FLOR@m
Floresta e Ambiente

ORIGINAL ARTICLE – Conservation of Nature

Fertilization with Nitrogen, Phosphorus, and Potassium Affects Composition of *Araucaria angustifolia* Needles, Branches and Stem

Valdeci Constantino[1] (ID)
Antônio Carlos Vargas Motta[2] (ID)
Julierme Zimmer Barbosa[3] (ID)
Eloá Moura Araujo[2] (ID)
Guilherme Quaresma Pedreira[2] (ID)
Flávio Zanette[1] (ID)

Abstract

Fertilization can be a sustainable management practice for the maintenance of the threatened species such as *Araucaria angustifolia*. Our objective was to evaluate the elemental composition of *A. angustifolia* fertilized with N, P, and K, and how the fertilization altered the soil fertility. Seven-month-old seedlings were transplanted to 16 dm³ soil pots, and three experiments were carried separately (one for each cited element) in a completely randomized design. Overall, the seedlings tended to accumulate nutrients differently among the compartments in the following order: needles > branches > stem. Application of N reduced the soil pH, boosted Mn concentration in more 10 times, decreased the P uptake, and changed the C:N and C:P ratios. Increased doses of P led to higher uptake rates but promoted a reduction in the absorption of Mg. High rates of K diminished of P, Ca, Mg, Mn, and B, confirming antagonism interaction with Ca and Mg.

Keywords: South American flora, macronutrients, nutrient deficiency, plant nutrition, nutrient ratio.

1. INTRODUCTION

Deforestation threatens the earth's biodiversity and the ecosystem services upon which humans depend (Rhodes et al., 2017). For instance, tropical vegetation provides a myriad of ecosystem services and at the same time is highly degraded (Martiniano et al., 2019). The Atlantic Forest is considered one of the most important biodiversity hotspots (Canei et al., 2018), characterized by areas that have lost ≥70% of their primary vegetation, and contain ≥1500 endemic vascular plant species (Kobayashi et al., 2019).

Among the Atlantic Forest Biome phytophysiognomies, the Mixed Ombrophilous Forest (FOM) (the so-called Araucaria Forest) is one of the most threatened (Higuchi et al., 2012; Canei et al., 2018). In this environment, the native *Araucaria angustifolia* trees have been intensely exploited, stands to the point of accentuated reduction of its natural reserves in the

late 1980s and is currently classified as vulnerable to extinction (Canei et al., 2018).

Formal regulation is a key mechanism by which governments seek to protect forests (Rhodes et al., 2017). However, scholars like Scheeren et al. (1999) and Hess et al. (2018) suggest that sustainable management is of utmost importance for future preservation, multiple-use, profitable production and enhancement of the Araucaria Forest in southern Brazil, being one more efficient way to conserve the remains of Araucaria Forest. However, for the management, socioenvironmental and socioeconomic maintenance, it is required the search for information that supports the elaboration of management plans based on models generated using multiple factors related to the species and the environment (Orellana & Vanclay, 2018a, 2018b; Ricken et al., 2018).

Despite the importance of *A. angustifolia*, Canei et al. (2018) highlight there is little knowledge of its silvicultural

[1]Universidade Federal do Paraná, Departamento de Fitotecnia e Fitossanidade, Curitiba, PR, Brasil

[2]Universidade Federal do Paraná, Departamento de Solos e Engenharia Agrícola, Programa de Pós-graduação em Ciência do Solo, Curitiba, PR, Brasil

[3]Centro Universitário Ingá, Departamento de Agronomia, Maringá, PR, Brasil.

requirements, specifically the planting techniques that favor the development of seedlings in the field. Thus, studies are needed relating to the edaphoclimatic conditions that can favor the success in *A. angustifolia* reforestation, since it is a native species with important ecosystem services. In this way, our objective was to evaluate the nutritional aspects of *A. angustifolia* fertilized with N, P and K, the elemental profile resulting from the nutrition of the species, and how the fertilization altered the soil fertility.

2. MATERIAL AND METHODS

The study was conducted in an outdoor nursery located in Curitiba – Paraná, Brazil (25°24'45.46" S; 49°14'55.15" W; altitude 911 m). Plastic pots (20 dm³) were filled with 16 dm³ of a Cambisol (Table 1) originally collected in an area of *A. angustifolia* natural occurrence (Pinhais County; latitude -25.38; longitude -49.12; altitude 920 m). Further information about the experiment, may be seen in Constantino et al. (2019).

In summary, the soil (sieved < 4 mm) was amended with 3.6 g kg⁻¹ of dolomitic lime (75.2% neutralizing power) to raise the base saturation to 70%. After lime application, the soil was homogenized and incubated for two months.

Each of the three experiments in this study had five treatments, in which one element was applied in five rates, while fixed rates were applied for the other two nutrients. Experiment I: N (0, 158, 315, 624, and 1238 mg dm⁻³), P (469 mg dm⁻³), and K (469 mg dm⁻³); Experiment II: P (0, 117, 234, 469, and 938 mg dm⁻³), N (624 mg dm⁻³), and K (469 mg dm⁻³); and Experiment III: K (0, 117, 234, 469, and 938 mg dm⁻³), N (624 mg dm⁻³), and P (469 mg dm⁻³). Respective sources used to provide N, P, and K was urea (45% N), triple superphosphate (41% P_2O_5), and K chloride (60% K_2O). The rates of N indicated above correspond to the total amount used in the first and second year. Half was applied at the installation of the experiment (December 2013). The remainder was divided into three

(25, 15, and 10%), applied every 60 days, starting December 2014. The experiments were carried out with four replicates in a completely randomized design.

Respective amounts of N (50 % total amount), P, and K for each treatment were applied to 16 dm³ of soil followed by homogenization before pot filling. Seven-month-old *A. angustifolia* seedlings (about 20 cm height) were transplanted to pots on 13th December 2013. Pots were randomly distributed in the nursery and placed on a plastic surface to avoid contact with the underlying soil. Weed control was performed manually. Irrigation occurred as needed especially during periods of no rainfall by adding approximately two liters of water to each pot in the morning. In September 2015 (21-month after planting), plants were harvested and divided into needles, branches, and stems; each fraction was oven-dried (60°C) and milled (< 1 mm).

The vegetal samples were submitted to 6 mL of HNO_3 + ultra-pure water solution (2:1; v/v ratio) and 2 mL of H_2O_2 (30%) in microwave-assisted digestion (MARS, CEM Microwave Technology Ltd). From the solution, P, Ca, Mg, Fe, Mn, Zn, Cu, B, Al, Ba, Cd, and Ti were determined using the optical emission spectrometer with inductively coupled plasma equipment (ICP-OES) (720-ES, Varian). To determine the elemental composition of K, a flame emission spectrometer (DM-62, Digimed) was used. The level of N e C was obtained from non-digested vegetal samples using an elementary analyzer (Vario EL III model, Elementar) only in the samples from Experiment I.

After the experiment, soil samples from each pot were collected, dry, ground, sieved and evaluated for chemical analysis according to Embrapa (2011).

Data were subjected to analysis of normality of the residues (Shapiro-Wilke test) variance ($p < 0.05$), and effects of N, P, and K rates were determined by regression analysis. The choice of regressions (linear or quadratic) was based on the highest coefficient of determination (R^2) and probability (p) values. For all analyses, the statistical software Assistat 7.7 was used.

Table 1. Granulometric and chemical properties of the soil before planting *Araucaria angustifolia* seedlings[1].

Liming	Clay[1]	pH	Ca²⁺	Mg²⁺	K⁺	Al³⁺	H+Al	CEC	V	m	P	OC
	g kg⁻¹		----------------- cmol$_c$ dm⁻³ -----------------						%	%	mg dm⁻³	g dm⁻³
Before	550	4.0	1.60	0.80	0.08	2.90	11.30	13.78	18	54	0.9	4.2
After²	---	5.5	4.17	3.25	0.07	0.00	5.58	13.50	55	0	1.4	6.6

[1]Prior to analysis, soil was sieved (2 mm) and dried at 40ºC to determine: sand, silt, and clay (hydrometer method); pH (CaCl$_2$ 0.01 mol L⁻¹); Ca²⁺, Mg²⁺, Al³⁺ (extracted with KCl 1 mol L⁻¹); H+Al (calcium acetate 0.5 mol L⁻¹ extraction); organic carbon (OC) (volumetric method by potassium dichromate); K⁺ and P (Mehlich-1 extraction); base saturation (V); cation exchange capacity (CEC) at pH 7; and Al³⁺ saturation (m%). ²Chemical characterization of the soil after the lime application.

3. RESULTS AND DISCUSSION

3.1. Effect of the N fertilization

The effectiveness of the lime was evident (Table 1). However, as N rates increased, there was a gradual reduction of the soil pH, making the soil more acidic, what may interfere with the assimilation of the other elements [Table 2 – also presented in Constantino et al. (2019)]. Studying the soil pH in planted forests in Northern China, Hong et al. (2019) found that N deposition affect directly and indirectly the

soil pH. NH_4^+ can replace the base cations, promoting the bases leaching and soil acidification (Hong et al., 2019), or through acidification of the rhizosphere via H^+ extrusion and nitrification process, or even by the organic acid production as a consequence of organic matter decomposition under high N application rates (Ata-Ul-Karim et al., 2020).

The application of N also had a reflection on the nutrient levels in needles, branches, and stem (Table 3). The N levels on needles increased 90%, while the levels in branches and stem increased less than 50% when compared the highest rate with the control treatment.

Table 2. Values of pH, C, P, and K after harvesting *Araucaria angustifolia* seedlings, submitted five rates of N, P and K fertilization.[1]

Variables	Rates of N (mg dm⁻³)					Rates of P (mg dm⁻³)					Rates of K (mg dm⁻³)				
	0	158	315	624	1238	0	118	233	469	938	0	117	234	469	938
pH-CaCl$_2$	5.5	5.6	5.3	4.6	4.3	4.8	5.0	4.9	4.8	4.8	4.4	4.7	4.9	4.8	4.5
Carbon (g dm⁻³)	6.7	5.1	10.6	7.8	10	4.3	4.7	5.8	6.8	3.0	8.9	8.7	8.4	10.7	9.5
P (mg dm⁻³)	30.0	35.4	37.9	45.6	34.7	1.4	7.5	16.4	58.2	135.6	34.8	43.6	42.7	43.5	50.1
K⁺ (cmol$_c$ dm⁻³)	0.50	0.48	0.42	0.30	0.21	0.41	0.38	0.45	0.37	0.33	0.07	0.11	0.15	0.28	0.69

[1]pH (CaCl$_2$ 0.01 mol L⁻¹); organic carbon (OC) (volumetric method by potassium dichromate); and K⁺ and P (Mehlich-1 extraction).

Table 3. Elemental composition of *Araucaria angustifolia* needles, branches and stem in response to nitrogen fertilization.

Var.	Rates of N (mg dm⁻³)					Eq.	R²	Var.	Rates of N (mg dm⁻³)					Eq.	R²
	0	158	315	624	1238				0	158	315	624	1238		
								Needles							
C/N	58	51	52	36	32	L **	0.87	Mn	35	46	47	193	330	Q**	0.96
C/P	137	239	267	291	276	L **	0.44	Zn	21	18	13	16	18	Q *	0.64
C	457	465	473	480	472	ns	-	Cu	1.6	2.1	1.9	3.3	2.4	L *	0.29
N	7.9	10.0	9.0	13.0	15.0	L **	0.88	B	15	10	9.5	11	11	ns	-
P	3.4	2.2	1.8	1.7	1.8	L **	0.41	Al	103	84	81	75	72	L **	0.65
K	14	13	19	17	13	ns	-	Ba	14	11	11	15	16	ns	-
Ca	8.5	7.6	7.4	8.9	9.2	ns	-	Cd	0.03	0.02	0.05	0.11	0.10	L **	0.69
Mg	3.2	3.2	3.0	2.9	3.1	ns	-	Ti	1.4	1.3	1.2	1.6	1.4	ns	-
Fe	91	82	81	84	90	ns									
								Branches							
C/N	103	93	89	75	72	L **	0.84	Mn	18	32	44	113	189	Q **	0.98
C/P	189	296	374	336	334	L *	0.28	Zn	33	24	17	15	17	L **	0.47
C	445	446	446	448	443	ns	-	Cu	2.2	2.1	1.8	1.8	2.0	ns	-
N	4.4	5.1	5.0	6.1	6.3	L **	0.83	B	21	15	15	13	12	L **	0.63
P	2.4	1.9	1.3	1.5	1.4	L *	0.45	Al	129	91	116	100	96	ns	-
K	12	10	10	14	10	ns	-	Ba	26	22	23	24	27	Q *	0.67
Ca	9.4	8.0	7.4	7.7	7.8	ns	-	Cd	0.15	0.11	0.16	0.31	0.23	L *	0.40
Mg	3.2	3.3	2.9	3.0	2.9	Q *	0.58	Ti	2.3	1.5	2.4	1.5	2.0	ns	-
Fe	122	86	108	79	95	ns	-								
								Stem							
C/N	116	111	107	84	76	L **	0.91	Mn	12	23	28	85	123	Q **	0.95
C/P	276	316	424	402	453	L *	0.69	Zn	13	20	10	11	11	ns	-
C	453	446	443	445	440	L **	0.65	Cu	1.8	2.4	1.8	2.4	2.3	ns	-
N	3.9	4.2	4.2	5.5	5.8	L **	0.87	B	11.0	10.0	8.1	11.0	9.4	ns	-
P	1.7	1.6	1.1	1.3	1.0	L *	0.65	Al	47	42	36	25	30	ns	-
K	9.8	9.0	7.5	7.6	8.6	ns	-	Ba	20	24	19	21	23	ns	-
Ca	5.4	5.7	4.4	5.5	5.1	ns	-	Cd	0.10	0.10	0.20	0.20	0.10	ns	-
Mg	2.2	3.0	2.3	2.8	2.7	ns	-	Ti	0.3	0.6	0.4	0.7	0.3	ns	-
Fe	29	33	27	65	26	ns	-								

Where: C, N, P, K, Ca and Mg in g kg⁻¹; Fe, Mn, Zn, Cu, B, Al, Ba, Cd and Ti in mg kg⁻¹; Var. = variable; Eq = equation; L = linear equation; Q = quadratic equation; * denotes $p<0.05$; ** denotes $p<0.01$; ns (no significant).

While the N levels increased and the P levels decreased, the C concentration remained steady. As a consequence, the C:N ratio decreased, and C:P ratio increased as function of the N application (Table 3). This pattern occurred in all the evaluated plant tissues. The C:N and C:P ratios were higher in stem, followed by branches. The ratios were about two times lowers in the needles, evidencing that these tissues would have a much lower turnover time when comparing to more fibrous tissues.

The linear response suggests that N and P concentration in the plant tissues is dependent on the rates used in the treatments. Probably, the structural and functional characteristics of each segment in the plant resulted in greater or lesser sensitivity to N supply. The order of largest to lowest N and P concentration found in the plant is as follows: needles > branches > stem. The high N input stimulates tree growth (Constantino et al., 2019), but it can be also accompanied by increasing foliar N:P ratios (Table 3), that might imply the beginning of P deficiency in a long-term perspective, depleting the P reserves of the wood (Netzer et al., 2019).

The N and P have synergistic interactions that require a relatively constant proportion to catalyze metabolic reactions and synthesize essential compounds with specific N:P ratios (Yuan & Chen, 2015). However, elevated inputs of either N or P may implicate shifts in nutrient cycles and nutrient balance (Peñuelas et al., 2012). The decreased plant P concentration under N addition, as observed in Table 3, may not be simply related to decreasing availability of P, but due to the massive imbalance in soil availability of N and P with greater N input, which stimulates plant to take up more N but limit P uptake (Deng et al., 2017).

The observed P concentration (Table 3) of needles are under normal level, since Simões & Couto (1973) found the concentration of 2.3 g kg^{-1} of P in above-ground tissues of *A. angustifolia* seedling submitted to full fertilization. In the same experiment, authors found that when submitted to fertilization minus P, the seedlings presented 1.0 g kg^{-1} of P in the above-ground tissue of one-year-old seedling. So, it was unlike that there was a lack of P for plant growth and did no compromise the N response.

In general, the other macronutrients (K, Ca and Mg) were not affected by the treatments with N, except for Mg which responded quadratically in the branches. The observed concentrations for needles can be considered normal since 7.2, 7.6 and 2.1 g kg^{-1} were observed for above-ground tissue by Simões & Couto (1973). Again, there was no indication of K, Ca and Mg deficiency. This was expected due to high level observed on soil evaluation (Tables 1 and 2).

Among the micronutrients, the answer to N application was erratic. The Mn was the most sensitive to N fertilization, presenting quadratic response in needles, branches, and stem. The highest concentration of the element was found in the needles (330 mg kg^{-1}), followed by the branches (189 mg kg^{-1}) and stem (123 mg kg^{-1}). The decrease in pH due to N application could explain this variation since Mn has been shown to be the most sensibility to variation on foliar concentration among the other micronutrients (Fe, Cu, Zn, Ni) and Al which have they availability inverse related to pH (Motta et al., 2007).

The Mn increment was not only boosted in all plant tissue but also impressed by the magnitude of increment with more than tenfold augment. Despite, the high increment on Mn concentration the observed values are in the range 200–560 mg kg^{-1} of Mn for heathy growth tree (Blum, 1980). In a pioneer work, De Hoog (1981) found in most of the sites sampled Mn contents between 100 and 700 mg kg^{-1}. The obtained increment of Mn should not result in plant toxicity for *A. angustifolia* trees, similar to what was observed for species from the same habitat of *A. angustifolia* like *Ilex paraguariensis*, *Mimosa scabrella*, *Persea major*, *Quillaja brasiliensis*, *Sloanea lasiocoma* and *Vernonia discolor* (Barbosa et al., 2018; Caldeira et al., 2006).

The change on soil acidity due to N application could also explain the enhancement on concentration of Cu by the needles, in the opposite, the concentrations of Al (in the needles) and Zn (needles and branches) decreased as response to N application, maybe in function of the elevated Mn uptake (Motta et al., 2007). The B and Ba only responded to the supply of N in the branches segment, with decreasing assimilation. Koohkan & Maftoun (2016) also found negative relation between B and N in the shoot of *Brassica napus* L., probably due to a dilution effect. Cd had a linear increase in concentration only in the needles and branches. Overall, the treatments had practically no effect on the elemental composition of the *A. angustifolia* stems.

3.2. Effect of P fertilization

The application of superphosphate had no effect on the soil pH (Table 2). So, we hypothesized that the differences in the elemental composition are mainly driven by the interactions between the elements (Table 4) and plant growth (Constantino et al. 2019). In addition, high

phosphate fertilization reduces mycorrhizal colonization in *A. angustifolia* (Moreira-Souza & Cardoso, 2002), which may contribute to reduce nutrient absorption.

P concentration in the needles, branches and stems linearly increased in function of the treatments. Branches were responsive, presenting approximately a 3-fold increase, while the P concentration in needles and stems were up to 71% higher than in the control treatment. P was accumulated in the order: needles > branches > stem. Barbosa et al. (2019) found higher P concentrations (2.77 to 5.99 g kg^{-1}) in *A. angustifolia* seeds, indicating probable remobilization of the nutrient, especially of the needles and part of the branches, which fall during the winter.

The response of the other nutrients and heavy metals was erratic (Table 4). The elemental composition of the needles was less subjected to changes, while branches and stems were more responsive to the P application. Mg was the only nutrient that presented a consistent and negative response to the P application on all plant fractions (needles, branches, and stem). K was linearly affected in branches and stems, with a reduction of about 30%. The interaction between P and Ba was significant and linear in all the plant fractions. In this case, the P application induced a reduction 42, 47, and 59% of the Ba levels in the needles, branches, and stem, respectively. This response similarity of Ba and Mg may be due to both being alkaline earth metals, that is, they may have similar plant metabolism aspects.

In the stem, the concentration of Ca linearly decreased with the P fertilization. Ca is a major constituent of cell walls, being largely immobile in wood tissue. Therefore, other elements may be referenced against Ca to indicate changes in their relative availability (Kohler et al., 2019). In the control treatment, Ca:P ratio in the stems was 11, at the highest P rate, the ratio was 4, reinforcing the substantial increase in the P availability.

Table 4. Elemental composition of *Araucaria angustifolia* needles, branches and stem in response to phosphorous fertilization.

Var.	Rates of P (mg dm^{-3})					Eq.	R^2	Var.	Rates of P (mg dm^{-3})					Eq.	R^2
	0	117	234	469	938				0	117	234	469	938		
							Needles								
P	1.11	1.48	1.50	1.54	1.79	L **	0.77	Cu	2.57	2.41	5.52	1.91	1.94	ns	-
K	14	15	15	14	13	ns	-	B	12.00	8.58	10.13	8.13	10.00	ns	-
Ca	9.02	9.06	8.90	7.80	7.66	ns	-	Al	98	94	121	69	75	ns	-
Mg	2.90	3.55	3.40	3.17	2.94	Q **	0.43	Ba	19	16	16	14	11	L *	0.93
Fe	104	103	106	72	79	ns	-	Cd	0.09	0.09	0.07	0.06	0.11	ns	-
Mn	184	125	95	141	103	L *	0.29	Ti	1.83	1.87	2.01	0.94	1.27	L *	0.47
Zn	16	14	13	13	14	ns	-								
							Branches								
P	0.50	0.90	0.97	1.22	1.33	L **	0.78	Cu	2.14	2.26	1.96	1.61	1.84	ns	-
K	15	13	11	12	11	L *	0.5	B	18	14	13	13	13	L **	0.38
Ca	8.67	8.45	8.17	7.12	7.60	ns	-	Al	122	144	160	114	132	ns	-
Mg	3.87	3.23	3.27	2.96	2.59	L **	0.83	Ba	38	31	31	26	20	L **	0.92
Fe	125	142	153	115	129	ns	-	Cd	0.05	0.08	0.12	0.20	0.23	L **	0.89
Mn	125	85	68	111	95	Q *	0.12	Ti	2.93	3.42	3.53	2.34	2.80	ns	-
Zn	20	15	16	14	17	ns	-								
							Stem								
P	0.59	0.70	0.92	0.82	1.01	L *	0.7	Cu	2.60	1.93	2.05	1.73	1.83	L **	0.43
K	11.00	9.02	7.13	6.86	7. 34	L **	0.8	B	14.00	10.00	10.00	8.38	8.62	L **	0.52
Ca	6.44	4.74	5.37	4.06	4.63	L **	0.37	Al	30	26	27	25	15	ns	-
Mg	3.32	2.59	2.87	2.24	2.16	L **	0.68	Ba	34	21	25	19	14	L **	0.71
Fe	29	23	28	31	50	ns	-	Cd	0.05	0.06	0.09	0.12	0.20	L **	0.99
Mn	61	45	36	61	44	ns	-	Ti	0.44	0.32	0.28	0.23	0.34	ns	-
Zn	12.00	9.31	10.00	8.21	9.41	ns	-								

Where: P, K, Ca and Mg in g kg^{-1}; Fe, Mn, Zn, Cu, B, Al, Ba, Cd and Ti in mg kg^{-1}; Var. = variable; Eq = equation; L = linear equation; Q = quadratic equation; * denotes $p<0.05$; ** denotes $p<0.01$; ns (no significant).

3.3. Effect of K fertilization

The K was accumulated in the order: needles > stem > branches (Table 5). The application of K chloride had a quadratic effect over all the macronutrients in the *A. angustifolia* needles. The highest concentration of K in the needles (15 mg kg^{-1}) was reached at the rate 469 mg dm^{-3} of K, but the rates 234 and 938 mg dm^{-3} had similar results, indicating a possible stabilization. Rates higher than 234 mg dm^{-3} of K reduced the concentration of P (34%), Ca (70%), and Mg (51%). Mn, B, and Ba also had their levels in the needles reduced by the K application. Considering that fertilization was performed using KCl, probably the decrease in absorption of cationic and anionic nutrients occurred due to the increase in the soil availability of K and Cl, respectively.

The element K is rarely a minimum growth-limiting nutrient in forests growing on mineral soils due to recycle potential offered by the litter (Sarkkola et al., 2016). However, our results show that the fertilization influence the absorption of other nutrients due to synergistic and antagonistic effects. Using scanning electron microscopy coupled with energy dispersive spectroscopy to assess the elemental distribution in *A. angustifolia* needles, Barbosa et al. (2017) observed that under low soil K condition, a higher Ca concentration occurs in the spongy mesophyll and more crystals containing Ca and Mg are formed, resulting in higher levels of these elements in the needles. In early studies, Simões & Couto (1973) already had suggested a competition between Ca and K for absorption through the root system

in *A. angustifolia*, where the lack of one favors absorption of the other. Despite the decrease in macronutrient concentrations due to K fertilization, Constantino et al. (2019) do not report reduced growth of *A. angustifolia*.

While the fertilization increased the K levels in needles by three times, in branches and stems, the levels increased up to seven times, indicating that these compartments are more sensitive to K. Similarly to what was observed in the needles, the application of K reduced the levels of P, Ca, and Mg in the more lignified tissues. Oppositely, the levels of Al and Ti in the branches and Fe and Ba increased in the branches and stems in function of the K rates.

In a pioneer work, Goor (1965) listed the levels of several nutrients in needles of A. angustifolia: N: 1.02 – 1.95%; P: 0.08 – 0.18%; K: 0.56 – 2.00%; Ca: 0.35 – 1.70%; Mg: 0.05 – 1.70%; Fe: 42 – 186 mg kg^{-1}; Mn: 18 – 1099 mg kg^{-1}; Cu: 2.2 – 22 mg kg^{-1}; Zn: 10 – 48 mg kg^{-1}; and B: 10.6 – 42.0 mg kg^{-1}. Compiling previous studies, Blum (1980) established medium foliar nutrient levels for healthy growth of *A. angustifolia*: N: 1.4 – 1.9%; P: 0.13 – 0.21%; K: 0.8 – 1.51; Ca: 0.37 – 1.00%; Mg: 0.14 – 0.35%. In this way, the adequate fertilization with the highest doses of N, P, and K guarantees adequate levels of the nutrients (Table 3, 4 and 5). For Hoogh et al. (1980), the most important nutrient that limits the growth of *A. angustifolia* is N, followed by the supply of P, other nutrients like K and Ca are required in minor concentration. Based on the effect of the fertilization over the other nutrients, our results support the finds of Hoogh et al. (1980).

Table 5. Elemental composition of *Araucaria angustifolia* needles, branches and stem in response to potassium fertilization.

Var.	Rates of K (mg dm^{-3})					Eq.	R²	Var.	Rates of K (mg dm^{-3})					Eq.	R²
	0	117	234	469	938				0	117	234	469	938		
---------							Needles								
P	1.56	1.84	1.85	1.39	1.21	Q *	0.66	Cu	2.67	2.82	2.49	2.17	2.16	ns	-
K	4.78	11.00	14.00	15.00	14.00	Q **	0.91	B	15.00	12.00	9.82	9.15	9.56	L **	0.94
Ca	24.00	11.00	10.00	9.00	7.66	Q **	0.75	Al	87	97	112	78	88	ns	-
Mg	6.31	4.02	3.83	3.43	3.09	Q **	0.82	Ba	26	15	13	16	19	Q **	0.59
Fe	101	114	115	81	104	ns	-	Cd	0.20	0.10	0.15	0.14	0.14	ns	-
Mn	427	161	147	199	190	Q**	0.52	Ti	1.40	1.94	1.66	1.30	1.82	ns	-
Zn	14	15	12	11	12	ns	-								
---------							Branches								
P	1.17	1.28	1.22	1.19	0.93	ns	-	Cu	2.38	2.49	1.95	2.10	1.82	ns	-
K	1.61	7.34	8.24	12.00	12.00	L **	0.67	B	11	15	14	14	13	ns	-
Ca	12.00	9.15	8.51	8.38	6.52	L **	0.76	Al	113	150	155	142	141	Q *	0.45
Mg	5.45	3.53	3.26	3.09	2.60	L**	0.58	Ba	22	22	23	29	38	Q *	0.98
Fe	112	145	147	146	150	L **	0.38	Cd	0.37	0.25	0.21	0.20	0.26	Q *	0.87
Mn	95	99	90	92	131	ns	-	Ti	2.16	4.06	3.64	2.91	3.24	Q *	0.12
Zn	13	15	14	19	14	ns	-								
---------							Stem								
P	0.99	0.90	0.68	0.62	0.58	L *	0.71	Cu	2.25	3.00	1.96	2.07	1.80	ns	-
K	1.74	4.59	4.34	7.00	8.05	L **	0.83	B	9.85	11.00	8.78	8.12	7.45	ns	-
Ca	7.00	5.06	4.79	5.21	4.19	L *	0.54	Al	30	68	24	20	40	ns	-
Mg	4.03	2.70	2.49	2.54	2.30	L **	0.46	Ba	16	16	16	22	29	Q *	0.96
Fe	24	53	28	16	83	L**	0.42	Cd	0.12	0.16	0.05	0.09	0.06	ns	-
Mn	59	58	42	53	77	ns	-	Ti	0.19	1.15	0.27	0.17	0.41	ns	-
Zn	8.67	7.73	6.34	7.26	7.93	ns	-								

Where: K, P, Ca and Mg in g kg^{-1}; Fe, Mn, Zn, Cu, B, Al, Ba, Cd and Ti in mg kg^{-1}; Var. = variable; Eq = equation; L = linear equation; Q = quadratic equation; * denotes $p<0.05$; ** denotes $p<0.01$; ns (no significant).

4. CONCLUSION

In this study, was evident that the use of urea as N supply affected the soil pH, which probably altered the other nutrients availability. All the three plant tissues linearly responded to the N application. Also, the increasing in the N in the system led to a reduction of P uptake, shifting the balance between theses nutrients. The consequent changes in the C:N and C:P ratios probably will alter the biogeochemical cycle of the nutrients in the forest system, but did not represent an imbalance among the nutrients. The Mn concentration enhanced by 10 times with N application which should give by acidification. The application of P and K had fewer effects on the absorption of the other nutrients and heavy metal studied. Antagonism interactions were observed by K x Ca, K x Mg, resulting in large decrease their concentration by K application. Based on the combination of the experiments, the application of 34.4, 17.5, and 13.7 kg ha^{-1} of N, P, and K, respectively, must guarantee and adequate seedling development.

CORRESPONDENCE TO

Eloá Moura Araujo

Universidade Federal do Paraná, Departamento de Solos e Engenharia Agrícola, Programa de Pós-graduação em Ciência do Solo, Rua Funcionários, 1540, CEP 80035–050, Curitiba, PR, Brasil
e-mail: eloamoura@alumni.usp.br

REFERENCES

Ata-Ul-Karim ST, Cang L, Wang Y, Zhou D. Interactions between nitrogen application and soil properties and their impacts on the transfer of cadmium from soil to wheat (Triticum aestivum L.) grain. Geoderma 2020; 357: 113923.

Barbosa JZ, Constantino V, Zanette F, Motta ACV, Prior SA. Soil fertility affects elemental distribution in needles of the conifer Araucaria angustifolia: A microanalytical study. Cerne 2017; 23: 257–266.

Barbosa JZ, dos Santos Domingues CR, Poggere GC, Motta ACV, dos Reis AR, de Moraes MF, Prior SA. Elemental composition and nutritional value of Araucaria angustifolia seeds from subtropical Brazil. Journal of Food Science and Technolgy. 2019; 56: 1073–1077.

Barbosa JZ, Motta ACV, Consalter R, Poggere GC, Santin D, Wendling I. Plant growth, nutrients and potentially toxic elements in leaves of yerba mate clones in response to phosphorus in acid soils. Anais da Academia Brasileira de Ciências 2018; 90: 557–571.

Blum WEH. Site - Nutrition - Growth interrelationship of Araucarias, in: Forestry Problems of the Genus Araucaria. Curitiba, pp. 119–130; 1980.

Caldeira MVW, Watzlawick LF, Soares RV, Valério AF. Teores de micronutrientes em espécies arbóreas da floresta ombrófila mista Montana-General Carneiro/PR. Ambiência 2006; 2: 29–50.

Canei AD, Hernández AG, Morales DML, da Silva EP, Souza, LF, Loss A, et al. Atributos microbiológicos e estrutura de comunidades bacterianas como indicadores da qualidade do solo em plantios florestais na Mata Atlântica. Ciência Florestal 2018; 28: 1405.

Constantino V, Barbosa JZ, Motta AV, Dolinski MA, Prior SA, Zanette F. Initial growth of Araucaria angustifolia (Bertol.) Kuntze in response to fertilization with nitrogen, phosphorus and potassium. Floresta 2019; 49: 99–108.

Deng Q, Hui D, Dennis S, Reddy KC. Responses of terrestrial ecosystem phosphorus cycling to nitrogen addition: A meta-analysis. Global Ecology and Biogeography 2017; 26: 713–728.

Embrapa. Manual de Métodos de Análise de Solo, 2nd ed. Embrapa Solos, Rio de Janeiro; 2011.

Goor CP Van. Reflorestamento com coníferas no Brasil. Rio de Janeiro; 1965.

Hess AF, Ricken P, Ciarnoschi LD. Dendrocronologia, incremento e manejo florestal em floresta de araucária - SC. Ciência Florestal 2018; 28: 1568.

Higuchi P, Silva AC da, Ferreira TDS, Souza ST de, Gomes JP, Silva KM da, et al. Influência de variáveis ambientais sobre o padrão estrutural e florístico do componente arbóreo, em um fragmento de Floresta Ombrófila Mista Montana em Lages, SC. Ciência Florestal 2012; 22 (1): 79-90.

Hong S, Gan P, Chen A. Environmental controls on soil pH in planted forest and its response to nitrogen deposition. Environmental Research 2019; 172: 159–165.

Hoog RJ DE. Site-nutrition-growth relationships of Araucaria angustifolia (Bert.) O. Ktze. in Southern Brazil. Universität Freiburg; 1981.

Hoogh RJ de, Goor CP van, Blum WEH. Response of planted Araucaria angustifolia to N, P, K, Ca and B fertilization, 3 and 7 years after application, in: Forestry Problems of the Genus Araucaria. Fundação de Pesquisas Florestais do Paraná, Curitiba, pp. 136–144; 1980.

Kobayashi Y, Okada, K, Mori AS. Reconsidering biodiversity hotspots based on the rate of historical land-use change. Biological Conservation 2019; 233: 268–275.

Kohler M, Niederberger J, Wichser A, Bierbaß P, Rötzer T, Spiecker H, Bauhus J. Using tree rings to reconstruct changes in soil P availability – Results from forest fertilization trials. Dendrochronologia 2019; 54: 11–19.

Koohkan H, Maftoun M. Effect of nitrogen– boron interaction on plant growth and tissue nutrient concentration of canola (Brassica napus L.). Journal of Plant Nutrition 2016; 39: 922–931.

Martiniano E, Silveira DO, Castro M de, Santos N, Eiji E, Weimar F, et al. Forest ecology and management carbon-diversity hotspots and their owners in Brazilian southeastern savanna, atlantic forest

and semi-arid woodland domains. Forest Ecology Management 2019; 452: 117575.

Moreira-Souza M, Cardoso EJBN. Dependência micorrízica de Araucaria Angustifolia (Bert.) O. Ktze. sob doses de fósforo. Revista Brasileira de Ciência do Solo 2002; 26: 905–912.

Motta ACV, Serrat BM, Reissmann CB, Dionísio JA. Micronutrientes na rocha, no solo e na planta. Curitiba; 2007.

Netzer F, Pozzi L, Dubbert D, Herschbach C. Improved photosynthesis and growth of poplar during nitrogen fertilization is accompanied by phosphorus depletion that indicates phosphorus remobilization from older stem tissues. Environmental Experimental Botany 2019; 162: 421–432.

Orellana E, Vanclay JK. Could native Araucaria forests be managed for timber production on small farms in southern Brazil? Forest Ecology Management 2018a; 430: 1–9.

Orellana E, Vanclay JK. Competition and dominance between angiosperms and Araucaria angustifolia (Bert.) O. Kuntze in the Atlantic Forest in southern Brazil. Forest Ecology Management 2018b; 425: 119–125.

Peñuelas J, Sardans J, Rivas-ubach A, Janssens IA. The human-induced imbalance between C, N and P in Earth's life system. Global Change Biology 2012; 18: 3–6.

Rhodes JR, Cattarino L, Seabrook L, Maron M. Assessing the effectiveness of regulation to protect threatened forests. Biological Conservation 2017; 216: 33–42.

Ricken P, Hess AF, Borsoi GA. Relações biométricas e ambientais no incremento diamétrico de Araucaria angustifolia no planalto serrano catarinense. Ciência Florestal , 2018; 28: 1592.

Sarkkola S, Ukonmaanaho L, Nieminen TM, Laiho R, Laurén A, Finér, L, Nieminen M. Should harvest residues be left on site in peatland forests to decrease the risk of potassium depletion? Forest Ecology Management 2016; 374: 136–145.

Scheeren LW, Finger CAG, Schumacher MV, Longhi SJ. Crescimento em altura de Araucaria angustifolia (Bert.) O. Ktze. em três sítios naturais, na região de Canela (RS). Ciência Florestal 1999; 9: 23.

Simões JW, Couto HTZ. Efeitos da omissão de nutrientes na alimentação mineral do pinheiro do Paraná Araucaria Angustifolia (BERT.) O. KTZE cultivado em vaso. Ipef 3–39; 1973.

Yuan ZY, Chen HYH. Decoupling of nitrogen and phosphorus in terrestrial plants associated with global changes. Nature Climate Change 2015; 5: 465–469.