SOIL CHEMICAL ATTRIBUTES RELATIONSHIPS AROUND THE *Araucaria angustifolia* TREES IN AGROFORESTRY SYSTEMS

RELAÇÕES DOS ATRIBUTOS QUÍMICOS DO SOLO NO ENTORNO DE ÁRVORES *Araucaria angustifolia* EM SISTEMAS AGROFLORESTAIS

João Bosco Vasconcellos Gomes[1]
https://orcid.org/0000-0002-7911-5331
Paulo Cesar Botosso[2]
https://orcid.org/ 0000-0001-5361-2543
Tomaz Longhi-Santos[3]
https://orcid.org/0000-0001-9700-2843

Submetido: 15/07/2021 / Aprovado: 10/12/2022 / Publicado: 10/08//2023.

Abstract

This work aimed to understand the relationships between araucaria trees and some abiotic factors (soil type, soil organic C and soil nutrient supply) in agroforestry systems (AFS). Soils of two production areas in south-central region of the state of Parana (Bituruna - B and São Mateus do Sul - M) were characterized and soil chemical attributes were determined in microsites close to araucaria trees. B area presented only "juvenile" trees, while M area was formed by "juvenile" and "adult" trees. According to the multiple linear regression analyses, the soil chemical attributes showed an almost total dependence of the microsites depth. Soil chemical attributes dependence was much more diffuse in relation to the distances from the tree insertion in the soil. The non-metric multidimensional scaling ordination according to soil chemical attributes showed a great overlap of behavior of these tree groups. The chemical attributes comparison generated, to a certain extent, a soil fertility deficiency gradient between the microsites of the three groups of trees (MJ < MA < BJ). AFS with shaded *Ilex paraguariensis* must consider the replacement of nutrients exported by leaf harvest, which will help in the sustainability of the activity. This includes the environmental services that the AFS promotes by maintaining, or even renewing, of the native trees from the local forest, especially araucaria trees, in a productive system.
Key-words: Forest soil. Ombrophilous Mixed Forest. Dendrochronology. Multiple linear regressions.

Resumo

[1]Doutor em Ciência do Solo, Embrapa Florestas, e-mail: joao.bv.gomes@embrapa.br
[2]Doutor em Engenharia Florestal, Embrapa Florestas, e-mail: paulo.botosso@embrapa.br
[3]Doutor em Engenharia Florestal. Dpto. de Zootecnia, Universidade Federal do Paraná, e-mail: longhi@ufpr.br

Este trabalho teve por objetivo compreender as relações entre árvores de araucária e alguns fatores abióticos (tipo de solo, C orgânico e atributos químicos do solo) de sistemas agroflorestais (SAF). Solos de duas áreas de produção da região centro-sul do estado do Paraná (Bituruna - B e São Mateus do Sul - M) foram caracterizados e os atributos químicos do solo determinados em micro-sítios ao redor de árvores de araucária. A área B apresentou apenas árvores “juvenis”, enquanto a área M foi formada por árvores “juvenis” e “adultas”. Nas análises de regressão linear múltipla, os atributos químicos do solo mostraram uma dependência quase total da profundidade dos micro-sítios. A dependência dos atributos químicos do solo foi muito mais difusa em relação à distância até o ponto de inserção das árvores no solo. O ordenamento pela “non-metric multidimensional scaling” em função de atributos químicos do solo mostrou uma grande sobreposição de comportamento desses grupos de árvores. A comparação dos atributos químicos gerou, em certa medida, um gradiente de deficiência de fertilidade do solo entre os micro-sítios dos três grupos de árvores (MJ < MA < BJ). Os SAFs que envolvem o sombreamento de *Ilex paraguariensis* devem considerar a reposição dos nutrientes exportados pela colheita das folhas, o que auxiliará na sustentabilidade da atividade. Isso inclui os serviços ambientais que o SAF promove ao manter, ou mesmo renovar, as árvores nativas da floresta local, especialmente indivíduos de araucária, em sistemas produtivos.

Palavras-chave: Solos florestais. Floresta Ombrófila Mista. Dendrocronologia. Análises multivariadas

1. INTRODUCTION

The significant reduction of the natural populations of *Araucaria angustifolia* was influenced, over time, by the agricultural expansion and by its excellent use as lumber or even for pulp production. The gradual replacement by plantations (grains, forests and pastures) began in the late 19th century. The economic exploitation of Araucaria trees was intensified around 1930 and later depleted by the simple exhaustion of its reserves, in the early 70's (BITTENCOURT 2007; RIBEIRO *et al.*, 2009; BERTINI *et al.*, 2015). This aggressive exploration resulted in a strong fragmentation of the Ombrophilous Mixed Forest in Southern Brazil, placing *A. angustifolia*, a key-species in the structure and functioning of this ecosystem, among species threatened with extinction (REIS *et al.*, 2014; PERALTA *et al.*, 2016). Besides its ecological and economic relevance, this subtropical conifer is considered a potential tree species for dendrochronological and dendroecological studies in Neotropical regions (ROIG, 2000), then providing evidences that the periodicity of the growth rings formation is annual (OLIVEIRA *et al.*, 2009; OLIVEIRA *et al.*, 2010).

Climatic aspects control the Ombrophilous Mixed Forest areas and even greater latitude regions of Brazil have the natural occurrence of araucaria limited by these aspects, thus favoring its presence lower temperatures, greater frost risk, greater water availability and lower insolation (FRITZSONS *et al.*, 2018). Except for oxygen deficiency (water excess), aspects of soil ambience do not define the natural occurrence of araucaria but help to explain its development (PULCHALSKI *et al.*, 2006). The plant size is positively influenced by the soil volume availability to be explored by the roots (PULCHALSKI *et al.*, 2006; SANTOS *et al.*, 2010). The relationships between araucaria development and nutrient supply are more complex, with few data available mixing the absence of correlations or negative and positive correlations (HOPPE; CALDEIRA, 2003; PULCHALSKI *et al.*, 2006). However, the positive effect of fertilization for initial growth of *A. angustifolia* is more accurate (ROSSA *et al.*, 2011; CONSTANTINO *et al.*, 2019).

DOI: http://dx.doi.org/10.24021/raac.v20i1.6570 V. 20, N. 1 (2023)

In addition to the Ombrophilous Mixed Forest fragments areas, one of the possibilities of araucaria survival is in agroforestry systems (AFS) (RADOMSKI *et al.*, 2014; MELLONI *et al.*, 2018). This is the case of *Ilex paraguariensis* production in AFS by family farming in some areas of southern Brazil and Misiones in Argentina, which are increasing in importance with the good market prices achieved by the crop. The production sites are small, occurring under various soil and landscape conditions. The araucaria trees, in addition to other native tree species, act in the partial shade of the *I. paraguariensis* plants and are present in different individual number, ages, and growth stages (EIBL *et al.*, 2000).

The aim of this work was to understand the relationships between araucaria trees at different ages and local abiotic factors (soil type, soil organic C and soil nutrient supply). The soils of two small production areas were characterized and, in each area, the superficial and sub-superficial soil chemical attributes were determined in microsites close to araucaria trees at different stages of growth (age). Understanding these relationships can help the management of AFS with *I. paraguariensis* St. Hil. and, consequently, reduce the loss of Araucaria genetic diversity, since the success of these systems guarantees the survival of a large number of araucaria individuals (RADOMSKI *et al.*, 2014). The following questions were tested: (i) Is there a spatial dependence of soil chemical attributes on the microsites according to their position in relation to the araucaria trees (depth and distance of the stem)? (ii) How is the behavior of soil chemical attributes in the microsites of each tree group as defined by area and age?

2. MATERIAL AND METHODS

2.1 Study areas and soil description

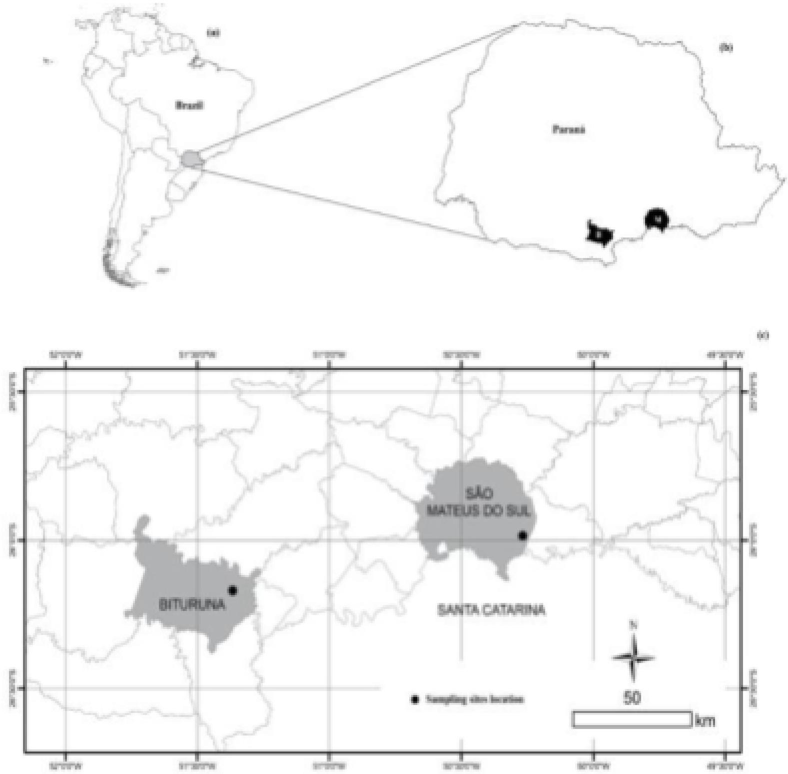
Two areas with AFS for the *I. paraguariensis* production in the south-central part of the Paraná state were defined for the study, and in each one an experimental plot of 0.25 ha was selected, Bitururа (B) and São Mateus do Sul (M) (Fig. 1 and Table 1). Both areas have a Cfb climate, according to the Köppen classification (ALVARES *et al.*, 2013), mesothermic, humid to superhumid, without dry season, with fresh summers and with average of the hottest month below 22°C. Frosts are frequent (WREGE *et al.*, 2018).

Both study areas had their soils described in trenches. Soil samples of the genetic horizons were collected. The soils were classified (SOIL SURVEY STAFF 2014; EMBRAPA, 2018) as being two profiles in B and one profile in M.

Regarding the management systems of the two areas, the degree of intervention is lower in B, with area M presenting higher *I. paraguariensis* plants density and greater nutrients input by corrections (liming) and, as a rule, organic fertilizations. In general, B area presents a denser grove than the M area, which generates more shading for *I. paraguariensis* plants of B area.

DOI: http://dx.doi.org/10.24021/raac.v20i1.6570 V. 20, N. 1 (2023)

Figure 1. Location of the studied areas: Paraná state, southern Brazil (a); Bituruna (B) and São Mateus do Sul (M) municipalities in the Paraná state (b); and sampling sites in B and M (c).



Source: Authors, 2021.

Table 1. Code, location, geographic coordinates and geomorphological and geological characteristics of the study areas.

Code	City	Geographic coordinates	Geomorphology/ Geology[1]
B	Bituruna	26°10'8" S 51°21'56" W G.	Medium to high dissection plateau, altitude around 950 m Mesozoic, São Bento Group, Serra Geral Formation, basic to intermediate effusive, rarely andesitic
M	São Mateus do Sul	25°59'9" S 50°16'03" W G.	Low dissection plateau, altitude around 815 m Permian-Devonian, Passa Dois Group, Serra Alta Formation and Irati Formation (lamitos, shales and argillites)

[1]Source: SANTOS *et al.*, 2006.

DOI: http://dx.doi.org/10.24021/raac.v20i1.6570 V. 20, N. 1 (2023)

2.2 Araucaria trees selection and soil sampling

The small size of the two areas (0.25 ha) comprises 18 araucaria trees in B and 7 in M. In each area, six araucaria trees were selected for their characteristics of canopy morphology, height and diameter at breast height (DBH ~1.3m of the soil). We attempted to select, empirically, two-stage growth trees: (a) juvenile stage and (b) adult stage. Three juvenile trees and three adult trees were, tentatively, selected in each area.

For each selected tree, soil samples were collected in microsites of a Cartesian plane (x:y), with the insertion of the tree into the soil as a starting point (0:0). For the soil samples, two depths (0 – 5 and 5 - 20 cm) and several distances were considered from the insertion of the tree in the soil. There were six distances for the smaller trees (25, 50, 100, 150, 200 e 300 cm), theoretically considered younger, and seven distances for larger trees (25, 50, 100, 150, 200, 300 and 400 cm), considered the older trees.

2.3 Biometrics and age estimates of the selected trees

DBH and total height data of each of the 12 selected trees were recorded. For each tree, cylindrical wood samples (increment cores with 5 mm in diameter) were collected, comprising two diametrically opposite rays of the trunk at DBH level (pith to bark direction), in a non-destructive way, by using an increment borer (Pressler). Each collected wood sample contains the entire tree ring time series for the tree ring analysis, according to the standard procedure used in dendrochronological studies (SHIMAMOTO *et al*., 2014). The wood samples were, still in the field, conditioned in plastic tubes. The samples were dried at room temperature in the laboratory and then glued on wooden supports. After that, cross sections were polished with sandpaper of decreasing grit sizes (80 - 400 grains cm-2), until the anatomical characteristics of the ring boundaries were clearly identifiable, by using a stereoscopic microscope (ROIG, 2000). The wood samples were scanned with a HP Scanjet G4050 scanner (1200 dpi resolution), and tree ring widths were measured with Image Pro Plus software. The annual variation of the growth rings width and the time series synchronization between rays of the same tree (by graphical analysis of the current increments) were obtained. These data allowed the dating and, therefore, the age estimate of the selected trees.

2.4 Soil analysis

The disturbed soil samples were air-dried, crushed, and sieved (2 mm mesh), in order to obtain Air-Dried Fine Earth (ADFE). The following analyzes were performed in ADFE (EMBRAPA, 2011): pH was measured in $CaCl_2$; organic C was determined according to the Walkley and Black method; Ca, Mg, and Al were determined through KCl extraction; K through HCl extraction; H+Al, through a calcium acetate extraction at pH 7; and P, through extraction by Mehlich-1. The sum of bases, cation exchange capacity (CEC), base saturation, Al saturation, and clay activity were calculated.

Only in the genetic horizons of soil profiles samples were collected using a volumetric ring. These samples were oven-dried (105-110°C) and their masses determined in order to calculate the bulk density (BD). Furthermore, the skeletal fractions (> 2 mm) percentage, by weight, was determined in the disturbed soil samples of these genetic horizons. In the ADFE of the same horizons, particle size distribution was determined by the pipette method (EMBRAPA, 2011), using a dispersant NaOH solution. The organic C stock of soil profiles up to 1 m deep, when possible, was calculated from the BD and organic C data from the genetic horizons.

DOI: http://dx.doi.org/10.24021/raac.v20i1.6570 V. 20, N. 1 (2023)

2.5 Statistical analyzes of the soil attributes by tree groups

We initially correlated and compared the dendrochronological and biometric attributes of the trees of the two study areas. From this analysis, the groups (named "juvenile" and "adult") were defined in each location.

Pearson correlation matrices of soil chemical attributes were performed for each sampling depth (0-5 and 5-20 cm).

For each sampling depth, the soil chemical attributes were also analyzed by one-way analysis of variance. Significant differences between tree groups (defined from dendrology results) averages were assessed by Duncan's post-hoc test at 5% of significance level (STATSOFT, 2010).

Multiple linear regression tests were performed for the same groups. The soil chemical attributes were the dependent variables and the micro-sites in relation to the tree insertion in the soil (soil depth and horizontal distance) were the independent variables.

To compare results by araucaria tree groups, the soil chemical attributes data at each soil depth were analyzed using multivariate ordination non-metric multidimensional scaling (NMS) with Sorensen distances. Ordination was performed using the PC-ORD v. 6.0 program in autopilot mode with the "slow and thorough" option selected (MCCUNE; MEFFORD, 2011). The number of dimensions to be interpreted was chosen according to the stress and stability of the graphical solutions. The variations between sites were also characterized by calculating Pearson correlation coefficients between individual values of the variables considered in this study and the NMS scaling scores (in the axes). Prior to analysis, the data were normalized by totals within each variable to account for the differences in the variable units.

3. RESULTS AND DISCUSSION

3.1 Soil characterization

The landscapes of the two areas are quite disparate (Table 1), which is reflected in the local soil conditions. The B area is dominated by soils of low to medium development degree. Predominate Typic Udorthents/Neossol Regolithic Humic leptfragmentary (clayey texture and gently sloping), with lower expression of Oxic Dystrudepts/Cambisol Humic Dystropherric leptfragmentary. The M area is dominated by deeper soils, classified as Typic Humudepts/Cambisol Humic Aluminic typical (fine loamy texture and nearly level).

In addition to the degree of soil development, moisture regime is a large difference between the two areas. The M area presents a subsurface moisture flow due to its landscape position that generates a seasonal and subsurface water excess in the local soils. The B area, besides free drainage, has shallow soils and many rock fragments (gravel and cobbles fractions). The M profile presents a very high clay activity, showing a significant presence of 2:1 minerals in the clay fraction of these soils (Table 2).

DOI: http://dx.doi.org/10.24021/raac.v20i1.6570 V. 20, N. 1 (2023)

Table 2. Genetic horizons characteristics of the soil profiles of the study areas: Bituruna (B1 and B2 profiles) and São Mateus do Sul (M profile).

Characteristic	Unity	B1 - **Typic Udorthents**[2]			B2 – **Oxic Dystrudepts**[2]					M – **Typic Humudepts**[2]				
Horizon	-	A	Bi	Cr	A	BA	Bi	BiCr	Cr	A1	A2	BA	Bi	BC
Upper limit	cm	0	5	16 (20)	0	9	24	47	70	0	18	34	77	90
Lower limit	cm	5	16 (20)	+	9	24	47	70	80+	18	34	77	90	100+
Humid soil color	-	5YR 3/3	5YR 4/4	mixed	5YR 3/3	5YR 4/6	5YR 4/5	3.5YR 4/5	-	7.5YR 3/4	7.5YR 3/2	7.5YR 3/4	6YR 4/4	5YR 4/5
Fraction < 2mm	%	38	5	-	67	17	7	12	-	100	100	100	100	100
Sand	$g\ kg^{-1}$	87	100	-	101	92,5	82	88,5	-	254	233	219	200	210
Silt	$g\ kg^{-1}$	374	380	-	399	407,5	418	331,5	-	348	380	486	502	472
Clay	$g\ kg^{-1}$	540	520	-	500	500	500	580	-	398	387	295	298	318
Bulk density	$g\ cm^{-3}$	0.80	0.88	-	0.80	0.93	1.00	1.18	-	1.31	1.28	1.26	1.29	1.34
Organic C	$g\ 100\ g^{-1}$	6.39	4.12	-	6.36	3.51	2.37	1.44	-	3.71	2.74	1.63	1.59	1.21
P-Mehlich	$mg\ kg^{-3}$	2.6	0.6	-	2.1	0.6	2.2	0.1	-	0.8	0.1	0.0	0.0	0.0
pH CaCl2	-	4.0	4.0	-	3.9	4.1	4.3	4.4	-	4.0	4.0	4.1	4.2	4.2
Al	$cmol_c\ kg^{-1}$	2.4	3.1	-	2.7	2.5	1.7	1.3	-	5.1	5.0	4.4	3.6	2.7
H + Al	$cmol_c\ kg^{-1}$	13.9	14.3	-	15.2	12.7	8.1	7.0	-	18.0	14.3	13.7	12.4	10.3
Ca	$cmol_c\ kg^{-1}$	1.4	0.4	-	1.2	0.4	0.3	0.1	-	0.3	0.1	0.1	0.1	0.1
Mg	$cmol_c\ kg^{-1}$	0.4	0.1	-	0.3	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0	0.0
K	$cmol_c\ kg^{-1}$	0.28	0.14	-	0.26	0.11	0.05	0.02	-	0.08	0.04	0.03	0.02	0.02
Sum of bases	$cmol_c\ kg^{-1}$	2.03	0.67	-	1.79	0.54	0.30	0.16	-	0.38	0.15	0.16	0.08	0.09
CEC[1]	$cmol_c\ kg^{-1}$	15.97	14.98	-	17.02	13.19	8.42	7.15	-	18.39	14.43	13.83	12.48	10.39
V[1]	%	13	4	-	11	4	4	2	-	2	1	1	1	1
m[1]	%	54	82	-	60	82	85	89	-	93	97	96	98	97
Clay activity	$cmol_c\ kg^{-1}$	29.6	28.8	-	34.0	26.4	16.8	12.3	-	46.2	37.3	46.9	41.9	32.7

[1]CEC = cation exchange capacity, V = base saturation, m = Al saturation. [2]Soil profiles B1 e B2 – Bituruna, PR; M – São Mateus do Sul, PR.
Source: Authors, 2021.

The soils of both study areas present low fertility regardless of the parent material (basic/intermediate rocks in B and sedimentary rocks in M). Both soils have high aluminum saturation from the surface, which is common for mild and rainy conditions in southern Brazil. These lands have a condition of high leaching and non-intensive weathering rate, although there may be substantial amounts of decomposable minerals.

As a competitive advantage, the soil organic C (SOC) of both areas is quite high. This high SOC is coupled with the mild climate condition, a reasonable altitude, considering the positive influence of altitude on the SOC (GIRARDIN, 2010; DIELEMAN *et al.*, 2013), and the current land use conditions, with low degree of soil intervention. C stock values vary widely between sites, mainly due to differences in soil depth, being the largest stock in the M profile. The B1 and

DOI: http://dx.doi.org/10.24021/raac.v20i1.6570 V. 20, N. 1 (2023)

B2 profiles find the Cr horizon, with predominance of regolithic material, before 1 m depth, which does not occur in M (Tables 2 and 3).

Table 3. Organic C stock of the soil profiles of the study areas: Bituruna (B1 and B2 profiles) and São Mateus do Sul (M profile), considering a maximum depth of 1.0 m.

Soil profile	Soil depth (cm)	Depth for calculation (cm)	Organic C stock (Mg ha^{-1})
B1	16 - 20	18	72.4
B2	70	70	188.5
M	> 100	100	274.2

Source: Authors, 2021.

3.2 Groups definition and araucaria trees biometry

The dendrochronological studies confirmed the existence of two age groups for the araucaria trees in M. In B, all trees are "juvenile". Thus, three groups were created, according to Table 4.

Table 4. Age and biometrics data in the "juveline" and "adult" tree groups for each study area (Bituruna and São Mateus do Sul).

Group code	Area	Tree age interval and group	n	Mean Age (years)	Mean Height (m)	Mean Diameter at breast height (m)
BJ	Bituruna	15 - 22 years, juveline	6	18	12.8	0.31
MJ	São Mateus do Sul	15 - 20 years, juveline	3	17	10.2	0.30
MA	São Mateus do Sul	41 - 90 years, adult	3	70	16.0	0.57

Source: Authors, 2021.

The small size of the areas and the small number of existing and sampled araucaria trees in each area are insufficient to model their growth. The two groups in the M area were well differentiated in terms of the two growth attributes analyzed (height and DBH).

3.3 Soil chemical attributes

Of the 45 variables pairs tested for each of the two depths (0 – 5 and 5 - 20 cm), most of them did not show significant correlations ($p<0.01$) (Table 5).

As for CEC, even the soils of B being much more clayey than those of M, the values of this attribute were higher in M for the two depths soil samples, a reflection of the greater clay activity of M in relation to B.

In addition to the strong influence of higher soil clay activity of M compared to B on soil chemical attributes, there are also differences in soil management between these two studied areas.

DOI: http://dx.doi.org/10.24021/raac.v20i1.6570 V. 20, N. 1 (2023)

M presents a more intensive management than B, with greater input of nutrients via correctives and fertilization, generating perceptible differences in the Ca, Mg and P Mehlich values (Table 6).

Table 5. Pearson correlation coefficients between soil chemical attributes (0-5 and 5-20 cm depth) of microsites related to araucaria trees (n = 78). Study areas: Bituruna and São Mateus do Sul.

	Al	H+Al	Ca	Mg	K	Sum of bases	CEC[1]	P-Mehlich	SOC[1]
				Soil chemical attributes from 0 – 5 cm depth					
pH CaCl2	-0.75**	-0.83**	0.93**	0.79**	0.20	0.94**	-0.04	0.29	-0.14
Al		0.93**	-0.78**	-0.61**	-0.24	-0.78**	0.41**	-0.18	-0.13
H+Al			-0.81**	-0.56**	-0.16	-0.78**	0.53**	-0.12	-0.08
Ca				0.72**	0.33*	0.97**	0.04	0.27	0.16
Mg					0.26	0.85**	0.28	0.29	-0.28
K						0.35*	0.23	0.05	0.31*
Sum of bases							0.13	0.29	0.04
CEC								0.20	-0.08
P-Mehlich									-0.26
				Soil chemical attributes from 5 – 20 cm depth					
pH CaCl2	-0.30*	-0.32*	0.91**	0.82**	-0.14	0.92**	0.08	0.46**	-0.23
Al		0.95**	-0.24	-0.17	0.18	-0.22	0.84**	-0.18	-0.13
H+Al			-0.21	-0.13	0.14	-0.19	0.91**	-0.09	-0.03
+Ca				0.81**	-0.02	0.98**	0.22	0.49**	-0.15
Mg					0.01	0.9**	0.26	0.44**	-0.22
K						0.02	0.15	-0.16	0.29
Sum of bases							0.25	0.49**	-0.17
CEC								0.12	-0.10
P-Mehlich									0.10

[1] CEC = cation exchange capacity, SOC = soil organic C. Correlation values followed by * and by ** are significant, respectively for *p<0.01* and for *p<0.001*.

Source: Authors, 2021.

Table 6. Mean values of soil chemical attributes in relation to microsites of araucaria tree groups (area and growth stage) at two soil depths. Study areas: Bituruna and São Mateus do Sul.

Soil chemical attributes		Soil depth - Araucaria trees groups[1]					
		0 - 5 cm			5 - 20 cm		
		BJ	MJ	MA	BJ	MJ	MA
N	-	39	18	21	39	18	21
pH $CaCl_2$	-	4.19b	4.68a	4.30b	4.00b	4.14a	4.05ab
Al	$cmol_c\ kg^{-1}$	1.7b	1.2b	2.7a	2.64b	4.47a	4.77a
H+Al	$cmol_c\ kg^{-1}$	12.3b	11.4b	15.1a	13.42b	17.38a	17.49a
Ca	$cmol_c\ kg^{-1}$	3.2b	4.9a	3.3b	0.80b	1.69a	0.90b
Mg	$cmol_c\ kg^{-1}$	0.6c	1.8a	1.3b	0.08b	0.41a	0.20b
K	$cmol_c\ kg^{-1}$	0.21a	0.20a	0.24a	0.11ab	0.10b	0.13a
Sum of bases	$cmol_c\ kg^{-1}$	3.98b	6.91a	4.88b	0.99b	2.20a	1.23b
Cation exchange capacity	$cmol_c\ kg^{-1}$	16.32c	18.33b	19.99a	14.41c	19.59a	18.72b

P-Mehlich	mg kg^{-1}	2.7b	14.3a	4.5b	0.85b	2.86a	0.69b
Organic C	g $100g^{-1}$	6.23a	4.47c	5.31b	3.67a	3.47a	3.60a

[1] Codes: BJ = juvenile trees of Bituruna; MJ = juvenile trees of São Mateus do Sul; and MA = adult trees of São Mateus do Sul.

[2] At each soil depth and for each attribute, averages followed by the same letter do not differ from one another by the Duncan test at 5%.

Source: Authors, 2021.

Regarding the best results of the chemical soil attributes of MJ in relation to those of MA, it is necessary to understand that the fertilizations carried out in the systems, basically in M, are focus on the *I. paraguariensis* plants and not in the araucaria trees. At this point, it can be inferred that the larger araucaria trees (the "adults"), by provoking a greater competition for space, exclude or hinder the presence of *I. paraguariensis* plants in their proximity. If true, the placement of fertilizers and correctives around adult trees relative to juvenile trees may be much smaller.

On the other hand, the actions to improve soil fertility in managed areas make the use of soil chemical attributes more complex in studies that seek to compare the soil quality of soils from native and planted araucaria forests, as carried out by Pereira *et al.* (2017).

3.4 Multiple linear regressions of microsites soil attributes by araucaria trees groups

The spatial dependence on soil depth was almost absolute ($p < 0.01$), and reflects the higher surface soil quality, which in turn is a consequence of the superficial soil horizon, rich in organic matter, and nutrient cycling, considering the large number of trees in the local systems (Table 7). The sign of the coefficients (negative or positive) was almost completely consistent with that described above, with one exception, the CEC in MJ, which was positive, showing a tendency to grow in depth.

Table 7. Presence and type of spatial dependence (D - depth, S – stem distance, N - negative coefficient and P - positive coefficient) of soil chemical attributes (dependent variables) in relation to microsites of araucaria tree groups (area and growth phase), as defined by multiple linear regressions. Study areas: Bituruna and São Mateus do Sul.

Soil chemical attribute	Spatial dependence					
	Bituruna		São Mateus do Sul			
	Juvenile		Juvenile		Adult	
	D	S	D	S	D	S
n	78		36		42	
pH $CaCl_2$	N**	N*	N**	–	N**	–
Al	P**	P*	P**	–	P**	–
H+Al	–	P*	P**	–	P**	–
Ca	N**	N*	N**	–	N**	–
Mg	N**	–	N**	–	N**	–
K	N**	–	N**	N**	N**	N**
Sum of bases	N**	N*	N**	–	N**	–
Cation exchange capacity	N**	–	P*	N**	N**	–
P-Mehlich	N**	–	N**	–	N**	–
Organic C	N**	–	N**	–	N**	N*

Coefficients values followed by * and by ** are significant, respectively for $p<0.05$ and for $p<0.01$.

Source: Authors, 2021.

In BJ, half of the soil chemical attributes presented spatial dependence in relation to the araucaria trees horizontal distance. The significance level was $p < 0.05$, always inferior to the one

DOI: http://dx.doi.org/10.24021/raac.v20i1.6570 V. 20, N. 1 (2023)

found for spatial dependence for soil depth. Spatial dependence on the horizontal distance in BJ showed coefficients with negative sign for pH CaCl2, Ca and SB and coefficients with positive sign for Al and H+Al. For the two groups of M (MJ and MA), the spatial dependence on the horizontal distance reached only two soil chemical attributes in each group, highlighting the K behavior, with negative coefficients and p <0.01. Two aspects can be considered in the dynamics of the values found, especially in B, a system with low or null input of nutrients via fertilization (some organic contribution). Regarding the araucaria trees, the great efficiency of the nutrients recycling by the species (SCHUMACHER *et al.*, 2004) may be favoring higher values of exchangeable bases closer to the trunk of these trees. The other aspect concerns the increase in the *I. paraguariensis* plants density, as we move away from araucaria trees. The *I. paraguariensis* plants generate strong nutrients export by successive leaf harvesting and therefore tend to depreciate nutrient values, increasing the soil extractable acidity in the microsites farther from the araucaria tree insertion in the soil. These hypotheses were diluted by the nutrients input with the use of correctives and fertilizations in M and were maintained only for the behavior of the K values.

3.5 Tree groups ordination by non-metric multidimensional scaling

The separation of tree groups by site and age in a multivariate manner was not efficient. In the NMS with 0 - 5 cm soil attributes, there is a strong overlap of the groups in the first axis, which explains most of the data variation (74%), with great dispersion of the sampling microsites of the tree groups along this first axis (Figure 2a).

In the second axis, it is still possible to visualize the set of BJ sampling microsites in the upper part of the ordering, related to the MJ and MA groups, influenced by significant correlations (p <0.01) of several attributes (Table 8), since that the highest correlation value with the second axis belongs to the P Mehlich and the only positive correlation occurs with the SOC. The MJ and MA groups are partially superimposed on this second axis, with a larger number of MJ sampling sites in the lower part of the ordination.

For the 5 - 20 cm soil attributes the NMS required only one axis to explain 93% of the data variation and again the overlap of the groups was very large, caused by a dispersion of the sampling microsites of the three tree groups along of this ordination axis (Figure 2b). As in the second NMS axis performed for the 0-5 cm attributes, several negative correlations with the single axis (pH CaCl2, Ca, Mg, SB, CTC and P Mehlich) pulled the sampling microsites with a more favorable nutrients supply to one side of the ordination, in this case to the left side (Figure 2b and Table 8).

Table 8. Pearson correlation coefficients between soil chemical attributes (0 – 5 and 5 - 20 cm depths) and non-metric multidimensional scaling axes (Figure 2).

Soil chemical attribute	Correlation coefficient (r)		
	0-5 cm depth		5-20 cm depth
	Axis 1	Axis 2	Single axis
pH CaCl2	0.924***	-0.465***	-0.876***
Al	-0.894***	0.176	0.18
H + Al	-0.867***	0.102	0.126

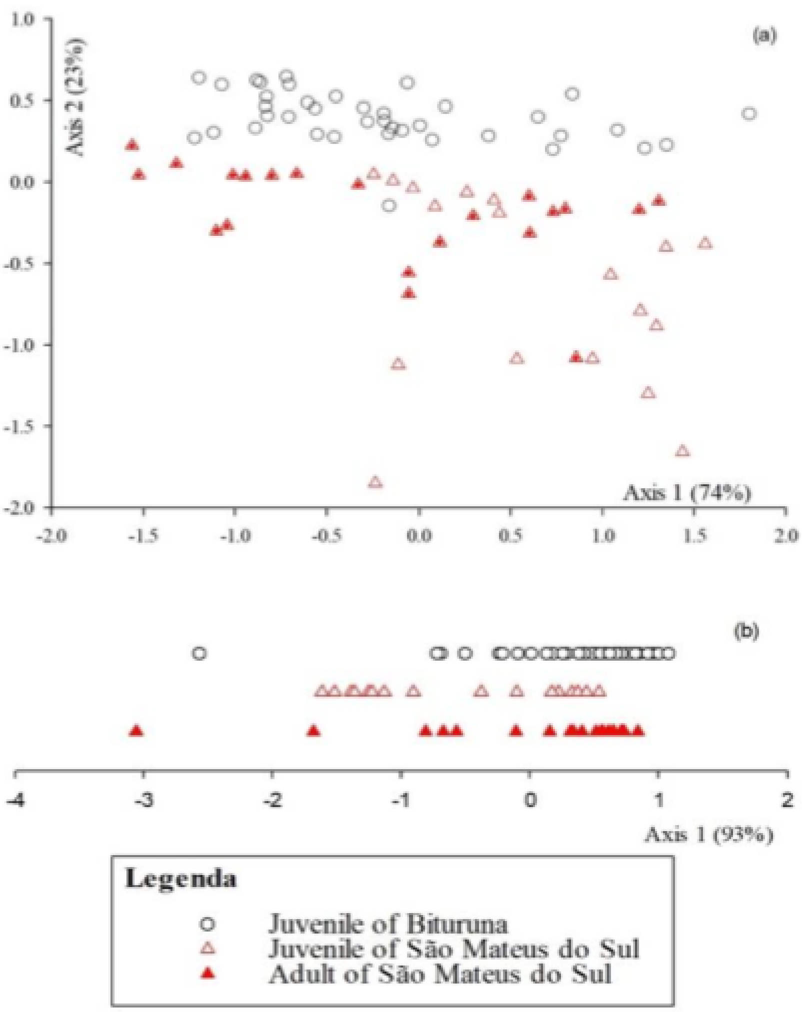
DOI: http://dx.doi.org/10.24021/raac.v20i1.6570 V. 20, N. 1 (2023)

Ca	0.929***	-0.394***	-0.938***
Mg	0.838***	-0.559***	-0.917***
K	0.355**	-0.098	-0.021
Sum of bases	0.962***	-0.472***	-0.97***
Cation exchange capacity	-0.067	-0.478***	-0.294*
P-Mehlich	0.296*	-0.859***	-0.606***
Organic C	0.021	0.423***	0.139

*, **, and *** = significant at 5, 1, and 0.1 % probability, respectively.

Source: Authors, 2021.

Figure 2. Ordinations obtained by the non-metric multidimensional scaling (NMS) of tree groups (by area and growth stage) due to ten soil chemical attributes at two depths, soil microsites related to araucaria trees. Juvenile trees of Bituruna - n = 38; juvenile trees of São Mateus do Sul – n = 18; and adult trees of São Mateus do Sul – n = 21. The ratio of the data variation explained by each axis is in parentheses: (a) NMS at 0 – 5 cm depth, and (b) NMS at 5 – 20 cm depth. In (b), the different positions of each group in the vertical are only to facilitate the visualization, considering the strong overlap of the points in the NMS single axis.



DOI: http://dx.doi.org/10.2 … , N. 1 (2023)

Source: Authors, 2021.

4. FINAL CONSIDERATIONS

The dendrochronological analysis (age estimation) defined one group of six trees in Bituruna, all "young" (BJ), and two groups, "young" and "adult", in São Mateus do Sul (respectively MJ and MA).

The multiple linear regression analysis performed for the three araucaria trees groups (BJ, MJ and MA), having as dependent variables the soil chemical attributes as a function of the microsites position relative to the insertion point of araucaria trees in the soil, showed an almost total dependence of the depth of the microsites. In the same analysis, the dependence of the soil chemical attributes was much more diffuse in relation to the distance of the trunk of the trees, occurring for half of the attributes in BJ and only in two of ten attributes of the MJ and MA groups.

The NMS according to 10 soil chemical attributes showed a great overlap of behavior of the tree groups (BJ, MJ and MA), even between the groups of the two areas (Bituruna and São Mateus do Sul).

The chemical attributes comparison generated, to a certain extent, a soil fertility deficiency gradient between the microsites of the three groups of trees (MJ < MA < BJ), an aspect very associated with the greater nutrients input (via fertilization) in the São Mateus do Sul agroforestry system (AFS) in relation to Bituruna. The difference between MJ and MA comes from the greater fertilization in the MJ sites, which tend to have a higher *I. paraguariensis* plants density, as they have smaller trees, compared to MA, and fertilization is always directed to the individuals *I. paraguariensis* plants.

AFS with shaded *I. paraguariensis* must consider the replacement of nutrients exported by leaf harvest, which will help in the sustainability of the activity. This includes the environmental services that the AFS promotes by maintaining, or even renewing, of the native trees from the local forest, especially araucaria trees, in a productive system.

5. REFERENCES

ALVARES CA, STAPE JL, SENTELHAS PC, GONÇALVES JLM, SPAROVEK, G. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, v. 22, n. 6, p. 711-728, 2013.

BERTINI SCB, AZEVEDO LCB, STROMBERGER ME, CARDOSO EJBN. (2015). Soil properties discriminating Araucaria forests with different disturbance levels. **Environmental Monitoring and Assessment**, v. 187, n. 194, 2015.

BITTENCOURT JVM. *Araucaria angustifolia* - its Geography and Ecology. **Geographical Paper 180** (15p). Reading: University of Reading, 2007.

CONSTANTINO V, BARBOSA JZ, MOTTA AV, DOLINSKI MA, PRIOR SA, ZANETTE F. (2019). Initial growth of *Araucaria angustifolia* (Bertol.) Kuntze in response to fertilization with nitrogen, phosphorus and potassium. **Floresta**, v. 49, n. 1, p. 99-108, 2019.

DOI: http://dx.doi.org/10.24021/raac.v20i1.6570 V. 20, N. 1 (2023)

DIELEMAN WIJ, VENTER M, RAMACHANDRA A, KROCKENBERGER AK, BIRD MI. Soil carbon stocks vary predictably with altitude in tropical forests: Implications for soil carbon storage. **Geoderma**, v. 204-205, n. 1, p. 59-67, 2013.

EIBL B, FERNANDEZ RA, KOZARIK JC, LUPI A, MONTAGNINI F, NOZZI D. Agroforestry systems with *Ilex paraguariensis* (American holly or yerba mate) and native timber trees on small farms in Misiones, Argentina. **Agroforestry Systems**, v. 48, n. 1, 2000, p. 1-8.

EMBRAPA. **Manual de métodos de análise de solo** (2.ed). Rio de Janeiro: Embrapa Solos, 2011.

EMBRAPA. **Sistema brasileiro de classificação de solos** (5.ed.). Brasília: Embrapa, 2018.

FRITZSONS E, WREGE MS, MANTOVANI LE. A distribuição natural do pinheiro-do-Paraná no estado do Rio Grande do Sul, Brasil: a influência de fatores climáticos. **Revista Brasileira de Climatologia**, v. 22, p. 117-132, 2018.

GIRARDIN CA. Net primary productivity allocation and cycling of carbon along a tropical forest elevational transect in the Peruvian Andes. **Global Change Biology**, v. 16, n. 12, p. 3176-3192, 2010.

GRÜNEBERG E, ZICHE D, WELLBROCK N. Organic carbon stocks and sequestration rates of forest soils in Germany. **Global Change Biology**, v. 20, n. 8, p. 2644-2662, 2014.

HOPPE JM, CALDEIRA MVW. Correlações entre o crescimento de Araucaria angustifólia (BERTOL.) KUNTZE, plantada na floresta nacional de Passo Fundo, RS com as características químicas do solo. **Revista Acadêmica Ciência Animal**, v. 1, n. 4, p. 33-40, 2003.

MCCUNE B, MEFFORD MJ. **PC-Ord. Multivariate analysis of ecological data, Version 6.04**. Gleneden Beach, MjM Software Design, 2011.

MELLONI R, COSTA NR, MELLONI EGP, LEMES MCS, ALVARENGA MIN, NUNES JN. Agroforestry system coffee-araucaria and its effect on soil microbiota and their processes. **Ciência Florestal**, v. 28, n. 2, p. 784-795, 2018.

SOUZA ES, CARMO JB, KELLER M, *et al.* Soil–atmosphere exchange of nitrous oxide, methane and carbon dioxide in a gradient of elevation in the coastal Brazilian Atlantic forest. **Biogeosciences**, v. 8, n. 3, p. 733-742, 2011.

OLIVEIRA JM, SANTAROSA E, PILLAR VD, ROIG FA. Seasonal cambium activity in the subtropical rain forest tree *Araucaria angustifolia*. **Trees**, v. 23, n. 1, p. 107–115, 2009.

OLIVEIRA JM, ROIG FA, PILLAR VD. Climatic signals in tree-rings of Araucaria angustifolia in the southern Brazilian highlands. **Austral Ecology**, v. 35, n. 2, p. 134-147, 2010.

DOI: http://dx.doi.org/10.24021/raac.v20i1.6570 V. 20, N. 1 (2023)

PERALTA RM, KOEHNLEIN EA, OLIVEIRA RF, *et al.* Biological activities and chemical constituents of *Araucaria angustifolia*: An effort to recover a species threatened by extinction. **Trends in Food Science & Technology**, v. 54, p. 85-93, 2016.

PEREIRA JM, SEGAT JC, BARETTA D, VASCONCELLOS RLF, BARETTA CRDM, CARDOSO EJBN. Soil macrofauna as a soil quality indicator in native and replanted Araucaria angustifolia forests. **Revista Brasileira de Ciência do Solo**, v. 41, p. e0160261, 2017.

PLANTE AF, CONANT RT, STEWART CE, PAUSTIAN K, SIX J. (2006). Impact of soil texture on the distribution of soil organic matter in physical and chemical fractions. **Soil Science Society of America Journal**, v. 70, n. 1, p. 287-296, 2006.

PUCHALSKI A, MANTOVANI M, REIS MS.Variação em populações naturais de *Araucaria angustifolia* (Bert.) O.Kuntze associada a condições edafo-climáticas. **Scientia Forestalis**, v. 70, p. 137-148, 2006.

RADOMSKI MI, LACERDA AEB, KELLERMANN B. **Sistemas agroflorestais: restauração ambiental e produção no âmbito da Floresta Ombrófila Mista.** Colombo: Embrapa Florestas, 2014.

REIS MS, LADIO A, PERONI N. Landscapes with Araucaria in South America: evidence for a cultural dimension. **Ecology and Society**, v. 19, n. 2, p. 43, 2014.

RIBEIRO MC, METZGER JP, MARTENSEN AC, PONZONI FJ, HIROTA MM. The Brazilian Atlantic forest: how much is left, and how is the remaining forest distributed? Implications for conservation. **Biological Conservation**, v. 142, n. 6, p. 1141–1153, 2009.
https://doi.org/10.1016/j.biocon.2009.02.021.

ROIG FA. Dendrocronología en los bosques del Neotrópico: revisión y prospección futura. In FA Roig (Ed.), **Dendrocronología en América Latina**. Mendonza, EDIUNC, 2000.

ROSSA UB, ANGELO AC, NOGUEIRA AC, REISSMANN CB, GROSSI F, RAMOS MR. Fertilizante de liberação lenta no crescimento de mudas de *Araucaria angustifolia* e *Ocotea odorifera*. **Floresta**, v. 41, n. 3, p. 491-500, 2011.

SALINAS N, MALHI Y, MEIR P. *et al.* The sensitivity of tropical leaf litter decomposition to temperature: results from a large-scale leaf translocation experiment along an elevation gradient in Peruvian forests. **New Phytologist**, v. 189, n. 4, p. 967-977, 2011.

SANTOS LJC, OKA-FIORI C, CANALI NE. *et al.* Mapeamento geomorfológico do estado do Paraná. **Revista Brasileira de Geomorfologia**, v. 7, n. 2, p. 3-12, 2006.

SANTOS WC, ROSOT NC, ROSOT MAD. Características edáficas relacionadas à produção de um povoamento de *Araucaria angustifolia* (Bert.) O. Kuntze. Floresta, v. 40, n. 1, p. 37-48, 2010.

DOI: http://dx.doi.org/10.24021/raac.v20i1.6570 V. 20, N. 1 (2023)

SCHUMACHER MV, BRUN EJ, HERNANDES JI, KÖNIG FG. Produção de serapilheira em uma floresta de *Araucaria angustifolia* (Bertol.) Kuntze no município de Pinhal - RS. **Revista Árvore**, v. 28, n. 1, p. 29-37, 2004.

SHIMAMOTO CY, BOTOSSO PC, MARQUES MCM. How much carbon is sequestered during the restoration of tropical forests? Estimates from tree species in the Brazilian Atlantic forest. **Forest Ecology and Management,** v. 329, n. 1, p. 1-9, 2014.

SOIL SURVEY STAFF. **Keys to soil taxonomy**. 12a.Edition. United States Department of Agriculture - Natural Resources Conservation Service, 2014.

STATSOFT. **Statistica**: data analysis software system: version 9.1, 2010.

WIESMEIER M, PRIETZEL J, BARTHOLD F. *et al.* Storage and drivers of organic carbon in forest soils of southeast Germany (Bavaria) - implications for carbon sequestration. **Forest Ecology and Management**, v. 295, p. 162-172, 2013.

WREGE MS, FRITZSONS E, SOARES MTS. *et al.* Risco de ocorrência de geada na região centro-sul do Brasil. **Revista Brasileira de Climatologia,** v. 22, p. 524-553, 2018.

DOI: http://dx.doi.org/10.24021/raac.v20i1.6570 V. 20, N. 1 (2023)