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ALTERATIONS OF SOIL CHEMICAL PROPERTIES BY EUCALYPTUS CULTIVATION IN FIVE REGIONS IN THE RIO DOCE VALLEY[1]

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SUMMARY

Little is currently known about modifications in edaphic characteristics caused by short-rotation eucalyptus and the impacts of these alterations on the sustainability of eucalyptus wood production. This study was carried out to identify theses changes at five sites of eucalyptus plantation in the region of the Rio Doce Valley, state of Minas Gerais, Brazil. Areas with more than three previous eucalyptus cycles, adjacent to pasture land or native forest, were chosen. Soil samples were collected and soil fertility analyzed by routine methods and other fractionation methods in order to measure alterations in the K, Ca and Mg contents as a consequence of eucalyptus cultivation. In the eucalyptus areas, reductions in the exchangeable Ca^{2+}, Mg^{2+} and K^+ contents and pH were observed and increased Al^{3+} and H + Al contents. Of all nutrients, only P contents (Mehlich-1 P) increased in the eucalyptus areas. The reduction in exchangeable forms and in medium-term soil nutrient pools indicates the need for higher nutrient rates than the currently applied in order to prevent nutritional limitations and soil nutrient exhaustion. After several eucalyptus rotations there was a recovery in the SOM content in comparison to degraded pasture soils, although not to the level of the native forest soil. The positive correlation between effective CEC and medium-term non-exchangeable Ca, Mg and K with SOM emphasizes the need for adequate fertilizer and plant residue management to sustain or even increase forest productivity in future cycles.

Index terms: exchangeable cations, fertilization, nutrient exhaustion, nutrient reserves.

RESUMO: *ALTERAÇÕES DE CARACTERÍSTICAS QUÍMICAS DE SOLOS PELO CULTIVO DE EUCALIPTO EM CINCO REGIÕES NO VALE DO RIO DOCE*

Modificações em características edáficas, assim como as consequências resultantes dessas alterações sobre a sustentabilidade do processo de produção de madeira de eucalipto, ainda são pouco conhecidas. Com o objetivo de identificar essas modificações, realizou-se este trabalho em cinco locais cultivados com eucalipto na região do Vale do Rio Doce-MG. Foram selecionadas áreas cultivadas com eucalipto por mais de três ciclos, lado a lado com áreas onde o uso do solo ainda fosse anterior ao do plantio do eucalipto. Nestas situações (área com floresta de eucalipto próxima à área de pastagem, área de pastagem, área de eucalipto próximo à área de floresta nativa e área de floresta nativa), amostras de solo foram coletadas e analisadas, utilizando-se métodos tradicionais de avaliação da fertilidade e, também, o fracionamento de formas de K, Ca e Mg, para se fazer uma avaliação das alterações ocorridas nessas características do solo como consequência do cultivo do eucalipto. Nas áreas cultivadas com eucalipto, constatou-se redução nos teores de Ca^{2+}, Mg^{2+} e K^+ trocáveis; redução no pH; e aumentos nos teores de Al^{3+} e de $H + Al$. Os teores de fósforo (P Mehlich-1) aumentaram nas áreas cultivadas com eucalipto. A redução das formas trocáveis e os baixos teores de nutrientes em frações não trocáveis do solo apontam para a necessidade de programas de fertilização com maior quantidade de nutrientes que a aplicada atualmente para prevenir limitações nutricionais e exaustão de nutrientes do solo. Após diversas rotações com eucalipto, houve recuperação no teor de MOS em comparação ao solo sob pastagem degradada; entretanto, esse teor ainda não retornou ao nível da floresta nativa. A correlação positiva entre CEC efetiva e reservas de médio prazo de Ca, Mg e K não trocáveis com a MOS enfatiza a necessidade de um adequado manejo de resíduos e fertilizantes com o objetivo de sustentar e até mesmo aumentar a produtividade das florestas em futuras rotações.

Termos de indexação: cátions trocáveis, exaustão de nutrientes, fertilização, reservas de nutrientes.

INTRODUCTION

Nowadays, the areas of eucalyptus forests in Brazil have completed a sufficient number of successive cultivation cycles (seven years per cycle) to allow the detection of alterations in some edaphic characteristics. The removal of significant amount of nutrients with the wood as well as the physical impact on the soil caused by the heavily mechanized logging process (Lira Filho et al., 1995; Dias Júnior, 2000) are considered the main causes of soil deterioration in these areas.

The introduction of clones with a higher yield potential and, consequently, with higher nutritional requirements, is most likely also an accelerating factor of chemical degradation of the soils, considering the close relationship between plant nutrient content and biomass productivity (Miller, 1984; Khanna & Ulrich, 1984; Herbert & Robertson, 1991; Novais & Barros, 1997; Hernández et al., 2009). In the study of a nine year-old *Eucalyptus dunnii* forest in temperate climate in Uruguay, it was found that commercial logs accounted for 61 % of the biomass produced, but that only 27 % of the total N, 35 % of the P, 8 % of the K, 16 % of the Ca and 41 % of the Mg present in the forest were exported with the product. When logs are exported with off-site debarking, nutrient exports increase to 41, 55, 46, 68 and 66 % of the total extraction of N, P, K, Ca and Mg, respectively (Hernández et al., 2009). Knowledge about the extent of possible deterioration, the chronology of occurrence and relations between the availability of these nutrients and forest productivity is therefore fundamental for the definition of management practices which aim at maintaining and improving in soil quality, essential for a maximum sustainable economic yield. This is particularly true in the Rio Doce Valley, Minas Gerais, a region with predominantly highly weathered soils and a mountainous landscape (Santos 1998; Amaral, 1999).

One form of quantifying the impact of eucalyptus cultivation on edaphic characteristics is a comparative evaluation of properties between soils of the same type growing eucalyptus and of adjacent areas under native vegetation or other land use, e.g., pastures (Fonseca et al., 1993; Pereira et al., 1996; Herbert, 1996; Alfredsson et al., 1998; Lima et al., 2008; Silva, 2008). In the Rio Doce Valley the soils now used for eucalyptus had predominantly been pasture or covered by native forest. These conditions serve as references since pasture and native forest soils are closer to their natural condition than the ones covered by eucalypt, and represent the other alternative of soil use in this region.

The properties that should be used as indicators of effects of eucalyptus cultivation on soil, especially the fertility-related, are not well defined since the same chemical extractors developed for the evaluation of the soil fertility of agricultural soils are being used for forest soils. An alternative way to evaluate this effect could be the fractionation of the essential elements in compartments of distinct availability. Some previously reported alterations of soil chemical properties due to eucalyptus cultivation are: (a) reduction in the pH (Rhoades & Binkley, 1996), the pH dependent-CEC and base saturation; (b) increase of exchangeable Al^{3+} (Pereira et al., 1996; Herbert, 1996); and (c) alteration in organic matter fractions (Lima et al., 2008). Lal (2005) pointed out that the soil C content depends on complex interactions among climate, soils, tree species and management, and the chemical composition of the litter, as determined by the dominant tree species. Substantial changes in soil organic matter (SOM) have been reported after substitution of the natural vegetation by short-rotation eucalyptus plantations (Pegoraro, 2007; Lima et al., 2008; Silva, 2008). In the Rio Doce Valley, the SOM content has been shown to be closely correlated with eucalyptus yield (Menezes, 2005). Knowledge about the impact of short-rotation eucalyptus on the short and medium-term soil nutrient reserves as well as on SOM is essential to define sustainable forestry practices. It is also likely that the changes in soil chemical properties, particularly in SOM, differ after several eucalyptus rotations, varying with the soil type and dominant climate conditions. The purpose of this study was to evaluate the effect of successive eucalyptus cultivation on a number of fertility-related edaphic characteristics in five regions in the Rio Doce Valley, Minas Gerais, Brazil.

MATERIAL AND METHODS

Five representative regions in terms of dominant soils and climatic conditions (Belo Oriente, Guanhães, Santa Bárbara, Virginópolis and Ferros) growing short-rotation eucalyptus were selected for the current study in the Rio Doce Valley, state of Minas Gerais, Brazil (Table 1). Commercial eucalyptus stands were first planted in this region in the late 60's and 70's in areas previously under unproductive pastures. Areas under eucalyptus for at least three successive rotations (over 21 years) adjacent to planted pasture or native forest (Atlantic Forest) were selected for sampling.

The *Eucalyptus grandis* seedlings were planted in 3 x 2 m spacing, totaling 1,667 plants ha^{-1}. Initial fertilization was applied in the planting furrow with 90 g plant^{-1} of 05-25-10 NPK fertilizer followed by side-dressing of 100 g/plant of 10-10-20 NPK fertilizer after six months. Additional cultural practices were minimal and involved hand weeding and herbicide application. In the first two rotations, burning was commonly used to eliminate eucalyptus harvest residues. Plant nutrient analysis and wood yields were used to estimate the nutrient amounts removed from the site by harvest products in the three rotations. Fertilization records of this period were used to calculate the amount of nutrients applied to the plantations as fertilizers. Based on these data, the nutrient balance (nutrients applied through fertilizer – exported from site) were estimated for the period.

The pastures (mostly *Melinis minutiflora*) were established decades before eucalyptus, without liming or fertilization at sowing. Due to the limiting soil fertility, frequent burning and poor cattle management, signs of pasture yield decline were already observed by the time of sampling, with patches of barren soil exposed by surface erosion.

In 1998, six composite samples were collected at depths of 0–10, 10–20, 20–40, and 40–60 cm at each of the five selected sites, within an area of about 3 ha, for every evaluated situation (eucalyptus next to native forest, eucalyptus next to pasture). The soil samples were air-dried, mixed and sieved (< 2 mm) and analyzed for: pH in water (2.5:1) and 1 mol L^{-1} KCl; the exchangeable Ca^{2+}, Mg^{2+} and Al^{3+} extracted by 1 mol L^{-1} KCl; the available K, P, Zn, Cu, Fe, and Mn by Mehlich-1; B extracted by hot water; H + Al

Table 1. Localization and characteristics of the studied sites and eucalyptus stands in the Rio Doce Valley region

Site[1]	Soil[2]	Lat. (W)	Long. (S)	Altitude	Climate	Prec.	Temperature	Year started planting	Average wood yield
				m		mm	°C		m³ ha^{-1} year^{-1}
Fe	RYL	42°48′	19°22′	930	Cwb	1281	20.7	1974	32
BO	RYL	42°24′	19°14′	250	Aw	1163	25.0	1977	26
Gua	RYL	42°57′	18°40′	850	Cwa	1192	21.6	1977	36
SB	CX	43°23′	19°59′	847	Cwa	1450	22.3	1969	30
Vir	RL	42°41′	18°42′	870	Cwa	1153	22.0	1975	42

[1] Fe: Ferros; BO: Belo Oriente; Gua: Guanhães; SB: Santa Bárbara; Vir: Virginópolis. [2] RYL: Red Yellow Latosol (Udox); RL: Red Latosol (Udox); CX: Cambissol (Udept).

with 1 mol L^{-1} NH_4OAc (pH 7.0); and organic carbon determined by wet oxidation of organic matter according to Walkley-Black (Embrapa, 1997). To assess the medium and long-term potential nutrient reserves of the soils, non-exchangeable, intermediate availability, K, Ca and Mg were also extracted by 2 mol L^{-1} boiling nitric acid (Lanyon & Heald, 1986), and more stable, low availability- K, Ca and Mg were extracted with concentrated sulfuric acid (Vettori, 1969).

The data were subjected to analysis of variance in a completely randomized design, with six replications. Orthogonal contrasts were used (p ≤ 0.10) for a pairwise comparison of treatment means (eucalyptus with pasture and eucalyptus with native forest) within each soil layer.

RESULTS AND DISCUSSION

The decrease in exchangeable fractions of K, Ca, and Mg in soils under eucalyptus as compared to those under pasture (Table 2) reflects the negative balance between input and output of these nutrients in the system (Table 3). The nutrient exported in the logs and also with plant residues removed off site after harvest may result in a significant reduction of these nutrients in the soil under the plantation management system applied in this region. The reductions in Ca and Mg were greater than of K. On the other hand, the concentration of available P (Mehlich-1) increased in the eucalyptus areas due to P fertilization, leading to a positive import-export balance (Table 3). In these highly weathered soils, P is one of the most limiting nutrients for initial eucalyptus growth (Novais & Barros, 1997), and its application is rarely neglected.

However, liming was not a common practice until recently because eucalyptus plants are highly Al-tolerant (Neves et al., 1982a; Vale et al., 1984; Silva et al., 2002, 2004) and grow well in acid soils with relatively low Ca content (Neves et al., 1982b; Vale et al., 1996). This may have added to further reduce the Ca and Mg contents of these soils.

The contents of soil organic matter (SOM) were considerably higher in soils cultivated with eucalyptus than in pasture areas (Table 2). The great amount of residues produced by the forest (leaves, branches, bark and especially roots) that remained in the areas is certainly one of the principal reasons. The quantity of harvest residues after seven years amounted to approximately, 17.0, 20.0, and 35.0 t ha^{-1} in Belo Oriente, Santa Barbara and Guanhães regions, respectively. Besides the elevated amounts of plant residues returned to the soil, the decomposition rate of these materials is presumably low, as a consequence of the low nutrient content in the dead plant material

Table 2. Chemical properties of soils under eucalyptus/pasture areas at different depths in five regions in the Rio Doce Valley

Site	Depth	pH-H_2O	pH-KCl	Δ pH	OM	P	K	Ca	Mg	Al	Total CEC	Ca/Al
					Eucalypt/Pasture							
	cm				g kg^{-1}	mg dm^{-3}		cmol$_c$ dm^{-3}				
Ferros	0–10	4.86/5.26$^{(1)**}$	4.27/4.35*	-0.59/-0.91**	34.5/30.5^{ns}	2.25/1.73*	23.2/28.8**	0.09/0.48**	0.07/0.25*	0.96/0.69^{ns}	6.42/6.67^{ns}	0.091/0.688**
	10–20	4.83/5.19**	4.35/4.39^{ns}	-0.49/-0.08**	26.0/22.0^{0}	1.64/1.17*	17.5/21.5^{0}	0.04/0.23**	0.05/0.13**	0.74/0.73^{ns}	6.87/5.39^{ns}	0.060/0.3100**
	20–40	4.89/5.12**	4.41/4.45^{ns}	-0.48/-0.67**	18.3/13.8^{ns}	0.75/0.67^{ns}	11.0/15.6**	0.02/0.10**	0.03/0.06**	0.63/0.52^{ns}	4.09/3.89^{ns}	0.035/0.186**
	40–60	4.91/5.06*	4.45/4.48^{ns}	-0.46/-0.58**	12.3/11.8^{ns}	0.47/0.54^{ns}	8.1/11.1*	0.01/0.09**	0.02/0.05^{ns}	0.57/0.45^{ns}	3.40/3.40^{ns}	0.022/0.189**
Belo Oriente	0–10	4.56/4.95**	4.06/4.13^{ns}	-0.5/ -0.83**	20.0/23.1^{ns}	2.73/1.42*	14.5/58.8**	0.80/0.93^{ns}	0.07/0.62**	1.00/0.63^{ns}	5.99/6.19^{ns}	0.805/1.462^{ns}
	10–20	4.46/4.79**	4.03/4.03^{ns}	-0.43/-0.76**	16.9/15.5^{ns}	1.32/0.93*	10.2/32.0**	0.24/0.63**	0.03/0.35**	1.13/0.82^{0}	4.86/5.30^{ns}	0.213/0.769*
	20–40	4.44/ 4.78**	4.07/4.02^{ns}	-0.37/-0.75**	12.6/10.8^{ns}	0.78/0.62^{0}	6.7/17.7**	0.08/0.52**	0.02/0.22**	1.19/0.79*	4.28/4.47^{ns}	0.064/0.655*
	40–60	4.53/4.85**	4.16/4.10^{ns}	-0.37/-0.75**	9.3/ 8.6^{ns}	0.62/0.31**	3.8/ 9.1*	0.08/0.41**	0.01/0.14**	0.90/0.74^{ns}	3.22/3.83*	0.091 /0.554*
Guanhães	0–10	4.45/4.88**	3.98/4.16**	-0.47/-0.73**	55.9/42.3**	2.86/2.46^{ns}	33.9/23.5**	0.11/0.44*	0.11/0.2^{ns}	2.73/1.67**	13.03/11.16*	0.041/0.26*
	10–20	4.57/4.83**	4.08/4.18**	-0.49/-0.65**	41.7/35.7^{0}	1.87/0.96**	27.7/19.0*	0.04/0.19*	0.07/0.11^{ns}	2.09/1.37**	11.72/9.57**	0.021/0.135*
	20–40	4.46/4.85**	4.17/4.25**	-0.29/-0.59**	27.7/22.1**	0.68/0.31**	14.6/10.1^{0}	0.02/0.04**	0.03/0.03^{ns}	1.37/1.03**	8.94/7.12**	0.014/0.042**
	40–60	4.38/4.72**	4.28/4.31^{ns}	-0.1/ -0.40**	26.2/16.5**	0.24/0.11^{0}	6.3/ 6.4^{ns}	0.02/0.02^{ns}	0.01/0.02^{ns}	0.96/0.61**	6.37/5.40**	0.016/0.031*
Santa Bárbara	0–10	4.46/5.30**	3.76/4.17**	-0.7/ -1.13**	28.3/21.0**	3.58/6.63^{0}	32.6/71.3*	0.09/0.48**	0.08/0.2**	2.08/0.61**	10.21/5.78**	0.041/0.798**
	10–20	4.48/5.03**	3.86/4.01**	-0.62/-1.02**	19.5/17.7^{ns}	1.83/1.87*	20.1/32.5*	0.04/0.55**	0.05/0.19**	1.78/0.97**	8.50/6.61**	0.023/0.568**
	20–40	4.55/4.79**	3.89/3.98**	-0.67/-0.81**	13.5/13.2^{ns}	1.11/0.99*	13.0/19.5**	0.02/0.18**	0.06/0.09**	1.64/1.14**	6.75/5.71*	0.015/0.159**
	40–60	4.65/4.79^{0}	3.93/4.02^{ns}	-0.72/-0.77**	5.9/10.6**	0.66/0.46^{ns}	10.8/13.1**	0.01/0.17**	0.08/0.04**	1.41/1.01**	5.41/4.61	0.007/0.168**
Virginópolis	0–10	4.89/5.07^{0}	4.06/4.10^{ns}	-0.83/-0.97^{0}	52.1/36.8**	2.40/0.83**	24.1/34.8*	0.73/0.59^{ns}	0.24/0.31^{ns}	1.71/1. 25*	11.83/9.40**	0.427/0.472^{ns}
	10–20	4.77/4.95*	4.08/4.10^{ns}	-0.69/-0.84**	45.2/30.1**	1.88/0.46**	19.9/20.8**	0.25/0.4^{ns}	0.13/0.11^{ns}	1.88/1.33**	11.81/8.18**	0.131/0.300^{ns}
	20–40	4.76/5.00*	4.11/4.15^{ns}	-0.65/-0.85**	33.1/19.9**	1.20/0.35**	13.2/15^{ns}	0.09/0.22^{0}	0.07/0.07^{ns}	1.68/1.28**	10.07/6.38**	0.054/0.174*
	40–60	4.74/5.11**	4.16/4.21^{0}	-0.58/-0.9**	25.9/15.8**	0.56/0.12**	8.3/10.7^{ns}	0.05/0.16*	0.04/0.05^{ns}	1.37/1.17^{0}	7.79/5.20**	0.039/0.133*
Overall mean	0–10	4.64/5.09**	4.02/4.18^{ns}	-0.62/ -0.91**	38.2/30.7^{ns}	2.76/2.61^{ns}	25.7/43.5*	0.36/0.58^{ns}	0.11/0.32**	1.69/0.97	9.49/7.84^{ns}	0.214/0.600^{ns}
	10–20	4.62/4.95^{0}	4.08/4.14^{ns}	-0.54/ -0.81**	29.9/24.2**	1.71/1.08*	19.1/25.1^{0}	0.12/0.40^{ns}	0.06/0.18^{ns}	1.52/1.04^{0}	8.75/7.01^{ns}	0.081/0.382^{ns}
	20–40	4.62/4.91**	4.13/4.17^{ns}	-0.49/ -0.73**	21.0/16.0^{ns}	0.90/0.59^{ns}	11.7/15.6^{0}	0.05/0.21*	0.04/0.10^{0}	1.30/0.95^{ns}	6.83/5.51^{ns}	0.036/0.223*
	40–60	4.64/4.90**	4.20/4.22^{ns}	-0.44/ -0.68**	15.9/12.6^{ns}	0.51/0.31^{ns}	7.5/10.1^{0}	0.03/0.17^{ns}	0.03/0.06^{ns}	1.04/0.8 0^{ns}	5.24/4.49^{ns}	0.033/0.211*

ns, ^{0},*, **: contrast not significant, significant at 10, 5 and 1 %, respectively.

Table 3. Nutrient quantities exported with the trunks and applied to the system via fertilization in eucalyptus areas during three cycles (sums) in five studied regions of the Rio Doce Valley

Site	Quantity exported with the trunk					Added via fertilization					Difference (Added - exported)				
	N	P	K	Ca	Mg	N	P	K	Ca	Mg	N	P	K	Ca	Mg
								kg ha^{-1}							
Fer	367.5	25.8	253.2	257.7	60.0	127.5	61.0	105.4	40.9	0.0	-240.0	35.2	-147.7	-216.7	-60.0
BO	342.3	32.7	273.3	543.6	64.2	127.5	61.0	105.4	40.9	0.0	-214.8	28.3	-167.8	-502.6	-64.2
Gua	563.1	29.1	387.6	502.2	78.6	127.5	61.0	105.4	40.9	0.0	-435.6	31.9	-282.1	-461.2	-78.6
SB	398.4	24.9	309.9	307.8	53.4	127.5	61.0	105.4	40.9	0.0	-237.1	36.1	-204.4	-266.8	-53.4
Vir	687.9	37.2	457.5	923.4	124.2	127.5	61.0	105.4	40.9	0.0	-560.4	23.8	-352.0	-882.4	124.2

Fer:Ferros; BO: Belo Oriente; Gua: Guanhães; SB: Santa Bárbara; Vir: Virginópolis.

and soils (Gama-Rodrigues & Barros, 2002; Zaia & Gama-Rodrigues et al., 2004; Cunha et al., 2005). The virtual absence of soil loss by runoff in eucalyptus stands, which is common in pasture soils, may also have contributed to improve the SOM.

Short-rotation eucalyptus caused a significant drop in the pH in water (pH_w) and in KCl (pH_K) in the four sampled soil layers, as compared to pasture (Table 2). Rhoades & Binkley (1996) found a reduction in soil pH from 5.9 to 5.0 after eight years of *E. saligna* cultivation. The values of ΔpH (pH_K–pH_w) also increased in the eucalyptus areas in comparison to those under pasture (Table 2), indicating that the abundance of positive charges in the soils under eucalyptus had increased, despite the increased SOM content. This pattern may affect the soil quality due to the reduction of the cation retention capacity, as well as the possibility of increase in the specific adsorption of anions such as phosphate and sulfate (Sanchez & Uehara, 1980).

The Al^{3+} content in the eucalyptus areas increased in comparison to the pasture (Table 2) and as a consequence, the Ca^{2+}/Al^{3+} ratio was lower (Table 2). This suggests, among other aspects, that the soil under eucalyptus might be a less favorable environment for fine-root growth (Khanna & Ulrich, 1984) than previously under pasture. Although eucalyptus is known to be an Al-tolerant species, fine-root growth may be restricted by high Al^{3+} activities (Silva et al., 2004), especially under conditions of low Ca^{2+} availability. This could undermine water and nutrient uptake and eventually reduce tree growth because eucalyptus biomass yield seems to be related to fine-root growth (diameter ≤ 3.0 mm) (Gatto et al., 2003).

The trends of available P, K, Ca, and Mg in the eucalyptus soil compared to native forest soil were similar as in the comparison of eucalyptus with pasture soil. In other words, the available P (Mehlich-1) increased and the exchangeable K, Ca, and Mg declined in the eucalyptus soils compared to the native forest areas (Table 2). However, in many cases these

differences were not statistically significant, suggesting that the impact of eucalyptus on soil fertility was smaller in comparison to the native forest soils than on pasture soils. There is little nutrient exportation from the native forest, besides the fact that a major part of nutrients in native forest ecosystems in tropical regions is stored in the live and dead biomass of the forest. This fact can result in non-significant differences when the fertility of native forest soil is compared to that under eucalypt. Although large nutrient amounts are exported when eucalyptus stands are harvested, the fertilization programs keep track of these losses and amendments and fertilizes are frequently applied. Similar patterns for soil fertility were reported by Rangel & Silva (2007) for soils under eucalypt, pasture and native forest in Lavras (MG).

The natural fertility of soils in the studied environments is low. Based on the evaluation of the nutrient reserve potential in some soils of this region, Santos et al. (1998) concluded that: a) the soil weathering stage was advanced, with predominantly kaolinitic clay material and iron and aluminum oxides (gibbsite, hematite, goethite and maghemite); b) there is practically no medium and long-term K reserve; and c) the relatively high exchangeable Ca/total Ca and exchangeable Mg/total Mg ratios indicate a low ability of these soils for reposition of these nutrients. Amaral (1999) evaluated physical and chemical characteristics and the capacity of nutrient supply by soils in the iron ore exploitation region in Minas Gerais, which lies in the Rio Doce basin. He found that there was virtually no soil Ca reserve, total soil K was limited and the total Mg content was also low, but with a yet lower reserve than K. Therefore, the exuberance of the native forests is not so much a consequence of soil fertility but is, in most cases, maintained by the efficiency of recycling and the accumulation of the scarce nutrients in the live and dead aboveground phytomass of the system (Jansen, 1973). Thus, fertilizers must be applied in order to avoid exhaustion of the already low soil nutrient reserves.

The pattern of nutrient content changes in soils observed in the unproductive, degraded pasture areas can be explained by the low biomass yield of the forage grasses grown in the region, and, consequently, by the lower exportation, and/or, the lower nutrient accumulation in the biomass components of the system. The average dry matter productivity of the main forage grass of the region (*Melinis minutiflora*), rarely reaches 5.0 t ha^{-1} (Embrapa, 1993) and is much lower than the 12.0–20.0 t ha^{-1} of wood yield of eucalyptus forests, indicating that the nutrient demand and hence the nutrient input, especially Ca, Mg and K must be increased in eucalyptus forests in order to maintain the system sustainability.

The total CEC was lower in the eucalyptus than in the native forest areas, although these differences were not significant in most cases (Table 5). The Al^{3+} content of eucalyptus soil, was lower than those of native forest, except in Virginópolis, indicating that possible negative effects of eucalyptus cultivation concerning these characteristics also occur in areas of native forests. Chaer & Tótola (2007) also reported a lower impact of eucalyptus cultivation on soil chemical properties in a comparison of native forest and eucalyptus under distinct managements. The soil pH was lower in the eucalyptus than in the native forest soil, although the difference was lower than in the comparison of eucalyptus with pasture soil (Table 5). This suggests that the determining factors of active soil acidity must be remarkably similar in both forest types (native and eucalyptus). The ΔpH values were higher in the eucalyptus than in the pasture and native forest soils. Costa et al. (1984) found smaller net negative charges in an Oxisol under eucalyptus than under native forest in the region of Viçosa, Minas Gerais. In both cases the driving force for such changes was most likely the decrease in SOM.

SOM contents *under eucalyptus* were lower than under native forest (Table 5), indicating that the rates of organic matter addition to soil were higher in undisturbed areas (native forest). In the eucalyptus areas, in spite of the high amounts of plant residues, their quality and also some management practices such as site preparation and residue burning certainly contributed to the majority of the deposited organic residues not being incorporated into the humified SOM pool (Chaer & Tótola, 2007; Lima et al., 2008). Much of this effect on SOM may still reflect the previous

Table 4. Concentrations of available (Mehlhich-1), non-exchangeable (extracted by HNO$_3$) and more "stable" (extracted by sulfuric acid) K, Ca, and Mg in soil samples at different depths cultivated with eucalyptus/pasture in five areas of the Rio Doce Valley region

Site	Depth	Eucalypt/Pasture					
		HNO$_3$-K	H$_2$SO$_4$-K	HNO$_3$-Ca	H$_2$SO$_4$-Ca	HNO$_3$-Mg	H$_2$SO$_4$-Mg
	cm	——— mg dm^{-3} ———		——————————— cmol$_c$ dm^{-3} ———————————			
Ferros	0–10	34.6/28.2[0]	78.0/84.3	0.169/0.609**	0.513/0.968	0.064/0.182**	0.463/0.765
	10–20	23.5/23.2[ns]	99.8/81.2	0.071/0.201**	0.494/0.576	0.024/0.053[ns]	0.918/0.518
	20–40	15.6/19.2[ns]	72.4/95.8	0.035/0.101**	0.197/0.572	0.002/0.022[ns]	0.675/0.446
	40–60	9.9/13.6**	90.6/81.2	0.018/0.053**	0.274/0.155	0.001/0.005*	0.279/0.083
Belo Oriente	0–10	23.3/38.7**	49.8/55.4	1.188/1.459[ns]	0.327/0.766	0.165/0.836**	0.440/1.627
	10–20	14.7/40.2*	62.2/50.3	0.569/0.937[ns]	0.556/0.467	0.085/0.432**	0.758/1.108
	20–40	13.1/17.9[ns]	37.3/87.1	0.228/0.481*	0.184/0.122	0.065/0.205**	0.001/0.200
	40–60	7.6/12.4**	24.9/99.5	0.131/0.340**	0.087/0.161	0.038/0.113**	0.079/0.409
Guanhães	0–10	44.1/26.9**	203.7/366.7	0.379/2.469[ns]	1.043/4.088	0.167/0.509[ns]	2.721/4.981
	10–20	38.5/19.2**	117.8/430.0	0.278/0.681[ns]	0.865/1.240	0.133/0.165[ns]	1.615/3.175
	20–40	22.1/11.6*	114.7/379.4	0.096/0.097[ns]	0.709/2.204	0.070/0.057[ns]	1.837/3.949
	40–60	10.0/12.3[ns]	111.6/392.0	0.064/0.040[ns]	0.019/6.079	0.052/0.042[ns]	0.626/7.529
Santa Bárbara	0–10	48.5/62.6*	1753.2/396.2	0.150/1.611**	0.203/1.808	0.125/0.304**	2.442/1.658
	10–20	42.7/45.6[ns]	1669.9/1075.9	0.074/0.716**	0.015/0.67	0.082/0.190*	2.282/3.552
	20–40	34.9/42.8[ns]	2351.3/1016.6	0.045/0.246**	0.228/0.157	0.053/0.050[ns]	4.180/3.279
	40–60	43.8/30.4[0]	2369.6/427.7	0.031/0.221**	0.335/0.318	0.054/0.015[0]	3.943/1.835
Virginópolis	0–10	38.6/42.3[ns]	112.5/136.9	3.620/0.663[0]	2.408/0.758	0.337/0.223[ns]	2.218/1.406
	10–20	35.2/37.1[ns]	121.9/130.6	0.674/0.640[ns]	1.070/0.393	0.175/0.116[ns]	1.685/1.088
	20–40	23.1/25.0[ns]	121.9/121.6	0.433/0.302[ns]	1.280/0.345	0.143/0.065[0]	2.311/0.902
	40–60	15.9/23.5[0]	121.9/137.3	0.165/0.284[ns]	0.890/0.218	0.083/0.065[ns]	1.441/0.968
Overall mean	0–10	37.8/39.7[ns]	439.4/207.9[0]	1.101/1.362[ns]	0.896/1.678[ns]	0.172/0.411[ns]	1.657/2.087[ns]
	10–20	30.9/33.1[ns]	414.3/353.6[ns]	0.333/0.635[0]	0.427/0.669[ns]	0.100/0.191[ns]	1.452/1.888[ns]
	20–40	21.8/23.3[ns]	656.3/340.1[ns]	0.167/0.245[ns]	0.600/0.680[ns]	0.066/0.080[ns]	2.082/1.755[ns]
	40–60	17.4/18.4[ns]	543.7/227.5[ns]	0.082/0.188[ns]	0.321/1.386[ns]	0.045/0.048[ns]	1.273/2.165[ns]

Table 5. Chemical characteristics of soil samples at different depths in areas with eucalyptus/native forest in five areas of the Rio Doce Valley region with their respective significance of the contrast values

Site	Depth	Eucalypt/Native Forest										
		pH-H_2O	pH-KCl	ΔpH	OM	P	K	Ca	Mg	Al	Total CEC	Ca/Al
	cm				g kg⁻¹	—— mg dm⁻³ ——		—————— cmol_c dm⁻³ ——————				
Ferros	0–10	4.97/5.32**	4.16/4.16ns	-0.81/-1.16**	48.8/58.3**	2.71/1.40**	28.6/33.3*	0.09/0.11ns	0.13/0.13ns	1.38/1.76*	9.55/11.08*	0.064/0.064ns
	10–20	4.96/5.41**	4.24/4.28ns	-0.72/-1.13**	35.4/45.8**	1.52/0.94**	22.8/28.3*	0.05/0.05ns	0.09/0.07⁰	1.01/1.25**	7.04/8.44ns	0.047/0.042ns
	20–40	4.98/5.45**	4.47/4.4ns	-0.52/-1.05**	19.8/33.5**	0.49/0.56ns	11.8/18.5**	0.01/0.02ns	0.04/0.05ns	0.54/0.93**	3.95/6.41**	0.027/0.021ns
	40–60	4.94/5.33**	4.6/4.55ns	-0.35/-0.78**	14.8/19.5*	0.32/0.32ns	4.9/10.8**	0.01/0.01ns	0.03/0.03ns	0.33/0.51**	3.16/4.24**	0.042/0.019ns
Belo Oriente	0–10	4.08/4.35*	3.75/3.84ns	-0.33/-0.51*	24.3/35.0**	3.01/1.78⁰	28.6/33.6ns	0.12/0.06ns	0.09/0.11ns	1.82/1.87ns	8.66/9.80ns	0.067/0.033ns
	10–20	4.13/4.32*	3.86/3.88ns	-0.27/-0.44*	17.5/25.8**	2.01/1.31**	19.5/26.2ns	0.05/0.05ns	0.05/0.08ns	1.61/1.72ns	6.60/8.50**	0.031/0.028ns
	20–40	4.16/4.45**	3.94/3.96ns	-0.22/-0.49**	14.7/18.0*	1.29/0.75**	11.5/21.3*	0.03/0.04ns	0.03/0.06ns	1.40/1.37ns	4.67/6.09**	0.018/0.026ns
	40–60	4.21/4.59**	4.03/4.08ns	-0.18/-0.52**	10.7/13.3*	0.91/0.44**	6.6/12.1**	0.02/0.07ns	0.02/0.04ns	1.28/1.09ns	3.69/4.55**	0.016/0.062ns
Guanhães	0–10	4.33/4.65**	3.83/3.94*	-0.49/-0.72**	48.2/54.7ns	2.02/1.52ns	37.2/38.2ns	0.08/0.07ns	0.12/0.09ns	2.09/2.03ns	14.82/14.81ns	0.038/0.035ns
	10–20	4.39/4.74**	4.00/4.06*	-0.4/-0.69**	33.3/43.4**	0.92/0.85ns	23/26.7ns	0.02/0.02ns	0.05/0.06ns	1.39/1.42ns	10.77/11.61ns	0.012/0.017ns
	20–40	4.33/4.81**	4.12/4.17**	-0.21/-0.64**	23.9/29.7**	0.42/0.41ns	13.2/14ns	0.01/0.01ns	0.03/0.03ns	0.93/0.94ns	7.86/8.75*	0.008/0.016ns
	40–60	4.22/4.86**	4.21/4.25**	-0.01/-0.62**	17.7/21.8⁰	0.15/0.19ns	8.8/9.8ns	0.01/0.02ns	0.02/0.02ns	0.60/0.57ns	5.58/634**	0.018/0.028ns
Santa Bárbara	0–10	4.53/4.55ns	3.96/3.84*	-0.57/-0.7*	23.6/28.4⁰	1.85/2.75ns	25.8/38.9ns	0.04/0.12ns	0.05/0.12ns	1.94/2.40**	7.64/9.07*	0.019/0.050ns
	10–20	4.57/4.57ns	3.99/3.92**	-0.58/-0.65ns	19.0/22.2*	0.97/1.80*	18.5/27.3⁰	0.03/007ns	0.04/0.07⁰	1.92/2.29**	7.06/7.54ns	0.013/0.031ns
	20–40	4.65/4.60ns	4.05/3.91**	-0.6/-0.69⁰	15.3/15.5ns	0.32/0.80**	9.6/16.5**	0.02/0.03ns	0.02/0.04ns	1.57/1.74ns	5.56/6.02ns	0.012/0.019ns
	40–60	4.76/4.79ns	4.09/3.95**	-0.67/-0.84**	11.2/8.9⁰	0.08/0.37⁰	7.1/10.7*	0.02/0.02ns	0.02/0.02ns	1.44/1.30ns	4.50/4.50ns	0.012/0.018ns
Virginópolis	0–10	4.74/5.16**	4.01/4.11**	-0.73/-1.04**	62.7/59.0*	2.33/1.43**	22.1/33.2*	0.05/0.67*	0.05/0.35	2.20/1.50**	11.37/11.22ns	0.023/0.445⁰
	10–20	4.71/5.13**	4.11/416**	-0.61/-0.97ns	49.3/45.0ns	1.68/1.23ns	18.3/23.8ns	0.02/0.30⁰	0.05/0.16	1.93/1.43**	10.09/9.22*	0.012/0.210ns
	20–40	4.78/5.14**	4.20/4.25⁰	-0.58/-0.9ns	39.3/33.7⁰	1.10/0.66⁰	12.3/13.3ns	0.01/0.12ns	0.04/0.08	1.38/1.07**	7.72/7.32ns	0.008/0.113ns
	40–60	4.98/5.16*	4.26/4.30⁰	-0.72/-0.86ns	30.8/25.8*	0.71/0.48*	8.1/9.8ns	0.01/0.07ns	0.02/0.06	1.06/0.93ns	6.39/5.79ns	0.007/0.080ns
Overall mean	0–10	4.53/4.81ns	3.94/3.98ns	-0.59/-0.83**	41.5/47.1ns	2.38/1.77ns	28.4/35.4ns	0.08/0.21ns	0.09/0.16ns	1.89/1.91ns	10.41/11.19ns	0.040/0.108ns
	10–20	4.55/4.83ns	4.04/4.06ns	-0.51/-0.77*	30.9/36.5ns	1.42/1.23ns	20.4/26.5⁰	0.03/0.10ns	0.06/0.09ns	1.57/1.62ns	8.31/9.06ns	0.021/0.061ns
	20–40	4.58/4.89ns	4.16/4.14ns	-0.43/-0.75**	22.6/26.1ns	0.72/0.63ns	11.7/16.7*	0.02/0.04ns	0.03/0.05ns	1.16/1.21ns	5.95/6.92ns	0.013/0.037ns
	40–60	4.62/4.95ns	4.24/4.22ns	-0.38/-0.72**	17.1/17.9ns	0.43/0.36ns	7.1/10.7*	0.01/0.04ns	0.02/0.03ns	0.94/0.88ns	4.66/5.09ns	0.015/0.043ns

ns; ⁰;*; **: contrast not significant; significant at 10; 5; and 1 %, respectively.

land use (unproductive pastures) and may therefore not be an exclusive effect of short-rotation eucalypt. In fact, studies using the natural abundance of the ^{13}C isotope indicate that the SOM content is slowly recovered after planting short-rotation eucalyptus in soils formerly under degraded, unproductive pastures (Lima et al., 2006).

The variations observed in the Ca^{2+}/Al^{3+} ratios between the eucalyptus and native forest soils were not significant. There larger decreases in this ratio were observed when comparing eucalyptus with pasture soils. Rangel & Silva (2007) found that in soils under eucalyptus the Ca^{2+}/Al^{3+} ratio (0.32) was close to that reported for soils under native forest (0.39), but much higher (13.5) than in pasture soil.

When establishing eucalyptus in pasture land, the sustainability of the wood production could be negatively affected by the low availability of K^+, Ca^{2+} and Mg^{2+} and the reduction of the pH and Ca^{2+}/Al^{3+} ratio, the higher Al^{3+} contents, and the increase of positive soil charges. Yet, the observed changes in properties such as SOM and Mehlich-1 P suggest that the activity would be sustainable.

Considering the native forest soil as reference, these alterations indicate that the sustainability of wood production as affected by the availability of K, Ca, Mg would be lower than in the system where pasture land is converted to eucalyptus forest.

However, the high SOM losses observed indicates that this property could reduce the sustainability. The results suggest that the main causes for yield reductions observed in some cases after the first rotation are most likely also due to alterations in soil physical rather than only chemical properties.

SOM contents were highly correlated with CEC (r = 0.9***), Al^{3+}(r = 0.5***), K^+ (r = 0.45***), and with P (r = 0.33**). However, no correlation was found with exchangeable Ca and Mg because most of the negative charges in these soils were occupied by Al^{3+}. The finding that most effective negative charges in these soils are SOM-dependent is not surprising because of the high weathering degree and dominance of the clay fraction by low-activity minerals. It also indicates the importance of maintaining SOM at these eucalyptus sites. For soils in the same region, Menezes (2005) found that SOM and solution equilibrium P were the only two soil properties correlated with eucalyptus yield. The author pointed out that SOM content and solution equilibrium P are properties associated to the extension of the surface as well as quality of the solid phase. Consequently, SOM plays an important role in production sustainability which is why it is widely used as soil quality indicator.

Evaluations of intermediate and more "stable" nutrient fractions indicated that intermediate availability (non-exchangeable) and long-term

("stable") reserves of K, Ca and Mg are limited, (Tables 4 and 6) and are consistent with the advanced weathering stage of these soils. According to limits suggested by Resende & Santana (1988) (Ki ≤ 0.75 and Kr ≤ 0.75), the soils of all five studied areas contained secondary minerals where the clay fraction consisted predominantly of gibbsite and sesquioxides, that is, highly weathered materials. In this study there was a significant correlation between SOM content and HNO_3-Ca and HNO_3-Mg (r = 0.3**), and HNO_3-K contents (r = 0.4***), indicating that SOM also contributes to nutrient supply in the medium term.

The HNO_3-K contents (available plus moderately available forms) were up to 3.8 times higher than those of Mehlich 1-K (available forms) (Table 7). Silva et al. (1996) found that some native woody species are able to use non-exchangeable K forms. If these K forms are really the most appropriate to estimate available K for eucalyptus (Melo et al., 1995), the current fertilization based on exchangeable K^+ contents would

be leading to inaccurate recommendations. On the other hand, not only exchangeable, but also non-exchangeable and more "stable" K fractions were depleted after three eucalyptus rotations, suggesting that higher K fertilizer doses than the currently used should be applied to eucalyptus stands on these soils. The negative balance between K exported from and K applied via fertilizers to the site (Table 3) support this hypothesis.

The HNO_3-K/Mehlich-1 K ratio differed markedly between the regions (Table 7); Belo Oriente had the lowest and the Santa Barbara region the highest ratio. The ratio increased with soil depth as a result of lower K values (Mehlich 1). Amaral (1999) also reported this pattern in soils of the Santa Barbara region. To create a fertilizer recommendation systems based on the nutritional balance for eucalypt, however, deeper layers should also be included. Melo et al. (1995) studied K and Mg forms in less weathered soils of southern Brazil and their relation to eucalyptus

Table 6. Concentrations of available/exchangeable forms and the intermediate availability (extracted with HNO_3) and "stable" forms (extracted by sulfuric acid) of K, Ca, and Mg in soil samples at different depths of eucalyptus or native forest in five areas of the Rio Doce Valley region with their respective significance of contrast values

Site	Depth	Eucalypt/Native forest					
		HNO_3-K	H_2SO_4-K	HNO_3-Ca	H_2SO_4-Ca	HNO_3-Mg	H_2SO_4-Mg
	cm	——— mg dm^{-3} ———		———————————————— $cmol_c$ dm^{-3} ————————————————			
Ferros	0–10	39.9/43.0 [ns]	43.7/87.2	0.186/0.140 [ns]	0.319/0.268	0.105/0.077 [ns]	1.440/0.511
	10–20	29.1/36.8*	49.9/80.9	0.082/0.091 [ns]	0.189/0.109	0.030/0.081 [ns]	0.740/0.622
	20–40	15.1/27.9**	43.7/77.8	0.019/0.035 [ns]	0.014/0.005	0.000/0.030*	0.532/1.050
	40–60	12.4/15.2**	62.4/77.8	0.012/0.001 [ns]	0.125/0.000	0.000/0.000 [ns]	0.988/0.438
Belo Oriente	0–10	30.2/38.6 [0]	849.0/70.5	0.126/0.111 [ns]	0.154/0.194	0.118/0.153 [ns]	0.600/0.743
	10–20	21.6/32.5 [ns]	25.2/30.2	0.062/0.074 [ns]	0.271/0.303	0.080/0.111 [ns]	0.686/0.675
	20–40	15.6/22.9*	75.4/32.7	0.045/0.057 [ns]	0.565/0.271	0.061/0.083 [ns]	0.810/0.749
	40–60	9.40/13.6**	140.0/22.7	0.033/0.037 [ns]	0.285/0.192	0.044/0.06 [ns]	0.827/0.456
Guanhães	0–10	41.0/46.4 [ns]	49.0/49.2	0.209/0.151 [ns]	0.126/0.142	0.158/0.139 [ns]	0.432/0.156
	10–20	30.6/30.7 [ns]	49.0/49.0	0.096/0.058 [ns]	0.077/0.357	0.096/0.083 [ns]	0.286/1.048
	20–40	15.4/20.4 [ns]	265.2/36.8	0.03/0.0220 [ns]	0.310/0.145	0.056/0.057 [ns]	2.774/0.583
	40–60	8.7/15.4**	265.6/36.8	0.009/0.022 [ns]	0.212/0.364	0.041/0.176*	3.785/1.533
Santa Bárbara	0–10	53.0/61.5 [ns]	1574.7/1930.9	0.094/0.213 [ns]	0.301/0.07	0.119/0.15 5 [ns]	3.524/2.848
	10–20	52.6/45.8 [ns]	2245.1/2082.4	0.083/0.121 [ns]	0.103/0.090	0.120/0.097 [ns]	4.309/2.837
	20–40	41.8/33.5 [ns]	2731.4/2104.2	0.047/0.064 [ns]	0.055/0.024	0.075/0.062 [ns]	5.083/2.937
	40–60	38.0/47.1 [ns]	2768.8/1774.3	0.033/0.031 [ns]	0.052/0.014	0.067/0. 112*	5.377/2.123
Virginópolis	0–10	37.9/48.7*	171.3/173.7	0.408/2.068 [ns]	0.327/0.622	0.178/0.551*	1.703/1.502
	10–20	32.3/31.6 [ns]	161.7/161.2	0.105/0.856*	0.255/0.485	0.103/0.256**	1.641/0.840
	20–40	21.9/20.9 [ns]	143.1/149.7	0.046/0.400 [0]	0.107/0.422	0.040/ 0.179**	0.888/1.527
	40–60	16.6/17.6 [ns]	171.1/153.1	0.059/0.290*	0.115/1.187	0.023/0.135**	1.068/1.995
Overall mean	0–10	40.4/47.6 [ns]	537.5/462.3 [ns]	0.205/0.537 [ns]	0.245/0.259 [ns]	0.136/0.215 [ns]	1.540/1.152 [ns]
	10–20	33.2/35.5 [ns]	506.2/480.8 [ns]	0.085/0.240 [ns]	0.179/0.268 [ns]	0.086/0.125 [ns]	1.532/1.205 [ns]
	20–40	22.0/25.1 [ns]	651.7/480.2 [ns]	0.038/0.116 [ns]	0.210/0.178 [ns]	0.046/0.082 [ns]	2.017/1.369 [ns]
	40–60	17.0/21.8 [ns]	681.6/412.9 [ns]	0.029/0.076 [ns]	0.158/0.351 [ns]	0.035/0.097*	2.409/1.309 [ns]

ns; [0];*; **: contrast not significant; significant at 10; 5; and 1 %, respectively.

Table 7. Non-exchangeable to exchangeable K, Ca, and Mg ratios in soil samples taken from eucalyptus stands at different depths in the five studied regions

Site	Depth (cm)											
	0–10	10–20	20–40	40–60	0–10	10–20	20–40	40–60	0–10	10–20	20–40	40–60
	Potassium				Calcium				Magnesium			
Ferros	1.31	1.28	1.41	1.54	1.39	1.17	1.19	0.65	0.73	0.55	0.29	0.04
Belo Oriente	0.97	1.27	1.27	1.44	1.40	1.58	1.15	0.87	1.36	1.34	1.23	1.18
Guanhães	1.21	1.26	1.36	1.50	4.44	3.93	2.87	2.22	1.80	1.64	1.85	4.33
Santa Bárbara	1.31	1.91	2.64	3.81	2.76	1.38	1.49	1.36	1.56	1.37	1.11	1.57
Virginópolis	1.50	1.66	1.67	1.96	3.46	2.51	2.64	2.68	1.42	1.51	1.66	1.70
Mean	1.25	1.48	1.69	2.15	2.55	1.94	1.70	1.40	1.36	1.29	1.22	1.48

growth and nutrient content, and concluded that the non-exchangeable K forms were essential for eucalyptus nutrition. Lana & Neves (1994) evaluated the capacity of K supply in eucalyptus soils and found that the non-exchangeable K forms (HNO_3-K minus NH_4OAc-K) were responsible, on average, for 70 % of the K taken up by the plants. The average H_2SO_4-K/HNO_3-K ratio at the evaluated sites varied from 1.54 to 53.61. These values also increased in greater soil depths, once again emphasizing the need to include the contribution of nutrients from deeper layers in the fertilizer recommendation programs.

The HNO_3-Ca contents were also considerably higher than those extracted by 1 mol L^{-1} KCl (Tables 4, and 6). The HNO_3-Ca/KCl-Ca ratio decreased with increasing depth (Table 7), suggesting that the contribution of mineral forms to Ca reserves. Indeed, up to 70 % of Ca taken up by eucalyptus is incorporated in the bark and slowly released during decomposition. Exchangeable Ca^{2+} contents found in the present study are below the critical levels suggested for eucalyptus (Novais & Barros, 1997). These findings, combined with the reduced non-exchangeable Ca (HNO_3-Ca minus KCl-Ca) and "stable" Ca forms of the soil (Ca-H_2SO_4), are further aggravated by the fact that the greatest reserves are found in the upper layers (and therefore more exposed to losses by erosive processes), supporting the idea that this nutrient is the most critical for the maintenance of the sustainability of eucalyptus forests on these soils. The reposition of this element through limestone would not only supply Ca, but also ameliorate soil acidity. Similar conclusions were drawn in a study evaluating nutrient use efficiency and yield sustainability of *E. grandis* and *E. saligna* in São Paulo State (Santana et al., 2002).

The contents of HNO_3-Mg and H_2SO_4-Mg were not very different from the exchangeable Mg^{2+} (Mg-KCl) (Tables 4, 6 and 7), indicating a reduced medium-term potential of Mg supply by these soils. Unlike K and Ca, no clear trend with increasing depth was observed for the HNO_3-Mg/KCl-Mg ratio.

CONCLUSIONS

1. The management practices applied in eucalyptus forests in the last three decades caused significant alterations in some soil chemical properties, indicating that independently of the previous land use (native forest or pasture), the readily available and long-term nutrient contents were reduced (except P). These differences were greater when soils under eucalyptus were compared to pasture than to forest soils.

2. Soil organic matter levels were recovered after several eucalyptus rotations, but they are still intermediary to the degraded pasture and native forest soils.

3. There are clear indications that in order to maintain and improve soil chemical properties under eucalyptus forests, the nutrient balance should be strictly controlled, mainly through fertilization, liming and harvest residue management to prevent soil nutrient depletion and plant deficiency.

4. The depletion of exchangeable and non-exchangeable K, Ca and Mg fractions and the increase in soil acidity and positive charges emphasizes the need for preservation of plant residues at the site in order to avoid drastic reductions in soil organic matter, which could undermine the sustainability of eucalyptus production. In this region, not only soil CEC, but also medium-term Ca, Mg and K pools are related to the soil organic matter content.

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