Liming and fertilisation in *Pinus taeda* plantations with severe nutrient deficiency in savanna soils

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ABSTRACT. Soils with high acidity and low exchangeable bases may be responsible for low yields of *Pinus taeda* in a forest plantation at Jaguariaíva, Paraná State, Brazil. The aim of this study was to evaluate the effect of liming and fertilisation, applied over litter, on two selected areas with *Pinus taeda* plantations. Soil, litter and pine needles were evaluated for K, Ca and Mg concentrations and soil acidity parameters. Seven treatments were applied: (i) complete (N, P, K, Zn, Cu, B, Mo, and lime); (ii) without N, P, and K; (iii) without Zn, Cu, B, and Mo; (iv) without K; (v) without Zn; (vi) without lime; and (vii) control (without nutrients and lime). Soil samples were collected at five soil depths (0-5, 5-10, 10-20, 20-40 and 40-60 cm) simultaneously with litter samples. Needles were also collected from the first and second pine flushes. Liming induced soil pH, Ca^{2+}, and Mg^{2+} increases, and the opposite was observed for Al^{3+} and Al saturation. Fertilisation increased soil exchangeable K^+ concentrations and needle and litter K concentrations. The low Ca and Mg concentrations found in the plant needles might be attributable to their low mobility.

Keywords: nutrient deficiency, reforestation, litter, soil reaction, acidification.

Calagem e adubação em plantios de *Pinus taeda* com severa deficiência nutricional em solos de cerrado

RESUMO. Solos com alta acidez e baixos teores de bases trocáveis podem ser a causa da baixa produtividade de plantios de *Pinus taeda*, em Jaguariaíva, PR, Brasil. O objetivo deste estudo foi avaliar o efeito da calagem e adubação aplicadas sobre a serapilheira, em duas áreas com Pinus taeda. Foram avaliadas as concentrações de K+, Ca2+ e Mg2+ no solo, serapilheira e acículas, além dos parâmetros da acidez do solo. Sete tratamentos foram aplicados: (i) completo (N, P, K, Zn, Cu, B, Mo e calagem); (ii) omissão de N, P e K; (iii) omissão de Zn, Cu, B e Mo; (iv) omissão de K; (v) omissão de Zn; (vi) omissão de calagem; (vii) controle. As amostras de solo foram coletadas nas profundidades de 0-5, 5-10, 10-20, 20-40 e 40-60 cm, simultaneamente às amostras de serapilheira. Foram coletadas amostras de acículas do primeiro e segundo lançamentos. A calagem induziu ao aumento do pH, Ca^{2+} e Mg^{2+} no solo, ocorrendo o oposto com os teores de Al^{3+} e saturação por Al. A adubação promoveu incremento nos teores de K^+ no solo, serapilheira e acículas. Não ocorreu variação nas concentrações de Ca e Mg nas acículas em relação aos tratamentos.

Palavras-chave: deficiência nutricional, reflorestamento, serapilheira, reação no solo, acidificação.

Introduction

Commercial pine plantations in southern Brazil generally show fast growth and no visual nutrient deficiency symptoms, which has led to the idea that these species could grow without liming and fertilisation (FERREIRA et al., 2001; REISSMANN; ZÖTTL, 1987; REISSMANN; WISNIEWSKI, 2004). This assumption has continued amongst most growers, as the majority of pine plantations do not receiving any fertiliser or lime application.

Since the commercial plantations were introduced, the planted areas have been spread over a wide range of vegetation types, climates and

geological and soil classes within a characteristic subtropical pattern. The expansion over the highly weathered soils of the Cerrado (Brazilian savannah) has tested the ability of commercial pine species to grow under very low levels of exchangeable bases and highly acidic soils. Under this natural condition, *Pinus caribaea* showed nutritional imbalances in some places, probably associated with Ca, Mg and Mn deficiencies, which may have caused plant death (CHAVES; CORREA, 2005). The above authors' findings suggest the need for lime or fertiliser application in very poor soils at the first planting time. Several regions are now in the second or third

pine planting cycles without the replacement of exported nutrients. Therefore, nutrient deficiency problems are expected to increase with time, especially in the low-nutrient soils of the Cerrado.

In the last few decades, the negative effects of inadequate soil management in Brazilian areas of forest plantations have been investigated and highlighted (CHAVES; CORREA, 2005; LILIENFEIN et al., 2000; REISSMANN; ZÖTTL, 1987) As reported in more recent trials, significant increases in productivity due to lime and fertiliser applications have been observed in coniferous forests (FERREIRA et al., 2001). However, according to Brito et al. (1986) *Pinus caribeae* forests planted in soils treated with liming and macronutrients showed increasing growth-ring mass production up to the third year; but opposite results were obtained with older trees. Reduced productivity and nutrient deficiencies in forest plantations in Germany, France and Norway have been investigated since the 1950's. Positive responses in wood production to liming and fertilisation (N, P, K) with reduced plant deficiency symptoms have been observed (HÜTTL, 1989). However, according to a survey done by Hüttl and Zöttl (1993), several factors must be taken into consideration before the recommendation of liming and fertilisation, as the negative effects may outweigh the benefits, especially the leaching of large amounts of NO_3^-.

Litter plays a key role in forest ecosystems, affecting soil protection and nutrient cycling. Several studies in southern Brazil have attempted to find relationships between litter quality and quantity and pinus yield (SCHUMACHER et al., 2008; VIERA; SCHUMACHER, 2010). Also, plant needle chemical analysis may be an interesting tool to evaluate pine nutrition and its demand for nutrients (ZÖTTL; TSCHINKEL, 1971). However, Chaves and Correa (2005) could not find clear evidence of nutrient imbalances using needle chemical analysis.

The aim of this study was to characterise the effect of superficial liming and mineral fertilisation on soil acidity, on soil K^+, Ca^{2+} and Mg^{2+} dynamics and on K, Ca and Mg concentrations in litter and pine needles in two five-year-old *Pinus taeda* plantations with severe nutrient deficiency visual symptoms.

Material and methods

Characterisation of the site

The experiment was performed in two selected areas of *Pinus taeda* commercial plantations of the Forest Value Company, located at Jaguariaíva county (area I) (24° 13' 29.13" S latitude and 49° 36' 21.12" W longitude) and Arapoti county (area II) (24° 18' 56.72" S latitude and 49° 44' 13.16" W longitude). The areas are situated in the second high plain of Paraná State, Brazil (960 to 1,320 m above sea level), where the soil parent material is derived from the geological sandstone formation of Itararé and Furnas. The vegetation was predominantly Cerrado (savannah) and was gradually replaced by forest plantations, agriculture and livestock (MELLO et al., 2003). Soil samples were collected and analysed in each area near the pinus plantation for the main physical and chemical characteristics (Table 1).

Table 1. Soil chemical analysis and particle size determination in samples from areas I (Jaguariaíva) and II (Arapoti), performed prior to treatments.

	Depth	pH CaCl$_2$	pH SMP	Al^{3+}	H + Al^{3+}	Ca^{2+}	Mg^{2+}	K$^+$	SB^2	P
	cm				cmol$_c$ kg^{-1}					mg dm^{-3}
Area I	0-20	3.83	4.98	2.70	10.88	0.38	0.20	0.05	0.63	6.38
	20-40	4.08	5.40	1.70	7.85	0.28	0.10	0.03	0.41	3.23
	40-60	4.10	5.53	1.60	7.13	0.25	0.10	0.03	0.38	1.93
Area II	0-20	3.85	5.65	1.25	6.45	0.15	0.06	0.03	0.24	0.38
	20-40	4.00	5.88	0.88	5.50	0.15	0.10	0.02	0.27	0.18
	40-60	4.05	5.93	0.75	5.30	0.14	0.08	0.02	0.25	0.10

	Depth	CEC^1 effective	CEC potential	O.M.^{3}	m^4	V^5	Sand	Silt	Clay	Textural class
	cm	cmol kg^{-1}			%			g kg^{-1}		
Area I	0-20	3.33	11.5	5	81	6	833	80	87	sandy
	20-40	2.11	8.26	4	81	5	827	83	90	sandy
	40-60	1.98	7.50	3	81	5	812	108	80	sandy
Area II	0-20	1.49	6.69	3	84	4	734	26	240	medium
	20-40	1.14	5.77	2	77	5	713	50	237	medium
	40-60	1.00	5.55	2	75	4	684	66	250	medium

[1]Cation Exchange capacity. [2]Sum of Bases. [3]Organic matter. [4]Al saturation. [5]Base saturation.

The regional climate is classified as subtropical (Cfa) transitioning to tropical (Cfb), according to Köppen. The average annual rainfall and temperature vary between 1,440 and 1,600 mm and 17 and 19°C, respectively. The winter is usually dry with low rainfall and occurrence of frost.

Experimental design

Two areas with commercial pine plantations were selected in 2008, both five years of age. The Jaguariaíva area (area I) showed an undulating topography and a thick litter layer. The Arapoti area (area II) is on uneven land and presents an irregular plant distribution due to the lower pine tree growth. The main disorders typically occur in the upper mid-portion of tree, with the ends of needles yellowing or necrotic. There is more premature plant death and slower growth compared with plants of the same age in other areas, which may be symptoms of severe nutrient deficiency.

Prior to this planting of *Pinus taeda*, currently at the second rotation, there was a *Eucalyptus* sp. plantation that, in turn, replaced the native cerrado vegetation. The two tree species were cultivated without liming and fertilisation. Before the current rotation, both areas were burnt after harvest. In the spring of 2008, both pinus plantations were pruned to a 2.0 m height using a manual saw, and the pruned material was left on the ground.

The experimental design consisted of randomised complete blocks with seven treatments and four replications. The experimental unit (plot) consisted of eight lines, each line with eight plants, totalling 64 plants in an area of 384 m². All areas together represent a total area of 10,752 m² (approximately 1 ha). The central 16 plants of each plot were considered for measurement and analysis.

The first fertiliser application occurred in October 2008 and the second in January 2010. The fertiliser inputs per 1 ha were: 40 kg nitrogen (89 kg urea, 45% N), 60 kg P_2O_5 (146 kg triple superphosphate, 41% P_2O_5), 80 kg K_2O (133 kg KCl, 60% K_2O), 3 kg zinc (20 kg $ZnSO_4$, 15% Zn), 2 kg boron (20 kg ulexite, 10% of B), 2 kg copper (8.3 kg $CuSO_4$, 24% Cu), and 20 g molybdenum (61 g Na_2MoO_4, 39% Mo).

Lime (1.3 Mg ha⁻¹) was manually broadcasted over litter after fertiliser application. The applied lime quantity was calculated to supply approximately 500 kg Ca, which is the amount exported by *Pinus* sp. in two cycles. The limestone used presented the following characteristics: CaO = 28.9%; MgO = 19.9%; NP (neutralisation power) = 99.4%; RE (reactivity efficiency) = 90%; and RPTN (relative power of total neutralisation) = 89.4%.

To diagnose the nutrient disorders, the following treatments with the omission of nutrients were adopted: (i) complete - application of all nutrients [N, P, K, Zn, Cu, B, Mo, Ca + Mg (dolomitic lime)]; (ii) without macro: application of nutrients without the macronutrients N, P, K; (iii) without micro: application of nutrients without the micronutrients Zn, Cu, B and Mo; (iv) without K: application of nutrients without K; (v) without Zn: application of nutrients without Zn; (vi) without lime: application of all nutrients except for lime (Ca + Mg); and (vii) control: no fertiliser or lime addition.

Sampling and soil analysis

The soil and litter sampling were performed in the same place at the same time. The soil samples were collected at the following depths: 0-5, 5-10, 10-20, 20-40, and 40-60 cm. The soil samples were air dried at room temperature, ground and sieved. Chemical analyses were performed according to the method of Embrapa (1997) for the determination of the following: active acidity (pH in 0.01 mol L⁻¹ $CaCl_2$ solution); potential exchangeable acidity (Al^{3+}), extracted with a 1 mol L⁻¹ KCl solution and determined by titration with a 0.2 mol L⁻¹ NaOH solution; exchangeable Ca^{2+} and Mg^{2+} extracted with a 1 mol L⁻¹ KCl solution and determined by atomic absorption spectrometry; and exchangeable K^+ extracted with Mehlich I and determined by flame photometry.

Sampling and analysis of litter and plants

Litter samples were collected from each plot and separated in Ln and La subsamples, according to Babel's (1972) definition: Ln (new litter) is composed of freshly fallen needles, and La (aged litter) consists of needles at the beginning of decomposition. Four points were randomly chosen within the plots. The litter was then marked by a wooden frame of 0.25 x 0.25 m, cut using a blade and removed. The material was collected in August 2010.

The needle samplings were conducted in November 2009 and December 2010. In each plot, five dominant trees were selected, which is equivalent to one hundred trees per hectare with a larger diameter at breast height (DBH). The needle samples were collected from the first and second releases (the second whorl) of the top at the north face.

The samples were dried in a forced-air oven at 60°C up to constant weight and were weighed and ground in a Willey type mill. Then, 1 g was submitted to dry digestion in a muffle furnace at 500°C, and the ashes were suspended in 10 mL of a 3 mol L⁻¹ HCl solution, according to method described by Martins and Reissmann (2007). The concentrations of Ca and Mg were determined by atomic absorption spectrophotometry, while the concentration of K was determined by flame photometry.

Statistical analysis

The experiment was arranged in a completely randomised design. All the data reported are average values of four replicates. The data were statistically evaluated using ANOVA, and significant differences between means were compared with the Tukey test normal distribution ($p < 0.05$). The statistical analyses were performed using Assistat 7.9 (SILVA, 2012).

Results and discussion

Influence of liming and fertilisation on pH and levels of Al^{3+} in soil

The soil analysis results for the control treatment revealed that areas I and II were both very acidic, with high levels of exchangeable Al^{3+}. The pH

values at a 0-5 cm depth were 3.03 and 3.18 for areas I and II, respectively (Table 2).

Table 2. Values of pH (in 0.01 mol dm^{-3} $CaCl_2$ solution), exchangeable Al^{3+} and Al saturation in soil samples from Jaguariaíva (Area I) and Arapoti (Area II), collected from five soil layer depths, in response to application of lime and fertilizer.

Soil depth	Treatments	pH		Al^{3+}		m[1]	
cm		Area I	Area II	Area I	Area II	Area I	Area II
				$cmol_c\ kg^{-1}$		%	
0-5	Complete	4.07ab	3.76ab	0.65b	1.35b	11b	42b
	Without macro	4.07ab	3.67ab	0.63b	1.48b	14b	57ab
	Without micro	3.82bc	4.09a	0.73b	0.98b	16b	34b
	Without K	4.15ab	3.75ab	0.50b	1.20b	9b	49b
	Without Zn	4.74a	3.73ab	0.15b	1.38b	2b	43b
	Without lime	3.20cd	2.95b	2.38a	2.85a	73a	78a
	Control	3.03d	3.18ab	2.55a	2.43a	86a	92a
5-10	Complete	3.74ab	3.83a	1.35ab	1.05a	44bc	51ab
	Without macro	4.36a	3.74ab	1.18b	1.30b	39c	65ab
	Without micro	3.85ab	3.96a	1.40b	0.93b	48abc	37b
	Without K	3.80ab	3.78ab	1.38ab	1.33ab	45bc	58ab
	Without Zn	4.05ab	3.76ab	1.18b	1.20b	41c	53ab
	Without lime	3.43b	3.14b	2.18a	2.28a	77ab	88a
	Control	3.41ab	3.44ab	2.00ab	1.88ab	81a	92a
10-20	Complete	3.70a	3.84a	1.68a	1.05a	78a	77a
	Without macro	3.72a	3.90a	1.55a	0.93a	72a	86a
	Without micro	3.75a	3.94a	1.68a	0.88a	77a	78a
	Without K	3.67a	3.88a	1.63a	1.00a	81a	86a
	Without Zn	3.89a	3.86a	1.63a	0.93a	71a	84a
	Without lime	3.71a	3.67a	1.93a	1.23a	79a	90a
	Control	3.66a	3.77a	1.73a	0.95a	81a	94a
20-40	Complete	3.57a	3.91a	1.70a	0.93a	79a	75a
	Without macro	3.73a	3.93a	1.65a	0.83a	80a	80a
	Without micro	3.77a	3.91a	1.78a	0.90a	80a	79a
	Without K	3.75a	3.89ab	1.50a	0.88a	79a	83a
	Without Zn	3.90a	3.89ab	1.53a	0.83a	75a	78a
	Without lime	3.78a	3.79b	1.80a	0.98a	79a	79a
	Control	3.73a	3.84ab	1.55a	0.90a	80a	87a
40-60	Complete	3.76a	3.93a	1.73a	0.88a	82a	78a
	Without macro	3.80a	3.94a	1.50a	0.83a	80a	82a
	Without micro	3.78a	3.78a	1.78a	0.93a	81a	81a
	Without K	3.78a	3.80a	2.00a	0.80a	83a	83a
	Without Zn	3.93a	3.93a	1.65a	0.83a	79a	81a
	Without lime	3.81a	3.85a	1.70a	0.95a	80a	83a
	Control	3.75a	3.92a	1.60a	1.00a	81a	85a

[1]Al saturation. Stand parameters with no letters in common represent means that are significantly different ($p < 0.05$).

Soil samples taken close to the experimental area and representing the same soil formation and supporting native vegetation showed similar pH values (Table 1). However, it is well known that pine plantations may acidify the soil (ALEXANDER; CRESSER, 1995; BRANDÃO; LIMA, 2002; INGERSLEV, 1997; LILIENTFEIN et al., 2000; SOUZA; SOUZA, 1981; PADUA et al., 2006).

The lime effect on soil pH was observed in both areas up to the 10 cm depth (Table 2). The results were highly satisfactory, considering the amount of low lime applied, the short period between applications and samplings and the high soil buffer capacity. Supporting this fast alteration under forestry conditions in Norway, Ingerslev (1997) showed changes in pH, Al, CEC and the sum of

bases up to a 35 cm depth after eight years of liming. Maeda et al. (2008), studying sandy soils in the state of Paraná, verified decreased soil acidity after one year of surface application of plant biomass ashes up to a 20 cm depth.

More significant changes in pH due to liming were found in area I (pH increased from 3.03 to 4.75) compared with area II (3.18 to 3.76). This result was not expected, as the highest soil potential acidity levels (H + Al) expressed by the buffering power were found in area I up to a 20 cm depth. Other differences between the two soils are the texture and organic matter content (Table 1). Such pH variation may be explained by the changes in exchangeable Al and Al saturation in the first 10 cm of the soil (Table 2).

Although pine species are considered tolerant to Al^{3+} (ALEXANDER; CRESSER, 1995; GONÇALVES, 1995; HÜTTL; ZÖTTL, 1993) some studies have clearly shown negative effects of the element on tree development (NOWAK; FRIEND, 2006).

Liming and fertilisation effects on the soil-exchangeable K^+, Ca^{2+} and Mg^{2+} concentrations

Lime application resulted in higher sum of bases (data not shown) and higher base saturation values (Table 3) within the 0-10 cm layer. The fertiliser alone did not significantly change SB compared with the control treatment. In addition to the direct effect of lime on neutralising exchangeable Al, the consequent pH rise also promotes deprotonation of the organic colloid and mineral surfaces, which are essential to increasing the soil CEC and base saturation.

The base availability under native conditions (Table 3) was far below the minimum recommended for agricultural crops (IAC, 1997) for both areas. The low available K concentration in the control treatment evidenced the poor primary mineral content in the source material (Furnas Sandstone and Itararé). The K application provided significant soil K increments up to the 20 and 40 cm depths for areas I and II, respectively, confirming the high mobility of the soil K. Although the applied amount of K fertiliser was not high, the combined effect of sandy texture, low effective CEC and high precipitation may explain the high K mobility. The present results are corroborated by other studies that showed close relationships between soil characteristics and nutrient movement. Frank and Stuanes (2003) obtained an increase in K^+ levels up to a 22 cm depth in sandy soils with high Al saturation under the cultivation of *Pinus* sp. in Norway.

Table 3. Values of soil K^+, Ca^{2+} and Mg^{2+} concentrations, effective CEC and base saturation (V%) in samples from Jaguariaíva (area I) and Arapoti (area II), at five soil layer depths in response to application of lime and fertilizer.

Soil depth	Treatment	K+ Area I	K+ Area II	Ca2+ Area I	Ca2+ Area II	Mg2+ Area I	Mg2+ Area II	CEC_effective Area I	CEC_effective Area II	V[1] Area I	V[1] Area II
cm		cmol$_c$ kg^{-1}						cmol$_c$ kg^{-1}		%	
	Complete	0.17 [ab]	0.12 [ab]	2.19 [a]	1.29 [a]	3.33 [a]	1.24 [a]	6.34 [a]	4.00 [a]	51 [ab]	24 [ab]
	Without macro	0.03 [c]	0.04 [b]	1.41 [ab]	0.45 [b]	2.92 [a]	0.69 [ab]	4.98 [ab]	2.50 [a]	45 [ab]	17 [ab]
	Without micro	0.13 [abc]	0.10 [ab]	1.44 [ab]	1.26 [a]	2.55 [a]	1.38 [a]	4.85 [ab]	3.75 [a]	42 [b]	34 [a]
0-5	Without K	0.07 [bc]	0.04 [b]	1.78 [ab]	0.85 [ab]	2.86 [a]	0.86 [ab]	5.22 [ab]	3.25 [a]	47 [ab]	27 [ab]
	Without Zn	0.19 [a]	0.16 [a]	2.38 [a]	0.88 [ab]	3.96 [a]	0.94 [ab]	6.67 [a]	3.25 [a]	61 [a]	26 [a]
	Without lime	0.14 [abc]	0.13 [ab]	0.47 [bc]	0.65 [b]	0.21 [b]	0.51 [ab]	3.19 [b]	4.14 [a]	11 [c]	13 [ab]
	Control	0.03 [c]	0.04 [b]	0.22 [c]	0.09 [c]	0.16 [b]	0.05 [b]	2.96 [b]	2.61 [a]	4 [c]	2 [b]
	Complete	0.15 [a]	0.11 [a]	0.59 [a]	0.52 [ab]	1.04 [ab]	0.53 [ab]	3.13 [a]	2.21 [a]	25 [ab]	16 [ab]
	Without macro	0.03 [b]	0.03 [b]	0.63 [a]	0.28 [b]	1.46 [a]	0.40 [ab]	3.29 [a]	2.02 [a]	29 [a]	12 [ab]
	Without micro	0.08 [ab]	0.09 [ab]	0.53 [ab]	0.85 [a]	1.04 [ab]	0.95 [a]	3.05 [a]	2.81 [a]	25 [ab]	27 [a]
5-10	Without K	0.03 [b]	0.03 [b]	0.63 [a]	0.50 [ab]	1.15 [ab]	0.50 [ab]	3.17 [a]	2.35 [a]	26 [ab]	15 [ab]
	Without Zn	0.15 [a]	0.13 [a]	0.75 [a]	0.49 [ab]	1.25 [ab]	0.51 [ab]	3.33 [a]	2.32 [a]	31 [a]	18 [ab]
	Without lime	0.11 [ab]	0.12 [a]	0.31 [b]	0.18 [b]	0.21 [b]	0.06 [b]	2.80 [b]	2.63 [a]	10 [ab]	4 [b]
	Control	0.03 [b]	0.03 [b]	0.22 [b]	0.08 [b]	0.21 [b]	0.05 [b]	2.45 [b]	2.03 [a]	7 [b]	2 [b]
	Complete	0.09 [a]	0.09 [a]	0.22 [a]	0.27 [a]	0.16 [a]	0.21 [a]	2.14 [a]	1.61 [a]	25 [a]	12 [a]
	Without macro	0.02 [b]	0.07 [ab]	0.25 [a]	0.16 [ab]	0.31 [a]	0.11 [ab]	2.14 [a]	1.25 [ab]	29 [a]	9 [a]
	Without micro	0.07 [ab]	0.07 [ab]	0.22 [a]	0.22 [ab]	0.21 [a]	0.19 [ab]	2.17 [a]	1.35 [ab]	25 [a]	12 [a]
10-20	Without K	0.01 [b]	0.02 [b]	0.16 [a]	0.17 [ab]	0.21 [a]	0.13 [ab]	2.00 [a]	1.31 [ab]	26 [a]	7 [a]
	Without Zn	0.10 [a]	0.09 [a]	0.22 [a]	0.17 [ab]	0.31 [a]	0.10 [ab]	2.26 [a]	1.27 [ab]	31 [a]	8 [a]
	Without lime	0.11 [a]	0.08 [a]	0.19 [a]	0.10 [bc]	0.21 [a]	0.05 [b]	2.43 [a]	1.45 [ab]	10 [a]	5 [a]
	Control	0.02 [b]	0.02 [b]	0.19 [a]	0.09 [c]	0.21 [a]	0.05 [b]	2.14 [a]	1.10 [b]	7 [a]	6 [a]

Soil depth	Treatment	K+ Area I	K+ Area II	Ca2+ Area I	Ca2+ Area II	Mg2+ Area I	Mg2+ Area II	CEC_effective Area I	CEC_effective Area II	V(1) Area I	V(1) Area II
cm		cmol$_c$ kg^{-1}						cmol$_c$ kg^{-1}		%	
	Complete	0.08 [a]	0.07 [ab]	0.16 [a]	0.16 [a]	0.21 [a]	0.08 [a]	2.14 [a]	1.24 [a]	11 [a]	10 [a]
	Without macro	0.01 [ab]	0.01 [b]	0.22 [a]	0.14 [a]	0.21 [a]	0.06 [ab]	2.08 [a]	1.03 [a]	8 [a]	6 [a]
	Without micro	0.05 [ab]	0.05 [ab]	0.19 [a]	0.13 [a]	0.21 [a]	0.07 [ab]	2.22 [a]	1.14 [a]	8 [a]	6 [a]
20-40	Without K	0.01 [ab]	0.01 [b]	0.19 [a]	0.12 [a]	0.21 [a]	0.06 [ab]	1.90 [a]	1.05 [a]	8 [a]	5 [a]
	Without Zn	0.07 [ab]	0.07 [ab]	0.22 [a]	0.12 [a]	0.21 [a]	0.05 [ab]	2.02 [a]	1.07 [a]	10 [a]	6 [a]
	Without lime	0.05 [ab]	0.11 [a]	0.22 [a]	0.09 [a]	0.21 [a]	0.05 [ab]	2.27 [a]	1.22 [a]	10 [a]	6 [a]
	Control	0.00 [b]	0.01 [ab]	0.19 [a]	0.09 [a]	0.21 [a]	0.03 [b]	1.95 [a]	1.03 [a]	7 [a]	4 [a]
	Complete	0.02 [ab]	0.05 [ab]	0.16 [a]	0.14 [a]	0.21 [a]	0.06 [a]	2.11 [ab]	1.13 [a]	9 [a]	7 [a]
	Without macro	0.01 [ab]	0.05 [a]	0.16 [a]	0.13 [a]	0.21 [a]	0.06 [a]	1.87 [b]	1.01 [a]	7 [a]	6 [a]
	Without micro	0.04 [a]	0.06 [a]	0.16 [a]	0.12 [a]	0.21 [a]	0.06 [a]	2.17 [ab]	1.16 [a]	8 [a]	6 [a]
40-60	Without K	0.01 [ab]	0.05 [a]	0.19 [a]	0.11 [a]	0.21 [a]	0.05 [a]	2.40 [a]	0.96 [a]	9 [a]	5 [a]
	Without Zn	0.03 [ab]	0.06 [a]	0.19 [a]	0.11 [a]	0.21 [a]	0.04 [a]	2.07 [ab]	1.03 [a]	7 [a]	6 [a]
	Without lime	0.02 [ab]	0.07 [a]	0.19 [a]	0.08 [a]	0.21 [a]	0.04 [a]	2.12 [ab]	1.14 [a]	9 [a]	5 [a]
	Control	0.00 [b]	0.07 [a]	0.16 [a]	0.07 [a]	0.21 [a]	0.04 [a]	1.96 [b]	1.18 [a]	6 [a]	6 [a]

[1]V = Base saturation. Stand parameters with no letters in common represent means that are significantly different ($p < 0.05$).

Available Ca concentration increments were observed up to the 5 cm (area I) and 20 cm (area II) layers (Table 3). The Ca availability increased below a 5 cm depth for area II, suggesting a higher mobility under this condition than area I. The low Ca backgrounds indicated the influence of broadcast lime application, the observed Ca increases can be considered low. By comparing the complete treatment to that without macronutrients and without lime to control, it was possible to verify that fertiliser enhanced Ca availability in the 0-5 cm layers. This result was not expected, as the only extra source of Ca was triple superphosphate, with approximately 10% of Ca [Ca $(H_2PO_4)_2 \cdot 2H_2O$]; that is, the Ca input was much smaller than that of lime. The Ca increment difference between soil areas was not expected either, as both received the same amount of lime, but a higher available Ca concentration was found in area I than area II.

Ingerslev (1997), after eight years of limestone application in an area with conifers, found differences in the soil Ca^{2+} and Mg^{2+} concentrations up to a 35 cm depth. Frank and Stuanes (2003), in a four-year study, observed increased Ca^{2+} concentrations up to a 22 cm depth in sandy soils under coniferous planting. This result can be compared with this research, as the differences were significant up to the 20 cm depth, in less than two years.

Significant effects of lime application on available Mg^{2+} concentrations were also observed up to the 10 cm depth in area I and the 40 cm depth in area II. Similarly to the Ca responses, differences in Mg concentrations were observed between the complete treatment and the other treatments with lime. Also, higher available Mg concentrations were found in area I than in area II (Tables 1 and 3). Again, there is no explanation for the differences found in available Mg concentrations between treatments that received the same amount of Mg from lime.

It is important that there was a greater increase in Mg^{2+} than in Ca^{2+} concentrations with soil profile depth, despite the two nutrients being derived from the same corrective. According to Hüttl and Zöttl (1993), when both nutrients come from dolomitic lime, as in the present study, the Mg^{2+} is generally more available than Ca^{2+}, which may be explained by the higher $MgCO_3$ (0.106 g L^{-1}) solubility than $CaCO_3$ (0.014 g L^{-1}) in the limestone (the first is 7.6 times more soluble).

The symptoms of Mg^{2+} deficiency in forest plantations and the study of appropriate rates of Mg fertiliser have been investigated since the 1980s in various regions of Germany (EVERS; HÜTTL, 1990; HÜTTL, 1989; HÜTTL; ZÖTTL, 1993; UEBEL; HEINSDORF, 1997). In a review paper on conifer plantations in Germany, Hüttl and Zöttl (1993) concluded that the application of Mg^{2+} through liming was effective at increasing the Mg level in the soil and reversing the nutrient deficiency symptoms. However, Uebel and Heinsdorf (1997), studying the application of fertilisers containing Mg^{2+} and K^+ in sandy soils under *Pinus* sp., observed no significant improvement in the two nutrient availability levels in the soil, despite the increased productivity. Nevertheless, the Mg^{2+} dynamics in soils under forest plantations are still unknown, and there are few answers about its addition to the soil, especially in soils under coniferous plantations in regions with warmer climates.

The responses achieved in the present study allow inferring that changes in the levels of K^+, Ca^{2+} and Mg^{2+} observed at even the most superficial depths (less than 10 cm) are important. The finest roots, responsible for most nutrient absorption, occupy the first 20 cm, including litter or the organic horizon. Thus, the surface application of fertilisers in forest areas can be considered an excellent procedure to correct low nutrient levels in the soil, even in established plantings.

Distribution of K^+, Ca^{2+} and Mg^{2+} in the new litter (Ln) and aged litter (La) in response to liming and fertilisation

The low K^+, Ca^{2+}, and Mg^{2+} concentrations found in the litter from the control treatment (Table 4) confirmed their low availability in the biogeochemical cycle of the studied areas. The obtained values were lower than those observed by Brum (1980) in *Pinus elliottii* plantations in northern Santa Catarina. Brum (1980) reported K^+ and Ca^{2+} levels of approximately 0.6 and 2.5 g kg^{-1}, respectively. Even more expressive differences are observed in comparison with the data reported by Viera and Schumacher (2010), who found Ca^{2+}

concentrations of 7.88 g kg^{-1} in the litter of *Pinus taeda* grown in basaltic soils of Rio Grande do Sul State.

Table 4. Concentrations of K^+, Ca^{2+}, and Mg^{2+} in the new litter (Ln) and aged litter (La) from Jaguariaíva (area I) and Arapoti (area II), in response to application of lime and fertilizers.

	Treatment	K		Ca		Mg	
		Ln	La	Ln	La	Ln	La
		g kg^{-1}					
Area I	Complete	1.18 a	0.53 ab	1.95 a	20.46 a	1.23 ab	8.90 a
	Without Macro	0.38 b	0.25 c	2.45 a	17.82 a	1.64 a	9.97 a
	Without micro	0.83 ab	0.45 abc	2.25 a	18.51 a	1.23 ab	10.13 a
	Without K	0.50 b	0.40 abc	2.39 a	13.38 a	1.50 ab	6.68 b
	Without Zn	1.13 a	0.43 abc	1.80 a	19.81 a	1.35 ab	7.43 a
	Without lime	1.08 a	0.58 a	1.23 a	2.79 b	0.55 b	0.30 b
	Control	0.35 b	0.33 bc	1.33 a	1.28 b	0.76 a	0.40 b
Área II	Complete	1.20 a	0.60 abc	2.45 ab	18.29 a	1.08 a	8.81 a
	Without Macro	0.30 b	0.28 cd	2.41 ab	13.35 abc	1.18 a	7.83 a
	Without micro	1.23 a	0.60 abc	1.58 abc	16.97 ab	0.78 ab	8.72 a
	Without K	0.45 b	0.40 bcd	2.84 a	8.86 ab	1.19 a	5.43 ab
	Without Zn	1.33 a	0.83 a	1.55 abc	6.93 abc	0.69 ab	4.46 ab
	Without lime	1.33 a	0.70 ab	0.83 bc	1.19 b	0.41 bc	0.34 b
	Control	0.35 b	0.25 d	0.48 c	3.01 bc	0.33 c	1.75 b

Stand parameters with no letters in common represent means that are significantly different ($p < 0.05$).

The results (Table 4) indicate a distinct behaviour between the K^+ and Ca^{2+} plus Mg^{2+} concentrations in the litter from the same treatment. Thus, the litter samples from the complete treatment showed higher K^+ levels in more recently fallen needles (Ln) than aged needles (La), suggesting K leaching by rainfall. However, the low-litter K concentrations were found in the litter samples from treatments without the addition of macronutrients or K and control, and the expected decrease in aged-needle K concentrations was either unclear or did not happen.

In the complete treatment, however, significantly lower concentrations of Ca^{2+} were observed in the new litter, Ln (1.95 and 2.45 g kg^{-1}, in areas I and II, respectively), than in the aged litter, La (20.46 and 18.29 g kg^{-1}, in areas I and II, respectively). Similar results were obtained for Mg^{2+}: 1.23 and 1.08 g kg^{-1} for Ln in areas I and II, respectively, and 8.90 and 8.81 for g kg^{-1} for La in areas I and II, respectively. The increase in Ca and Mg concentrations during the aging process may be due to these elements not being easily lixiviated. Nevertheless, different limestone effects on Ca concentrations were observed between the two areas. In area I, significantly higher Ca concentrations with lime addition were only observed in the aged litter (La). In area II, significantly higher Ca concentrations with lime addition were found in both the La and Ln litter samples. Similar behaviour was observed for Mg. From these results, it might be inferred that the thick litter layer retained non-reacted lime in the organic layer and restricted the lime contact with soil, with consequent lower Ca and Mg availability to the soil-plant system. This hypothesis was supported by visual

observation during the litter sampling. Another hypothesis is that part of lime reacted but that the released Ca and Mg remained bound to the litter exchange sites, becoming unavailable.

Effect of treatments on the needle K$^+$, Ca^{2+}, and Mg^{2+} concentrations in the first and second flushes during the years 2009 and 2010

A clear positive effect of K fertiliser on the needle K concentration was observed for both flushes and years at area I (Table 5). At area II, this effect was significant for the year 2010. These results confirm the soil K availability enhancement (Table 2). Also, lime omission resulted in higher needle K concentration in the first flush at area I due to the antagonic effect of increased Ca and Mg on decreasing K uptake by pine plants.

Table 5. Concentrations of K$^+$, Ca^{2+} and Mg^{2+} in the first and second needle flushes, at Jaguariaíva (area I) and Arapoti (area II), during 2009 and 2010, in response to lime and fertilizer application.

	Treatment	K 2009	K 2010	Ca 2009	Ca 2010	Mg 2009	Mg 2010
				g kg^{-1}			
Area I 1° L¹	Complete	3.74^a	3.61^a	0.82^a	2.02^a	0.61^{ab}	0.50^a
	Without Macro	2.74^b	2.35^{bc}	1.06^a	2.38^a	1.01^a	0.65^a
	Without micro	3.84^a	3.77^a	0.58^a	1.91^a	0.52^b	0.42^a
	Without K	2.54^b	2.17^c	0.91^a	2.18^a	0.87^{ab}	0.57^a
	Without Zn	3.60^a	3.59^{ab}	0.67^a	1.81^a	0.55^b	0.38^a
	Without lime	3.89^a	4.39^a	0.85^a	1.52^a	0.59^{ab}	0.30^a
	Control	2.42^b	2.24^c	0.66^a	2.23^a	0.62^a	0.55^a
Area I 2° L²	Complete	3.74^{ab}	3.94^a	1.00^a	2.12^a	0.92^{ab}	0.64^{ab}
	Without Macro	2.69^{bc}	2.55^b	1.37^a	2.78^a	1.16^a	0.75^a
	Without micro	4.09^a	3.87^a	0.64^{bc}	2.08^a	0.56^a	0.56^{ab}
	Without K	2.64^{bc}	2.49^b	1.31^{ab}	2.58^a	1.17^a	0.84^a
	Without Zn	3.27^{abc}	4.13^a	0.87^{abc}	2.53^a	0.67^{ab}	0.64^{ab}
	Without lime	3.66^{ab}	4.01^a	0.50^c	2.53^a	0.52^b	0.31^b
	Control	2.34^c	2.49^b	0.77^{abc}	2.80^a	0.72^{ab}	0.49^{ab}
Area II 1° L¹	Complete	3.04^a	3.34^{ab}	2.21^a	1.49^a	0.60^a	0.52^a
	Without Macro	2.37^a	2.07^c	2.40^a	1.09^a	0.76^a	0.49^a
	Without micro	3.37^a	3.62^a	1.86^a	0.70^a	0.45^a	0.39^a
	Without K	2.52^a	1.97^c	1.95^a	1.21^a	0.61^a	0.47^a
	Without Zn	3.14^a	2.85^b	2.14^a	1.29^a	0.54^a	0.53^a
	Without lime	3.39^a	3.11^{ab}	1.86^a	0.46^a	0.39^a	0.27^a
	Control	2.54^a	1.90^c	2.15^a	0.91^a	0.57^a	0.42^a
Area II 2° L²	Complete	2.81^a	3.58^a	2.18^a	1.66^a	0.50^a	0.57^a
	Without Macro	2.37^a	2.27^b	2.31^a	1.41^a	0.77^a	0.76^a
	Without micro	2.94^a	3.47^a	2.04^a	1.51^a	0.49^a	0.52^a
	Without K	2.27^a	2.19^b	2.24^a	1.32^a	0.67^a	0.55^a
	Without Zn	2.69^a	3.26^a	2.14^a	1.15^a	0.45^a	0.38^a
	Without lime	2.94^a	3.61^a	2.05^a	0.92^a	0.48^a	0.31^a
	Control	2.32^a	2.21^b	2.07^a	0.87^a	0.59^a	0.40^a

[1]First flush. [2]Second flush. Stand parameters with no letters in common represent means that are significantly different (p < 0.05).

However the observed K values were lower than the average K concentration (6 g kg^{-1}) suggested as

adequate for pine trees by several authors (REISSMANN; WISNIEWSKI, 2004; VOGEL, 2003). Apparently, K fertilisation was not enough to reach the satisfactory value (6.0 g kg^{-1}), despite the high soil K concentration observed in the 0-20 cm layer. Nevertheless, the abovementioned authors indicated an adequate K concentration for pine trees without taking into consideration the sampling time and species. Chaves and Correa (2005) found no K deficiency symptoms in *Pinus caribeae* with needle K of 3.8 mg kg^{-1}.

Although many authors did not relate K$^+$ with yield (CHAVES; CORRÊA, 2005; HÜTTL; ZÖTTL, 1993), studies with *Pinus* sp. in the second plateau of Paraná, indicated that K is one of the most growth-limiting nutrients (REISSMANN; WISNIEWSKI, 2004). The present results indicate that more research is needed to better evaluate the effects of K on pinus nutrition and development. However, a low needle K concentration in the control treatment and a consistent increasing needle K concentration in fertilised treatments were observed. These results suggest that there must be concern over pinus tree demand for K and that this nutrient may be responsible for the deficiency symptoms observed in the field.

Reissmann and Wisniewski (2004) observed higher demand for K$^+$ than for Ca^{2+} in this species. The authors concluded that plots with poor quality soil showed K Ca^{-1} ratios close to 1, while the best areas showed K Ca^{-1} ratios above 3. In this study, the K Ca^{-1} ratios were observed to be close to 1, except for some results where the ratios approached 3 in response to the treatments. Low ratios confirmed plant K deficiency.

In contrast, significant differences in the Ca concentrations appeared only in the second flush in 2009 (Table 5), despite their increase in the superficial soil layer (Table 3).

In some samples, the needle Ca concentration was below 1.0 or 1.5 g kg^{-1}, values that are considered adequate for pine trees by Zöttl and Tschinkel (1971) and Allen (1987), respectively. However, the needle Ca concentration was above 1 g kg^{-1} in the control treatment, where the natural soil Ca^{2+} levels were very low, indicating the influence of other factors on Ca uptake by pine trees. Furthermore, Chaves and Corrêa (2005), studying plantations of *Pinus caribeae* in the Cerrado of Minas Gerais State, Brazil, found visual symptoms of mineral deficiency followed by early death in plants with Ca^{2+} ranging from 0.1 to 0.2 g kg^{-1}. Meanwhile normal plants showed needle Ca concentrations ranging from 0.6 to 2.0 g kg^{-1}. Therefore, the results obtained in the present

research do not allow certainty that the Ca deficiency occurred under this experimental condition.

The needle Mg concentrations obtained in this study were consistently lower than 0.8 and 0.6 g kg^{-1}, values indicated as adequate for pine trees by Zöttl and Tschinkel (1971) and Reismann and Wisniewski (2004), respectively. Significant differences for this nutrient were only observed in area I. The highest needle Mg^{2+} concentration was observed in the first and second flushes in the plots without macro in 2009 and in the second flush in 2010 (Table 5). The K omission in this treatment may have contributed to the increased Mg^{2+} absorption. The needle chemical analysis confirmed the low Mg concentrations previously observed in the soil and litter samples, indicating that Mg deficiency was much more plausible than Ca in this study.

In general, there was close agreement between the first and second needle flushes for predicting Ca, Mg and K nutritional status. The large and irregular span between years for the Ca results did not allow a conclusion to be made, and further studies are required. The distinct movements of nutrients in plant tissues evidenced the well-known high K and Mg mobility in the plants compared with Ca (REISSMANN; WISNIEWSKI, 2004), which explains the high K/Ca ratio in young tissues.

The present results indicate that low levels of soil exchangeable bases, high acidity and Al^{3+} saturation were partially corrected in a short-term experiment with *Pinus taeda* plantations. However, more research is needed and long-term experiments must be performed to better evaluate the effects of increasing fertilisation and liming rates on both soil and plant nutrient concentrations. Specific lime and fertiliser calibration curves for pine forest plantations should be investigated to ensure the maximum positive effects of this type of crop management in pine tree productivity.

Conclusion

Potassium concentration increments in soils, plants and litter were more evident than those of other macronutrients in response to fertilisation. These responses suggest that surface fertilisation may be effective to correct K disorders in pine trees. However, the same cannot be said for Ca and Mg, as their needle concentrations showed irregular responses to the treatments.

There is no doubt about the need to provide nutrients via liming and fertilisation, even in forest plantations. This management is essential to maintaining the quality of soils and plants. However, more studies such as analysis of height increments and diameter are essential to evaluate the efficiency of liming and fertilisation on reversing the nutritional deficiency and improving the low growth rates in sites with these kinds of problems. A long period between application and sampling is needed for a more accurate conclusion.

Acknowledgements

References

ALEXANDER, C. E.; CRESSER, M. S. An assessment of the possible impact of expansion of native woodland on the chemistry of Scottish freshwater. **Forest Ecology Management**, v. 73, n. 1, p. 1-27, 1995.

ALLEN, H. L. Forest fertilizers: nutrient amendment, stand productivity and environmental impact. **Journal of Forestry**, v. 85, n. 2, p. 37- 46, 1987.

BABEL, U. **Moderprofile in waldern**. Ulmen: Stuttgart, 1972.

BRANDÃO, S. L.; LIMA, S. C. pH e condutividade elétrica de *Pinus* e cerrado na Chapada, em Uberlândia (MG). **Caminhos de Geografia**, v. 3, n. 1, p. 46-54, 2002.

BRITO, J. O.; FERRAZ, E. S. B.; BARRICHELO, L. E.; COUTO, H. T. Z. A adubação mineral e seus efeitos sobre os anéis de crescimento da madeira de *Pinus caribaea* VAR. *bahamensis*. **IPEF**, v. 32, n. 1, p. 5-17, 1986.

BRUM, E. Composição química de acículas verdes e da litteira de *Pinus elliottii* Engelm. **Revista Floresta**, v. 11, n. 1, p. 17-23, 1980.

CHAVES, R. Q.; CORRÊA, G. F. Macronutrientes no sistema solo - *Pinus caribaea* Morelet em plantios apresentando amarelecimento das acículas e morte das plantas. **Revista Árvore**, v. 29, n. 5, p. 691-700, 2005.

EMBRAPA-Empresa Brasileira de Pesquisa Agropecuária. **Manual de análises químicas de solos, plantas e fertilizantes**. Brasília: Embrapa Comunicação para Transferência de Tecnologia, 1997.

EVERS, F. H.; HÜTTL, R. F. A new fertilization strategy in declining forests. **Water, Air and Soil Pollution**, v. 54, n. 1, p. 495-508, 1990.

FERREIRA, C. A.; SILVA, H. D.; REISSMANN, C. B.; BELLOTE, A. F. J.; MARQUES, R. **Nutrição de *Pinus* no sul do Brasil, diagnóstico e prioridades de pesquisa**. Colombo: Embrapa Florestas, 2001.

FRANK, J.; STUANES, A. O. Short-term effects of liming and nutrient leaching in a Scots pine ecosystem in

Norway. **Forest Ecology Management**, v. 176, n. 1-3, p. 371-386, 2003.

GONÇALVES, J. L. M. Recomendações de adubação para *Eucalyptus*, *Pinus* e espécies típicas da Mata Atlântica. **Documentos Florestais**, v. 15, n. 1, p. 1-23, 1995.

HÜTTL, R. F. Liming and fertilization as mitigation tools in declining forest ecosystems. **Water, Air and Soil Pollution**, v. 44, n. 1, p. 93-118, 1989.

HÜTTL, R. F.; ZÖTTL, H. W. Liming as a mitigation tool in Germany's declining forests- reviewing results from former and recent trials. **Forest Ecology Management**, v. 61, n. 3-4, p. 325-338, 1993.

IAC-Instituto Agronômico de Campinas. **Recomendação de adubação e calagem para o Estado de São Paulo**. Campinas: Instituto Agronômico; Fundação IAC, 1997.

INGERSLEV, M. Effects of liming and fertilization on growth, soil chemistry and soil water chemistry in a Norway spruce plantation on a nutrient-poor soil in Denmark. **Forest Ecology Management**, v. 92, n. 1, p. 55-66, 1997.

LILIENFEIN, W. W.; AYARZA, M. A.; VILELA, L.; LIMA, S. C.; ZECH, W. Soil acidification in *Pinus caribaea* forests on Brazilian savanna Oxisols. **Forest Ecology Management**, v. 73, n. 1, p. 1-27, 2000.

MAEDA, S.; SILVA, H. D.; CARDOSO, C. Resposta de *Pinus taeda* à aplicação de cinza de biomassa vegetal em Cambissolo Húmico, em vaso. **Pesquisa Florestal Brasileira**, v. 56, n. 1, p. 43-52. 2008.

MARTINS, A. P. L.; REISSMANN, C. B. Material vegetal e as rotinas laboratoriais nos procedimentos químico-analíticos. **Scientia Agraria**, v. 8, n. 1, p. 1-17, 2007.

MELLO, M. S.; MORO, R. S.; GUIMARÃES, G. B. **Patrimônio natural dos campos gerais**. Ponta Grossa: UEPG, 2003.

NOWAK, J.; FRIEND, A. Loblolly pine and slash pine responses to acute aluminum and acid exposures. **Tree Physiology**, v. 26, n. 9, p. 1207-1215, 2006.

PADUA, T. R. P.; SILVA, C. A.; MELO, C. A. Calagem em latossolo sob influência de coberturas vegetais: neutralização da acidez. **Revista Brasileira de Ciência do Solo**, v. 30, n. 5, p. 869-878, 2006.

REISSMANN, C. B.; WISNIEWSKI, C. Nutricional aspects of pine plantation. In: GONÇALVES, J. L. M.;

BENEDETTI, V. (Org). **Forest nutrition and fertilization**. Piracicaba: IPEF, 2004. p. 141-170.

REISSMANN, C. B.; ZÖTTL, H. W. Problemas nutricionais em povoamentos de *Pinus taeda* em áreas do arenito da formação Rio Bonito-Grupo Guatá. **Revista Ciência Agrária**, v. 9, n. 1, p. 75-80, 1987.

SCHUMACHER, M. V.; VIERA, M.; WITSCHORECK, R. Produção de serapilheira e tranferência de nutrientes em área de segunda rotação com floresta de *Pinus taeda* no município de Cambará do Sul, RS. **Ciência Florestal**, v. 18, n. 4, p. 471- 480, 2008.

SILVA, F. A. **ASSISTAT versão beta**. Grande: Assistência Estatística, Departamento de Engenharia Agrícola do CTRN – Universidade Federal de Campina Grande, Campus de Campina. Available from: <http://www.assistat.com>. Access on: Aug. 5 2012.

SOUZA, D. M. P.; SOUZA, M. L. P. Alterações provocadas pelo florestamento de *Pinus sp*. na fertilidade de solos da região da Lapa-PR. **Revista Floresta**, v. 12, n. 1, p. 36-50, 1981.

UEBEL, E.; HEINSDORF, D. Results of long-term K and Mg fertilizer experiments in afforestation. **Forest Ecology Management**, v. 91, n. 1, p. 47-52, 1997.

VIERA, M.; SCHUMACHER, M. V. Teores e aporte de nutrientes na serapilheira de *Pinus taeda* L., e sua relação com a temperatura do ar e pluviosidade. **Revista Árvore**, v. 34, n. 1, p. 85-94, 2010.

VOGEL, H. L. M. Crescimento de *Pinus taeda*, relacionado a doses de N, P, K e sua diagnose nutricional pelo DRIS. R. **Ciência Florestal**, v. 13, n. 1, p. 182-188, 2003.

ZÖTTL, H. M.; TSCHINKEL, H. **Nutrición y fertilización forestall**: una guía práctica. Medellin: Universidade Nacional de Colombia, 1971.