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Litterfall production, nutrient input and soil fertility in yerba-mate agroforestry systems

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Adoption of agroforestry systems (AFS) for yerba mate (*Ilex paraguariensis* St. Hil.) production contributes to improvement of soil quality due to intense litterfall input. This study aimed (i) to quantify the litterfall input and its nutrients, as well as soil fertility attributes in yerba mate AFS (ii) to discriminate which soil fertility attributes and litterfall nutrients enabled differentiation of yerba mate AFS and (iii) to verify relations between the soil fertility attributes and nutrients supplied. Six yerba mate AFS were studied in three different soils in the Center-South region of Paraná State, Brazil. The canonical discriminant analysis was applied to the soil fertility attributes, for the 0-5, 5-10, 10-20 and 20-40 cm soil layers; and for the nutrients annual input. The study of the relation between the nutrient input and nutrients soil content was carried out through the canonical correlation analysis. Litterfall input varied from 7132 to 9402 kg ha^{-1} year^{-1}, and showed an important source of nutrients. Copper and aluminum soil content were the variables responsible for differentiating AFS, by canonical discriminant analysis. There was strait relation between calcium, magnesium, copper, manganese and zinc input and these nutrients content in the soil in yerba mate AFS.

Key words: *Ilex paraguariensis* St. Hill., discriminant analysis, variable charge soils.

INTRODUCTION

Yerba mate (*Ilex paraguariensis* St. Hil.) is a medium size tree species native to a relatively large region encompassing eastern Paraguay, northeastern Argentina, and southern Brazil (Montagnini et al., 2011). In Brazil, the yerba mate occurs natively or cultivated way (Signor et al., 2015; Santin et al., 2017), being historically, socially and economically relevant (Bonfatti Júnior et al., 2018; Nimmo et al., 2020). The total cultivated area in Brazil is approximately 67,000 ha, with annual production above 517,000 tons (FAOSTAT, 2019). In Paraná State, the cultivation area of yerba mate is approximately 37,000 ha, with annual production above 345,000 tons (IBGE, 2018). In this State, the traditional yerba mate production systems are typically agroforestry systems

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(AFS) (De Souza and Chaimsonh, 2013) [growing crops in combination with trees (Montagnini et al., 2011)], mainly in understory environment of the Mixed Ombrophilous Forest (or Araucaria Forest), typical of the highlands of the region, legally recognized as the Atlantic Forest biome (Chaimsohn and De Souza, 2013). These systems occur mainly on small family farms where AFS are integrated with a variety of food crops and other non-timber forest products, including yerba-mate, native fruits, corn, beans, rice, and vegetables, as well as pigs, cattle and chickens (Nimmo et al., 2020).

The yerba mate harvesting causes considerable export of nutrients because the harvested product consists predominantly of thin leaves and branches, which have a high nutrients concentration (Santin et al., 2016). The amounts of nutrient removed is dependent upon the harvest time (Ribeiro et al., 2008), kind of trimming (Souza et al., 2008), site characteristics and age of the leaves collected (Jacques et al., 2007). Successive harvesting of leaves and thin branches, with no nutrient reposition by fertilization (Chaimsohn and De Souza, 2013) is potentially responsible for the continuous decrease in Brazilian productivity of yerba mate (Santin et al., 2017). In AFS, the accumulated litterfall is the main mineral transfer source to the soil (Flor et al., 2017), which is important in the nutrient biogeochemical cycling process (Torres et al., 2014). Accumulation of litterfall and the amount of minerals reaching the soil, vary as a function of several factors, mainly the species that contribute to the vegetable material deposition, climate conditions and natural disturbances (Caldeira et al., 2007).

Another important issue for understanding the functioning and dynamics of the soil-plant system in yerba-mate production relates to the low efficacy of univariate statistical procedures to explain the phenomena observed. This is because no single variable can adequately characterize the experimental unit, and it is necessary to understand the relations between the different variables (Manly, 2008). In this context, the use of multivariate statistical methods becomes interesting, for example, canonical discriminant analysis (CDA) and canonical correlation analysis (CCA). Such methods, might contribute to a more refined analysis (Baretta et al., 2008; Marcelo et al., 2015); therefore, the dexterity of the approaches made them suitable for the study of variables, evidencing links, similarities or differences between them, with minimal information loss (Manly, 2008), favoring and improving the comprehension of nutrient cycling and soil quality in yerba-mate AFS.

Thus, the objectives of this study were: (i) to quantify the litterfall production and the nutrient input originating from litterfall and the soil fertility attributes in six yerba mate AFS in the Center-South of Paraná State; (ii) to determine which among the soil properties influenced by the litterfall are more important in differentiating the yerba mate AFS; and (iii) to verify relationship between the soil chemical properties and nutrient input, aiming to better comprehend the soil fertility under yerba mate AFS in this region.

MATERIALS AND METHODS

Areas description

The study was carried out in six AFS (two in each city) located in the Center-South region of Paraná State, namely:

AFS 1 – located in the city of São Mateus do Sul, under the geographic coordinates 25º58'15,4''S; 50º13'45,8''W, altitude of 851 m, in a Haplic Cambisol Ta Aluminic leptic, originated from basalt dikes, with 520 g kg^{-1} of clay in the 0-20 cm soil layer;
AFS 2 – located in the city of São Mateus do Sul, under the geographic coordinates 25º59'12,4''S; 50º16'04,4''W; altitude of 800 m, in a Bruno Oxisol Aluminic typical, of sedimentary origin, with 530 g kg^{-1} of clay in the 0-20 cm soil layer;
AFS 3 – located in the city of Bituruna, under the geographic coordinates 26º12'04,5''S ; 51º26'30,0''W; altitude of 1021 m, in a Haplic Cambisol Aluminic petroplinthic, originated from basalt, with 600 g kg^{-1} of clay in the 0-20 cm soil layer;
AFS 4 – located in the city of Bituruna, under the geographic coordinates 26º10'08, 5''S; 51º21'51,3''W; altitude of 920 m, in a Humic Cambisol Tb Aluminic leptic, originated from basalt, with 540 g kg^{-1} of clay in the 0-20 cm soil layer.
AFS 5 – located in the city of Cruz Machado, under the geographic coordinates 26º01'10,4''S; 51º16'18,0''W; altitude of 949 m, in a Gray-Brown Argisol distrofic, originated from basalt, with 600 g kg^{-1} of clay in the 0-20 cm soil layer;
AFS 6 – located in the city of Cruz Machado, under the geographic coordinates 25º59'23,1''S; 51º14'30,1''W; altitude of 1051 m, in a Haplic Cambisol Ta Aluminic leptic, originated from basalt, with 650 g kg^{-1} of clay in the 0-20 cm soil layer.

The climate in the region, according to Köppen classification is Cfb – sub-tropical, super-humid, without dry season, with annual average rainfall between 1.600 to 1.700 mm, mild mesothermal with annual average temperatures between 15 and 18ºC, with mild summers and severe and frequent occurrence of frost in winter (IAPAR, 1994). The six AFS studied were characterized by the presence of native or cultivated yerba mate inside parts of Araucaria Forest (Mixed Ombrophilous Forests). The predominant vegetation and its phytosociological indices in each AFS are shown in Table 1.

Litterfall sampling and analytical determinations

In October 2011, plot of 2,500 m^2 (50 x 50 m) was demarcated in each AFS for physical and biological characterization. Litterfall was collected with collectors measuring 0.5 m^2, made of circular iron rebar, with 0.8 m diameter, and 1-mm mesh nylon net, forming a 0.5 m deep bag, which were suspended approximately 1.0 m from the ground, fixed with wood posts. The collectors were distributed equidistantly 10 m from the plot edge and 10 m between each collector, totaling 16 collectors per AFS. Litterfall was collected on the 30th day after the collector's installation (October/2011) and other collections were carried out every 30 days, totaling 12 samples along study period.

Herbaceous/shrub biomass was collected with 0.5 × 0.5 m square frame, carried out only once a year, between May and June/2012, according to the mowing season. Mowing is usually done just before harvest, mainly to facilitate harvesting and

Table 1. Phytosociological índices, absolute density (AD), relative density (RD), frequency (fr), absolute dominance (ADo), relative dominance (RDo), cover value (CV) and importance value (IV), of species with the highest representativeness in the tree extract, in six yerba mate agroforestry systems (AFS1, AFS 2, AFS 3, AFS 4, AFS 5 and AFS 6).

AFS	Specie	AD	RD	Fr	ADo	RDo	CV (%)	IV (%)
1	*Mosiera prismatica*	404	47.4	100	3.8	17.0	32.2	23.8
	Myrsine coriacea	88	10.3	100	1.7	7.5	8.9	8.2
	Ocotea porosa	24	2.8	75	2.4	10.9	6.9	6.3
	Myrcia rostrata	52	6.1	100	1.1	5.1	5.6	6.0
	Ocotea puberula	32	3.8	75	1.7	7.6	5.7	5.5
	Total	852	100	-	22.4	100	100	100
2	*Ocotea porosa*	60	21.4	100	6.8	37.1	29.2	23.0
	Araucaria angustifolia	28	10.0	100	2.4	13.1	11.5	11.2
	Campomanesia xanthocarpa	28	10.0	100	2.2	11.9	10.9	10.8
	Casearia decandra	32	11.4	75	0.5	2.9	7.2	7.4
	Lithraea brasiliensis	16	5.7	100	0.7	3.7	4.7	6.6
	Ilex theezanss	24	8.6	75	0.5	3.0	5.8	6.5
	Total	280	100	-	18.4	100	100	100
3	*Piptocarpha angustifolia*	164	21.6	100	4.3	21.8	21.7	17.2
	Vernonia discolor	144	19.0	75	4.6	23.8	21.4	16.3
	Ocotea puberula	148	19.5	100	1.1	5.8	12.6	11.2
	Mimosa scabrella	76	10.0	100	1.2	6.3	8.2	8.2
	Solanum granuloso-leprosum	52	6.8	75	0.8	4.1	5.5	5.7
	Total	760	100	-	19.5	100	100	100
4	*Vernonia discolor*	132	24.4	100	3.7	30.4	27.4	21.3
	Piptocarpha angustifolia	124	23.0	100	1.9	15.7	19.3	15.9
	Araucaria angustifolia	72	13.3	100	1.5	12.3	12.8	11.6
	Ocotea porosa	12	2.2	75	1.6	13.1	7.7	7.4
	Sapium glandulatum	56	10.4	75	0.5	3.9	7.1	7.0
	Total	540	100	-	12.3	100	100	100
5	*Ocotea porosa*	196	62.8	100	15.5	54.9	58.9	46.6
	Araucaria angustifolia	44	14.1	100	5.7	20.1	17.1	18.8
	Vernonia discolor	32	10.3	100	3.4	12.0	11.1	14.8
	Ocotea puberula	28	9.0	75	3.1	10.9	9.9	12.2
	Total	312	100	-	28.3	100	100	100
6	*Clethra scabra*	196	21.8	100	6.4	22.9	22.3	16.9
	Piptocarpha angustifolia	80	8.9	100	5.5	19.5	14.2	11.4
	Ocotea puberula	76	8.4	100	3.1	10.9	9.7	8.5
	Ocotea porosa	104	11.6	100	2.0	7.3	9.4	8.3
	Vernonia discolor	68	7.6	100	2.5	8.7	8.2	7.4
	Araucaria angustifolia	68	7.6	100	2.2	8.0	7.8	7.2
	Total	900	100	-	28.1	100	100	100

transportation activities, in addition to reducing competition for resources between yerba mate and other species, being carried out only around yerba mate tree and in the access roads (Signor et al., 2015). In this case, composite samples (n = 3) were collected from the plant material deposited around each collector.

Litterfall and biomass samples were put in paper bags and sent to the laboratory for the washing, drying, grinding procedures and analytical determinations, employing the methods suggested by Malavolta et al. (1997). Samples were washed with deionized water, dried in oven at 65ºC with air forced flow until constant mass, ground in a "Wiley" mill equipped with 0.85-mm mesh and stored in sealed plastic containers until the chemical analyses were done. The concentrations of nitrogen (N) were determined upon sulfuric digestion and read through the semi-micro-Kjeldahl. Determinations of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), cupper (Cu), manganese (Mn) and zinc (Zn) concentrations were realized through nitric-perchloric digestion and reading through molecular absorption spectrometry for P; flame emission spectrophotometry for K; flame atomization atomic absorption spectrometry for Ca, Mg, Cu, Mn and Zn; and turbidimetry for S.

Soil sampling and analytical determinations

In September 2012, soil samples were collected from sixteen collectors on each AFS, from the soil layers of 0-5, 5-10, 10-20 and 20-40 cm. After collection, the samples were taken to the laboratory, dried in oven at 40ºC with air forced flow, ground, sieved in a 2.0 mm mesh sieve. Then, the soil was used to determine active acidity (pH), potential acidity (H+Al), exchangeable acidity (Al), exchangeable Ca, Mg and K concentrations, available P (Mehlich-1) and total organic Carbon (TOC) - Walkley-Black, employing the methods suggested by Pavan et al. (1992). Available S were determined according to Vitti and Suzuki (1978) and available Cu, Mn and Zn in Mehlich-1 solution, according to the methods of Silva (2009).

Statistical analysis

Biomass litterfall input per hectare was estimated for the fractions of leaves, branches and miscellaneous litterfall (such as petioles and reproductive structures), from each collector. The amount of mineral input per hectare was calculated for each collector, through the sum of mineral input generated by the deposition of litterfall and herbaceous/shrub dry biomass.

Outliers for nutrient inputs and soil attributes variables was verified, disregarding the values indicated as inconsistent for data analysis. Homogeneity of variance assumptions (Bartlett test) and normality of data (Shapiro test) were verified for each variable, following the variable data transformation through the Box-Cox method when the assumptions were not satisfied. Identification of differences between yerba mate AFS and variables that most contributed to differentiate AFSs was realized through canonical discriminant analysis (CDA) for each soil layer, submitting the standardized canonical coefficient averages to the LSD test at 5% significance.

The relation between micro and macronutrients content in different soil layers and soil nutrient input by plant deposition was carried out through the canonical correlation analysis (CCA). All statistical analyses were realized by employing the software SAS 9.1 (SAS, 2004).

RESULTS AND DISCUSSION

Litterfall production

The annual total input of leaves, branches, miscellaneous litterfall, herbaceous/shrub biomass and total litterfall is presented in Figure 1. The total litterfall produced in the six yerba mate AFS varied from 7132 to 9402 kg ha^{-1} year^{-1}, values which are considered close to those observed in fragments of non-managed Mixed Ombrophilous Forests (MOF) [6527 kg ha^{-1} year^{-1} found by Britez et al. (1992); 8354 kg ha^{-1} year^{-1} found by Longhi et al. (2011); and 7080 kg ha^{-1} year^{-1} found by Sanquetta et al. (2016)].

The leaves, branches, miscellaneous litterfall and herbaceous/shrub biomass litterfall represented on average 52, 17, 8.5 and 22.5%, respectively, of the total litterfall input in the yerba mate AFS. Britez et al. (1992) observed that, in a MOF located in São Mateus do Sul/PR, leaves, branches and miscellaneous litterfall represented 62.2%; 22.0% and 7.6% of litterfall, respectively. Sanquetta et al. (2016), in a MOF located in São João do Triunfo, Paraná State, observed that litterfall was composed of leaves (31.3%), branches (11.7%), *Araucaria angustifolia* needle-shaped branches (41%) and miscellaneous litterfall (16%). These same authors observed that yerba mate produced 71.01 kg ha^{-1} year^{-1} of leaves, corresponding to 6.8% of total of leaves in litterfall input.

The highest litterfall inputs were observed throughout the spring months (September, October and November) (Figure 2). Monthly deposition of leaves was higher in the spring months (September, October and November) in all AFS studied, due partly to partial or total replacement of leaves aged by new leaves as a consequence of intense growth in this season (Sanquetta et al., 2016) and due partly to the increase in rainfall and temperature (Longhi et al., 2011; Antoneli and Thomaz, 2012). Regarding branches, the highest inputs were observed in autumn months (March, April and May) in AFS 1, AFS 2, AFS 4 and AFS 5, with deposition peaks in April; in AFS 3 and AFS 6 the highest branches inputs were observed in winter (June, July and August) and summer months (December, January and February), respectively. Antoneli and Thomaz (2012) verified that branches deposition was higher during summer probably due to intense precipitation associated with strong winds.

Several factors may affect litterfall deposition, such as species composition, latitude, altitude, temperature, precipitation, light availability during the growing season, photoperiod, evapotranspiration, relief, deciduousness, successional stage, water availability, soil nutrient content and herbivory (Caldeira et al., 2007; Schumacher et al., 2011; Sanquetta et al., 2016; Flor et al., 2017; Carmo et al., 2018). The lowest variations in litterfall deposition along the time were observed in AFS 3 (Figure 2), justified by the dominant presence of tree species of a pioneer character (Table 1) (Pezzatto and Wisniewski, 2006).

Nutrient input originating from litterfall

Wide variations were observed between the AFS with respect to their contents of primary and secondary nutrients (Table 2). The pattern of differences amongst the AFS are as follows: (i) N total input varied from 45.0 (AFS 2) to 250.3 kg ha^{-1} year^{-1} (AFS 4), with average of 130.3 kg ha^{-1} year^{-1}; (ii) P total input varied from 2.6 (AFS 4) to 13.1 kg ha^{-1} year^{-1} (AFS 1) with average of 6.5 kg ha^{-1} year^{-1}; (iii) K total input varied from 17.4 (AFS 4) to 85.7 kg ha^{-1} year^{-1} (AFS 1), with average of 45.5 kg ha^{-1} year^{-1}; (iv) Ca total input varied from 20.0 (AFS 3) to 124.7 kg ha^{-1} year^{-1} (AFS 4), with average of 50.2 kg ha^{-1}

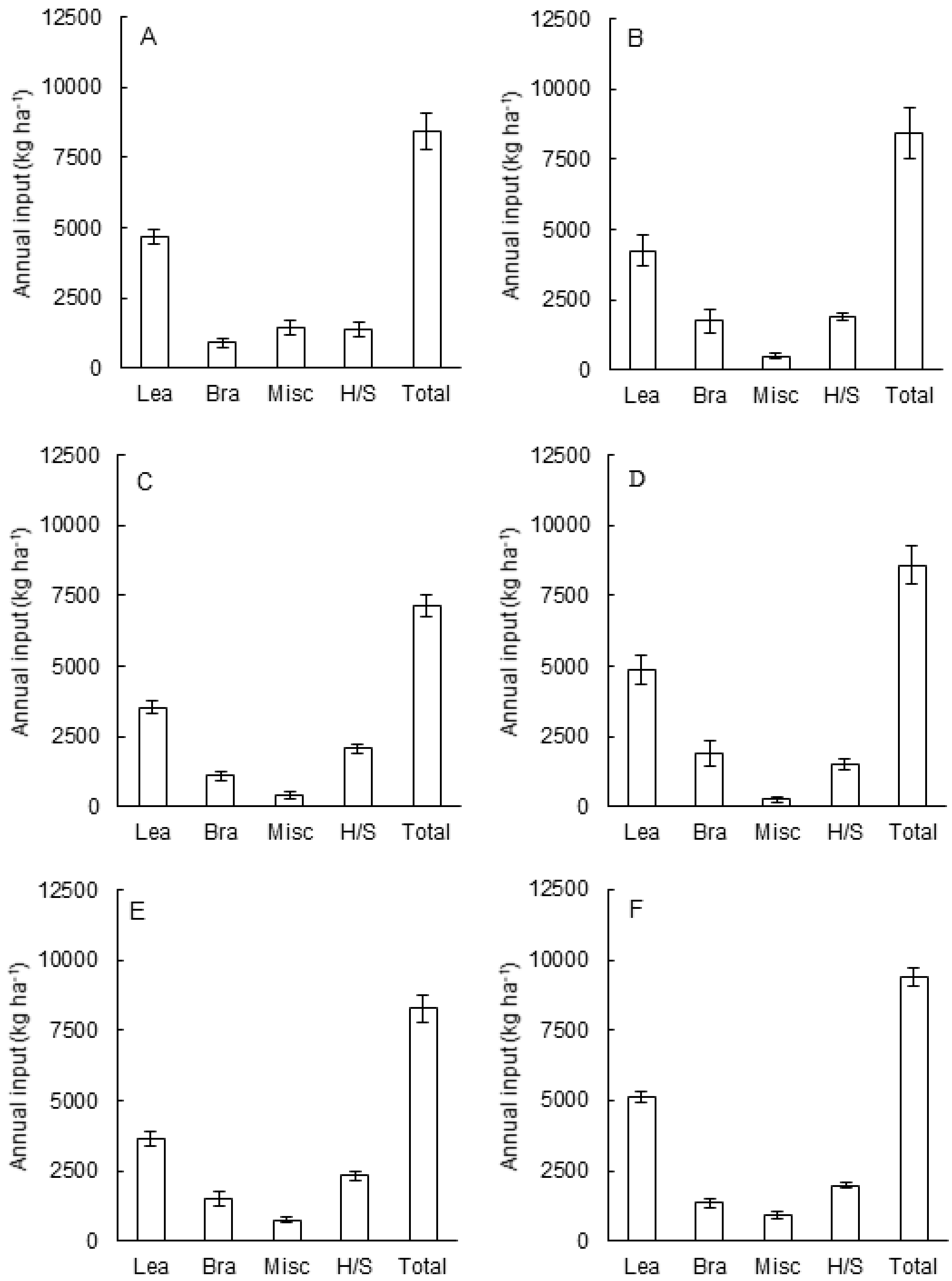

Figure 1. Leave (Lea), branch (Bra), miscellaneous litterfall (Misc), herbaceous/shrub biomass (H/S) and total litterfall annual input (kg ha^{-1}) for the six yerba mate agroforestry systems (AFS). A – AFS 1; B – AFS 2; C – AFS 3; D – AFS 4; E – AFS 5; F – AFS 6. Bars correspond to the mean standard error (n=16).

$year^{-1}$; (v) Mg total input varied from 7.3 (AFS 3) to 23.8 kg ha^{-1} $year^{-1}$(AFS 4), with average of 14.6 kg ha^{-1} $year^{-1}$; (vi) S total input varied from 5.4 (AFS 1) to 18.8 kg ha^{-1} $year^{-1}$ (AFS 6), with average of 11.6 kg ha^{-1} $year^{-1}$. These values are close to those observed by Britez et al. (1992) and Longhi et al. (2011) in MOF tree litterfall. These authors observed annual inputs of N, P, K, Ca, Mg and S around 89.2 to 148.2; 5.32 to 17.53; 31.9 to 46.58; 31.9 to 123.26; 5.7 to 22.16; 9.52 to 12.03 kg ha^{-1}, respectively.

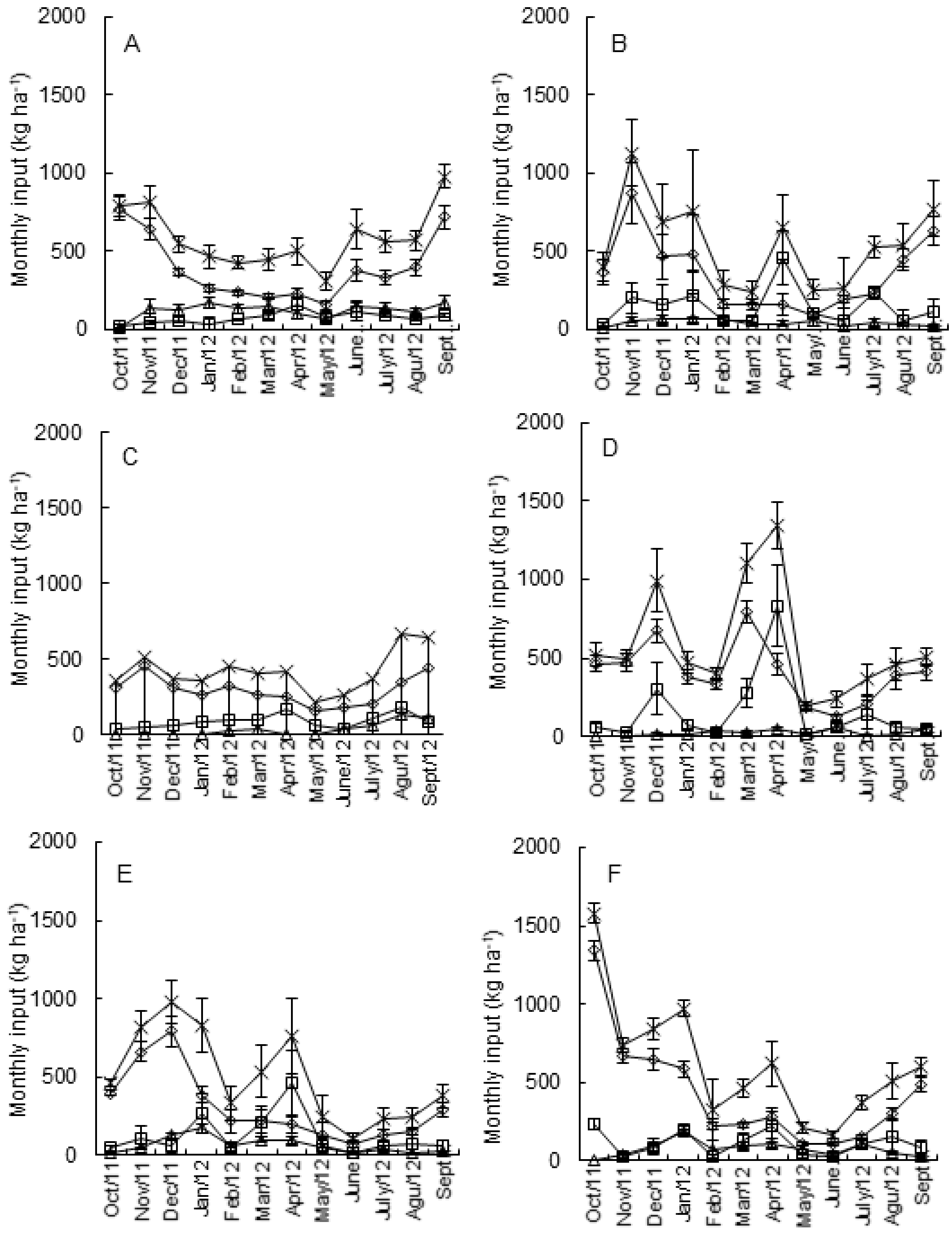

Figure 2. Leaves (◊◊◊), branches (□□□), miscellaneous litterfall (∆∆∆), and total (×××) litterfall monthly input for the six yerba mate agroforestry systems (AFS). A – AFS 1; B – AFS 2; C – AFS 3; D – AFS 4; E – AFS 5; F – AFS 6. Bars correspond to the mean standard error (n=16).

Amounts of nutrients varied between yerba mate compartments, with the highest contents observed in the leaf. Similar finding was reported by Santin et al. (2013). N and K are the macronutrients most absorbed and exported by yerba mate (SBCS/NEPAR, 2017) and consequently return to the soil in larger quantities. The N is an important element related to caffeine, tannin and theobromine (Borille et al., 2005), components responsible for the nutritional and physiological properties of yerba mate (Rossa et al., 2017). The P levels in yerba mate are often low, possibly due to the specie characteristic and due to its adaptation mechanisms for

Table 2. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), manganese (Mn), zinc (Zn) and copper (Cu) annual input (±mean standard error) in six yerba mate agroforestry systems (AFS 1, AFS 2, AFS 2, AFS 4, AFS 5 and AFS 6).

AFS	N	P	K	Ca	Mg	S	Mn	Zn	Cu
	kg ha^{-1}							g ha^{-1}	
1	128.6±9.9	6.8±0.9	58.5±8.2	44.4±4.6	15.3±1.4	10.9±1.1	6.9±0.7	169.6±16.2	66.1±7.3
2	122.8±16.4	6.6±0.8	46.3±4.2	59.9±12.3	15.7±1.8	12.6±1.2	3.2±0.4	198.6±21.1	60.5±6.6
3	124.5±8.3	5.5±0.6	40.9±1.7	30.6±2.5	11.0±0.7	9.1±0.4	7.7±0.5	177.9±8.7	93.4±9.0
4	150.1±11.7	5.8±0.8	28.7±2.0	62.3±7.4	16.4±1.3	11.1±0.7	10.0±0.7	152.2±39.8	114.2±7.5
5	114.0±5.1	6.5±0.5	52.1±3.3	50.7±3.7	11.7±0.8	11.8±0.5	5.8±0.4	200.6±11.1	60.8±2.9
6	141.8±7.0	8.0±0.9	44.7±2.3	53.2±2.6	17.2±1.0	14.1±0.8	11.6±1.0	266.3±14.8	102.5±14.2

low levels of soil P (Oliva et al., 2014). Yerba mate grown in a shaded environment, as in AFS, tends to accumulate more K, especially in leaves (Caron et al., 2014). Plants in these conditions need greater photosynthetic efficiency, demanding higher K concentrations, in order to control the osmotic regulation and transpiration processes, closely linked with the photosynthesis process (Taiz and Zeiger, 2004). The low soil pH values, characteristic of AFS, may have reduced the absorption of Ca and Mg by yerba mate, due probably to the mutual inhibition between these elements and Al in terms of absorption, as a result of competition for the absorption sites in the plant as was earlier suggested by Ricardi et al. (2020).

As with the primary and secondary nutrients, the six AFS varied widely with respect to their input of micronutrients (Table 2), where (i) Mn total input varied from 1.8 (AFS 2) to 18.6 kg ha^{-1} year^{-1} (AFS 6), with average of 7.6 kg ha^{-1} year^{-1}; (ii) Zn total input varied from 89.4 (AFS 1) to 349.7 g ha^{-1} year^{-1} (AFS 2), with average of 194.2 g ha^{-1} year^{-1}; (iii) Cu total input varied from 29.9 (AFS 1) to 180.4 g ha^{-1} year^{-1} (AFS 4), with average of 82.9 g ha^{-1} year^{-1}. Micronutrients average inputs followed the order: Mn > Zn > Cu in all yerba mate AFS. Caldeira et al. (2007) observed high variation in micronutrient content, and also higher Mn contents in the MOF tree species biomass, ascribing the variations observed to the species differentiated nutritional requirements. Yerba mate absorbs and exports large amounts of Mn (Oliva et al., 2014; SBCS/NEPAR, 2017), and can be considered as accumulating Mn plants (Oliva et al., 2014), indicating that the plant has tolerance mechanisms to high levels of Mn (Barbosa et al., 2018).

Soil fertility attributes as influenced by the yerba mate AFS

Soils under all the yerba mate AFS had high acidity and low exchangeable cations (Table 3). The active (pH), potential (H+Al) and exchangeable (Al) acidity varied from 3.4 to 4.4; 78 to 320 mmol$_c$ dm^{-3}; and 0.5 to 113 mmol$_c$ dm^{-3}, respectively. In yerba mate AFS typical soils, Signor et al. (2015) observed pH, H+Al and Al values varying from 3.7 to 4.1; 98 to 171 and 16 to 56 mmol$_c$ dm^{-3}, respectively, in the 0-20 cm layer.

The exchangeable base content decreased when the soil depth increased, with the contents of Ca, Mg and K varying from 1.0 to 52, 1.0 to 27 and 0.4 to 37.4 mmol$_c$ dm^{-3}, respectively. The Ca content was considered low in all layers of the AFS soils under study, except for the 0-5 cm layer in AFS 2, with Ca content considered medium (Table 3) (SBCS/NEPAR, 2017). Mg content in the 0-5 cm soil layer was considered medium in all AFS (SBCS/NEPAR, 2017). Santos (2009), when studying yerba mate AFS in the same region determined average Ca, Mg and K content varying from 8.8 to 17.6, 6.4 to 16.3 and 1.5 to 4.2 mmol$_c$ dm^{-3}, respectively.

Variations observed for Ca and Mg content in the different AFS soils, were partly related to the floristic composition of the tree extract. Species such as *Piptocarpha angustifolia* and *Vernonia discolor*, which present low Ca content in their leaves, and *Mimosa scabrella* with low Mg content in their leaves (Caldeira et al., 2007), resulted in lower Ca and Mg input. These species were predominant in AFS 3 (Table 1) and Ca and Mg soil content was the lowest among the AFS under study (Table 3).

The TOC, P and S content varied from 11.9 to 60.3 g dm^{-3}, 0.5 to 17.7 mg dm^{-3}; and 0.1 to 1.4 mg dm^{-3}, respectively. Higher TOC and P contents were determined in more superficial soil layers, and no significant variation was observed in S content with increased depth (Table 3). The TOC high content found in yerba mate AFS was probably due to management practices that reduced the occurrence of disturbances to the soil/vegetation system, and the constant litterfall deposition. Signor et al. (2015) found the TOC content varying from 31.5 to 63.7 g dm^{-3}, in the layer 0-20 cm. The same author found P varying from 1.7 to 8.3 mg dm^{-3} in the 0-20 cm soil layer. Santos (2009) reported that P values found in soils under yerba mate AFS are either low or very low, varying from 1.23 to 2.77 mg dm^{-3}, with a tendency to P content reducing with increasing depth. This is due to the higher organic matter content in the soil superficial layers, since the incorporation of organic matter to the soil might increase P cycling, thereby increasing its availability to the plants (Silva and

Table 3. Soil chemical attributes (±mean standard error) in six yerba mate agroforestry systems (AFS 1, AFS 2, AFS 3, AFS 4, AFS 5 and AFS 6).

AFS	0-5 cm	5-10 cm	10-20 cm	20-40 cm
pH				
1	3.8±0.01	3.7±0.02	3.6±0.02	3.6±0.01
2	4.1±0.03	3.8±0.03	3.8±0.03	3.9±0.01
3	3.5±0.02	3.6±0.02	3.7±0.02	3.7±0.01
4	3.9±0.07	3.8±0.07	3.9±0.07	3.9±0.02
5	3.8±0.03	3.8±0.03	3.8±0.03	3.7±0.01
6	3.8±0.05	3.8±0.05	3.9±0.05	3.8±0.01
Aluminium (mmol$_c$ dm^{-3})				
1	57±2.30	77.0±3.46	82.0±2.40	104.0±1.38
2	19.9±1.47	38.0±5.02	41.0±4.25	51.0±1.01
3	54.5±1.62	57.0±5.51	56.0±8.35	54.0±1.33
4	18±1.62	27±4.39	27.0±5.08	19.0±1.40
5	36.5±1.95	45.0±5.34	46.0±6.60	44.0±0.90
6	24.5±1.90	29.0±5.73	28.0±6.02	26.0±0.67
Magnesium (mmol$_c$ dm^{-3})				
1	16.2±1.08	6.4±0.70	4.0±0.30	3.0±0.20
2	17.9±1.24	5.2±0.66	3.0±0.35	2.0±0.25
3	7.2±0.55	4.7±0.30	4.0±0.21	3.0±0.18
4	14.3±1.31	8.4±1.18	6.0±1.01	4.0±0.42
5	9.3±0.87	4.7±0.40	3.0±0.25	2.0±0.13
6	12.9±0.71	6.1±0.42	4.0±0.16	3.0±0.29
Total Organic Carbon (g dm^{-3})				
1	40.4±1.70	26.1±0.78	21.8±1.23	19.6±0.69
2	43±0.66	34.1±0.66	28.3±0.53	25.6±0.46
3	50.5±1.33	42.4±1.60	38.2±1.41	31.9±1.18
4	45.4±1.15	36.8±1.06	30.0±0.95	23.0±0.85
5	52.2±1.01	40.2±1.27	34.9±0.84	28.1±0.76
6	43.6±1.21	32.8±1.13	28.2±0.76	21.9±0.57
Sulfur (mg dm^{-3})				
1	1.1±0.03	1.2±0.05	1.2±0.04	1.0±0.05
2	1,1±0.05	1,2±0.05	1.3±0.06	1.0±0.04
3	0.7±0.09	0.5±0.04	0.5±0.04	0.7±0.05
4	0.5±0.04	0.4±0.03	0.4±0.03	0.3±0.06
5	0.8±0.06	0.8±0.07	0.7±0.07	0.5±0.04
6	1.0±0.04	1.0±0.04	1.1±0.05	1.0±0.08
Manganese (mg dm^{-3})				
1	223.0±18.90	101.0±5.78	78.0±3.94	49.0±1.25
2	44.0±6.30	21.1±2.44	16.1±3.13	7.9±0.25
3	101.0±19.32	63.0±1.25	50.0±1.89	26.9±2.31
4	304.0±32.69	225.0±5.08	161.0±1.74	100±15.47
5	124.0±18.15	44.3±1.12	28.8±0.86	9.3±0.65
6	486.0±29.88	322.0±0.98	228.0±0.52	112.0±12.31
H+Al (mmol$_c$ dm^{-3})				
1	222±7.92	203±0.15	203±0.13	215±1.76
2	154±4.32	189±0.11	189±0.12	164±1.90
3	279±5.92	269±0.19	242±0.18	201±7.64
4	164±7.40	180±0.25	165±0.23	106±3.31

Table 3. Contd.

5	212±5.75	217.0.17	202±0.15	167±2.49
6	189±6.28	181±0.20	156±0.18	130±1.38
Calcium (mmol$_c$ dm^{-3})				
1	15.1±1.48	5.1±0.70	3.0±0.40	3.0±0.18
2	24.6±2.65	5.8±0.73	3.0±0.37	3.0±0.39
3	7.3±1.81	3.7±1.38	2.0±0.68	2.0±0.26
4	12.0±4.70	4.1±0.71	2.0±0.42	3.0±0.61
5	11.2±1.58	3.2±0.74	2.0±0.29	2.0±0.18
6	15.2±2.87	4.2±0.88	2.0±0.45	2.0±0.11
Potassium (mmol$_c$ dm^{-3})				
1	4.2±0.32	2.9±0.30	2.3±0.22	2.2±0.13
2	2.3±0.20	1.5±0.11	1.0±0.05	0.6±0.03
3	2.7±0.11	2.0±0.10	1.2±0.05	0.6±0.02
4	2.4±0.13	1.6±0.10	1.0±0.05	0.6±0.04
5	3.1±0.21	2.0±0.13	1.2±0.08	0.8±0.06
6	11.7±0.35	6.3±0.19	3.1±0.08	0.5±0.02
Phosphorus (mg dm^{-3})				
1	10.0±0.70	4.4±0.28	2.9±0.14	0.8±0.06
2	3.4±047	1.7±0.27	1.1±0.15	0.6±0.19
3	3.7±0.33	2.3±0.19	1.8±0.13	0.7±0.05
4	6.2±0.45	3.2±0.22	1.8±0.11	0.7±0.12
5	2.0±0.13	1.3±0.10	1.2±0.09	0.7±0.05
6	2.4±0.18	2.1±0.38	1.2±0.10	0.9±0.13
Copper (mg dm^{-3})				
1	0.7±0.09	0.6±0.07	0.5±0.06	0.7±0.17
2	2.1±0.17	2.2±0.14	2.4±0.13	2.8±0.16
3	15.2±0.70	16.7±0.78	17.5±0.90	18.2±0.97
4	24.0±1.08	26.9±1.40	28.0±1.15	25.3±0.95
5	14.3±0.54	17.5±0.69	19.2±0.67	18.5±0.65
6	22.7±0.47	26.7±0.37	28.9±0.38	29.4±0.39
Zinc (mg dm^{3})				
1	5.4±0.60	2.9±0.17	2.6±0.14	5.8±1.14
2	3.0±0.33	2.0±0.11	1.7±0.07	1.5±0.41
3	2.6±0.16	1.9±0.15	1.8±0.11	3.0±0.49
4	4.0±0.55	3.1±0.12	2.0±0.14	3.7±0.49
5	3.2±0.31	1.4±0.12	1.1±0.08	1.6±0.11
6	3.3±0.24	1.7±0.13	1.0±0.09	2.4±0.34

Mendonça, 2007).

Regarding micronutrient content determined in the AFS soil under study, amounts of Cu, Mn and Zn varied from 0.2 to 38, 3.2 to 731 and 0.6 to 15.2 mg dm^{-3}; respectively (Table 3). Fossati (1997), comparing 10 sites of cultivated yerba mate, differing in toposequence, observed Cu, Mn and Zn content varying from 0.52 to 6.6, 8.0 to 150.0 and 1.42 to 5.96 mg dm^{-3}, respectively.

Yerba mate AFS discrimination

First canonical discriminant function (CDF1) was the most important for the four soil layers (0-5, 5-10, 10-20 and 20-40 cm) since it presented 99% canonical correlation. Eigenvalues for 0-5, 5-10, 10-20 and 20-40 cm layers were 67.55, 103.23, 106.17 and 184.11, respectively, explaining great proportion of properties variability.

Table 4. Standard canonical coefficients average (±mean standard error) for the first (CDF1) and second (CDF2) canonical discriminant functions for the six yerba mate agroforestry systems (AFS 1, AFS 2, AFS 3, AFS 4, AFS 5 and AFS 6) in four soil layers.

CDF	AFS 1	AFS 2	AFS 3	AFS 4	AFS 5	AFS 6
			0-5 cm			
CDF1	-16.97±0.32[e]	-4.12±0.18[d]	1.93±0.26[c]	7.35±0.33[a]	3.08±0.29[b]	6.58±0.21[a]
CDF2	3.99±0.32[b]	-10.90±0.29[f]	5.27±0.21[a]	-1.36±0.29[e]	-0.30±0.27[d]	2.17±0.25[c]
			5-10 cm			
CDF1	-20.31±0.29[f]	-6.96±0.24[e]	2.77±0.27[d]	9.32±0.36[a]	4.21±0.25[c]	8.14±0.21[b]
CDF2	4.07±0.36[b]	-8.02±0.32[f]	4.73±0.24[a]	0.23±0.24[d]	-1.65±0.20[e]	0.65±0.24[c]
			10-20 cm			
CDF1	-20.95±0.30[f]	-5.39±0.16[e]	1.89±0.34[d]	8.14±0.30[b]	4.54±0.28[c]	9.15±0.59[a]
CDF2	3.25±0.33[b]	-8.27±0.32[f]	5.11±0.30[a]	1.45±0.27[c]	-1.02±0.25[e]	-0.20±0.17[d]
			20-40 cm			
CDF1	-29.30±0.30[f]	-5.79±0.37[e]	4.07±0.26[d]	10.46±0.30[a]	6.68±0.15[c]	9.45±0.19[b]
CDF2	2.69±0.32[b]	-7.46±0.25[e]	4.75±0.23[a]	-0.54±0.31[c]	-1.82±0.27[d]	2.00±0.24[b]

Means followed by the same lowercase letter, in lines, do not differ to 5% by t test.

Variability proportion was 60, 75, 76 and 85% explained by CDF1 in 0-5, 5-10, 10-20 and 20-40 cm layers, respectively. Eigenvalues for second canonical discriminant function (CDF2) were lower than those observed in CDF1, except for 0-5 cm layer. CDF2 eigenvalues observed were 29.89, 19.28, 20.0 and 17.19 for 0-5, 5-10, 10-20 and 20-40 cm layers, respectively. Variability proportion was 26, 14, 14 and 8% explained by CDF2 in 0-5, 5-10, 10-20 and 20-40 cm layers, respectively. The remaining canonical functions did not present significant variability of the properties under study. Also, occasions on which the first CDF eigenvectors observed were relatively higher, the remaining CDFs had little relevance in data analysis (Manly 2008). Therefore, throughout this study only CDF1 and CDF2 of each soil layer were considered for discussion, since they could explain over 85% of the variability proportion.

In 0-5 cm layer, standardized canonical coefficient averages (SCCs) were distinct regarding each CDF, except in AFSs 4 and 6 for CDF1 (Table 4). In 5-10 and 10-20 cm layers, the SCCs averages differed for both CDFs (Table 4). In 20-40 cm layer, SCC averages were distinct regarding different CDFs, except for AFS 1 and AFS 6 and CDF 2 (Table 4).

The more strongly distributed sites on the horizontal axis differed due to CDF1 higher explaining proportion, for all soil layers under study (Figure 3). When it was not possible to see the distinction on the horizontal axis, as in the case of AFSs 4 and 6 for 0-5 cm layer, the differentiation was realized upon observation of the vertical axis (Figure 3).

Analysis of parallel discrimination rate (PDR) indicated that available Cu and exchangeable Al in the soil were the ones that most influenced in AFSs distinction, for both CDFs in four layers (Table 2). Soil and plant remaining variables presented very low or inexpressive PDR values (Table 5), The PDR – resulting from the product between the standard canonical coefficient (ACC) and the correlations between original and canonical variables (r) – presented values related to the r and SCC joint contribution (Baretta et al., 2008). Therefore, this method (PDR) has been recommended to discriminate areas through the canonical discriminant analysis (CDA) (Cruz-Castillo et al., 1994), including the presence of soil properties in the analysis (Mattias et al., 2010).

In order to better understand the available Cu and exchangeable Al relations in the sites under study, *r* values were considered, as suggested by Manly (2008). In such case, it was evident that the *r* values in the available Cu and exchangeable Al were inversely proportional (Table 5). Variations in the soil exchangeable Al concentrations were due to its weathering and the pH value (Kämpf et al., 2009; Malavolta et al., 1997). For each pH unit, the Al^{3+} in solution activity was increased from 42 to 1000 times, depending on the kind of mineral with which Al^{3+} was in equilibrium (Lindsay, 1979).

In the exchange complex, when there was high Al^{3+}, Cu adsorption tended to decrease. However, the availability to the plants, when compared to the remaining cationic micronutrients, was less dependent on pH and more influenced by the kind of soil due to the mineralogical composition (Alleoni et al., 2005; Vendrame et al., 2007) and TOC content. The TOC content presented direct effect in the Cu availability reduction (Mouta et al., 2008), ascribed to the formation of high energy complexes with

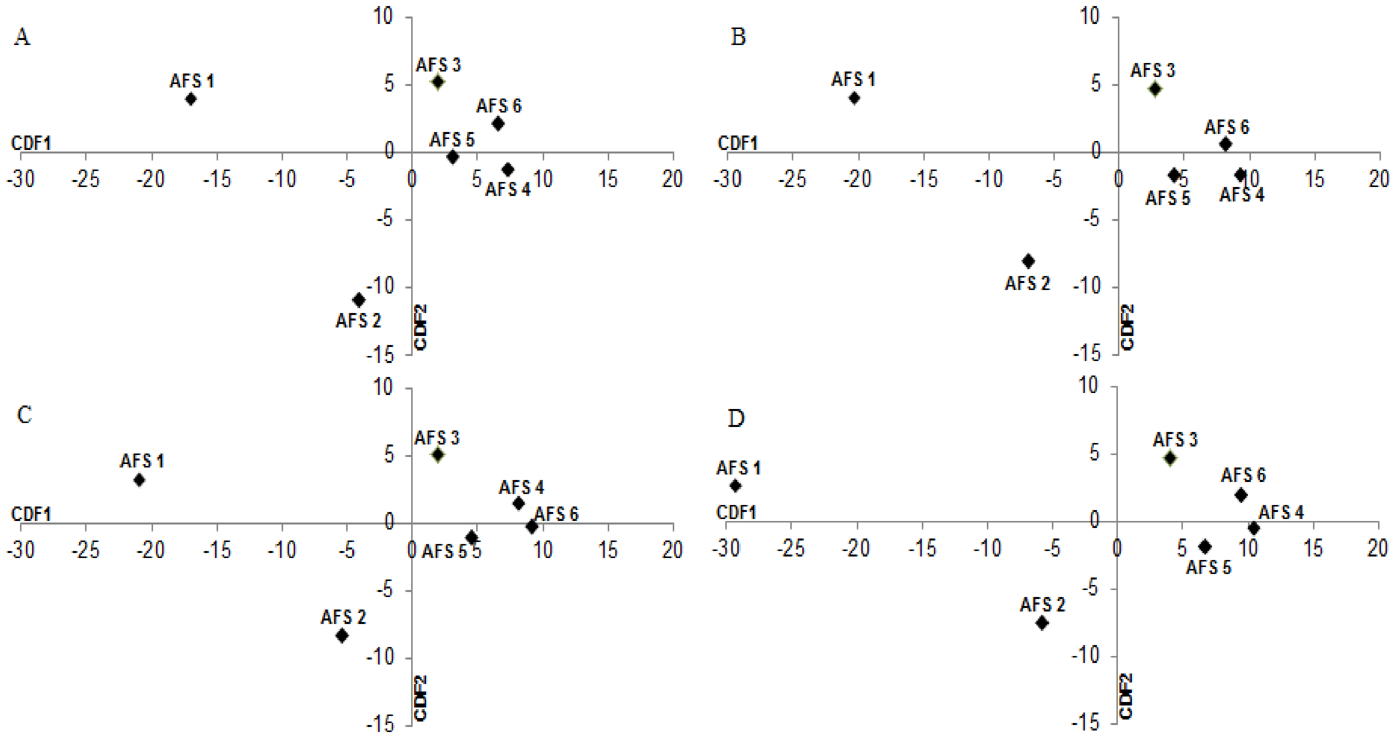

Figure 3. Average of first function canonical coefficient of the first canonical discriminant function (CDF1) against the coefficients of the second canonical discriminant function (CDF2), regarding input and soil mineral content in the layers 0-5 (A), 5-10 (B), 10-20 (C) and 20-40 cm (D), for the six yerba mate agroforestry systems (AFS).

humic acids (Arias et al., 2006).

The proximity of canonical coefficient averages in AFS 3, AFS 4, AFS 5 and AFS 6 (Figure 3), occurred due to higher Cu content in the soil, in relation to Cu content observed in AFS 1 and AFS 2. Soils developed from basalt presented, in general, higher solubilized Cu content than those of sedimentary origin (Oliveira and Costa, 2004).

Canonical correlation

All correlations with eigenvalues over 1 were selected, as suggested by Manly (2008). Correlations 1 (canonical correlation = 0.91; eigenvalue = 5.02), 2 (canonical correlation = 0.84; eigenvalue = 2.44) and 3 (canonical correlation = 0.74; eigenvalue = 1.23) were the most relevant for 0-5 cm layer, as they explained 87% of the variability. For 5-10 cm layer, correlations 1 (canonical correlation = 0.91; eigenvalue = 4.53) and 2 (canonical correlation = 0.74; eigenvalue = 1.29) explained 80% of the variability. Correlations 1 (canonical correlation = 0.91; eigenvalue = 4.69) and 2 (canonical correlation = 0.72; eigenvalue = 1.06) were the most relevant for 10-20 cm layer, due to the fact that they explained 80% of variability. In 20-40 cm layer, only correlation 1 (canonical correlation = 0.88; eigenvalue = 3.60) was important, as it explained 57% of variability.

Higher canonical correlation (CC) positive values were observed for Cu and Mn input and Cu and Mn soil content in the first canonical correlation, for all soil layers. For Cu input, CC was 0.62; 0.63; 0.64 and 0.70 for 0-5 cm, 5-10 cm, 10-20 cm and 20-40 cm layers, respectively. For Cu soil content, CC was 0.81; 0.80; 0.82 and 0.86 for 0-5 cm, 5-10 cm, 10-20 cm and 20-40 cm layers, respectively. CC values for Mn input were 0.87; 0.85; 0.83 and 0.91 for 0-5 cm, 5-10 cm, 10-20 cm and 20-40 cm layers, respectively. For Mn soil content, CC was 0.66; 0.74; 0.70 and 0.74 for 0-5 cm, 5-10 cm, 10-20 cm and 20-40 cm layers, respectively. This indicated that there was close relation between the Cu and Mn content input through vegetable material deposition, and these elements content was found in the soil of all yerba mate AFS. Reports in the literature informing the close positive relation between available Cu in the soil and in the forest species aerial parts are common (Rodrigues et al., 2010). Another factor determining Cu availability to plants is related to its decrease when there is increase in the TOC content in the soil (Mouta et al., 2008). However, in this study, despite the variations observed in soil TOC (Table 3), it was not enough to differentiate AFS or to influence Cu in the soil-plant system. In native forest species (for example, yerba mate), Mn contents are usually high (over 1000 mg kg^{-1}) (Reissmann and Carneiro, 2004; Heinrichs

Table 5. Standard canonical coefficients (SCC), canonical correction coefficient (*r*) and parallel discrimination rate (PDR) in the first (CDF1) and second (CDF2) canonical discriminant functions in the four layers, regarding nutrient amount input and soil properties.

Variable	Layer of 0-5 cm			Layer of 5-10 cm			Layer of 10-20 cm			Layer of 20-40 cm		
	SCC	***r***	**PDR**	**SCC**	***r***	**PDR**	**SCC**	***r***	**PDR**	**SCC**	***r***	**PDR**
CDF 1												
N input	-0.02	0.17	0.00	0.23	0.17	0.04	0.06	0.16	0.01	0.76	0.13	0.10
P input	0.47	0.08	0.04	0.74	0.07	0.05	0.27	0.11	0.03	0.06	0.07	0.00
K input	-0.53	-0.45	0.24	-0.08	-0.44	0.04	-0.03	-0.42	0.01	-0.20	-0.42	0.08
S input	0.19	0.13	0.02	-0.35	0.10	-0.04	0.01	0.15	0.00	0.13	0.11	0.01
Ca input	0.27	-0.15	-0.04	0.39	-0.11	-0.04	0.07	-0.16	-0.01	0.23	-0.13	-0.03
Mg input	-0.07	-0.01	0.00	-0.30	-0.04	0.01	-0.09	-0.01	0.00	0.50	-0.07	-0.04
Cu input	0.13	0.50	0.07	0.42	0.50	0.21	0.23	0.48	0.11	0.23	0.45	0.10
Mn input	-0.26	0.43	-0.11	-0.45	0.47	-0.21	-0.32	0.44	-0.14	0.16	0.37	0.06
Zn input	-0.08	0.31	-0.02	0.00	0.28	0.00	-0.13	0.33	-0.04	0.05	0.29	0.01
C soil	0.31	0.38	0.12	1.07	0.56	0.60	1.16	0.48	0.56	1.17	0.39	0.46
P soil	-0.65	-0.54	0.35	0.27	-0.33	-0.09	-0.22	-0.52	0.11	0.12	0.00	0.00
K soil	0.16	0.21	0.03	-0.15	-0.03	0.00	0.21	0.33	0.07	0.78	0.83	0.65
S soil	0.03	-0.43	-0.01	0.20	-0.57	-0.11	0.46	-0.52	-0.24	-0.62	-0.44	0.27
Ca soil	0.42	0.29	0.12	0.36	0.31	0.11	0.25	0.37	0.09	0.00	0.34	0.00
Mg soil	-0.60	-0.32	0.19	0.34	-0.11	-0.04	0.31	0.01	0.00	-0.43	0.02	-0.01
Cu soil	5.35	0.94	5.03	7.82	0.98	7.66	6.91	0.96	6.63	4.76	0.91	4.33
Mn soil	-0.58	0.25	-0.15	-0.49	0.36	-0.18	-0.48	0.29	-0.14	1.24	-0.09	-0.11
Zn soil	-0.08	-0.25	0.02	0.08	0.19	0.02	0.19	0.45	0.09	0.20	0.19	0.04
Al soil	-3.83	-0.54	2.07	-2.84	-0.73	2.07	-3.75	-0.85	3.19	-8.93	-0.93	8.30
H+Al soil	0.23	-0.11	-0.03	-0.78	0.00	0.00	-0.31	-0.27	0.08	1.27	-0.61	-0.77
pH soil	1.04	0.05	0.05	-0.59	0.32	-0.19	-0.60	0.58	-0.35	0.62	-0.47	-0.29
CDF 2												
N input	0.77	0.21	0.16	1.22	0.17	0.21	0.83	0.18	0.15	1.00	0.20	0.20
P input	-0.11	-0.05	0.01	-0.58	-0.16	0.09	-0.22	-0.20	0.04	-0.23	-0.09	0.02
K input	0.37	0.15	0.06	-0.14	0.01	0.00	-0.12	-0.05	0.01	-0.24	0.00	0.00
S input	-0.62	-0.20	0.12	-0.47	-0.32	0.15	-0.53	-0.36	0.19	-0.24	-0.25	0.06
Ca input	0.88	0.48	0.42	0.76	0.54	0.41	0.94	0.54	0.51	1.09	0.52	0.57
Mg input	-0.05	-0.23	0.01	-0.21	-0.21	0.04	-0.13	-0.25	0.03	-0.52	-0.18	0.09
Cu input	0.06	0.25	0.02	0.54	0.24	0.13	0.64	0.28	0.18	0.22	0.30	0.07
Mn input	0.53	0.59	0.31	0.34	0.56	0.19	0.53	0.56	0.30	1.02	0.62	0.63
Zn input	0.22	0.08	0.02	-0.24	-0.09	0.02	-0.16	-0.14	0.02	0.07	0.03	0.00
C soil	-0.02	0.15	0.00	-0.64	-0.03	0.02	0.06	0.19	0.01	-0.31	0.01	0.00
P soil	0.21	0.23	0.05	0.20	0.45	0.09	-0.02	0.53	-0.01	0.04	-0.24	-0.01
K soil	-0.32	-0.38	0.12	0.22	0.24	0.05	-0.04	-0.29	0.01	0.62	-0.12	-0.07
S soil	0.19	-0.24	-0.05	0.49	-0.36	-0.18	-0.43	-0.49	0.21	0.29	-0.08	-0.02
Ca soil	-1.07	0.57	-0.61	-0.46	0.23	-0.11	-0.21	0.27	-0.06	0.21	0.34	0.07
Mg soil	-0.79	-0.51	0.40	0.22	-0.04	-0.01	-0.04	-0.34	0.01	0.09	0.23	0.02
Cu soil	2.04	0.30	0.61	2.60	0.18	0.47	2.47	0.26	0.64	2.69	0.34	0.91
Mn soil	2.20	0.41	0.90	1.58	0.42	0.66	1.45	0.43	0.62	-1.14	-0.52	0.59
Zn soil	0.13	0.12	0.02	-0.41	-0.24	0.10	-0.24	-0.24	0.06	-0.24	-0.45	0.11
Al soil	4.00	0.68	2.72	3.63	0.49	1.78	3.95	0.39	1.54	2.89	0.20	0.58
H+Al soil	0.31	0.71	0.22	0.60	0.47	0.28	0.13	0.34	0.04	1.08	0.23	0.25
pH soil	-0.12	0.80	-0.10	0.12	-0.59	-0.07	0.19	-0.47	-0.09	0.15	0.44	0.07

and Malavolta, 2001), as a result of high input and concentration of these micronutrients available in the soil (Boeger et al., 2005). Also, pH values usually observed in yerba mate AFS (Table 3) are in the band (pH < 5.5) which favors Mn availability to the plants (Abreu et al., 1994).

For soil Ca content in 0-5 cm layer, CC values were positively high in the first canonical correlation (CC=0.52), indicating higher Ca content, which demonstrated the litterfall importance in this nutrient cycling, since the litterfall accumulated on the soil surface was the main source of Ca mineralization (Costa et al., 2005). Low mobility in vegetable tissues and the leaves long life are among the factors that contributed to Ca content in litterfall (Caldeira et al., 2007).

In 0-5 cm layer, the second canonical correlation presented negative CC values for variables input and soil Ca content (CC= -0.49 and -0.44, respectively), and CC positive values for variables input and soil Mg content (CC= 0.71 and 0.73, respectively), which indicated the inverse relation between Ca and Mg, both in the input of these nutrients through vegetable material deposition and in the soil content found. The low Ca:Mg relation in yerba mate AFS soils studied, favored Mg absorption and accumulation by plants, as observed in yerba mate, species in which high Mg content was found in dry leaves (Heinrich and Malavolta, 2001).

Higher CC negative values were observed for soil S content in the first canonical correlation, for 0-5 cm (CC= -0.59), 5-10 cm (CC= -0.67) and 10-20 cm (CC= -0.68) layers, which could be due to the low soil S content, caused by the S repulsion in the soluble form (SO_4^{-2}), which occurs as soon as S is mineralized from the organic matter (Furtini Neto et al., 2001).

Regarding second canonical correlation, higher CC positive values were observed for S input (CC= 0.52 and 0.58 in 5-10 and 10-20 cm layers, respectively). Lower CC were observed for soil P content in second canonical correlation, in order of -0.76 and -0.73 in 5-10 and 10-20 cm layer, respectively. This resulted from a higher annual S input, approximately double the P input (Table 2), since the interactions are negligible due to their low soil content of most AFS (Table 3). Suitable S and P supply in forest species is guaranteed through associations with mycorrhizal fungi (Faria et al., 2017). Yerba mate presents abounding association with endomycorrhizae (Gaiad and Lopes, 1986), and was shown to present low P content in its leaves without any evidence of P deficiency symptoms, for being a species adapted to the low soil P content conditions (Radomski et al., 1992).

The affinity relation between soil Zn content and this mineral input was also described by second canonical correlation in 10-20 cm layer, in which CC values were 0.70 and 0.63 for input and soil content, respectively. Micronutrient (Cu, Mn and Zn) content in the soil was related to these mineral elements input through vegetable material deposition; however, Cu and Mn were more important in the correlation between soil and plant contents. The micronutrient dynamics was related, directly or indirectly with the continuous vegetable material input, which along the time, after the decomposition process was released and later on absorbed by the plants (Carmo et al., 2012).

Conclusions

The adoption of agroforestry systems in yerba mate production contributed significantly to litterfall deposition on the soil with the addition varying from 7132 to 9402 kg ha^{-1} $year^{-1}$. Litterfall was an important nutrient source to yerba mate AFS, underscoring its the contribution of the macronutrients N, K and Ca, and the micronutrient, Mn. The floristic composition and the soil class and origin influenced nutrient input and soil nutrient content in yerba mate AFS. Canonical discriminant analysis was efficient to evaluate differences between yerba mate AFS, revealing Cu and Al content variable in the soil as responsible for the site differentiation. Soil fertility depended on nutrient input through litterfall deposition in yerba mate AFS. There was strait relation between Ca, Mg, Cu, Mn and Zn input and their soil content in yerba mate AFS.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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