and is easily prepared for consumption; however, in the Savannah (Brazilian Cerrado), due to high temperatures during most of the year, the production of broccoli is still a major challenge (Seabra Júnior *et al*., 2014).

Vegetables such as those found in

the Brassicaceae plant family are grown in a conventional farming method, with intensive tillage and use of high solubility fertilizers and agrochemicals (Torres *et al.*, 2017). These plants present high rates of nutrient extraction from the soil, requiring high amounts of mineral fertilizers in short periods, becoming crops highly dependent on industrialized inputs. However, Altiere & Nicholls (2003) emphasize that the intensive use of mineral fertilizers in high quantities can cause the nutritional imbalance of plants and influence the quality of production.

An alternative to reduce the dependence and intense application of crop inputs is the no-tillage system of vegetable production (Diniz *et al.*, 2017). The cycling of nutrients from the cultural residues from the cover plants used in crop rotation provides positive changes in the physical, chemical and biological attributes of the soil (Torres *et al.*, 2008; Carvalho *et al.*, 2011). However, the no-tillage system is not commonly used in broccoli production due to the seedbed design and the soil incorporation of crop residues and mineral fertilizers, making the no-tillage system not viable (Santos *et al.*, 2016).

The no-tillage system of vegetable production reduces the dependence on fertilizers due to the maintenance, or increase, of the organic matter levels of the soil. This increment occurs due to the biological nitrogen fixation from the Fabaceae plant family and by the cycling of macro and micronutrients contained in the residues from the different cover crops used (Assis *et al.*, 2017; Pacheco *et al.*, 2017). The implementation of the no-tillage system for broccoli production has the potential to reduce the use of mineral and agrochemical fertilizers (Doane *et al.*, 2009).

Cover crops such as signal grass (SG), sunn hemp (SH) and pearl millet (PM) present great results of biomass production in summer: 6 to 13 t ha^{-1}, 7 to 12 t ha^{-1} and 4 to 9 t ha^{-1}, respectively (Torres *et al.*, 2015; Assis *et al.*, 2017). In winter, these values decrease, reaching 2.0 to 3.0 t ha^{-1}, 2.0 to 4.0 t ha^{-1} and 3.5 to 5.3 t ha^{-1}, respectively (Torres *et al.*, 2008; Crusciol & Soratto, 2009). Signal grass, sunn hemp and pearl millet are among the plants that return great amounts of nutrients to the soil (Assis *et al.*, 2017, Pacheco *et al.*, 2017).

Pacheco *et al.* (2013) observed that brachiaria and millet presented high dry biomass production, accumulation and cycling of macronutrients (N, P, K, Ca and Mg) in the Savannah conditions in two consecutive harvests (2008/09 and 2009/10). However, Teixeira *et al.* (2009), observed that the highest dry biomass production, accumulation and cycling of nutrients occurred when millet is cropped in monoculture and in mixture with sunn hemp.

The introduction of the no-tillage system has improved crop performance due to the supply of organic matter after each crop cycle, improved cycling of nutrients, low thermal amplitude and maintenance of soil moisture. Additionally, the crop residues left on the soil (without incorporation) provide soil protection against the erosive processes and leachate losses. The cultivation of broccoli (Diniz *et al.*, 2017), cabbage (Vargas *et al.*, 2011; Torres *et al.*, 2015), and cauliflower (Torres *et al.*, 2017) on residues of SG, PM and SH in no-tillage system demonstrated improved agronomic performance (great fresh and dry biomass, head diameter and crop productivity) when compared to the conventional tillage.

Therefore, this study aimed to evaluate the effects of cover crops plant residues on soil and nutrient cycling for the production of broccoli.

MATERIAL AND METHODS

The study was conducted at the experimental farm of the Instituto Federal do Triângulo Mineiro (IFTM), campus Uberaba, Minas Gerais, Brazil (19º39'19"S, 47º57'27''W, 795 m altitude), from October 2015 to June 2016.

The soil of the experimental area was classified as an Oxisol of medium texture (Santos *et al.*, 2018). The 0-0.2 m soil layer presented: clay = 210 g kg^{-1}; sand = 720 g kg^{-1}; silt = 70 g kg^{-1}; pH H_2O = 5.9, P (Mehlich) = 14.7 mg dm^{-3}; K = 12 mg dm^{-3}; Ca = 1.1 cmolc dm^{-3}; Mg = 0.4 cmolc dm^{-3}; H+Al = 1.7 cmolc dm^{-3}; CEC = 3.49 cmolc dm^{-3}; SB (sum of bases) = 1.78 cmolc dm^{-3}; V (base saturation) = 51%; OM (organic matter) = 10.34 g kg^{-1}.

The climate of the region is classified as Aw, tropical hot, with hot rainy summers and cold dry winter (Beck *et al.*, 2018). The annual average rainfall and temperature for the region of this study are 1,600 mm and 22.6ºC, respectively. The accumulated annual precipitation was 1,430 mm for 2015 and 1,571 mm for 2016 (Inmet, 2019).

The experiment was conducted in a factorial scheme 4x3, being four cover crops: signal grass (SG) (*Urochloa brizantha* cv *marandu*), pearl millet (PM) (*Pennisetum glaucum*, cultivar ADR 500), sunn hemp (SH) (*Crotalaria juncea*), and pearl millet + sunn hemp (PM+SH); and three mineral fertilizer doses: 0, 50% (200 kg ha^{-1} of P_2O_5, 50 kg ha^{-1} of K_2O and 75 kg ha^{-1} of N) and 100% (400 kg ha^{-1} of P_2O_5, 100 kg ha^{-1} of K_2O, and 150 kg ha^{-1} of N) of the recommended mineral fertilizer dose (applied before broccoli planting) (Ribeiro *et al.*, 1999). The experiment was arranged in a randomized block design with four replications. The area of each plot was 4×10 m (40 m^2), and the hybrid Avenger (single head) was studied.

The experimental area was prepared with subsoiling and harrowing before cover crops were sown. The cover crops were mechanically sown without any fertilization. The cover crop was dried with herbicide and common bean (*Phaseolus vulgaris*) was sown. After the common bean harvest, the area was kept in fallow for six months. Soybean was then sown, and after its cultivation, on top of the soybean residues, the cover crop treatments were set. The installation of this study with broccoli occurred after the cover crop dissection.

In October 2015, cover crops were sown, spaced 0.20 m between the lines, and with 50 (SG), 25 (SH), 50 (PM) and 13 + 25 (PM+SH) seeds per meter. When 50% of the plants reached maximum flowering, the cover crops were desiccated (glyphosate + 2.4-D dimethylamine salt, at 2 kg ha^{-1} and 2 L ha^{-1} doses, respectively). The dissection happened on January 2016, approximately 100 days after sowing.

Four plants at each sub-sample were taken for cover crops shoot fresh-biomass (FB) measurement, four sub-samples were collected in each plot. After dried at 65ºC for 72 hours, the shoot dry biomass was measured and estimated in t ha^{-1}. After the dissection, plants were mechanically moved close to the soil level and let covering the soil. Fifteen days after the management of cover crop residues, in a no-tillage system, broccoli was transplanted to the field at 0.8×0.5 m spacing when seedlings presented 4 to 5 leaves. Broccoli seedlings were acquired in a certified producer and were arranged in polystyrene trays (128 cells) containing commercial substrate.

Before transplanting, the organic compost (bovine manure) was incorporated into the pits (20 t ha^{-1} or 0.4 kg $plant^{-1}$). Other application (20 t ha^{-1} organic compost) was repeated only in the treatment with no mineral amendment (0% mineral fertilizer), which was divided half at 30 days (0.2 kg $plant^{-1}$) and half at 45 days (0.2 kg $plant^{-1}$) after seedling transplantation. The composition of this bovine manure was as follows: pH $CaCl_2$ 0.01M = 7.60; total humidity = 37.65%; organic matter = 16.18%; total N = 0.67%; P = 0.59%; K = 0.47%; Ca = 0.85%; Mg = 0.17%, and S = 0.14%. These nutrients in the organic compost were not considered in the calculation of the crop's need.

During the broccoli transplanting the mineral fertilizer (NPK) treatments were applied as simple superphosphate, potassium chloride and urea that provided, 6 and 12 g of N $plant^{-1}$, 8 and 16 g of P_2O_5 $plant^{-1}$, and 4 and 8 g of K_2O $plant^{-1}$, respectively for the 50 and 100% doses. The P fertilization during the broccoli transplanting was fully applied, while N and K were 30% of full recommendation. The side dresser N and K fertilization was sliced in three applications at 20, 40 and 60 days after transplanting and at the proportion of 40, 30 and 30% of total recommendation, respectively. In the same periods of N and K application, boric acid (1 g L^{-1}) plus ammonium molybdate (0.5 g L^{-1}) were applied.

Broccoli crop was irrigated to keep soil moisture near field capacity. The irrigation was done by a conventional spraying system, equipped with sectoral sprinklers spaced 9 meters away from each other and water flowing 560 L h^{-1}. The irrigation system was activated for 20 minutes every day. Weeds were manually or mechanically controlled, whenever necessary.

The two central planting lines (eight useful broccoli plants) were evaluated. The evaluation of the residue decomposition rate was done using the method of decomposition in bags (Pacheco *et al*., 2013; Torres *et al*., 2017; Ceballos *et al*., 2018). According to this method, 48 nylon bags (0.2×0.2 m with 2 mm aperture) containing 20 g of dry biomass (dried at 65°C) of the respective cover crop dry residue were distributed in each plot. Four bags per plot were collected at each sampling time, which occurred at 15, 30, 60, 90 and 120 days after the distribution of the bags in the area. After the collection of the bags, the remaining plant residues were manually collected, dried in a forced air circulation oven at 65°C until constant weight to determine the biomass (kg ha^{-1}).

The residues in the nylon bags were ground after being weighed and taken to the laboratory to determine the nutrient composition. Nitrogen was established by the Kjeldahl method (Tedesco *et al*., 1985), K by the nitric-perchloric digestion and P by colorimetry (Bataglia *et al*., 1983); Ca and Mg were determined by spectrophotometry (Bataglia *et al*., 1983) and S by turbidimetry (Tedesco *et al*., 1985). The average content of macronutrients in the plant residues was multiplied by the corresponding dry mass and represented in kg ha^{-1}. The average levels of nutrients in the plant residues were related to the respective dry biomass of the samples at each interval of evaluation.

To describe the decomposition of the plant residues, the exponential mathematical model described by Thomas & Asakawa (1993) was used: $X = Xo\ e^{-kt}$, where: X = quantity of remaining DB (t ha^{-1}) after a t time (days); Xo = initial amount of DB (t ha^{-1}), and k = constant of residue decomposition. The k value allows the estimation of the half-life time ($T^{½}$ life) of the cover crop residues using the formula: $T^{½}$ life = 0.693/k (Paul & Clark, 1996), which expresses the period required for half of the crop residues to decompose. Equations of the DB decomposition progress were developed using Sigma Plot® (version 10) software.

Broccoli was harvested 90 days after sowing, when the inflorescences were fully developed, buds closed (not-flowering) with compact and firm heads. The harvest extended for 30 days and evaluations were performed every three days. After harvesting, the plants were sent to the laboratory for assessments of the number of leaves (NL), head height (HH), stem diameter (SD), head diameter (HD), head fresh-biomass (FB), head dry biomass (DB) and yield.

The data were submitted to analysis of variance (*F* test), using AgroEstat® software. When significant differences were detected (p<0.05) among treatments, the averages were compared by Tukey test (p<0.05) or by regression analyzes.

RESULTS AND DISCUSSION

Biomass production

The aboveground fresh-biomass (FB) production from pearl millet (PM) (25.9 t ha^{-1}), signal grass (SG) (23.3 t ha^{-1}) and pearl millet + sunn hemp (PM+SH) (23.9 t ha^{-1}), were superior to the FB production from sunn hemp (SH) (16.6 t ha^{-1}). However, the aboveground dry biomass (DB) production from SG (11.9 t ha^{-1}) and SH (5.0 t ha^{-1}) were the greatest and the lowest amounts observed, respectively (Table 1).

The results of the present study for SG, PM and SH dry biomass production are in the range of 6 to 13, 7 to 12 and 4 and 9 t ha^{-1}, respectively; these results were similar to those found by Crusciol & Soratto (2009), Carvalho *et al*. (2011), Torres *et al*. (2008, 2015) and Assis *et al*. (2017) in studies conducted in the same period and region (Savannah). Thus, the biomasses produced in the present study are within the ranges reported in the literature, evidencing that these cover crops are well adapted

Table 1. Aboveground fresh-biomass (FB) and dry biomass (DB) of cover crops preceding broccoli cultivation in the irrigated area. Uberaba, IFTM, 2015/16.

Cover crop	FB (t ha^{-1})	DB (t ha^{-1})
Signal grass (SG)	23.3 a	11.9 a
Pearl millet (PM)	25.9 a	8.3 b
Sunn hemp (SH)	16.6 b	5.0 c
PM+SH	23.9 a	6.9 b
CV (%)	7.25	9.43

Averages followed by the same letter in the column do not differ by the Tukey test (p<0,05).

Table 2. Decomposition constant (k) and half-life time (T^{½}) of remaining cover crop biomass, in the irrigated area. Uberaba, IFTM, 2015/16.

Cover crop	Dry biomass		
	Total (t ha^{-1})	k (g g^{-1})	T^{½} life (days)
Signal grass (SG)	11.9 a	0.0272	25.5 b
Pearl millet (PM)	8.3 b	0.0245	28.3 a
Sunn hemp (SH)	5.0 c	0.0297	23.3 c
PM+SH	6.9 b	0.0242	28.6 a
CV (%)	9.43	--	4.21

Table 3. Aboveground dry biomass (DB), nutrient accumulation (kg ha^{-1}), decomposition constant (k) and half-life time (T^{½}) of macronutrients in cover crop residues, in irrigated area. Uberaba, IFTM, 2015/16.

Cover crop	DB (t ha^{-1})	Nutrient	Accumulated nutrient (kg ha^{-1})	k (g g^{-1})	T^{½} life (days)
Signal grass (SG)	11.9	N	105.19	0.0273	25.4
		P	18.51	0.0308	22.5
		K	189.73	0.0454	15.3
		Ca	61.79	0.0164	42.3
		Mg	31.18	0.0267	25.9
		S	10.45	0.0297	23.3
Pearl millet (PM)	8.3	N	113.60	0.0228	30.4
		P	13.90	0.0401	17.3
		K	93.56	0.0441	15.7
		Ca	32.68	0.0185	37.5
		Mg	16.63	0.0349	19.9
		S	9.61	0.0477	14.5
Sunn hemp (SH)	5.0	N	103.35	0.0366	18.9
		P	16.82	0.0272	25.5
		K	57.30	0.0411	16.9
		Ca	40.42	0.0195	35.5
		Mg	16.29	0.0316	21.9
		S	5.84	0.0383	18.1
PM+SH	6.9	N	105.57	0.0554	12.5
		P	10.61	0.0304	22.8
		K	94.25	0.0215	32.2
		Ca	33.94	0.0135	51.3
		Mg	16.70	0.0263	26.3
		S	6.95	0.0305	22.7

to the edaphoclimatic conditions of the Savannah biome.

The mixture of leguminous (SH) with grass (PM) in the same area was carried out to provide soil coverage with more quantity, quality and resilient biomass. This assumption was proved to be reasonable in the present study since the cover crop mixture (PM+SH) produced 6.9 t ha^{-1} of DB, an amount intermediary between the DB produced by PM (8.3 t ha^{-1}) and SH (5.0 t ha^{-1}), when cultivated as monocrop (Table 1). The highest production of DB from cover crops occurs where grass species were present, with emphasis on the signal grass. Similar results were observed by Teixeira *et al*. (2009) who reported high biomass production where PM was cropped in mixture with SH.

Crop residue decomposition

The decomposition rate of cover crop residues, 120 days after samples let to decompose naturally in the area, remained at 55.7% for PM+SH, 54.7% for SH, 54.4% for PM and 48.9% for SG (Figure 1).

The mixing of cover crop species with different carbon/nitrogen (C/N) ratio will produce crop residues with intermediary C/N ratio. This mixture of different cover crops results in low rates of plant residue decomposition and durable soil coverage, as highlighted by Ceballos *et al*. (2018). Most of the studies evaluating the decomposition of SG, PM and SH residues in the Savannah were performed in natural conditions, which demonstrated that the rates of decomposition of leguminous (low C/N ratio) are faster than of grass species (Torres *et al*., 2008, 2015; Carvalho *et al*., 2011; Assis *et al*., 2017).

In irrigated areas, the rates of initial decomposition of residues of Fabaceae or Poaceae are even faster. This situation can be observed by the magnitude of the half-life time of the cover crop residues deposited on the soil surface. Half of the plant residues from SG, PM, SH and PM+SH decomposed, respectively, in 25.5; 28.3; 23.3 and 28.6 days after the bags were distributed in the area (Table 2). These results demonstrate that the decomposition process is directly influenced by the conditions of humidity and temperature of the environment (Carvalho *et al.*, 2011; Pacheco *et al.*, 2013 and Torres *et al.*, 2017). The decomposition rates observed in the present study were at least three times faster than the rates observed for the same plants in studies conducted under natural conditions (no artificial irrigation), as noted by Torres *et al.* (2015), Pacheco *et al.* (2017) and Assis *et al.* (2017).

In the same irrigated area of the present study, in the previous year, Torres *et al.* (2017) quantified the T½ life of crop residues in 11 days for SG, 12 days for PM and, 12 and 17 days for SH. These short T½ life periods generated a high rate of residue decomposition, corroborating with the results found in the present study, and highlighted the improvement of plant residue cycling in irrigated areas. The same plant species cultivated in an area under natural conditions presented extended periods of residue decomposition in a 5-year study (Torres *et al.*, 2015); however, the authors reported that the T½ life changed significantly according to the grain crop grown over the residues. Ceballos *et al.* (2018), in 2015/2016 in the same area under natural conditions, quantified T½ life of 102, 151 and 162 days for SG, PM and SH, respectively. The low rate of crop residue decomposition and great half-life time occurred where pearl millet was present.

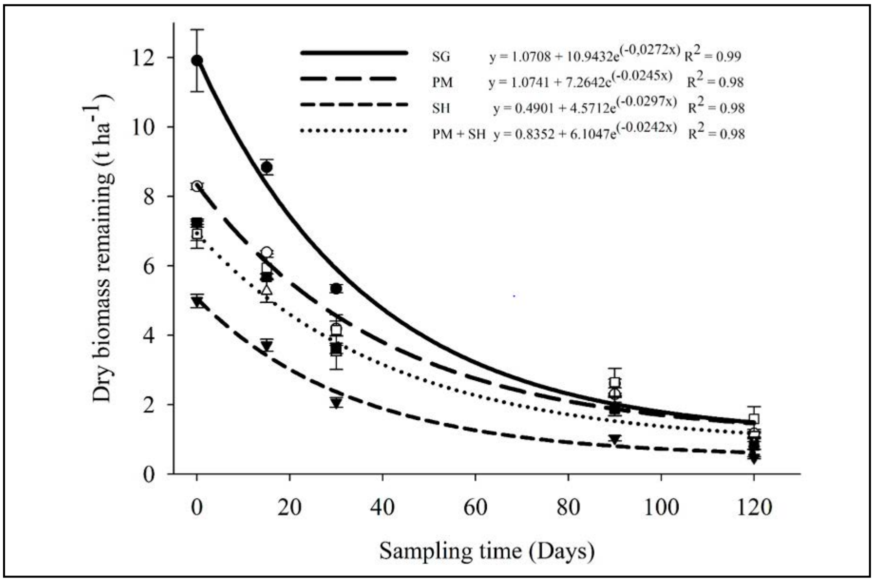

Figure 1. Decomposition progress of residues of signal grass (SG), pearl millet (PM), sunn hemp (SH) and PM+SH, in irrigated area. Uberaba, IFTM, 2015/16.

Table 4. Aboveground dry biomass (DB), accumulation (kg ha^{-1}), decomposition constant (k) and half-life time (T½) of micronutrients in cover crop residues, in irrigated area. Uberaba, IFTM, 2015/16.

Cover crop	DB (t ha^{-1})	Nutrient	Accumulated nutrient (kg ha^{-1})	k (g g^{-1})	T½ life (days)
Signal grass	11.9	B	0.08	0.0045	154.00
		Cu	0.07	0.0357	19.41
		Mn	0.87	0.0114	60.79
		Zn	0.42	0.0141	49.15
Pear millet (PM)	8.3	B	0.07	0.0092	75.33
		Cu	0.06	0.0443	15.64
		Mn	0.72	0.0175	39.60
		Zn	0.34	0.0139	49.86
Sunn hemp (SH)	5.0	B	0.07	0.0045	154.00
		Cu	0.05	0.0357	19.41
		Mn	0.26	0.0114	60.79
		Zn	0.19	0.0141	49.15
PM+SH	6.9	B	0.08	0.0062	111.77
		Cu	0.05	0.0259	26.76
		Mn	0.42	0.0162	42.78
		Zn	0.31	0.0119	58.24

Nutrient cycling

A great portion of plant nutrients is in their tissues, exerting a structural or reserve function, however, after harvest and crop residues deposition on the soil surface, the nutrients start to be released to the soil solution by mineralization and becoming available for the following crop (Torres *et al.*, 2008). In a study of Brassicaceae plant family, Fontanétti *et al.* (2006) highlight that the absorption of nutrients from the organic matter mineralization depends on the synchronism between the decomposition and release of nutrients from cover crop residues, and also on the time of the greatest nutritional requirement by the crop.

Nitrogen (N) and potassium (K) were the nutrients accumulated in the largest quantities in plant tissues, and sulfur (S) was one of the lowest present in all cover crops studied. Potassium was notoriously superior in the signal grass tissue (Table 3). Sunn hemp presented the lowest DB (Table 1); however, it accumulated a significant amount of N (Table 3) due to the efficient biological N fixation.

According to Brady (1989), N and K are the nutrients required in large quantities by most crops, being 4 to 5 times greater in crop residues than P, and 2 to 3 times greater than Ca as evidenced in this study. Other studies such as those conducted by Torres *et al.* (2008), Pacheco *et al.* (2013) and Ceballos *et al.* (2018), found similar

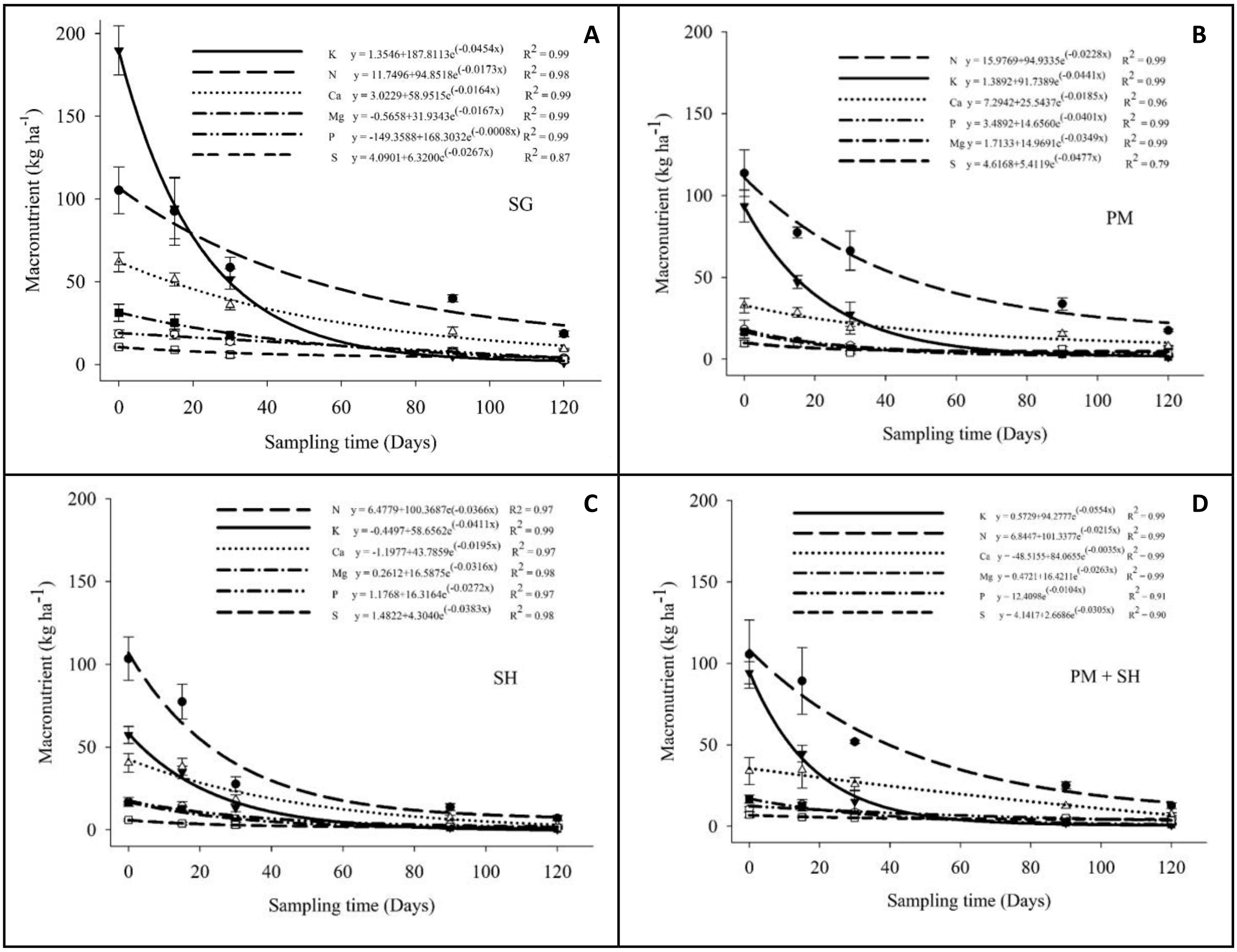

Figure 2. Macronutrients released during the decomposition process of A = signal grass (SG), B = pearl millet (PM), C = sunn hemp (SH) and D = PM+SH plant residues, in irrigated area. Uberaba, IFTM, 2015/16.

Table 5. Agronomic evaluations of broccoli cultivated on cover crop residues and fertilizer doses, in irrigated area. Uberaba, IFTM, 2015/16.

Cover crops (CC)	NL	PH (cm)	SD (mm)	HD (mm)	FB (kg/ha)	DB (kg/ha)	Yield (t ha^{-1})
Signal grass (SG)	31	16.0	45.90 b	175.73	0.82 b	0.06	20.5 b
Sunn hemp (SH)	32	15.2	50.67 a	183.48	0.97 a	0.07	24.7 a
Pear millet (PM)	31	14.8	46.70 b	171.89	0.81 b	0.06	21.4 b
PM+SH	33	16.2	51.44 a	187.41	1.00 a	0.07	24.9 a
F test	0.32^{ns}	1.85^{ns}	2.88*	1.85^{ns}	2.74*	1.65^{ns}	3.14*
Fertilizer doses (FD)							
0%	31 b	15.9	45.21 b	169.44 b	0.79 b	0.05 b	20.5 b
50%	31 b	15.4	48.86 a	181.46 a	0.90 b	0.07 a	22.8 b
100%	33 a	16.2	51.95 a	187.97 a	1.01 a	0.08 a	25.3 a
F test	0.03^{*}	1.88^{ns}	5.65*	4.35*	4.61*	5.02*	4.48*
Interaction CC x FD							
F test	0.72^{ns}	0.27^{ns}	0.34^{ns}	0.59^{ns}	0.20^{ns}	0.85^{ns}	0.36^{ns}
CV (%)	6.91	8.91	10.11	8.69	11.06	12.28	9.44

^{ns} = not significant (p>0.05). * = significant differences (p<0,05). Averages followed by the same letter in the column do not differ by the Tukey test (p<0,05). NL = number of leaves; PH = plant height; SD = stem diameter; HD = head diameter; FB = head fresh-biomass; DB = head dry biomass; yield = yield of broccoli.

results for the nutrient accumulation in the plant, but, low results for the $T^{½}$ life of the cover crop residues.

The decomposition of plant residues is accelerated in irrigated areas and the $T^{½}$ life is an indication of this rate of plant residue decomposition, which in this study, ranged between 23.3 and 28.6 days (Table 2). Therefore, the release and cycling of nutrients to soil solution are also accelerated (Table 3), ranging between 12.5 and 51.3 days. The drought season (fall and winter) in the Savannah region reflects this condition where the decomposition process of crop residues and consequently, the cycling of nutrients is slow as demonstrated by Carvalho *et al*. (2011) and Pacheco *et al*. (2013, 2017).

The regression curves indicated that K, N and Ca were the macronutrients most accumulated and the fastest initially released from the plant residues. Signal grass and PM (grasses) stood out on the accumulation of K when compared to SH (leguminous); the accumulation of N and K in the PM+SH were also improved (Figure 2).

The regression curves also showed that the N and K release occurs in two distinct phases, a rapid initial phase and other slower. This situation was already observed in other studies carried out under natural conditions; however, in irrigated cropping this initial release is maximized, decreasing the $T^{½}$ of these nutrients in crop residue by at least half when compared to the studies of Torres *et al*. (2008), Pacheco *et al*. (2013), and Assis *et al*. (2017).

The N and K showed the lowest $T^{½}$ life in crop residues, ranging between 15.3 and 32.2 days (average of 24 days), and between 12.5 and 30.4 days (average of 21.4 days), i.e., 50% of the N and K retained in plant residues were, on average, released 24 and 21 days after the cover crops were managed, respectively.

According to Meurer (2006), the high K mobility is due to this element not be a part of any structure, or organic molecule, being found adsorbed, or as a free cation. Nitrogen is one of the most required nutrients by the plants and a limiting factor for their growth since it is a component of proteins, nucleic acids, and many other important cellular constituents, besides being one of the most mobile elements in

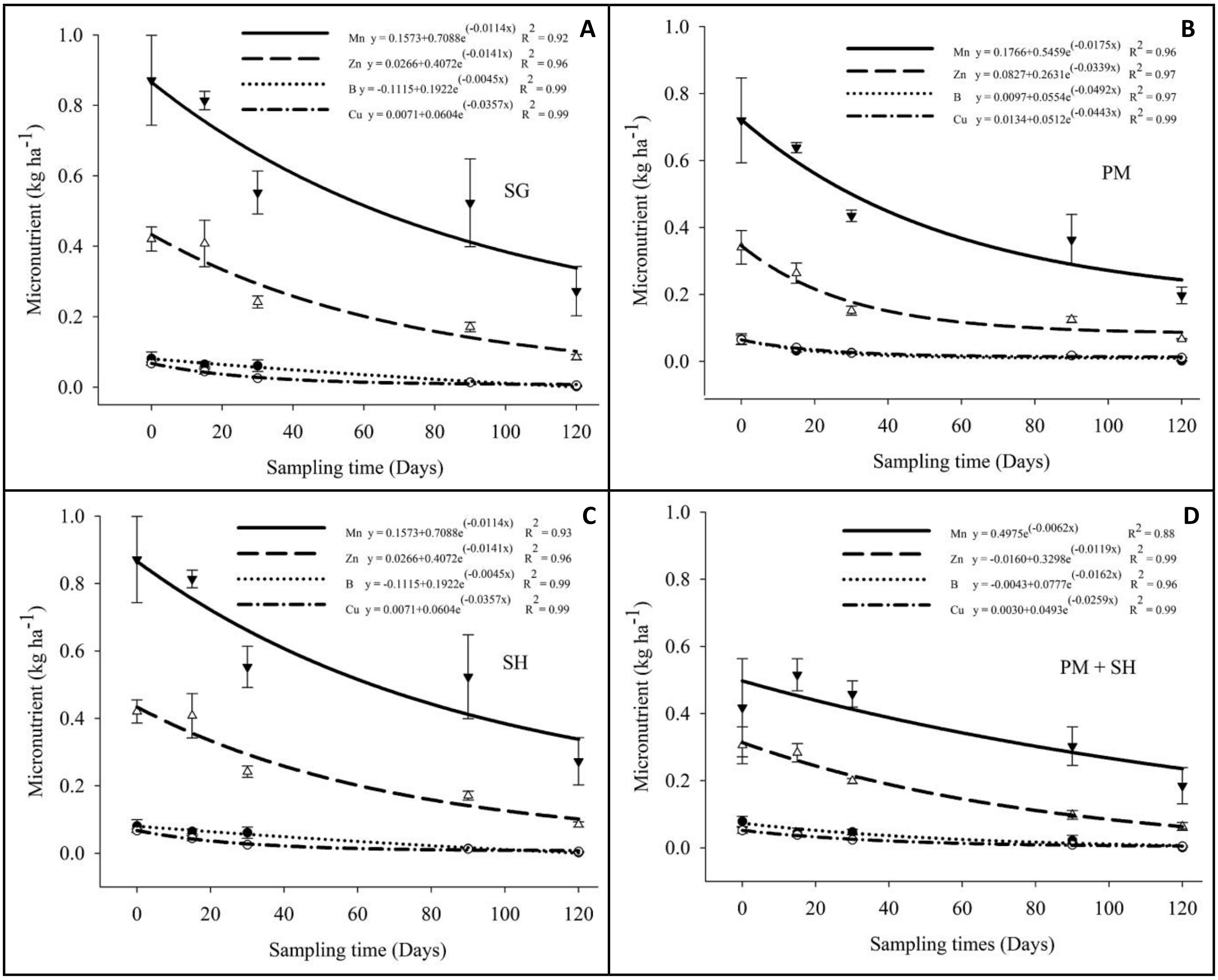

Figure 3. Micronutrients released during the decomposition process of A = signal grass (SG), B = pearl millet (PM), C = sunn hemp (SH) and D = PM+SH plant residues in irrigated area. Uberaba, IFTM, 2015/16.

the plant. The N present in the crop residues is quickly released to the soil through changes mediated by various decomposer microorganisms. These microorganisms determine the relations of mineralization, immobilization, fixation, leaching, and many other N reactions (Pacheco *et al*., 2013, 2017).

The T½ life of Ca in the crop residues ranged from 35.5 to 51.3 days (average: 43.4 days), which demonstrates the low mobility of Ca in the plant. This low Ca mobility is due to its position in the plant (Ca is a component of the cell wall, a hard degrading component). Calcium is also necessary to the translocation and storage of carbohydrates, proteins and very important to the root development (Vitti *et al*., 2006). The lowest concentrations of nutrients observed were for Mg (from 16.3 to 31.2 kg ha^{-1}), P (10.6 to 18.5 kg ha^{-1}) and S (5.8 to 10.5 kg ha^{-1}) (Table 3). The regression curves were similar and demonstrated an initial pronounced release of those nutrients during the first 30 days after the crop residue management (Figure 3).

The accumulated values of micronutrients for SG, PM, SH and PM+SH cover crops (11.9; 8.3; 5.0 and 6.9 t ha^{-1} of DB, respectively) indicated that Mn (0.26 to 0.87 kg ha^{-1}) and Zn (0.19 to 0.42 kg ha^{-1}) were the most accumulated and presented the greatest T½ life. However, B (0.07 to 0.08 kg ha^{-1}) and Cu (0.05 to 0.07 kg ha^{-1}) were the lowest accumulated and presented the smallest crop residue T½ life (Table 4).

These micronutrients are essential for plant development and are characterized by being absorbed in small quantities; the micronutrients generally do not participate in plant structures but enzymes or in the performance of plant activators (Dechen & Nachtigall, 2006). The accumulated Mn, Zn, B, and Cu in the crop residue demonstrate that nutrient extraction from the soil by the cover crops occurs differently. The manganese (Mn) and zinc (Zn) were quickly released after crop residue managed, while B and Cu were slow, as evidenced by the regression curves adjusted (Figure 3).

The increase of the soil organic matter (SOM) increases the level of micronutrients (Brady, 1989); however, if the SOM content is very high, immobilization of micronutrients will occur in the form of organic compounds. This process protects the nutrients but reduces their availability to plants due to the formation of chelates.

In the present study, at 120 days after residue management, more than 48% of the organic matter were still on the soil, even having accelerated initial values. The constant input of organic matter after the stabilization of the no-tillage system, which usually occurs above 10 years (Ceballos *et al*., 2018), might result in micronutrient deficiencies in the soil.

The presented results demonstrate that the greatest accumulation and nutrient cycling occur as the following sequence K>N>Ca>Mg>P>S and Mn>Zn>B>Cu for all evaluated cover crops. This similarity indicated that the proportion absorbed of each nutrient by broccoli is not significantly affected by the cover crop previously cultivated.

Crop biometrics

The broccoli agronomic characteristics grown in succession to cover crop plants presented no interaction between factors (cover crop species and fertilizer doses) (Table 5). Among the cover crops, there were no differences for the broccoli variables number of leaves (NL), head diameter (HD), head fresh-biomass (FB) and head dry biomass (DB); however, broccoli yield differs among cover crop treatments. The treatments that included SH presented superior yield compared to where only grass species were present (SG or PM in monocrop). This can be explained by the great FB production and the fast nutrient cycling from crop residues where SH (*C. juncea*) was present.

Broccoli height (PH) was similar among fertilizer doses (average of 15.8 cm); however, characteristics of SD, HD and DB were similar between the 50 and 100% fertilizer doses and superior to where no fertilizer was added. The NL, FB and yield were superior when the 100% fertilizer dose was applied. This observation indicates that the speed of nutrient cycling from the cover crop residues is not sufficient to fully supply the nutritional requirement of a succeeding broccoli crop. However, the presence of certain cover crop species or combinations can improve the results of broccoli crop production.

Other studies observed the benefits of soil covering with cover crops. Diniz *et al*. (2017) applied 8.6 t ha^{-1} of velvet bean (*Stizolobium cinereum*) ash, plus 12 t ha^{-1} of organic compost and observed an increase in the soil mineral N, and broccoli production. According to Vargas *et al*. (2011), vegetables grown with green manure amendments from SH and jack bean (*Canavalia ensiformis*) received 46.1 and 55.5% more soil N from the biological process of N fixation. The authors also observed that cultivating leguminous cover crops the mineral fertilization dose could be reduced to 50% without compromising crop productivity. Fontanétti *et al*. (2006) evaluated SH, *Stizolobium cinereum*, *Canavalia ensiformis* and weeds preceding cabbage crop, and observed head weights of 1.4, 1.2, 1.2 and 2.0 kg, respectively, highlighting the importance of soil covering with plants.

The highest production of FB presented by pearl millet (25.9 t ha^{-1}), signal grass (23.3 t ha^{-1}) and the mixture pearl millet + sunn hemp (23.9 t ha^{-1}) were statistically similar, while the highest dry biomass production occurred for signal grass (11.9 t ha^{-1}). The lowest rate of decomposition and the most prolonged half-life of residues occurred where millet was present.

Thus, the results observed in the present study enable to conclude that the nutrient cycling sequence follows K>N>Ca>Mg>P>S and Mn>Zn>B>Cu in broccoli crop for cover crop treatments evaluated. Also, the highest values of SD (51.95; 51.44 and 50.67 mm), HD (187.97; 187.41 and 183.48 mm), FB (1.01; 1.00 and 0.97 kg), DB (0.08; 0.07 and 0.07 kg) and yield (25.3; 24.9 and 24.7 t ha^{-1}) of broccoli was observed when 100% of the dose of mineral fertilizer was applied on the residues of SH or PM + SH mixture, respectively.

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