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Nutrient-use efficiency of *Eucalyptus* genotypes grown in Luvisol

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ABSTRACT

Superior productivity of genotypes in forest plantations depends on the supply, capture and use-efficiency of resources. In this context, knowledge regarding the nutritional efficiency of *Eucalyptus* influences farmers and researchers in decision-making and in the management of forest ecosystems. The aim of this research was to estimate nutrient-use efficiency in *Eucalyptus* genotypes planted in the state of Rio Grande do Sul, Brazil. We evaluated six potential genotypes at 43-month-old stands. Nutrient-use efficiency was calculated using the ratio of biomass and the amount of nutrients for each component of the biomass. Results here presented confirmed that there is synergism and antagonism between nutrients at the shoot level in the *Eucalyptus* genotypes. For stemwood, *E. saligna* showed the best utilization efficiency of N, P, K, S, and Mn; and *E. urophylla* × *E. globulus* for Mg, B, and Zn. Metabolic pathways control the production of biomass synthesized by each genotype and the differences between genotypes groups were on the basis of their nutrient-use efficiency in the biomass components. Stemwood was the component that showed the highest nutrient-use efficiency, while leaves presented the lowest nutrient-use efficiency. Additionally, our analyses identified how different each *Eucalyptus* genotype is and these traits may be used for clone allocation according to soil fertility.

Keywords: *Eucalyptus* clones, nutritional efficiency, sustainability.

Eficiência de utilização de nutrientes de genótipos de *Eucalyptus* implantados em um Luvissolo

RESUMO

A produtividade de genótipos superiores em plantações florestais está em função da oferta, captura e eficiência de uso dos recursos. Nesse contexto, o conhecimento sobre a eficiência nutricional do *Eucalyptus* influencia agricultores e pesquisadores na tomada de decisões e no manejo de ecossistemas florestais. A pesquisa teve como objetivo estimar a eficiência no uso de nutrientes em genótipos de *Eucalyptus* plantados no Estado do Rio Grande do Sul, Brasil. Foram avaliados seis genótipos potenciais e as avaliações foram realizadas em povoamentos de 43 meses de idade. A eficiência do uso de nutrientes foi calculada usando a razão de biomassa e a quantidade de nutrientes para cada componente da biomassa. Os resultados aqui apresentados confirmam que existe sinergismo e antagonismo entre os nutrientes no nível da parte aérea nos genótipos de *Eucalyptus*. Para a madeira do fuste, *E. saligna* apresentou a melhor eficiência de utilização de N, P, K, S e Mn; e *E. urophylla* × *E. globulus* para Mg, B e Zn. As vias metabólicas controlam a produção de biomassa sintetizada por cada genótipo e as diferenças entre os grupos de genótipos foram baseadas na eficiência do uso de nutrientes nos componentes da biomassa. A madeira do caule foi o componente que apresentou maior eficiência de uso de nutrientes, enquanto as folhas apresentaram a menor eficiência de uso de nutrientes. Mas, além disso, nossas análises identificaram o quão diferente é cada genótipo de *Eucalyptus* e essas características podem ser usadas para alocação de clones de acordo com a fertilidade do solo.

Palavras-chave: clones de *Eucalyptus*, eficiência nutricional, sustentabilidade.

1. INTRODUCTION

The wide range of *Eucalyptus* species and hybrids, their suitability to different climatic and edaphic conditions, and their ease of propagation by seeds and cloning allowed the adaptation of this genus to various tropical and subtropical regions in Brazil (Queiroz *et al.*, 2020). The possibility of using *Eucalyptus* wood for a range of purposes has led to large and small enterprises to establish *Eucalyptus* forests for multiple uses (Gonçalves *et al.*, 2013). However, the rapid growth of these forests imposes high demand on soil resources, which is reflected in their water-carrying capacity, sustainability and nutrient-use efficiency (NUE) (Bellote *et al.*, 2008).

Recently, *Eucalyptus* selection programs in Brazil started to consider NUE as a criterion for choosing superior genotypes, in addition to productivity, wood quality, tree shape, and disease resistance (Camargo *et al.*, 2004). In this context, information about the mechanisms involved in the adaptive capacity of genotypes of interest, especially in conditions of low soil fertility, can guide the agriculture (Abenavoli *et al.*, 2016) and the forestry sectors (Batista *et al.*, 2015) to select those genotypes that can efficiently utilize existing nutrients in the soil or to improve the soil via fertilization (Batista *et al*., 2015).

Optimum NUE and nutrient cycling can be achieved through the use of management techniques that conserve crop residues as much as possible on the site by carrying out the least possible anthropic interventions and by analyzing which growth cycle is long enough to allow such cycling (Santana *et al*., 2002). Planting forests with superior genotypes in relation to nutritional efficiency can guarantee the sustainability of forest production (Batista *et al.*, 2015) and the continuous success of future plantations will depend on the ability of forest managers to obtain high productivity of quality wood in an environmentally and sustainable manner (Gonçalves *et al.*, 2013). The objective of the present study was to estimate the NUE of six genotypes of *Eucalyptus* in Rio Grande do Sul and also to recommend them according to nutritional status.

2. MATERIALS AND METHODS

The research was carried out in an experimental area belonging to the Celulose Riograndense Company (CMPC) in Horto Florestal Batovi, in the municipality of São Gabriel, Rio Grande do Sul, Brazil. The area is located under the geographical coordinates of 30°26′51.68″ S, 54°32′25.89″ W. The climate, according to the Köppen climate classification, is characterized as humid subtropical (Cfa). The average annual temperature is approximately

18-20°C and the average annual precipitation reaches 1,600 mm (Alvares *et al*., 2013).

Planting was initiated in November 2012, with a spacing of 3.50 m × 2.14 m. The following *Eucalyptus* clones were planted: *E. benthamii* (P1), *E. benthamii* (P2), *E. saligna*, *E. dunnii*, hybrid of *E. urophylla* × *E. globulus* (*E. uroglobulus*), and hybrid of *E. urophylla* × *E. grandis* (*E. urograndis*). *Eucalyptus benthamii* (P1) is a provenance originating from Guarapuava, Paraná, Brazil and *E. benthamii* (P2) is from Telêmaco Borba, Paraná, Brazil. At the time of data collection, the stands were 43 months old. The soil of the experimental area is of the typical Luvisol haptic optic type. Physical and chemical attributes of the soil at depths of 0-60 cm are shown in Table 1.

For implantation of forest population, liming was performed using 2 Mg ha^{-1} of limestone, subsoiling down to 50 cm was performed, and ridges of 40 cm high were set up. During planting, 200 kg ha^{-1} of single superphosphate was applied to the groove at a rate of 100 g $plant^{-1}$ in the form of N-P_2O_5-K_2O (06:30:06) + Zn on the occasion of planting. Subsequently, two post-planting fertilizations were performed at six and twelve months in the form of 150 kg ha^{-1} of N-P_2O_5-K_2O (12:00:20) + 0.5% B and 150 kg ha^{-1} of N-P_2O_5-K_2O (24:00:26), respectively. The following cultural practices were also performed: chemical weeding, prior to planting in a total area of 2.5 kg ha^{-1} Scout (glyphosate), pre-emergent Oxyfluorfen (3.5 L ha^{-1}) treatment at 10 days after planting, and hand weeding and chemical weeding using 1.7 kg ha^{-1} of Scout (glyphosate) at 4 and 9 months after planting.

For each genotype, a plot of 599.2 m^2 was demarcated, where the DBH (diameter at breast height, measured at 1.30 m above ground level) and the heights were measured. Based on the data obtained in the plot inventory, three trees were sampled for each genotype. The selected trees were felled and separated into the components of leaves, branches, stembark and stemwood. All biomass samples were weighed in the field with a precision scale and packed in paper bags. Subsequently, they were sent to the laboratory and dried in an oven at 70°C to determine the moisture content. Based on the dry biomass of each component and the number of trees per hectare of each genotype, the total biomass per hectare was estimated (Table 2).

For the determination of nutrients, the samples were ground and subsequently subjected to chemical analysis to determine macronutrient (N, P, K, Ca, Mg, and S) and micronutrients (B, Cu, Fe, Mn, and Zn) concentrations according to the methodology of Tedesco *et al*. (1995) and Miyazawa *et al.* (1999). The estimates of the nutrient stock for each component was obtained by multiplying the dried biomass by the concentration of nutrients. The estimate per hectare was performed by extrapolating the stock per individual based on the number of individuals present in each sampling unit (Table 3). The values of nutrient utilization efficiency (NUE) were obtained according to a calculation proposed by Barros *et al* (1986) (Equation 1) using the relationship between the amount of dry biomass of each component and the amount of nutrients stored in the respective biomass.

$$NUE = \frac{(Quantity\ of\ biomass)}{(Quantity\ of\ nutrient)} \qquad (1)$$

For analysis of our data, we used the free software R Project (R Core Team, 2014). Data corresponding to the amount of nutrients in the biomass components of *Eucalyptus* genotypes (four repetitions) subjected to the same culture conditions were analyzed. These data were subjected to Pearson's correlation analyses using the 'color' function of the 'stats' package. In addition, a heatmap was used to visualize hierarchical clustering that ordered similar groups to amount of nutrients in the biomass components (leaves, branches, stembark and stemwood) taken from the UPGMA (Unweighted Pair Grouping with Arithmetic Mean) by means of the 'heatmaply' function.

Table 1. Clay and chemical attributes of the soil of the area implanted area with different genotypes *Eucalyptus* at 43-month-old in São Gabriel, RS, Brazil.

Depth	Coarse sand	Fine sand	Silt	Clay	D.F	V	m	O.C	pH	T	Al
	2-0.02mm	0.2-0.05mm	0.05-0.002mm	<0.002	%				H_2O	cmol$_c$ dm^{-3}	
0-40	9.3	14.8	57.0	19.0	82	53	24	1.65	5.0	10.5	1.7
40-60	9.9	5.8	43.6	40.8	48	65	26	0.94	5.3	21.6	4.3
60-85	4.3	3.5	73.8	18.5	25	89	5	0.51	5.8	28.9	1.0
85-110+	6.0	4.8	84.5	4.7	21	96	0	0.17	6.8	29.9	0.0
Depth	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**B**	**Zn**	**Mn**	**Cu**	**Fe**
	%	mg g^{-1}	cmol$_c$ dm^{-3}				mg dm^{-3}				g dm^{3}
0-40	0.15	3.7	0.06	3.7	1.5	13.1	0.5	0.6	4.0	1.2	0.2
40-60	0.11	2.0	0.16	10.3	3.3	9.8	0.5	0.5	2.0	1.2	0.1
60-85	0.07	1.5	0.23	17.7	6.0	8.9	0.5	0.5	4.0	1.0	0.1
85-110+	0.03	1.2	0.18	20.3	6.1	6.4	0.3	0.3	4.0	0.5	0.1

D.F: Degree flocculation; V: base saturation; m: saturation by aluminum; O.C: organic carbon; pH in H_2O (1:1); T: pH7 cation exchange capacity.

Table 2. Production and partition of biomass for the different components of genotypes *Eucalyptus* at 43 months old, established in São Gabriel, Rio Grande do Sul, Brazil.

Genotypes	Leaves	Branches	Stembark	Stemwood	Total
	Mg ha^{-1}				
E. benthamii (P1)	6.09c	10.16c	5.93a	33.16c	55.34c
E. benthamii (P2)	3.70d	6.12e	4.42b	33.60c	47.84c
E. saligna	5.85c	12.70b	6.19a	43.58b	68.32b
E. dunnii	2.85d	8.26d	3.76b	18.81d	33.68d
E. uroglobulus	10.39a	11.53b	6.72a	55.36a	84.00a
E. urograndis	9.04b	20.75a	6.67a	44.33b	80.79a

Averages of each component of biomass in different treatments (genotypes) followed by equal letters, do not differ significantly by the Tukey test at the 5% level of error.
Source: Santos *et al.* (2019).

Table 3. Amount of nutrients in the biomass components of different genotypes of *Eucalyptus* at 43 months old, established in São Gabriel, Rio Grande do Sul, Brazil.

Genotypes	Components	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
		kg ha^{-1}						g ha^{-1}				
E. benthamii (P1)	Leaves	110.29	6.36	36.30	69.09	16.89	9.51	232.91	34.96	807.86	7246.14	72.86
	Branches	20.17	1.39	19.27	103.17	17.40	2.89	103.52	37.84	633.15	7724.68	89.40
	Stembark	23.99	2.43	24.72	83.85	18.51	2.55	93.01	15.10	269.57	6619.54	65.78
	Stemwood	52.27	5.08	64.61	38.78	16.14	6.60	185.40	26.61	938.24	5893.36	191.70
E. benthamii (P2)	Leaves	78.82	4.28	22.31	22.41	8.85	4.56	97.25	26.29	393.68	3568.63	48.04
	Branches	18.48	1.38	15.27	29.67	5.18	1.46	71.64	26.45	192.24	3902.22	46.94
	Stembark	18.01	2.18	16.62	46.40	14.50	1.68	92.13	15.54	117.35	4793.05	52.87
	Stemwood	50.34	5.34	60.06	17.06	7.48	4.68	128.72	66.64	552.20	3707.66	242.54
E. saligna	Leaves	92.87	4.66	37.16	63.83	18.18	5.11	175.35	31.89	567.13	4657.27	62.03
	Branches	20.71	1.13	23.35	133.81	25.39	2.80	148.13	61.46	1032.35	8514.80	132.11
	Stembark	28.28	1.53	15.48	68.17	22.67	1.79	98.11	14.18	225.10	6032.84	35.32
	Stemwood	51.29	3.64	59.05	36.77	21.69	5.31	240.94	69.78	1765.68	3309.26	307.66
E. dunnii	Leaves	49.58	2.60	16.05	30.42	9.31	3.00	75.49	23.37	457.13	2802.39	26.87
	Branches	19.40	1.43	28.60	72.05	14.85	2.17	117.45	39.06	543.18	5873.21	66.11
	Stembark	9.82	1.49	24.32	34.85	10.88	0.93	69.71	5.17	194.45	3308.41	26.86
	Stemwood	26.92	2.72	41.61	28.23	17.87	3.61	111.26	38.79	323.09	2884.73	74.93
E. uroglobulus	Leaves	133.34	7.59	48.76	83.30	14.54	8.46	250.35	45.93	623.97	9884.07	84.10
	Branches	18.19	1.52	27.98	74.96	6.75	2.75	127.94	40.39	430.87	6556.34	52.94
	Stembark	22.61	2.96	32.25	60.29	18.63	1.95	125.44	16.35	325.35	6195.22	42.41
	Stemwood	71.89	5.32	100.21	30.90	11.24	9.94	168.88	102.30	1013.28	5126.07	171.83
E. urograndis	Leaves	142.99	8.03	59.01	117.18	21.60	7.76	387.63	64.75	1026.00	7967.63	109.80
	Branches	32.43	3.38	44.77	222.54	38.96	4.52	234.21	102.64	1777.39	15634.53	173.32
	Stembark	21.70	2.49	24.23	80.53	23.61	1.61	97.86	15.35	244.60	6526.83	51.82
	Stemwood	64.32	6.40	91.76	36.14	22.92	8.04	231.87	105.97	966.68	5086.16	240.82

3. RESULTS AND DISCUSSION

Results presented here confirmed that there is synergism and antagonism between nutrients at the shoot level in the *Eucalyptus* genotypes in a Luvisol. Figure 1 shows the correlation for the amount of essential plant nutrients (macronutrients N, P, K, Ca, Mg, and S and micronutrients Fe, B, Mn, Zn and Cu) of genotypes of *Eucalyptus* implanted in Luvisol; blue and red lines are positive and negative correlations, respectively, and their correlation intensity is expressed by the thickness of the line that connects each nutrient. The efficiency of mineral elements in plants is determined by the amount of nutrients in plant tissues so it is an answer to metabolism and characteristics of the electrophysics of plants (Shabala, 2006).

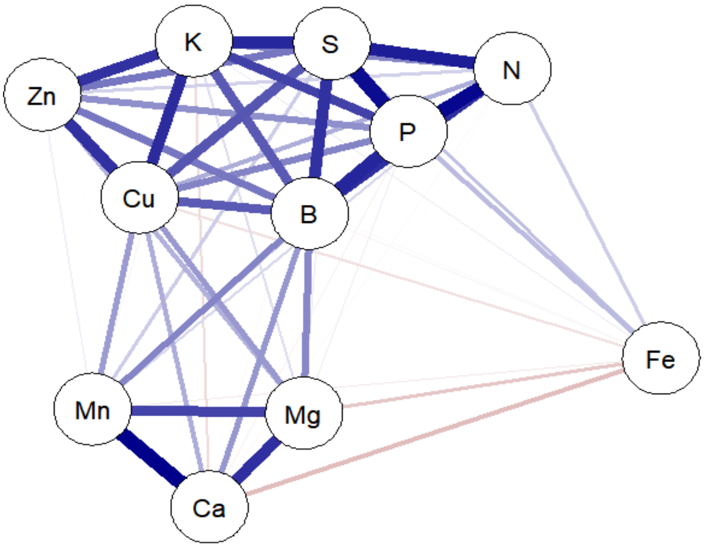

Figure 1. Diagram of Pearson's correlation coefficients matrix among nutrients of the analyzed *Eucalyptus* genotypes in a Luvisol (see Table 5 Supplementary material).

Manganese (Mn) and calcium (Ca) are strongly (> 0.9) associated in *Eucalyptus* genotypes implanted in a Luvisol. This is supported by metal transport from the cytosol to the vacuole antiporter CAX2 (calcium exchanger 2) due to expression from isolated root tonoplast vesicles (Wu *et al*., 2003; Pii *et al*., 2015). Therefore, some heterologous species improve Mn tolerance via its accumulation within plant tissues (Hirschi *et al*., 2000).

Despite iron (Fe) being essential to plant development, it shows weak correlation with other nutrients. It makes part of the enzyme composition in peroxidase, cytochrome oxidase, leghemoglobin and ferredoxin and also it participates in photosynthesis processes, respiration, nitrogen fixation, hormone synthesis and electron transfer (Layer *et al*., 2010; Krohling *et al*., 2016). For most macronutrients, the mutual interactions on yield levels are synergistic, whereas divalent cations show antagonistic effects on yield (Rietra *et al*., 2017). Therefore, interaction between elements can yield antagonistic or synergistic works to nutrient-use efficiency.

The NUE represents how many units of biomass are formed per unit of nutrient; that is, the higher the value of NUE the more efficient is the conversion of nutrients into biomass (Schumacher *et al.*, 2019). Results obtained from this study showed that besides P and K in *E. benthamii* (P1) (branches), Fe and Zn in *E. saligna* (stembark), and Cu in *E. dunnii* and *E. urograndis* (stembark), stemwood was the component that presented the highest NUE values for the analyzed elements (Table 4). This is a very important fact in forestry because stemwood is the main product taken from the stands. According to Reis and Barros (1990), NUE in the production of wood varies with type of soil (availability of nutrients), population of plants, and plant species.

Table 4. Nutrient-use efficiency in the biomass components of different genotypes of *Eucalyptus at* 43 months old, established in São Gabriel, Rio Grande do Sul, Brazil.

Genotype	Component	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
E. benthamii (P1)	Leaves	55	958	168	88	361	641	26,161	174,265	7,542	841	83,624
	Branches	504	7,315	527	98	584	3,514	98,124	268,425	16,043	1,315	113,629
	Stembark	247	2,437	240	71	320	2,325	63,766	392,642	22,001	896	90,159
	Stemwood	634	6,527	513	855	2,054	5,023	178,834	1,245,970	35,339	5,626	172,958
E. benthamii (P2)	Leaves	47	865	166	165	418	811	38,045	140,720	9,398	1,037	77,015
	Branches	331	4,432	401	206	1,181	4,198	85,456	231,500	31,847	1,569	130,416
	Stembark	245	2,030	266	95	305	2,625	47,951	284,259	37,646	922	83,556
	Stemwood	668	6,289	559	1,970	4,490	7,174	261,043	504,225	60,852	9,063	138,542
E. saligna	Leaves	63	1,254	157	92	322	1,143	33,348	183,344	10,311	1,256	94,274
	Branches	613	11,234	544	95	500	4,538	85,720	206,606	12,299	1,491	96,113
	Stembark	219	4,051	400	91	273	3,461	63,113	436,773	27,508	1,026	175,298
	Stemwood	850	11,988	738	1,185	2,009	8,213	180,876	624,557	24,682	13,169	141,650
E. dunnii	Leaves	57	1,098	178	94	306	949	37,733	121,883	6,231	1,016	106,014
	Branches	426	5,768	289	115	556	3,810	70,318	211,441	15,205	1,406	124,926
	Stembark	383	2,525	154	108	345	4,056	53,887	726,610	19,318	1,135	139,869
	Stemwood	699	6,912	452	666	1,053	5,211	169,089	485,008	58,229	6,522	251,069
E. uroglobulus	Leaves	78	1,369	213	125	715	1,229	41,518	226,306	16,658	1,052	123,592
	Branches	634	7,609	412	154	1,708	4,199	90,116	285,483	26,759	1,759	217,794
	Stembark	297	2,273	208	111	361	3,445	53,552	410,851	20,647	1,084	158,378
	Stemwood	770	10,401	552	1,791	4,927	5,571	327,797	541,126	54,633	10,799	322,165
E. urograndis	Leaves	63	1,125	153	77	418	1,165	23,319	139,607	8,810	1,134	82,325
	Branches	640	6,131	464	93	533	4,594	88,601	202,164	11,675	1,327	119,725
	Stembark	307	2,681	275	83	282	4,131	68,119	434,381	27,254	1,021	128,658
	Stemwood	689	6,927	483	1,227	1,934	5,512	191,179	418,304	45,857	8,716	184,073

In Luvisol, for the different species, the lowest NUE elements were observed for Ca, Mg and Mn (*E. benthamii* (P2) and *E. saligna*); K, Ca and Mg (*E. uroglobulus*); Ca and Mg (*E. benthamii* (P1); Mg and Mn (*E. urograndis*); and K (*E. dunnii*) obtained from stembark. In general, the results confirm the hypothesis that the NUE of the leaves would be very similar for genotypes. There is a broad consensus that the concentration of nutrients in *Eucalyptus* genus follows the order of leaves > bark > branches > wood (Resquin *et al*., 2020). Although wood nutrients are a smaller fraction, they are important in the nutrient cycling and in the balance of nutrients for the *Eucalyptus* stand (especially for P, S, B, Cu, Fe and Zn). In the same context, if wood with bark is harvested, Ca and Mg nutrients may greatly limit the productivity of the next cycle; however this limitation may be reduced if only the wood is harvested. According to Reis and Barros (1990), the allocation of nutrients in the bark is of great importance in choosing the type of exploitation to be adopted, that is, whether the stem should be exploited or only wood.

Results also revealed that micronutrients showed the best NUE, with Cu being the most prominent in all components, presenting the highest values for stemwood, with the exception of *E. dunnii*, where the highest value was found for stembark. The micronutrient with the lowest NUE value for all the components was Mn. NUE of the micronutrients in stemwood followed this order: Cu > B > Zn > Fe > Mn, with the exception of *E. dunnii*, where the value of Zn was higher than that of B. This same trend for most genotypes was reported by Ludvichak (2016) for a 9-year-old hybrid of *E. urograndis* in Pinheiro Machado, RS, Brazil. Viera *et al*. (2015) evaluated a hybrid population of *E. urophylla* × *E. globulus* of 10 years in Eldorado do Sul, RS, Brazil and also reported the same trend.

Among the macronutrients, P showed the highest conversion rate for stemwood in all genotypes, except in *E. benthamii* (P2) where the highest NUE value was found in S. In contrast, K presented the lowest conversion rate. Besides *E. benthamii* (P2), which had superior S to P, and *E. dunnii*, which had superior N to Ca, the NUE of stemwood decreased in this order: P > S > Mg > Ca > N > K.

This same trend was reported by Ludvichak (2016) and Viera *et al*. (2015). Schumacher *et al*. (2019), on the other hand, studied *Eucalyptus* spp. stands in small farms located in Rio Grande do Sul state, Brazil, and reported a trend different from the one found in this study (P > S > Mg > K > N > Ca). According to Santana *et al*. (2002), variation in NUE could occur due to several factors, such as the intrinsic characteristics of the genetic material, failure to obtain the optimal or critical nutritional balance between soil plant and all nutrients (that is, there may have been a limitation of one or more available nutrients), and water relations.

For stemwood, *E. saligna* had the highest NUE of N, P, K, S and Mn; *E. uroglobulus* had the highest NUE of Mg, B and Zn; and *E. benthamii* (P2) had the highest NUE of Ca and Fe. The NUE of P in *E. saligna* was 46 and 48% higher than that in clones *E. benthamii* (P1) and *E. benthamii* (P2), respectively. The NUE of K in *E. Saligna* was 35 and 39% higher than that in *E. urograndis* and *E. dunnii*, respectively. According to Caldeira *et al.* (2002), the evaluation of NUE in different forest species, their origins, and/or clones is important to a forester as it helps in choosing the genotype to be used for reforestation. However, it is important to note that it is difficult to select a genotype that has a high NUE of all the essential elements (Camargo *et al*., 2004). Therefore, forest managers should use genetic materials with high NUE that is compatible with the fertility of the soils because if materials with high NUEs are planted in low fertility soils that do not receive fertilization, soil depletion would occur rapidly (Santana *et al*., 2002).

To select genotypes, the breeder needs to use information about NUE and variation in the shoot-nutrient content. The analysis of the dependence of the efficiency of accumulation of a number of basic micro- and macronutrients made it possible to identify its dependence in the biomass components of different genotypes of *Eucalyptus*. Heatmap is a wrapper accompanied by dendrograms for visualizing observations correlations through color (Figure 2). Trends of nutrients (N, P, K, Ca, Mg, S, B, Cu, Fe, Mn and Zn) can be readily assessed from a heatmap depiction. In this figure, yellow is a positive correlation and blue is a negative correlation. The rows and columns of the matrix are ordered to highlight patterns of *Eucalyptus* genotypes and the amount of nutrients per dry biomass in the tree components so heatmap clustering comprises the nutrient-use efficiency.

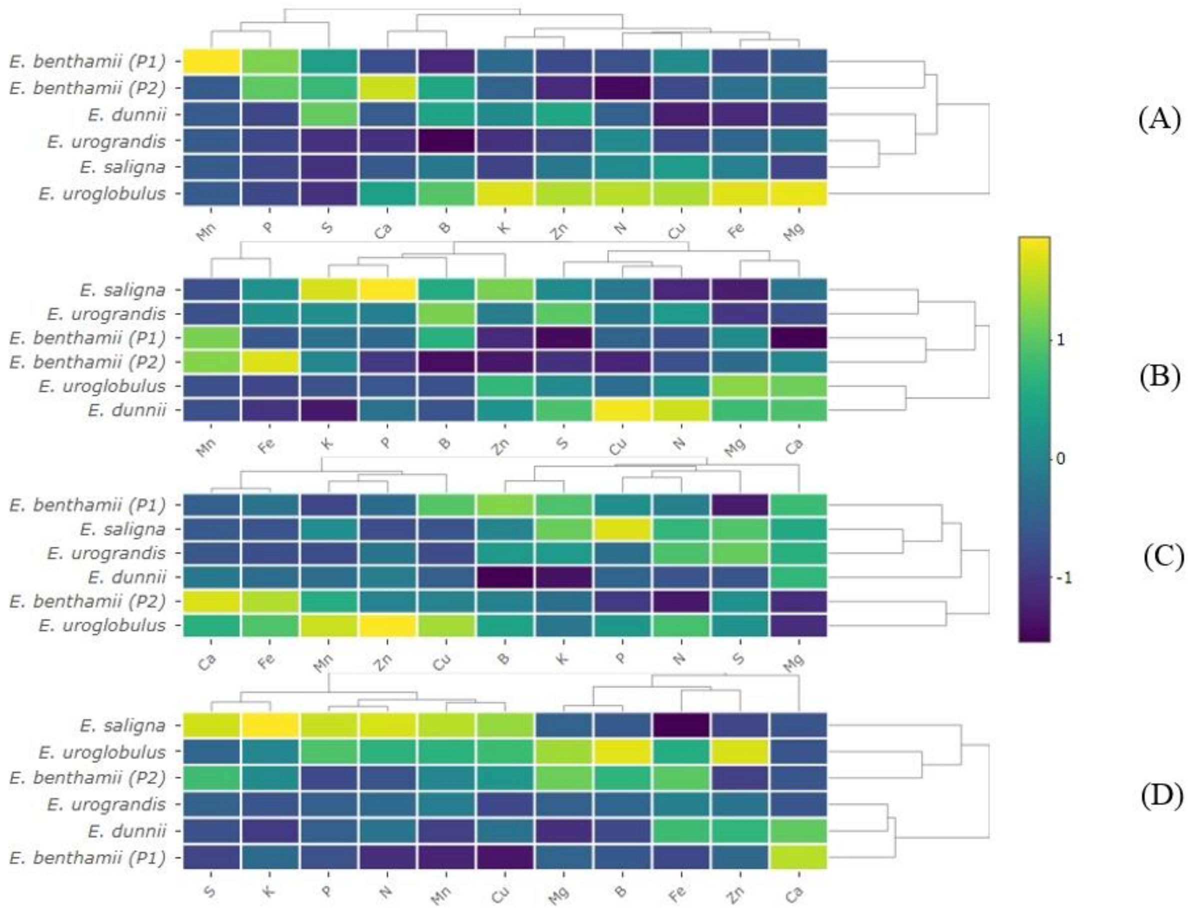

Figure 2. Heatmap used for visualizing data of Pearson's correlation coefficients matrix of nutrient-use efficiency in the biomass components (A - leaves; B - stembark; C - branches and D - stemwood) of different *Eucalyptus* genotypes implanted in a Luvisol.

The characteristics of soil type and lower excited electron states of chlorophyll, carotenoids, chromophores of the phytochromic and cryptochromic system provides to intra- and intermolecular charge separation reactions and thereby generates polarization and mechanism of transport to the nutrients for each biomass component in the plants (Kholmanskiy *et al.*, 2019). *Eucalyptus uroglobulus* and *E. dunni* genotypes differ much in their nutrient utilization efficiency under field conditions because of the capacity for the absorption, translocation and conversion of the nutrients into the biomass. *Eucalyptus urogobulus* showed the highest performance for stemwood biomass (55.36 Mg ha^{-1}). A negative correlation indicates that nutrient-use efficiency in the biomass components (leaves, stembark and stemwood) move in opposite directions, and that the relationship also becomes stronger the closer to minus 1.

4. CONCLUSIONS

Interaction between elements can yield antagonistic or synergistic effects on nutrient-use efficiency and *Eucalyptus* genotypes differed in terms of nutritional efficiency and nutrient function according to biomass components. In general, stemwood is the biomass component that showed the highest efficiency in nutrient use. The leaf component showed the lowest efficiency.

Nutrient-use efficiency is dependent on genotype traits. *Eucalyptus saligna* had the highest NUE of N, P, K, S and Mn, and *E. uroglobulus* had the highest NUE of Mg, B and Zn. The data presented here could facilitate tree breeding by enhancing phenotypic analyses based on nutritional factors during the allocation process for specific site conditions.

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Supplementary material

Table 5. Correlation matrix used in the diagram of Pearson's correlation coefficients matrix among nutrients of the analyzed *Eucalyptus* genotypes implanted in a Luvisol.

	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
N	1.00	0.91	0.45	0.01	0.00	0.82	0.77	0.30	0.18	0.15	0.17
P	0.91	1.00	0.70	-0.05	0.06	0.89	0.79	0.45	0.25	0.15	0.41
K	0.45	0.70	1.00	-0.13	0.12	0.79	0.60	0.78	0.08	0.03	0.75
Ca	0.01	-0.05	-0.13	1.00	0.76	-0.02	0.38	0.30	-0.24	0.93	0.01
Mg	0.00	0.06	0.12	0.76	1.00	0.08	0.44	0.37	-0.21	0.69	0.28
S	0.82	0.89	0.79	-0.02	0.08	1.00	0.75	0.62	0.23	0.18	0.50
B	0.77	0.79	0.60	0.38	0.44	0.75	1.00	0.60	-0.04	0.45	0.50
Cu	0.30	0.45	0.78	0.30	0.37	0.62	0.60	1.00	-0.11	0.36	0.75
Fe	0.18	0.25	0.08	-0.24	-0.21	0.23	-0.04	-0.11	1.00	-0.08	0.02
Mn	0.15	0.15	0.03	0.93	0.69	0.18	0.45	0.36	-0.08	1.00	0.08
Zn	0.17	0.41	0.75	0.01	0.28	0.50	0.50	0.75	0.08	0.02	1.00