

ORIGINAL ARTICLE

Wood annual average increment and K, Ca and Mg mineral compartments in soils cultivated with eucalypt

Incremento médio anual de madeira e teores de K, Ca e Mg em compartimentos minerais de solos cultivados com eucalipto

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Abstract

Forestry continuously grows in Brazil and it increases the concerns among planted forest companies regarding sustainable production. Knowledge about soil mineral reserves and nutrient release kinetics may introduce an opportunity to optimize fertility management, improving production. The objectives of this study were to evaluate the contents of K, Ca and Mg in the reserve, non-exchangeable, exchangeable and available soil compartments and the nutrient release speed, as well as their correlations and effects on eucalypt productivity. Soil samples were collected from eucalypt plantation sites at the state of Rio Grande do Sul, Brazil, comprising seven soil classes. The contents of K, Ca and Mg were determined in sulfuric digestion extract, boiling nitric acid, ammonium chloride, Mehlich-1 and potassium chloride. Nutrient release kinetics were evaluated per Sparks (1989), while CMPC Celulose Riograndense provided the wood volumetric annual average increment (AAI) from the eucalypt plantations. The contents of K, Ca and Mg varied between compartments and depths and were concentrated in the reserve compartment, indicating the importance of this compartment for mid- and long-term nutrient supply. Most compartments of K, Ca and Mg showed significant correlation; and eucalypt wood productivity (AAI) correlated significantly with the different compartments in both depths, mainly with the reserve compartment and release kinetics expressing their relevance for productivity; in particular for the case of long-cycle plant species, where nutrient release at intermediate and long terms is important.

Keywords: Macronutrient reserves; Release kinetics; Eucalypt nutrition.

Resumo

A atividade florestal tem crescido de forma contínua no Brasil e, com ela, aumentam preocupações quanto a obtenção de produções sustentáveis entre empresas deste setor. Conhecimento sobre as reservas minerais e a cinética de liberação de nutrientes pode otimizar o manejo da fertilidade, melhorando a produtividade. Os objetivos deste trabalho foram analisar os teores de K, Ca e Mg nos compartimentos de reserva, não-trocáveis, trocáveis e disponíveis, assim como a velocidade de liberação de nutrientes e suas correlações e efeitos na produtividade de eucalipto. Amostras de solo foram coletadas de sítios cultivados com eucalipto no estado do Rio Grande do Sul, Brasil, perfazendo 7 classes de solo. Os teores de K, Ca e Mg foram determinados em extrato de digestão sulfúrica, em ácido nítrico fervente, em cloreto de amônio, em Mehlich-1 e cloreto de potássio. A cinética de liberação de nutrientes foi determinada conforme Sparks (1989) e o incremento médio anual de madeira (IMA) volumétrico de eucalipto foi fornecido pela CMPC Celulose Riograndense. Os teores de K, Ca e Mg variaram entre compartimentos e profundidades e se concentraram no compartimento de reserva, indicando a importância deste para o fornecimento de nutrientes em médio e longo prazo. A maioria dos compartimentos

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apresentaram correlação significativa e o IMA correlacionou-se significativamente com diferentes compartimentos e profundidades, especialmente com o compartimento de reserva e a cinética de liberação, evidenciando suas relevâncias para a produtividade, especialmente para espécies de ciclo longo, para as quais a liberação de nutrientes em médio e longo prazo tornam-se importantes.

Palavras-chave: Reservas de macronutrientes; Cinética de liberação; Nutrição de eucalipto.

INTRODUCTION

Forestry is growing continuously across Brazil and is responsible for supplying new job opportunities, driving the economy on many fronts of the productive chain. Presently, planted forest areas occupy over 7.7 million hectares, corresponding to 0.9% of the Brazilian territory, and supplying 91% of the country's wood demands for industrial purposes (Indústria Brasileira de Árvores, 2015). According to the prospects of growth and expansion, forestry companies face the challenge of achieving long-term continuous productivity in economically viable manners while minimizing the impact upon the environment, especially when it comes to adequate soil use.

Given its multitude of uses and its fast-growing nature, eucalypt plantations represent the majority of planted forests in Brazil, occupying around 5.6 million hectares (Indústria Brasileira de Árvores, 2015). Such scenario amplifies the concerns about forest cultivation, as eucalypt plantations demand high quantities of nutrients in the course of its cycles, especially K, Ca and Mg (Andrade et al., 2011). Santana et al. (2008) observed that to produce 100 tons of biomass, eucalypt trees require an average of 154 kg of K, 270 kg of Ca and 55 kg of Mg, with peak demands prior to 4.5 years of growth, due to plants' high needs of these nutrients in order to form the canopy (Schumacher & Caldeira, 2001).

Supplying K, Ca and Mg adequately to eucalypt plantations via the addition of fertilizers and mineral amendments in order to promote a sustainable management demands an understanding about nutrient dynamics within soils. Thus, considering that plant demands for K, Ca and Mg can be partially provided by the soils' mineral compartments (Alves et al., 2013), the assessment of soil capacity to release such nutrients could be important to improve forest plantation management. K, Ca and Mg contained in mineral reserve compartments indicate the soil potential to deliver these nutrients to plants (Castilhos & Meurer, 2002): non-exchangeable compartments contribute to mid-term plant nutrition, especially after successive rotations (Kaminski et al., 2007; Werle et al., 2008), while exchangeable and available compartments signify immediate availability of these nutrients to plants. (Fraga et al., 2009; Kaminski et al., 2007). Consequently, eucalypt productivity is directly related to how fast these nutrients are released from its compartments (Amaral et al., 2015).

Several studies analyzed the contents of K, Ca and Mg contained in soils' reserve, exchangeable and non-exchangeable compartments (Castro et al., 2010; Marchi et al., 2012; Reatto et al., 1998; Silva et al., 2000; Staugaitis & Rutkauskienė, 2010; Villa et al., 2004). It was found that contents vary based on parent material, mineralogy, soil development stage and soil depth (Alves et al., 2013; Castro et al., 2010; Martins et al., 2004; Melo et al., 2000, 2003). Variation of K, Ca and Mg contents between compartments, as well as their release speeds and their relationship with eucalypt productivity indicate soil capacity to deliver these nutrients to plants.

This study has the objective of assessing K, Ca and Mg contents within reserve, non-exchangeable, exchangeable and available compartments; its nutrient release speeds and the correlation between these compartments and the eucalypt plantation productivity (wood annual average increment – AAI) in sites located in Rio Grande do Sul state, Brazil.

MATERIAL AND METHODS

Soil samples were obtained in areas commercially cultivated with *Eucalyptus* sp., located in the geomorphologic regions of the Peripheral Depression, Sul-Riograndense shield and Coastal Plain of Rio Grande do Sul, belonging to Celulose Riograndense Ltda – CMPC. According to the Köppen classification system (Köppen, 1931), the climate in the region is predominantly Cfa, characterized by warm, dry summers and cold, wet winters and with mean annual rainfall of 1,500 mm, evenly distributed along the year (Fundação Estadual de Pesquisa Agropecuária do Rio Grande do Sul, 2012). The vegetation found in the region comprises subtropical forests, pastures, annual cultures and planted forests. Collected soil samples derive from seven distinct soil classes (Table 1), classified by

the third categorical level according to the Brazilian Soil Classification System (Empresa Brasileira de Pesquisa Agropecuária, 2013).

Table 1. Abbreviations and geographic coordinates of soils classified by the third categorical level according to the Brazilian Soil Classification System (Empresa Brasileira de Pesquisa Agropecuária, 2013) collected at depths 0 – 0.20 and 0.20 – 0.40 m in areas cultivated with eucalypt at the state of Rio Grande do Sul, Brazil.

Soil Classification	Abbreviation	Coordinates
Dystrophic Red Argisol	PVd	30°04'16,71"S ¹ – 51°45'47,72"W ²
Dystrophic Red-Yellow Argisol	PVAd	30°03'28,53"S – 51°46'10,27"W
Dystrophic Yellow Argisol	PAd	30°03'28,53"S – 51°45'40,00"W
Eutrophic Haplic Cambisol	CXve	30°30'59,07"S – 54°02'35,28"W
Dystrophic Regolitic Neosol	RRd	30°31'22,41"S – 54°03'46,11"W
Orthic Argiluvic Chernosol	MTo	30°32'40,81"S – 54°02'34,67"W
Orthic Quartzarenic Neosol	RQo	30°24'00,00"S – 51°08'21,00"W

¹ = Latitude South; ² = Longitude West. ¹ = Latitude Sul; ² = Longitude Oeste.

Sampling was done in trenches across each soil class profile, from where samples were collected in depths of 0.00-0.20 and 0.20-0.40 m. Samples were air dried and passed through a 2 mm sieve to obtain air-dried fine earth – ADFE. For each soil class, one aliquot was separated for attribute characterization and particle size analysis (Table 2).

Table 2. Chemical properties, exchangeable Ca/Mg ratios and particle size analyses in soils collected at depths of 0-2.0 and 0.20-0.40 m in areas cultivated with eucalypt at the state of Rio Grande do Sul, Brazil.

Proprieties	Units	Soil classes						
		PVd	PVAd	PAd	CXve	RRd	MTo	RQo
----- 0 – 0.20 m -----								
pH	-	5.5	5.5	5.2	5.3	5.1	5.7	5.8
K	mg dm ⁻³	119.7	43.3	39.3	95.7	139.1	122.8	40.5
P	mg dm ⁻³	44.4	61.9	46.9	32.8	70.9	48.3	100.1
Ca	cmolc dm ⁻³	1.9	0.9	1.3	3.3	0.7	4.3	0.6
Mg	cmolc dm ⁻³	0.7	0.6	0.6	4.0	0.5	1.6	0.2
SB	cmolc dm ⁻³	5.1	3.1	2.9	6.2	1.9	10.9	1.0
T	cmolc dm ⁻³	9.1	5.4	8.2	9.4	6.3	17.3	2.6
Ca/Mg	-	2.7	3.5	1.4	2.3	4.5	5.0	5.0
V	%	55.6	57.1	39.8	65.6	29.4	63.3	37.9
SOM	%	2.4	1.6	2	3.1	1.5	2.4	0.8
Clay	%	20	23	26	27	12	21	3.0
Silt	%	18	7	26	22	12	20	3.0
Sand	%	62	70	48	51	76	59	94
K-RK	mg kg ⁻¹ h ⁻¹	5.7	7.1	2.6	8.5	5.7	10.3	2.1
Ca-RK	mg kg ⁻¹ h ⁻¹	5.7	1.3	1.5	2.2	0.7	4.4	1.2
Mg-RK	mg kg ⁻¹ h ⁻¹	6.6	1.3	0.9	1.3	0.7	5.3	1.9
----- 0.20 – 0.40 m -----								
pH	-	5.8	5.7	4.9	5.9	5.3	5.4	4.9
K	mg dm ⁻³	49.1	34.8	27.2	52	118.9	98.7	35.4
P	mg dm ⁻³	52.9	62.5	58.6	60.6	79.7	53.1	93.2
Ca	cmolc dm ⁻³	0.3	0.8	0.3	2.1	0.6	3.3	0.1
Mg	cmolc dm ⁻³	0.2	0.4	0.3	3.7	0.4	0.8	0.2
SB	cmolc dm ⁻³	1.3	1.3	0.8	5.3	1.4	9.7	0.4
T	cmolc dm ⁻³	13.2	6.1	9.9	10.2	4.5	18.4	1.8
Ca/Mg	-	4.8	2.7	3.5	1.4	2.3	4.5	5.0
V	%	13.2	22.1	7.7	52.4	31.9	52.9	22.5
SOM	%	1.6	1.2	1.2	1.6	1.6	1.6	0.3
Clay	%	23	22	26	27	15	18	3
Silt	%	20	10	29	29	13	22	3
Sand	%	57	68	45	44	72	60	94
K-RK	mg kg ⁻¹ h ⁻¹	5.8	7.9	3.6	8.0	5.4	12.0	2.1
Ca-RK	mg kg ⁻¹ h ⁻¹	1.8	0.5	0.8	2.2	0.6	4.7	0.7
Mg-RK	mg kg ⁻¹ h ⁻¹	2.3	2.1	0.5	1.4	0.5	7.2	0.1

pH: measured in water at a soil/solution ratio of 1:2.5; K⁺: available potassium in Mehlich-1; exchangeable Ca and Mg in potassium chloride (KCl 1.0 mol L⁻¹); SB: sum of bases; T: cation exchange capacity at pH 7.0; V: base saturation; SOM: soil organic matter (oxidation in sodium dichromate, described by Walkley & Black, 1934); RK: release kinetic. K-RK, Ca-RK and Mg-RK determined per Sparks (1989) and obtained from Amaral et al. (2015).

Clay aliquots of samples from both depths and each soil class were submitted to X-ray diffractometry – XRD analysis (Figure 1) – by the powder method. The equipment used for this XRD analysis was the Rigaku Miniflex II system, Cuka radiation, operated at 30 kV and 15mA with Ni filter and graphite monochromatic. XRD analysis was performed at the soil mineralogy laboratory of the soil science department of the Luiz de Queiroz College of Agriculture (ESALQ - USP).

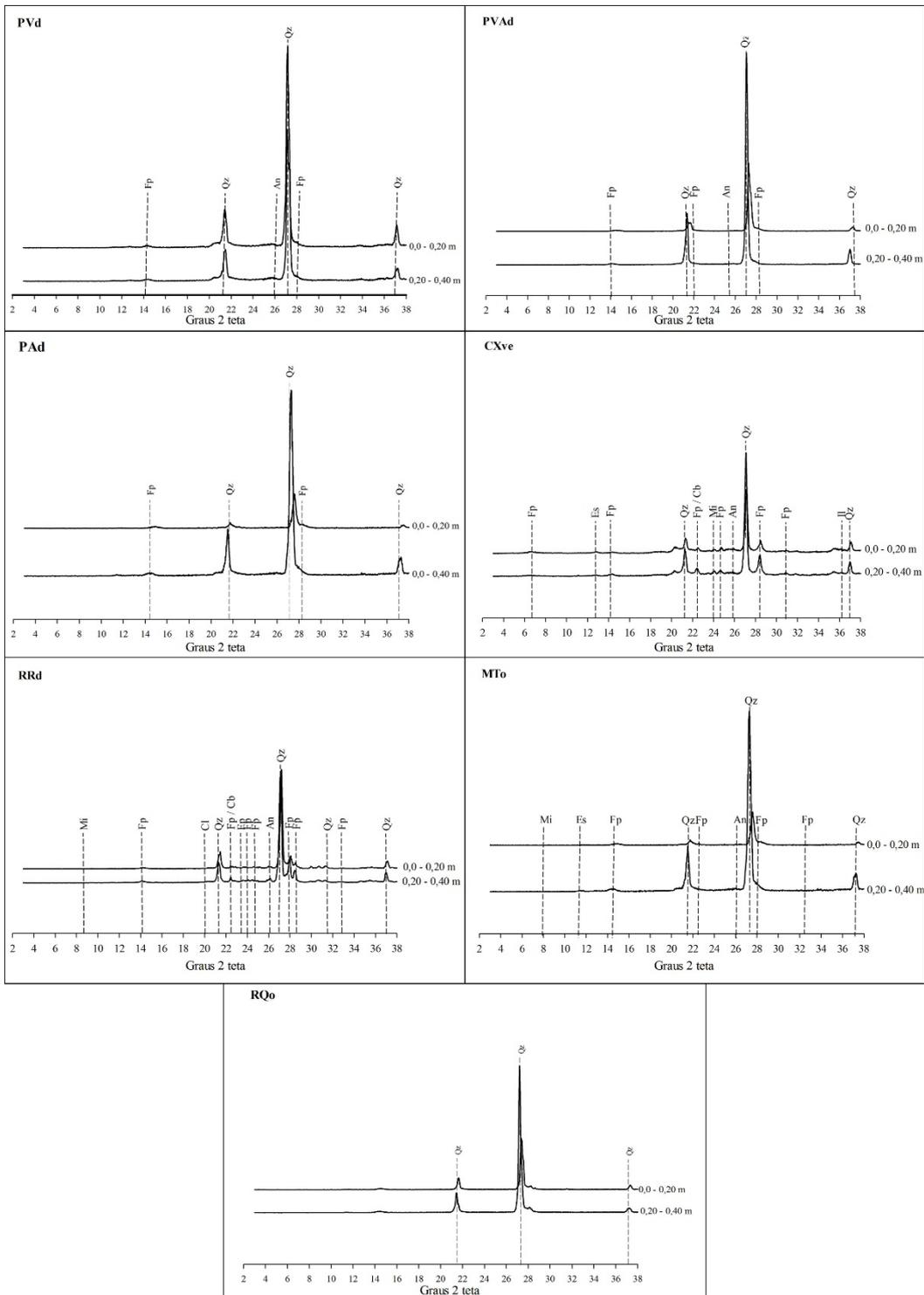


Figure 1. Powder X-ray diffractograms (XRD) from clay of all seven studied soil classes (PVd, PVAd, PAd, CXve, RRd, MTo e RQo) in both depths (0.0 – 0.20 and 0.20 – 0.40 m). Mi – mica, Qz – quartz, An – anatase, Fp – feldspar, Cb – cristobalite, Il – ilmenite and Es – smectite.

Contents of K, Ca and Mg in the reserve compartments (R) were obtained by sulfuric digestion, according to Vettori (1969), as described per Embrapa (Empresa Brasileira de Pesquisa Agropecuária, 1997). For extraction, 1 g of ADFE was transferred to a 500 ml Erlenmeyer, 20 ml of sulfuric acid diluted in 1:1 ratio was added and the solution boiled for 30 minutes. After cooling, 50 ml of distilled water were added before the suspensions were filtered to a 250 ml volumetric balloon, washing the residues until the volume was completed.

Non-exchangeable contents for K (K-NE), Ca (Ca-NE) and Mg (Mg-NE) were obtained per the difference between the contents determined in boiled nitric acid (HNO₃) and contents determined in ammonium chloride, since HNO₃ extracts non-exchangeable forms (Helmeke & Sparks, 1996), whilst ammonium chloride extracts the exchangeable forms of these nutrients (Rajj et al., 2001).

Determination in boiling HNO₃ was realized as described by Knudsen et al. (1982), initially transferring 1 g of soil to a 50 ml Erlenmeyer, adding 3 ml of HNO₃ at 1 mol L⁻¹ concentration and heated in sand to 113 °C, boiled during 25 min. The extract was passed through a slow filtering paper into a 50 ml volumetric balloon and the residue was washed with 4 ml of 0.1 mol L⁻¹ nitric acid. After the filtering process the balloon's volume was completed.

The contents for available K (K-A) and exchangeable Ca (Ca-E) and Mg (Mg-E) were obtained per Coscione et al. (2001). Initially 5 cm³ of ADFE were added into plastic flasks and 50 ml of ammonium chloride solution at the concentration of 1 mol L⁻¹ was added. Flasks were sealed and agitated for 5 minutes at 220 rpm. Afterwards, flasks rested for 12 h for decantation. On the following day aliquots from the supernatant were collected for analysis.

For the extraction of available K (K-A), analytical procedures described by Embrapa (Empresa Brasileira de Pesquisa Agropecuária, 2009) were applied. Initially 10 cm³ of ADFE were inserted into a 125 ml Erlenmeyer and 100 ml of Mehlich-1 (HCl 0.05 mol L⁻¹ + H₂SO₄ 0.0125 mol L⁻¹) solution was added. After agitating the solution in a circular horizontal agitator for 5 min, the Erlenmeyer rested for 12 h for decantation. After this process, an aliquot of approximately 20 ml of the extract was collected for analysis. The extractions of exchangeable Ca and Mg were also detailed by Embrapa (Empresa Brasileira de Pesquisa Agropecuária, 2009). Initially 10 cm³ of ADFE were inserted into a 125 ml Erlenmeyer with the addition of 100 ml of 1 mol L⁻¹ KCl solution. Next, samples were agitated in a circular horizontal agitator for 5 minutes and rested for 12 h for decantation. On the next day an aliquot of the extract was collected for analysis.

Release kinetics for K (K-RK), Ca (Ca-RK) and Mg (Mg-RK) were obtained according to Sparks (1989). In 50 ml centrifuge tubes, 3 g of ADFE were added with 30 ml of citric acid (0.01 mol L⁻¹). Samples rested during the equilibrium times: 2; 8; 20; 55; 90; 148; 245; 403; 655; 1,096 and 1,808 hours. After each equilibrium time was reached the samples were centrifuged at 3,200 g during 15 minutes and the supernatant was collected.

The contents of Ca and Mg were measured separately in the supernatant by atomic absorption spectrometry and the contents of K were determined with flame photometry. Estimations for release kinetics were done per the mathematical equations applying the zero order, first order models, from Elovich, and the parabolic diffusion, detailed in Sparks (1989).

Contents for K were determined directly through the supernatant obtained posterior to the extractions and were quantified in a flame photometer (Pratt & Morse, 1954). The determination of the contents for Ca and Mg were made through the obtained extracts, by initially pipetting 1 ml of the extract into a 25 ml flask, to which 10 ml of lanthanum prepared at a 1 g L⁻¹ concentration was added. Analyses were made in an atomic absorption spectrophotometer, with a flame atomizer.

Mean values of wood volumetric AAI for *Eucalyptus* sp. were provided by the CMPC Celulose Riograndense (Table 3) and were calculated from five portions of each forest site containing one of the studied soils classes (Table 1). The spacing between plants in all portion were of 3 m between each tree and 3 m between each plantation line. AAI is the measure that represents the mean total growth of a tree to a determined age and can be calculated as described per Reatto et al. (1998).

The data descriptive analysis was performed using the R software (R Core Team, 2019). Additionally, variables were submitted to the correlation and principal component analysis (PCA).

Table 3. Means and standard deviation of the volumetric wood annual average increment (AAI) of *Eucalyptus* sp. estimated for 7 years-old plants in soils of the state of Rio Grande do Sul, Brazil (data provided by the CMPC Celulose Riograndense).

Soils	Mean AAI (m ³ ha ⁻¹ year ⁻¹)	Standard deviation
PVd	47.68	0.68
PVAd	46.30	0.43
PAd	43.10	0.55
CXve	44.11	0.52
RRd	50.56	1.84
MTo	53.70	1.55
RQo	31.99	0.01

Means calculated from five repetitions.

RESULTS AND DISCUSSION

Highest contents of K, Ca and Mg were observed in soils CXve, RRd and MTo (Table 4). This is a consequence of the presence of mineral sources of these nutrients, especially feldspars, micas and smectites (Figure 1). These minerals tend to remain preserved in soil sand and silt (Bortoluzzi et al., 2005). Several studies have also observed highest contents of these nutrients in the reserve compartments (Castro et al., 2010; Marchi et al., 2012; Reatto et al., 1998; Silva et al., 2000; Staugaitis & Rutkauskienė, 2010; Villa et al., 2004). However, it is important to notice that the proportion between such compartments vary, especially depending on parent material, soil development degree and depth (Alves et al., 2013; Castro et al., 2010; Martins et al., 2004; Melo et al., 2000, 2003), and mineralogy (Figure 1).

Table 4. Mean, standard deviation (SD) and range of: reserve compartments (R), non-exchangeable compartments (NE), exchangeable compartments (E) and available compartments (A) in soils collected at depths of 0-0.20 and 0.20-0.40 m in areas cultivated with eucalypt in the state of Rio Grande do Sul, Brazil.

	CXve			MTo			PAd			PVAd		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
----- 0-0.20 m -----												
K-R	4339.56	6.13	15.69	4087.61	11.10	27.17	884.75	12.17	31.38	1133.20	5.99	15.69
K-NE	70.43	2.93	6.68	108.01	2.85	7.30	19.40	3.40	7.16	12.68	1.14	2.44
K-A	95.76	1.91	4.70	122.88	3.15	6.30	39.30	0.92	2.10	43.26	1.15	2.10
Ca-R	1359.42	132.62	360.72	1619.38	2.99	8.39	462.34	14.52	40.08	478.98	20.65	41.00
Ca-NE	415.02	20.28	52.99	26.12	14.98	37.04	105.93	25.57	64.25	143.20	7.82	21.25
Ca-E	670.58	1.51	3.13	868.35	10.23	26.76	264.57	0.52	1.10	180.90	2.13	4.29
Mg-R	992.27	11.85	28.09	2416.40	14.32	38.99	143.35	3.20	7.54	271.73	10.30	24.89
Mg-NE	380.69	24.70	67.00	95.78	12.46	33.50	16.78	3.30	7.95	57.39	10.23	27.07
Mg-E	483.26	5.89	15.92	191.57	5.27	12.16	74.76	2.52	5.06	67.70	2.08	5.00
----- 0.21-0.40 m -----												
K-R	2623.86	12.18	31.38	6782.52	5.43	13.27	1275.14	11.98	31.38	917.96	3.94	11.02
K-NE	67.97	3.76	9.26	105.39	4.23	11.36	15.42	0.91	2.10	22.52	1.85	4.40
K-A	52.08	2.74	6.30	98.76	2.58	6.30	34.86	1.15	2.10	27.24	1.49	4.20
Ca-R	1205.25	17.10	48.12	1744.23	446.84	1008.51	284.14	8.69	19.75	263.95	5.58	14.75
Ca-NE	629.92	28.34	71.42	241.93	55.82	153.28	9.13	4.12	10.91	31.59	2.83	6.35
Ca-E	421.38	2.09	5.78	659.75	15.56	42.00	65.77	3.67	8.94	167.17	2.25	4.79
Mg-R	1068.23	10.40	23.63	5164.04	11.98	33.79	253.89	4.04	11.32	91.55	5.16	13.06
Mg-NE	44.56	10.77	23.11	67.49	8.56	21.16	14.05	6.85	17.62	24.93	2.70	7.00
Mg-E	453.57	8.23	16.93	93.16	4.97	12.16	48.10	1.17	2.62	36.47	0.00	0.00
----- 0-0.20 m -----												
PVd			RQo			RRd						
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range			
K-R	1826.29	13.14	27.17	754.35	0.00	0.00	2826.94	7.18	18.11			
K-NE	15.97	5.63	10.44	67.71	2.87	7.04	88.64	4.72	11.80			
K-A	119.70	0.00	0.00	40.48	0.00	0.00	139.10	4.03	10.50			
Ca-R	811.50	17.04	40.08	181.29	7.46	20.15	324.97	9.84	27.63			
Ca-NE	230.88	19.45	51.75	25.11	3.40	8.32	33.08	7.39	18.24			
Ca-E	387.32	1.46	3.13	121.03	1.66	3.76	149.93	3.56	7.60			
Mg-R	624.25	8.87	22.69	110.92	0.72	1.56	186.27	6.03	16.85			
Mg-NE	16.45	4.78	12.35	9.84	1.95	5.25	70.90	8.55	21.91			
Mg-E	81.27	4.20	10.00	24.31	0.00	0.00	64.30	5.03	12.16			

Table 4. Continued...

	PVd			RQo			RRd		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
	----- 0.21-0.40 m -----								
K-R	1708.23	3.62	8.86	616.20	2.71	6.63	2479.23	13.01	27.18
K-NE	37.07	2.70	6.28	4.51	0.28	0.67	61.34	1.89	4.60
K-A	49.14	2.39	6.30	35.42	0.00	0.00	118.92	3.53	8.40
Ca-R	156.21	0.75	1.80	106.15	6.49	16.25	272.00	8.54	24.00
Ca-NE	54.78	5.23	13.37	73.25	1.24	3.03	39.22	8.82	22.92
Ca-E	58.07	0.95	1.95	20.78	1.28	2.96	127.58	1.49	3.16
Mg-R	451.91	5.52	15.57	69.39	2.90	6.65	302.65	2.95	7.50
Mg-NE	14.43	2.01	5.56	3.57	0.56	1.50	42.40	3.42	7.37
Mg-E	24.31	0.00	0.00	24.31	0.00	0.00	48.30	0.72	1.62

Every K, Ca and Mg compartment is relevant for plant mineral nutrition (Han et al., 2019; Gurav et al., 2018; Wang et al., 2016). The reserve compartments (K-R, Ca-R and Mg-R) represent the long-term reservoirs of these nutrients, made available as physical and chemical alterations take place within minerals contained in the soils. This compartment may indicate the potential capacity of a soil to release these nutrients to plants over long-term periods (Castilhos & Meurer, 2002). Available K compartments (K-A) and exchangeable Ca (Ca-E) and Mg (Mg-E) can be described as the fractions connected electrostatically to the negative charges of the organic and inorganic colloids in soils (Ernani et al., 2007). Nutrients in exchangeable and available compartments are easily available to plants and therefore important for the short-term nutrient supply. The compartment K-A, however, is not capable of supplying enough nutrients to fulfill the plants' demands in the mid- to long-term periods (Fraga et al., 2009; Kaminski et al., 2007). Finally, the non-exchangeable compartment of K, Ca and Mg works as an indicator of the soil's capacity to supply these nutrients in the mid-term periods, contributing to plant nutrition after successive cultivations (Kaminski et al., 2007; Werle et al., 2008).

The percentage of K varied between analyzed soils and compartments (Figures 2A and B), with their highest values observed in compartment K-R within both depths. The remaining compartments, in both depths, represented less than 10% of K reserves in all soils, which presented the following decreasing order: %K-A > %K-NE.

The predominance of K in K-R compartment might be related to the structural forms of these nutrients in the soils; given that these forms tend to be preserved in environments where soils are less liable to weathering. According to Sparks (2000), roughly 98% of total K in soils is associated with primary and secondary mineral structures. In fact, in the studied region the climate factor does not affect soil development intensely.

The percentage of Ca varies between studied soils and compartments (Figure 2C and D), with the highest values found in the Ca-R compartments in both studied depths. With the exception of soils RQo and CXve in the depth 0.20-0.40 m, the mean decreasing order of the remaining Ca compartments were: %Ca-E > %Ca-NE in both depths. In all soils, Ca-E compartments represent approximately 50% in the depth of 0.00-0.20 m and 30% in 0.20-0.40 m, relatively to Ca-R.

Mg percentage varied between compartments and soils, showing highest values in compartments Mg-R, in both studied depths (Figure 2E and F). The remaining compartments presented decreasing percentage means following the order: %Mg-E > %Mg-NE in both studied depths. The occurrence of high values for K-R, Ca-R and Mg-R in these compartments is evidence that a significant percentage of these nutrients are associated with feldspar and micaceous minerals (Figure 1), which dissolve when subjected to acid digestion (Melo et al., 2009), releasing considerable amounts of these nutrients in the solution.

Nutrient release rates are higher in topsoil than in subsoil (Table 2), an expected result, since shallower horizons are more liable to weathering when compared to deeper horizons. PVd shows high release rates in topsoil compared to other soil classes, although AAI is not distinctively higher, which may signify that the application of fertilizers in the same amount as other soils might be unnecessary.

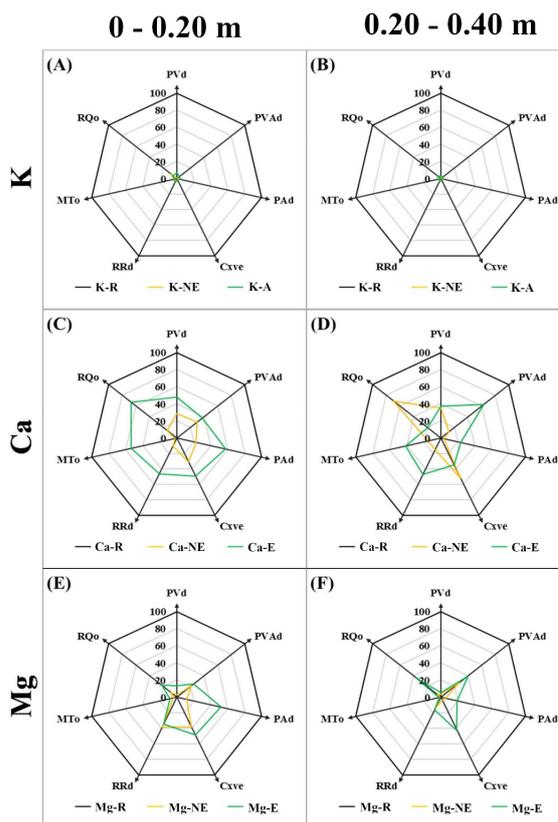


Figure 2. Percentage of K (A and B), Ca (C and D) and Mg (E and F) in: reserve compartments (K-R, Ca-R and Mg-R), non-exchangeable compartments (K-NE, Ca-NE and Mg-NE), exchangeable compartments (Ca-E and Mg-E) and available compartments (K-A) in soils collected at depths of 0-0.20 and 0.20-0.40 m in areas cultivated with eucalypt at the state of Rio Grande do Sul, Brazil.

Observing the similarity dendrogram, obtained per cluster analysis, nine similarity groups were formed for variables at depth 0.00-0.20 m (Figure 3A) and five groups for variables studied at depth 0.20-0.40 m (Figure 3B). The formation of a larger number of groups at shallower depths indicates the existence of greater variability in the superficial layers of the analyzed soils.

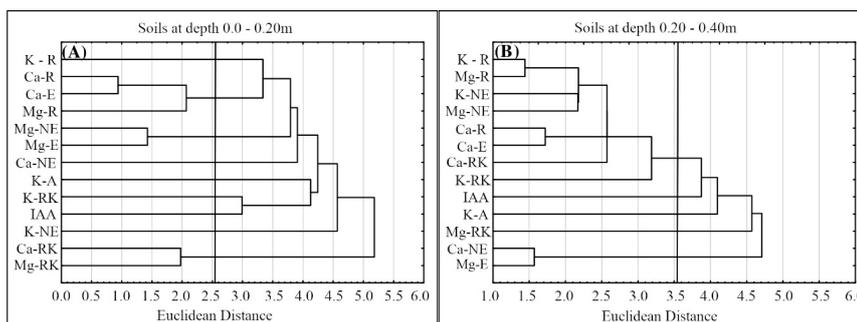


Figure 3. Similarity dendrograms for K, Ca and Mg contents in: reserve compartments (K-R, Ca-R and Mg-R), non-exchangeable compartments (K-NE, Ca-NE and Mg-NE), exchangeable compartments (Ca-E and Mg-E) and available compartments (K-A) in soils collected at depths 0-0.20 (A) and 0.20-0.40 m (B) in areas cultivated with eucalypt at the state of Rio Grande do Sul, Brazil.

The presence of Ca-R and Mg-R compartments in the same similarity group at 0.00-0.20 m and K-R and Mg-R at 0.20-0.40 m (Figure 3B) is evidence that the content of these nutrients found in the respective depths is similar in studied soils. The absence of K-RK

within the similarity group composed by Ca-RK and Mg-RK at 0.00-0.20 m demonstrates that Ca and Mg release by soil mineral reserves occurs at speeds that differ from those observed for K. Ca-RK and Mg-RK in both depths show less similarity to AAI than K-RK, an indication that plant development might be more sensitive to alterations in K release dynamics than that of Ca and Mg. This might be explained in the K compartment by the observed relations (Figures 2A and B): K-A and K-NE represent less than 10% in relation to K-R, which means the K mechanisms of release play an important role in providing this nutrient to plants. This matches with observed release kinetic results (Table 2), since soils with low AAI (Table 3) show lower K-RK, although Ca-RK and Mg-RK show similar values.

Fatemi (2017) observed that K release varies depending on fertilizer application. Further studies of how nutrient release kinetics varies in soils in tandem with the effect of each fertilizer upon nutrient liberation mechanisms are advised, as they should help to understand the adequate fertilizer application needs in each situation.

Considering that the highest percentage of K, Ca and Mg contents are found in the reserve compartments (Figure 2), it can be inferred that soils possess potential to furnish these nutrients to plants in the long-term, implying the importance of understanding the mechanisms through which these nutrients are made available. Previous studies involving these same soils and depths confirmed the presence of higher K, Ca and Mg percentages associated with the reserve compartments (Castro et al., 2010), which was strongly correlated with the AAI of seven years-old Eucalyptus trees (Amaral et al., 2015). Similarly, this leads to infer that soils with lower nutrient reserves might be more dependent on fertilizers to maintain AAI, as is the case of RQo (Tables 2 and 3), which shows low mean AAI compared to the remaining studied soils.

Moterle et al. (2016) observed that highly weathered soils can also significantly furnish K to crops, despite their known lack of 2:1 minerals. However, they found that under low K content conditions, plant growth may affect clay mineralogy and alter K contents stored in the different compartments, especially non-exchangeable K, possibly compromising a sustained productivity. Besides, under poor K conditions, release kinetics might not be able to supply enough nutrients for crops. Therefore, nutrient release dynamics should be understood to preserve soil capacity in order to provide nutrient sustainably.

Many authors have studied nutrient release from eucalypt residues (Ferreira et al., 2016; Turner; Lambert, 2016), like bark and litterfall, but little is known about how successive rotations affect mineral release kinetics. McMahon et al. (2019) observed an increase tendency in soils stocks of Ca and K after multiple eucalypt rotations, but it is unknown how this tendency affects nutrient release rates. This study indicates the connection of mineral nutrient reserves in different compartments and release kinetics with productivity; thus, further study of their variations through multiple eucalypt rotations is advised.

The principal component analysis for K, Ca, Mg and for soil classes shows that components PC1 and PC2 explain 75.5% of the total variance in soils at 0.00-0.20 m depth (Figure 4A and B) and 84.87% of the total variance in soils at 0.20-0.40 m depth (Figure 4C and D).

The superposition of variables Ca-RK and Mg-RK and variables Ca-R and Ca-E in both depths (Figures 4A and B) is evidence that they hold the same graphical representation, which can be confirmed by the Cluster analysis, where they depict a significant similarity by having the same Euclidian distances (Figures 3A and B). In both analyzed depths (Figures 4A and C), variables K-R, Ca-R, Mg-R and Mg-E are found close to the unitary circle; this is an indication of their expressive contribution to explain the variation in K, Ca and Mg compartments within the studied soils.

Table 5. Pearson correlation coefficients for: reserve compartments (K-R, Ca-R and Mg-R), non-exchangeable compartments (K-NE, Ca-NE and Mg-NE), exchangeable compartments (Ca-E and Mg-E), available compartments (K-A), release kinetics (K-RK, Ca-RK and Mg-RK) and wood annual average increment (AAI) in soils collected at depths 0-0.20 and 0.20-0.40 m in areas cultivated with eucalypt at the state of Rio Grande do Sul, Brazil.

Correlation Matrix	K-R	K-NE	K-A	K-RK	AAI
	K compartments				
----- 0 - 0.20 m -----					
K-R	0.81**	0.69**	0.72**	0.61**	0.60**
K-NE			0.54**	0.45**	0.26 ^{ns}
K-A				0.62**	0.73**
K-RK					0.88**
----- 0.20 - 0.40 m -----					
K-R	0.86**	0.93**	0.68**	0.81**	0.70**
K-NE			0.76**	0.82**	0.76**
K-A				0.66**	0.68**
K-RK					0.78**
Correlation Matrix	Ca-R	Ca-NE	Ca-E	Ca-RK	AAI
	Ca compartments				
----- 0 - 0.20 m -----					
Ca-R	0.95**	0.42*	0.99**	0.37*	0.55**
Ca-NE			0.33 ^{ns}	-0.12 ^{ns}	0.02 ^{ns}
Ca-E				0.38*	0.51*
Ca-RK					0.53*
----- 0.20 - 0.40 m -----					
Ca-R	0.90**	0.67**	0.96**	0.61**	0.47**
Ca-NE			0.65**	0.01 ^{ns}	0.08 ^{ns}
Ca-E				0.65**	0.56**
Ca-RK					0.67**
Correlation Matrix	Mg-R	Mg-NE	Mg-E	Mg-RK	AAI
	Mg compartments				
----- 0 - 0.20 m -----					
Mg-R	0.37*	0.33 ^{ns}	0.46**	0.51**	0.57**
Mg-NE			0.97**	-0.29 ^{ns}	0.14 ^{ns}
Mg-E				-0.15 ^{ns}	0.18 ^{ns}
Mg-RK					0.39*
----- 0.20 - 0.40 m -----					
Mg-R	0.24 ^{ns}	0.78**	0.14 ^{ns}	0.68**	0.56**
Mg-NE			0.40*	0.64**	0.76**
Mg-E				-0.13 ^{ns}	0.04 ^{ns}
Mg-RK					0.70**

K-A: available potassium in Mehlich-1; Ca-E and Mg-E: exchangeable Ca and Mg in potassium chloride (KCl 1.0 mol L⁻¹); K-NE: non-exchangeable potassium in nitric acid (HNO₃ 1.0 mol L⁻¹); K-R, Ca-R and Mg-R: K, Ca and Mg in the reserve compartment by sulfuric acid digestion (Vettori, 1969); K-RK, Ca-RK and Mg-RK: K, Ca and Mg obtained with citric acid (Sparks, 1989); ns (not significant); * and ** (significant at 5 and 1% probability, respectively).

Higher correlation coefficients between K-R, Ca-R, Mg-R and AAI (Table 5) indicate that part of plantations' demands for these nutrients are coming from these reserves, especially until 4.5 years of age, when plants' demands for K, Ca and Mg are higher (Santana et al., 2008). After this period, nutrient cycling by plant litter assumes great importance for plant nutrient supply (Cunha et al., 2005; Turner & Lambert, 2016).

Although exchangeable and non-exchangeable compartments correlations with AAI (Table 5) achieved non-significant values in some cases, e.g. Ca-NE and Mg-E, most AAI correlations with reserve compartments and release kinetics were higher than 0.5, sometimes reaching or surpassing 0.7 (K-RK and Mg-RK). This shows the influence in plant development of nutrients that are not readily available and their respective release dynamics. Additionally, AAI correlation with K-R is significantly lower than with K-RK in the topsoil (0.60 and 0.88, respectively), showing the important role of the release mechanisms of these nutrients to achieve better productivity. Therefore, in accordance with Moterle et al. (2016), a sustainable fertility management should account for the preexisting reserves and their release processes to preserve sustained high productivity without affecting the soil.

CONCLUSIONS

Knowledge about the variability of mineral reserves and the release kinetics for K, Ca and Mg in different soil classes and depths may prove to be an important auxiliary tool to adequate fertilization, helping in the balance of nutrients in soils destined to forest plantations, in which the yields demand longer times to be reached.

Contents of K, Ca and Mg vary between compartments and depth in the studied soil classes. Higher concentrations of these nutrients are found within the reserve compartment, indicating its importance as a nutrient supplier to plants in mid- and long-term periods.

Nutrient release rates are closely related to soil nutrient compartments. Nutrients found in higher contents in reserve compartments, as happens with K, show higher release rates. Mg and Ca release rates were overall lower compared to K. Nutrient release happens more intensely in topsoil, where weathering is more intense.

Eucalypt wood productivity (AAI) correlates positively and significantly with K, Ca and Mg contents present in the different compartments. Correlation is higher with the reserve compartment and the release kinetics, showing their importance for planted trees' productivity, especially to plant species with longer growth cycles, for which mid- and long-term nutrient release is important.

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