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Use of exchangeable and nonexchangeable forms of calcium, magnesium, and potassium in soils without fertilization after successive cultivations with *Pinus taeda* in southern Brazil

Luciano Colpo Gatiboni[1] · Walquiria Chaves da Silva[2] · Gilmar Luiz Mumbach[2] · Djalma Eugênio Schmitt[3] · Daniel Alexandre Iochims[2] · James Stahl[4] · Cristiane Ottes Vargas[2]

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Abstract

Purpose The aim of this study was to quantify the contents and stocks of exchangeable and nonexchangeable fractions of potassium (K), calcium (Ca), and magnesium (Mg) after one and three successive *Pinus taeda* crops without fertilization and to predict the soil supply for further cultivations.

Materials and methods The soil was analyzed in layers up to 80 cm in two *Pinus* forests, one at the end of the first cultivation and other at the end of the third successive crop, in a subtropical region in southern Brazil. Stocks of exchangeable and semi-total fractions of K, Ca, and Mg in the soil were calculated, and the potential number of crop rotations of *Pinus* without fertilization was estimated.

Results and discussion After three *Pinus* crops, there was an average reduction of 46.9, 90.8, and 45.5% of exchangeable K, Ca, and Mg fractions respectively. Semi-total Ca content reduced in all depths, and semi-total K contents, in turn, only decreased until 20 cm of depth. The semi-total Mg contents have not been modified over the cultivations. Considering crop management with the export of plant twigs and needles and relying just on the availability of exchangeable Ca, the stocks of these nutrients in the soil would be sufficient for only one more *Pinus* cultivation, even when considering the absorption of nutrients on an 80-cm soil depth profile.

Conclusions The management adopted in the region must be modified, replacing the nutrients exported via harvesting, especially Ca. Thus, the establishment of new cultivation of *Pinus* without fertilization may have its yield impaired, especially by the Ca availability.

Keywords Exchangeable and semi-total fractions · Forest fertilization · Successive crops · Stocks of nutrient in soil

1 Introduction

Commercial *Pinus* cultivations are mostly centered in soils of low natural fertility (Smethurst 2010; Abrão et al. 2015). Moreover, the non-replacement of soil nutrients between cycles of cultivation is assigned to the lowest response in terms of fertilization of forest crops such as *Pinus*, often characterizing them as low requirement species (CQFS/RS-SC 2016). However, even in little responsive plants, the increased soil fertility has often proved to be effective in increasing the productivity of crops (Turner and Lambert 2013; Batista et al. 2015; Vogel et al. 2015; Maggard et al. 2017; Bracho et al. 2018) and maintaining the productivity levels for further rotations (Vieira et al. 2015).

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✉ Walquiria Chaves da Silva
walquiria.chs@gmail.com

1 North Carolina State University (NCSU), 101 Derieux St., Raleigh, NC 27695-7620, USA

2 Santa Catarina State University (UDESC), 2090 Luís de Camões Av., Lages, SC 88520-000, Brazil

3 Federal University of Santa Catarina (UFSC), 3000 Ulysses Gaboardi Rd., Curitibanos, SC 89520-000, Brazil

4 Klabin Inc., 26 Brasil Av., Telêmaco Borba, PR 84279-000, Brazil

The cultivation of *Pinus* without fertilization is a common practice in the south of Brazil. That said, the stock of nutrients in the soil, including potassium (K), calcium (Ca), and magnesium (Mg), which are important for the proper growth of plants (Albaugh et al. 2012), tends to be reduced throughout successive cultivations (Turner and Lambert 2013; Abrão et al. 2015). Despite the high total nutrient content in many soils, the fraction available is usually reduced and, in cultivation situations, tends to decrease gradually (Senthurpandian et al. 2009). Given this, in forest soils, due to the long crop cycles, K, Ca, and Mg contents regarded as exchangeable/available may not be the only ones to act in the plant's supply, with the participation of at least part of less labile forms of nutrients (Das et al. 2018).

The amounts of K, Ca, and Mg considered available to plants, found in the soil solution and adsorbed with low energy to negative electrical charges, are usually low in comparison with the total contents within the soil (Li et al. 2017). Less lability fractions of these nutrients are usually prevalent, and the number of different fractions varies according to the type of soil (Das et al. 2018; Portela et al. 2019). Much of the total K in the soil is in structural form, linked to primary minerals, often of minor contribution to plant nutrition (Alves et al. 2013). Similarly, the other cationic nutrients in the soil, such as Ca and Mg, can be found in primary minerals or precipitated forms, with a reduced rate of nutrient release to the soil solution in a short term (Melo et al. 2000). The contribution of less lability K, Ca, and Mg fractions is typically reduced in short-cycle crops but can be significantly important for forest species due to the several years comprising the plant's development cycle. Under a low nutrient availability in the soil, more recalcitrant fractions—forming part of the structure of minerals, may contribute to plant nutrition (Gatiboni et al. 2017; Li et al. 2017; Das et al. 2018).

The critical content for forest cultures may vary over time and is greater in the first years due to the smaller volume of soil exploited, as observed by Novais et al. (1986). In adult forests, the bigger root system, the nutrient recycled from plant residues, and the lower growth rate reduce the demand for soil nutrients. Hence, soils with naturally low fertility, albeit meeting the needs of mature crops, can be limiting the establishment of cultures (Albaugh et al. 2008), requiring early fertilization for the speedy installation of the plants (Faustino et al. 2013). In addition, the amount of accumulated nutrients in plants of forest species is significantly, especially Ca, built up in older organs. Given this, depending on what is removed from the area during harvest (Yan et al. 2017), the non-replacement of nutrients via fertilization may limit plant efficiency in future crops (Turner and Lambert 2013). The maintenance of crop residues in the soil can reduce by more than 50% the amount of nutrients removed from the growing area (Yan et al. 2017), decreasing significantly the nutrient demand of the next crop cycle.

As there is a lack of studies in southern Brazil that assess the levels and stocks of K, Ca, and Mg fractions remaining in the soil after successive *Pinus* cultivations without fertilization, such quantification may assist in the evaluation of soil capacity to withstand successive crops and in the determination of fertilization need and frequency. Thus, we aimed to quantify the levels and stocks of exchangeable and semi-total fractions of K, Ca, and Mg, and to simulate the possibility of support for new cultivation cycles in a Humic Cambisol under successive crops of *Pinus taeda*.

2 Material and methods

The study was conducted in the state of Santa Catarina, south of Brazil, in *Pinus taeda* forests with 16 and 17 years of age, in first (27° 30′ 03.38″ S and 50° 05′ 17.78″ W) and third successive cultivation (27° 29′ 59.92″ S and 50° 03′ 25.84″ W), respectively (Fig. 1). For the latter, successive cultivation totaled 49 years of successive *Pinus taeda* cultivations (three cultivation). The regional climate is Cfb–Temperate (humid mesothermal and mild summers) according to the Köppen classification (Alvares et al. 2013). The soil was classified as a Humic Cambisol according to the WRB/FAO system (FAO 1998), derived from siltstone, where kaolinite is the predominant clay mineral (Sixel et al. 2015). Forests evaluated were planted in 2 × 3-m spacing and received no fertilization. The studied area was treated with management for cellulose production. The sampling areas were selected after preliminary homogeneity assessment of soil type, altitude, sun exposure, and relief between the first and third rotation of *Pinus taeda.* Based on this, a modal unit was selected in each forest. Experimental units of 750 m^2 were delineated for the two cultivation systems, and soil samples were collected with six repetitions in each forest area, in the 0–10-, 10–20-, 20–40-, 40–60-, and 60–80-cm-deep layers, for chemical analyses, as well as undisturbed samples with volumetric rings, for determining bulk density. For chemical analyses, the soil samples were dried in an oven at 60 °C, sift in a 2-mm mesh sieve, and subjected to physicochemical characterization analysis (Table 1), according to Embrapa (2017). They were also subjected to analyses of K, Ca, and Mg fractionation as follows: the exchangeable K (K-NH_4OAc fraction) was extracted with ammonium acetate 1.0 mol L^{-1} at pH 7.0, with soil to solution ratio of 1:10. After shaking for 5 min on an orbital shaker (60 rpm) and a 16-h rest, an aliquot of the supernatant was withdrawn for quantification. The exchangeable Ca and Mg were extracted with KCl 1.0 mol L^{-1} in the soil to solution ratio of 1:20, with 120-min agitation in an orbital shaker (60 rpm) and 16-h rest (Embrapa 2017). Semi-total fractions of K, Ca, and Mg were extracted by digestion in a solution of aqua regia with 1:3 HNO_3 to HCl ratio (USEPA method

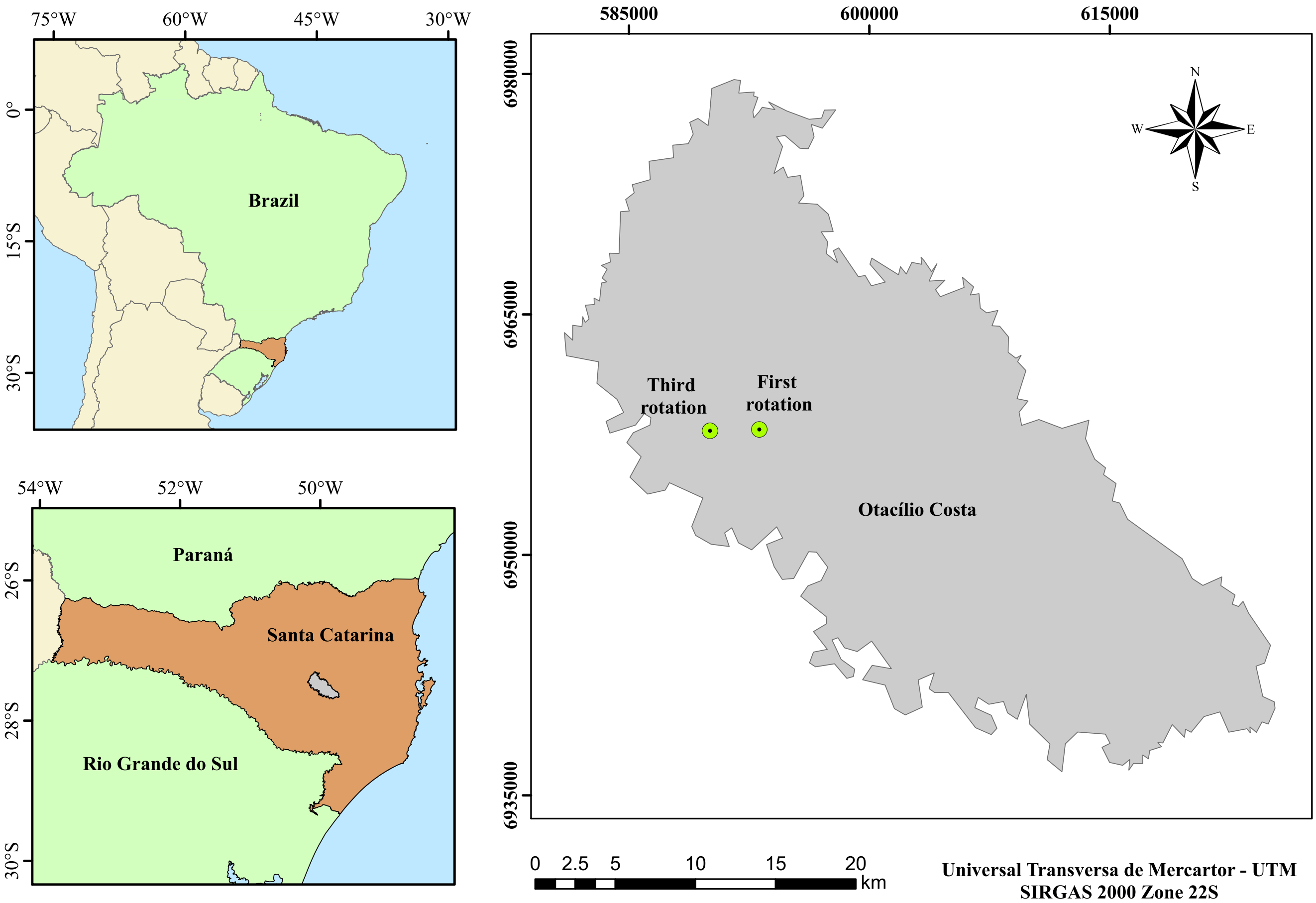

Fig. 1 Localization of study area, in the city of Otacílio Costa, state of Santa Catarina, south of Brazil

3050B): 1.0 g of soil was used, which was digested in 2.5 mL of HNO_3 and 10.0 mL of HCl, heated for 15 min (95 °C ± 5 °C). After cooling, the samples were filtered and assessed an aliquot for quantification (USEPA 1996). The quantification

Table 1 Physicochemical characterization of the soil depths evaluated, in the first and third cultivation of *Pinus taeda*

Soil depth (cm)	pH H_2O	C (g kg^{-1})	Al ($cmol_c$ dm^{-3})	Ca	Mg	CEC[a]	K (mg kg^{-1})	P	Sand (g kg^{-1})	Silt	Clay	m[b] (%)	V[c]	BD[d] (g cm^3)
Pinus taeda in first cultivation														
0–10	4.3	36.0	9.6	7.0	2.5	53.0	65.0	8.2	182.0	336.0	482.0	49.8	15.1	1.08
10–20	4.4	30.0	8.2	8.4	2.5	54.4	67.0	6.0	147.0	415.0	438.0	42.5	17.0	1.08
20–40	4.5	31.0	10.2	7.2	2.1	58.1	61.0	3.6	120.0	278.0	602.0	52.4	13.7	1.01
40–60	4.4	31.0	6.6	4.0	2.0	49.4	55.3	2.2	120.0	278.0	602.0	49.8	10.6	1.02
60–80	4.4	23.0	6.6	3.0	1.5	48.0	59.4	1.8	145.0	259.0	596.0	58.7	8.1	1.01
Pinus taeda in third cultivation														
0–10	4.0	33.0	12.3	0.5	1.2	50.4	36.3	5.7	178.0	358.0	464.0	87.2	2.9	0.92
10–20	4.1	31.0	10.3	0.7	1.1	50.5	25.0	2.5	228.0	359.0	413.0	84.4	3.0	0.97
20–40	4.1	29.0	9.7	0.4	1.4	45.2	28.4	1.1	236.0	255.0	509.0	83.6	3.0	1.04
40–60	4.2	15.0	8.7	0.6	1.0	45.0	31.6	1.8	197.0	354.0	449.0	83.6	3.2	1.12
60–80	4.3	8.0	9.1	0.5	1.0	44.9	32.5	2.6	180.0	264.0	556.0	85.0	3.0	1.12

[a] Cation-exchange capacity at a pH of 7.0

[b] Aluminum saturation

[c] Bases saturation

[d] Bulk density

of K aliquots was performed in a flame emission spectrophotometer, whereas Ca and Mg were carried out through atomic absorption spectrophotometry.

With the data of each nutrient fractions and bulk density, the calculation of K, Ca, and Mg stocks of each fraction was performed in the five layers of soil sampled. The accumulated leaf litter was collected in a 0.25-m^2 area, in triplicate. Samples were dried in an oven (60 °C) with forced ventilation and ground into a Willey-type mill. Nutrients K, Ca, and Mg were extracted by wet digestion (H_2O_2 and H_2SO_4) and determined according to the methodologies proposed by Embrapa (2017).

To estimate the potential number of crop rotations, two harvesting intensities were considered (removal only of wood or removal of wood, twigs, and needles), as well as two scenarios of soil nutrients use (use only of exchangeable contents or use of exchangeable contents + 10% of semi-total contents). The concentration of nutrients in the wood, twigs, and needles was based on the estimate proposed by Sixel et al. (2015). In all scenarios, no fertilization for nutrient replacement was considered. Four scenarios were estimated: in scenario 1, the nutritional balance accounted for the stocks of nutrients (K, Ca, and Mg) contained in the soil (exchangeable fraction (E) + leaf litter (L)) and in the plant (twigs (T) + needles (N) + roots (R)), dividing it by the amount of nutrients exported with the removal only of wood (W) in each cultivation rotation (Scenario $1 = (E + L + T + N + R)/W)$); in scenario 2, the nutritional balance accounted for the stocks of nutrients (K, Ca, and Mg) contained in the soil (exchangeable fraction (E) + leaf litter (L)) and in the plant (roots (R)), dividing it by the amount of nutrients exported with the removal of wood (W), twigs (T), and needles (N) in each cultivation rotation (Scenario $2 = (E + L + R)/(W + T + N)$); in scenario 3, the nutritional balance accounted for the stocks of nutrients (K, Ca, and Mg) contained in the soil (exchangeable fraction (E) + 10% of the semi-total fraction (ST) + leaf litter (L)) and in the plant (twigs (T) + needles (N) + roots (R)), dividing it by the amount of nutrients exported with the removal only of wood (W) in each cultivation rotation (Scenario $3 = (E + 10\,\%\,ST + L + T + N + R)/W$); in scenario 4, the nutritional balance accounted for the stocks of nutrients (K, Ca, and Mg) contained in the soil (exchangeable fraction (E) + 10% of the semi-total fraction (ST) + leaf litter (L)) and in the plant (roots (R)), dividing it by the amount of nutrients exported with the removal of wood (W), twigs (T), and needles (N) in each cultivation rotation (Scenario $4 = (E + 10\,\%\,ST + L + R)/(W + T + N)$) (Table 2).

Data were submitted to Shapiro-Wilk normality test and to the analysis of variance. The averages of data with significant effects ($P < 0.05$) were compared with the Paired Student's t test ($P < 0.05$). The R Statistical Package was used for statistical analysis.

3 Results

3.1 Fractions of K, Ca, and Mg in the soil

Higher values of exchangeable K in the soil were observed in the first *Pinus* cultivation when compared with the third cultivation, in all soil layers analyzed (Fig. 2a). Average contents of exchangeable K in the 0–80-cm layer were 66.3 and 35.2 mg kg^{-1} after the first and third cultivations, respectively. Semi-total K contents were lower after the third cultivation, in comparison with the first one, up to the 20-cm depth; average contents in the 0–80-cm layer were 1477.0 and 1232.0 mg kg^{-1} after the first and third cultivations, respectively (Fig. 2b). In addition, in the first cultivation, the exchangeable K represented, on average, 4.5% of the semi-total K, whereas in the third cultivation the contents of exchangeable K were only 2.8% of the semi-total K.

Contents of exchangeable and semi-total Ca in the soil were higher in the first *Pinus taeda* cultivation when compared with the soil with three cultivations, in all layers sampled (Fig. 3). Average values of exchangeable Ca in the 0–80-cm layer were 117.0 and 10.7 mg kg^{-1} in the soil of first and third cultivation, respectively (Fig. 3a). However, similar to the values of the exchangeable Ca, contents of semi-total Ca in the 0–80-cm layer were 157.2 and 41.3 mg kg^{-1} in the soil of first and third cultivation, respectively (Fig. 3b). In addition, in the first cultivation, the exchangeable Ca represented, on average, 74% of the semi-total Ca, whereas in the third cultivation the contents of exchangeable Ca were only 26% of the semi-total Ca.

The contents of exchangeable Mg were higher in the first cultivation in comparison with the soil of the third cultivation, at all depths (Fig. 4). Average values of exchangeable Mg in the 0–80-cm layer were 41.5 and 22.6 mg kg^{-1} in the soil of first and third cultivation, respectively (Fig. 4a). Contents of semi-total Mg in the 0–80-cm layers showed no differences between *Pinus taeda* forests (Fig. 4b), in any soil layer. Average values of semi-total Mg in the 0–80-cm layer were 1214.2 and 1177.6 mg kg^{-1} in the first and third cultivations, respectively. In the first cultivation, the exchangeable Mg represented, on average, 3% of the semi-total Mg, whereas in the third cultivation the contents of exchangeable Mg were 2% of the semi-total Ca.

3.2 Stocks of K, Ca, and Mg fractions in the soil and potential number of cultivation rotations with *Pinus taeda*

Stocks of exchangeable K fractions were higher in the first cultivation in comparison with the third, in all soil layers, whereas the semi-total K only has changed in the 0–10- and 10–20-cm layers. Considering average values, the stocks of exchangeable and semi-total K were 111.0 and 61.0 kg ha^{-1},

Table 2 Estimate of the potential number of rotations for the areas of *Pinus taeda* in first and third rotation, in four different scenarios, considering the stocks of K, Ca, and Mg of the exchangeable and semi-total fractions of the soil, in addition to the stocks in the leaf litter, twigs, needles, and roots

Component	1st rotation			3rd rotation		
	K	Ca	Mg	K	Ca	Mg
	kg ha^{-1}					
Soil						
Exchangeable fraction (*E*)	555.0	893.0	326.0	303.0	88.0	188.0
Semi-total fraction (ST)	11,830.0	1159.0	10,673.0	9862.0	352.0	10,079.0
Leaf Litter (*L*)	11.0	13.0	22.0	42.0	32.0	15.0
Plant[a]						
Wood (*W*)	101.0	112.0	36.0	107.0	119.0	38.0
Twigs (*T*)	14.0	41.0	11.0	15.0	44.0	12.0
Needles (*N*)	27.0	15.0	4.0	29.0	16.0	4.0
Roots (*R*)	54.0	130.0	30.0	57.0	138.0	32.0
	Potential number of cultivation rotations					
Balance						
Scenario 1 $(E + L + T + N + R)/W$	6.5	9.8	10.9	4.2	2.7	6.6
Scenario 2 $(E + L + R)/(W + T + N)$	4.4	6.2	7.4	2.7	1.4	4.4
Scenario 3 $(E + 10\%\text{ST} + L + T + N + R)/W$	18.3	10.8	40.6	13.4	3.0	33.1
Scenario 4 $(E + 10\%\text{ST} + L + R)/(W + T + \text{N})$	12.7	6.9	28.3	9.2	1.6	23.0

[a] Estimate according to Sixel et al. (2015), considering the 1st rotation with 16 years of age and the 3rd rotation with 17 years of age

and 2424.0 and 2033.0 kg ha^{-1} for the first and third cultivations, respectively (Fig. 5). Exchangeable K stocks have reduced 60%, 61%, 50%, 30%, and 42% in the 0–10-, 10–20-, 20–40-, 40–60-, and 60–80-cm-deep layers between the first and third cultivations, respectively (Fig. 5a). Semi-total stocks of K, in turn, decreased by 49% and 45% in the 0–10- and 10–20-cm-deep layers between the first and third cultivations, respectively (Fig. 5b).

Stocks of exchangeable and semi-total Ca fractions were higher in the first cultivation in comparison with the soil of third cultivation, for all soil layers assessed (Fig. 6). Average stocks of exchangeable Ca in the 0–80-cm layer were 178.6 and 17.6 kg ha^{-1} in the first and third cultivations of *Pinus taeda*, respectively, whereas the stocks of semi-total Ca in the 0–80 layer were 231.9 and 70.4 kg ha^{-1} in the first and third cultivations, respectively. Exchangeable Ca stocks have reduced 92%, 92%, 94%, 85%, and 83% in the 0–10-, 10–20-, 20–40-, 40–60-, and 60–80-cm-deep layers between the first and third cultivations, respectively (Fig. 6a). Semi-total stocks of Ca, in turn, decreased 86%, 78%, 61%, 55%, and 72% in the 0–10-, 10–20-, 20–40-, 40–60-, and 60–80-cm-deep layers between the first and third cultivations, respectively (Fig. 6b).

Stocks of exchangeable Mg were higher in the first cultivation in comparison with the third cultivation soil, in all layers assessed (Fig. 7a), whereas the semi-total Mg has not changed between cultivations for any of the soil layers sampled (Fig. 7b). Average stocks of exchangeable Mg in the 0–80-cm layer were 65.3 and 37.7 kg ha^{-1} in the first and third cultivations, respectively, whereas the stocks of semi-total Mg were 2134.7 and 2015.8 kg ha^{-1} in the first and third *Pinus taeda* rotations, respectively. Exchangeable Mg stocks have reduced 53%, 57%, 34%, 43%, and 33% in the 0–10-, 10–20-, 20–40-, 40–60-, and 60–80-cm-deep layers between the first and third cultivations, respectively.

The stocks of nutrients in the soil and the nutrient export intensity have influenced the number of possible *Pinus taeda* cultivations (Table 2). For the four management scenarios designed, the depletion of nutrients in the system presented the following sequence: Ca > K > Mg. Considering the most exhaustive management scenario adopted in the forest crops of the region (removal of wood, twigs, and needles), with average export of 142.0 kg ha^{-1} of K, 168.0 kg ha^{-1} of Ca, and 51.0 kg ha^{-1} of Mg per cultivation cycle (Sixel et al. 2015), in scenario 2, after three successive *Pinus taeda* cultivations, there would be K, Ca, and Mg for more 2.7, 1.4, and 4.4 crops, respectively. However, in the scenario 4 (exchangeable fraction plus 10% of semi-total K, Ca, and Mg), the number of potential crop rotations increased to 9.2, 1.6, and 23.0 cultivations, respectively (Table 2).

For less exhaustive scenarios, where only the wood is removed during harvest, the number of potential cycles is higher. In scenario 1, after three successive *Pinus taeda* cultivations, there would be K, Ca, and Mg for more 4.2, 2.7, and 6.6 crops, respectively. In scenario 3, where in addition to the exchangeable fraction 10% of K, Ca, and Mg stocks contained in the semi-total fraction of the soil was considered, the number of potential crop rotations increased to 13.4, 3.0, and 33.1 cultivations, respectively (Table 2).

4 Discussion

4.1 Changes in the K, Ca, and Mg contents in the soil

There was a reduction of the exchangeable K contents in the soil after three successive *Pinus taeda* cultivations. Considering the average of the 0–20-cm-deep layer used as a diagnosis of nutrient contents in the soils of the study region, exchangeable K contents in the soil can be classified as "low" and "very low" availability for the first and third rotations, respectively (CQFS/RS-SC 2016). In this sense, there may be the participation of less labile fractions in the plant nutrition in cultivation systems without fertilization. However, despite the higher concentration, the release rate of nonexchangeable K fractions (semi-total K) and consequent absorption by the plant may be insufficient for the proper growth of cultures (Mengel 1994; Das et al. 2018), depending highly on the soil characteristics (Alves et al. 2013) and the cycle of the crop of interest (Li et al. 2017). In this sense, the semi-total fraction of K can be considered an important source of nutrients for longer-cycle plants, as observed in this study with *Pinus taeda*, in which there was a significant reduction in contents of this fraction in the surface layers of the soil. Such contribution of less labile nutrient fractions for *Pinus* species had been studied in other locations with the use of organic non-labile phosphorus (Chen et al. 2004) and the decrease of organic fractions of P in soils of the same study (Gatiboni et al. 2017).

The low availability of nutrients in the labile fraction may result in the contribution of the more stable fraction to plant nutrition. Li et al. (2017), aiming at evaluating the changes in K fractions in soils of the Chinese plains, cultivated with a

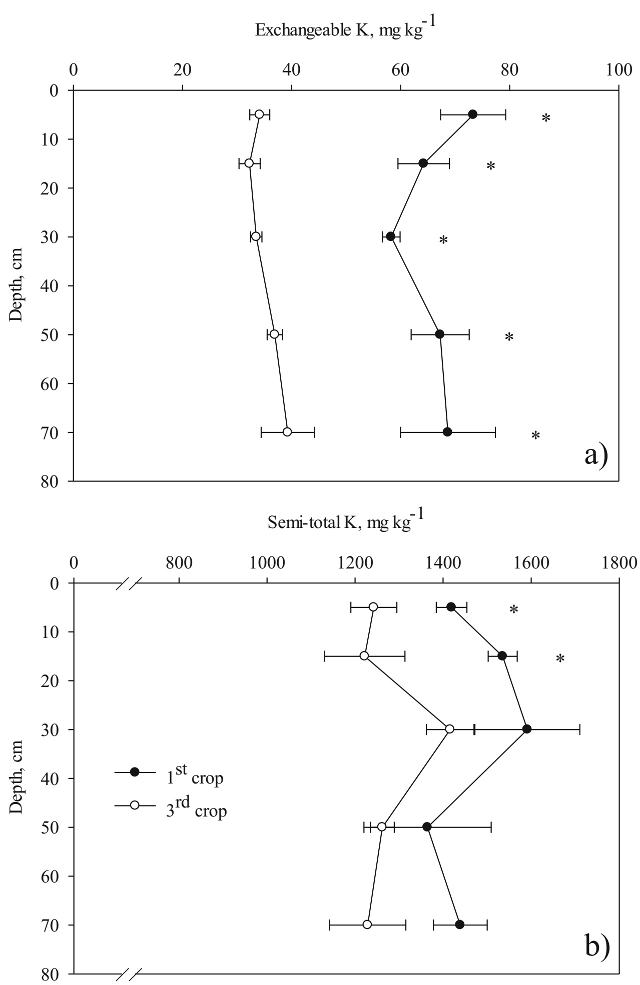

Fig. 2 Mean levels of exchangeable (**a**) and semi-total (**b**) potassium extracted from the soil in *Pinus taeda* forests in the first and third rotation. Means at the same depth followed by an asterisk (*) present significant statistical difference by the Student's *t* test ($P < 0.05$). Horizontal lines represent the standard error

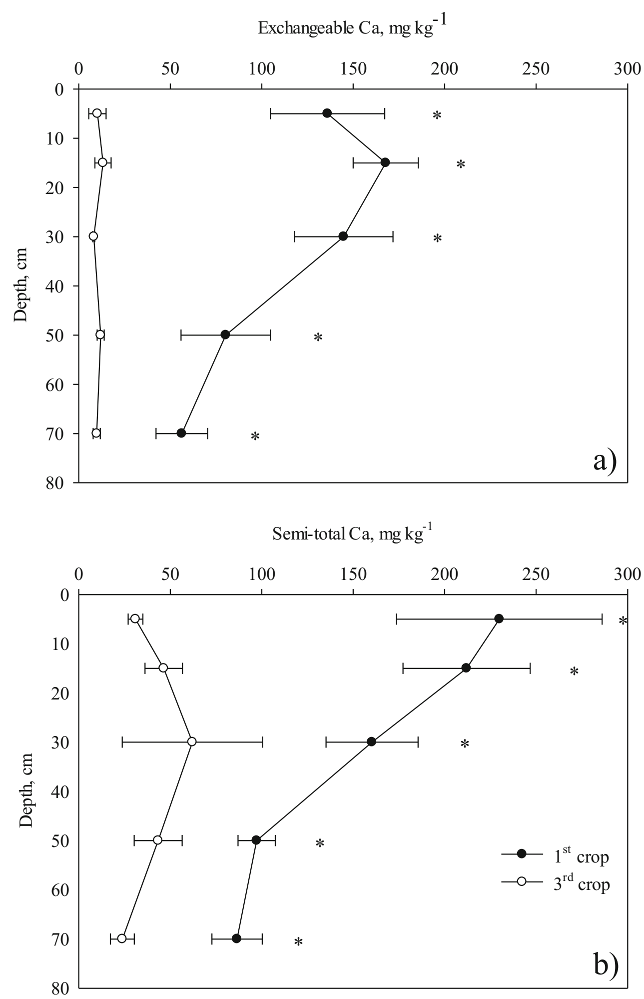

Fig. 3 Mean levels of exchangeable (**a**) and semi-total (**b**) calcium extracted from the soil in *Pinus taeda* forests in the first and third rotation. Means at the same depth followed by an asterisk (*) present significant statistical difference by the Student's *t* test ($P < 0.05$). Horizontal lines represent the standard error

succession of corn-wheat for 25 years without potassium fertilization, observed that the exhaustion of the exchangeable fraction of K promoted the conversion of the total nutrient fraction into intermediary-lability forms and, later, into the exchangeable form. Over time, however, there was a significant reduction in the concentration of exchangeable K, reducing crop productivity. Such a reduction is due to the lower capacity of recalcitrant forms to satisfy the plant's absorption rate (Das et al. 2018), especially in the short term.

Exchangeable Ca contents in the experiment site are classified as "low" for the cultivation of *Pinus* in soils of the study region (CQFS/RS-SC 2016). In this sense, the concentration of exchangeable Ca, after three successive cultivations, is about 40 times less than the recommended for the *Pinus* crop (CQFS/RS-SC 2016), justifying the use by part of the plants and the consequent reduction of semi-total fraction contents (Fig. 4b). Evaluating changes in the availability of nutrients in a natural field subjected to one and two *Pinus* cultivations without fertilization, Abrão et al. (2015) observed a decrease in exchangeable Ca only in the 0–5-cm-deep layer after the first cultivation and in the 0–20-cm-deep layer after the second successive crop, indicating some depletion of the exchangeable fraction as the cultivations progressed, in addition to the possible participation of less available forms in the plant nutrition. Calcium is one of the nutrients required in larger quantity by forest species, resulting in an intense reduction of its content in the soil (Sixel et al. 2015). Also, *Pinus taeda* presents large amounts of fine roots and coarse roots in deeper layers of soil (75–100 cm) (Simms et al. 2017) which can increase the uptake of nutrients such as Ca.

Considering the average of the 0–20-cm-deep layer and considering the two cultivations used for the diagnosis of nutrient contents in the soils of the study region, exchangeable Mg contents in the soil can be classified as "adequate" (CQFS/RS-SC 2016). Only the exchangeable fraction of Mg was reduced in the soil after the third *Pinus* cultivations (Fig. 4a). Semi-total Mg contents had no significant change between cultivations, which shows that, for this nutrient, the

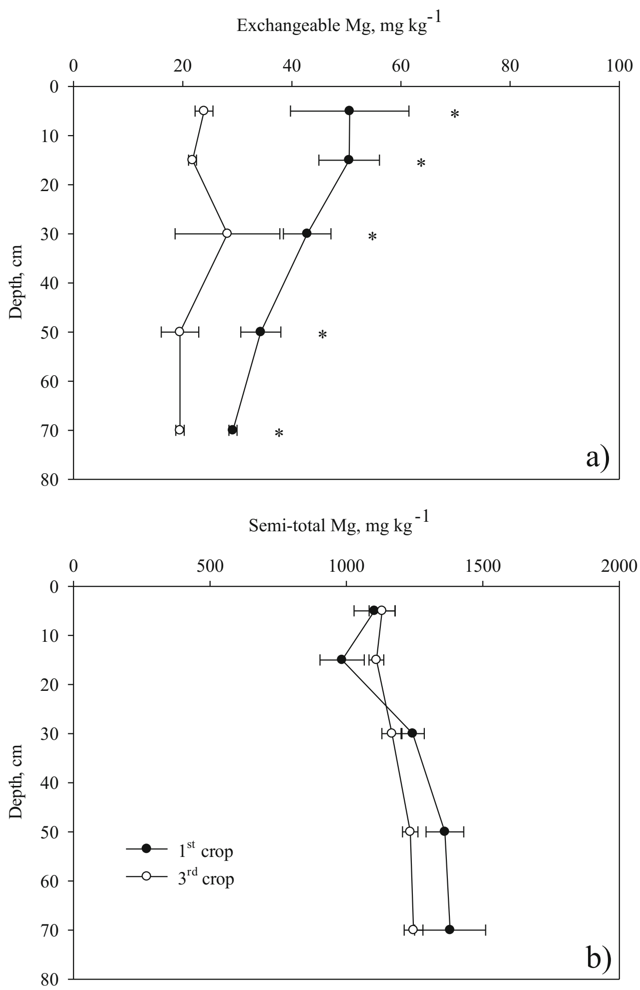

Fig. 4 Mean levels of exchangeable (**a**) and semi-total (**b**) magnesium extracted from the soil in *Pinus taeda* forests in the first and third rotation. Means at the same depth followed by an asterisk (*) present significant statistical difference by the Student's *t* test ($P < 0.05$). Horizontal lines represent the standard error

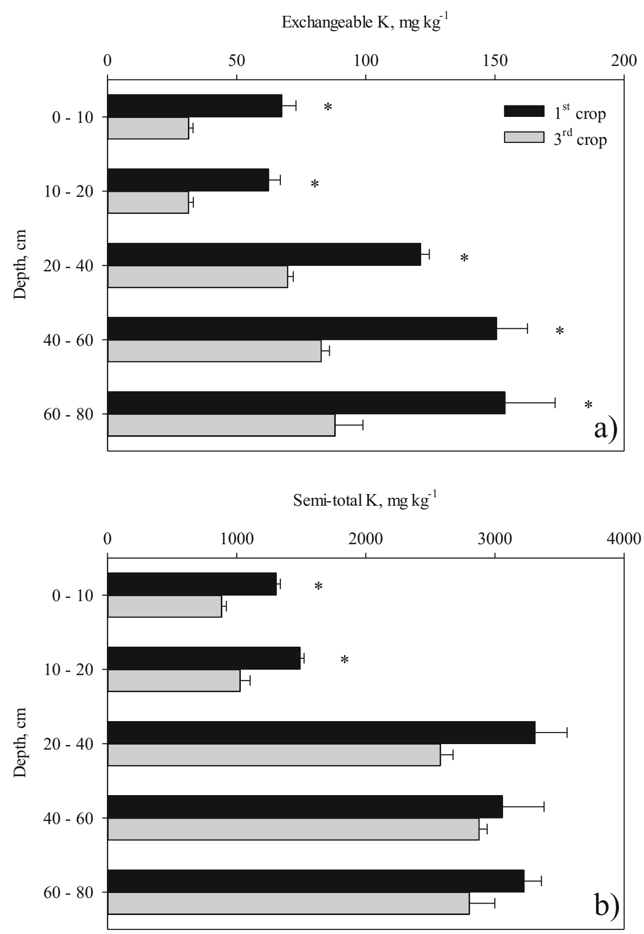

Fig. 5 Stocks of exchangeable (**a**) and semi-total (**b**) potassium, in the five depths evaluated (0–10, 10–20, 20–40, 40–60, and 60–80). Means at the same depth followed by an asterisk (*) present significant statistical difference by the Student's *t* test ($P < 0.05$)

exchangeable fraction was enough for plant nutrition. Total contents of Mg in Humic Cambisol in southern Brazil may vary from 1400.0 to 2000.0 mg kg^{-1}, in which almost all the nutrient (95.4 to 99.7%) is associated with biotite particles (Melo et al. 2000). In the study of Abrão et al. (2015), highlighted above, even after two successive *Pinus taeda* cultivations without fertilization, there was a reduction of exchangeable Mg only in the 0–5-cm-deep layer, showing this nutrient is less critical for the species of interest.

4.2 Changes in the stocks of K, Ca, and Mg fractions in the soil and potential number of *Pinus taeda* rotations

Stocks of exchangeable and semi-total K have decreased between the first and third cultivations with *Pinus*, indicating that all fractions were absorbed by the *Pinus taeda*, which may have occurred due to the non-replacement of this nutrient via fertilization. Stocks of K fractions are mainly related to the source material of the soil (Li et al. 2017; Das et al. 2018) and for fertilizer supply. In a large portion of the acidic soils and with excessive rainfall (precipitation above evapotranspiration), K reserves are limited and will be exhausted if there is no replacement. For K, soil exhaustion may occur between 3 and 15 cultivations, depending on the management system (Table 2). However, it is worth noting that, albeit the total content of K in the soil is enough for new cultivations, the plant performance may be below the expected (Mengel 1994; Turner and Lambert 2013; Das et al. 2018), greatly due to the predominance of less labile forms of the nutrient (Portela et al. 2019) (Fig. 2).

The stock of Ca in the soil was significantly reduced after the third rotation, in both fractions analyzed. For the nutritional balance estimated in this study, the Ca appears as the most limiting nutrient, whose export without any replacement may limit the offer of this nutrient in the soil for the next cultivations. The very most recalcitrant fraction (semi-total Ca) has suffered a substantial reduction after the third cultivation, showing the great demand of this nutrient for the *Pinus taeda* culture (Sixel et al. 2015), which is one of the nutrients most affected by the harvesting system (Vieira et al. 2015). The

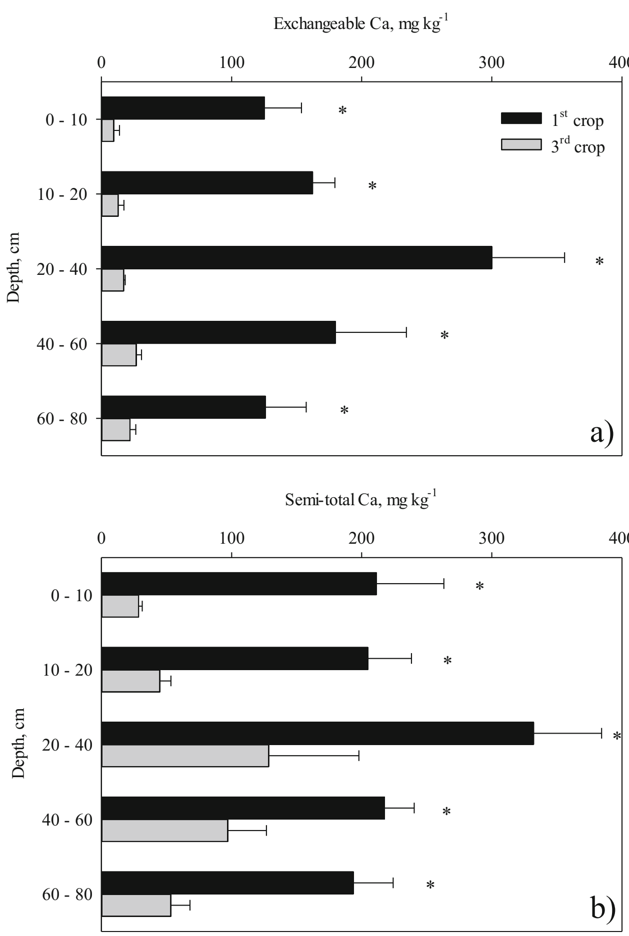

Fig. 6 Stocks of exchangeable (**a**) and semi-total (**b**) calcium, in the five depths evaluated (0–10, 10–20, 20–40, 40–60, and 60–80). Means at the same depth followed by an asterisk (*) present significant statistical difference by the Student's *t* test ($P < 0.05$)

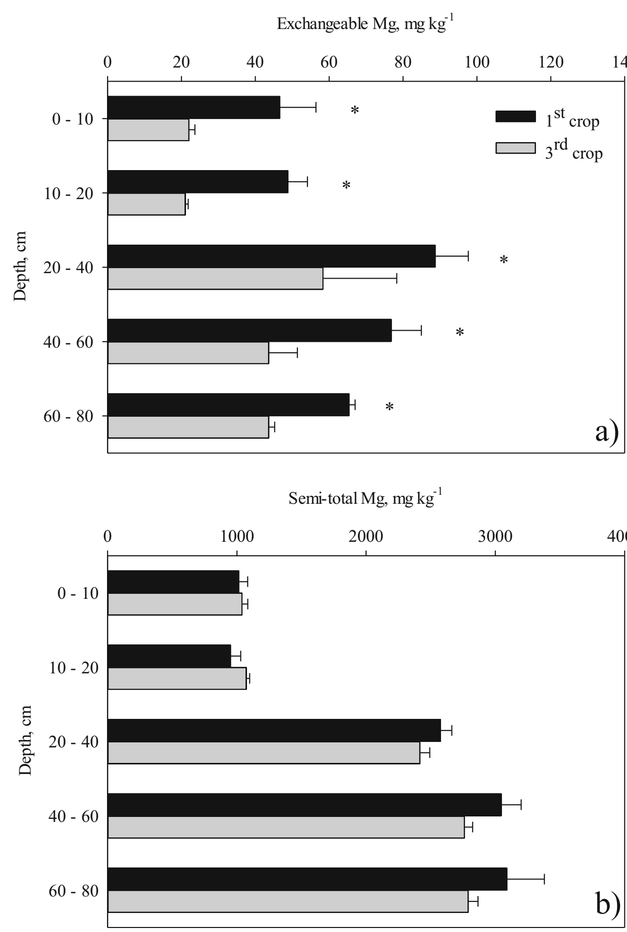

Fig. 7 Stocks of exchangeable (**a**) and semi-total (**b**) magnesium, in the five depths evaluated (0–10, 10–20, 20–40, 40–60, and 60–80). Means at the same depth followed by an asterisk (*) present significant statistical difference by the Student's *t* test ($P < 0.05$)

release and use of the semi-total fraction of Ca can be optimized by its greater instability under low pH conditions (Sharpley et al. 1987), which is the case of the soil under study (Table 1). In the sense, the importance of the harvesting method adopted is emphasized: the maintenance of plant debris on the soil may increase the leaf litter on the soil surface, contributing to the nutrition of *Pinus taeda* (Hopmans and Elms 2009).

Stocks of Mg in the soil after the third *Pinus taeda* cultivation can still be considered sufficient for new crops, especially when one considers the participation of the semi-total fraction, which was not reduced in this 49-year period of cultivation. The Mg stocks are sufficient for at least four crops (scenario 2, third rotation) up to 41 crops (scenario 3, first rotation), greatly due to the fact that its exportation by plants is lower than that observed for other nutrients. Considering the 16-year-old *Pinus taeda* exports about 51.0 kg ha^{-1} of Mg (Sixel et al. 2015), it is estimated that exports of 153.0 kg ha^{-1} of Mg in three rotation would be less than the total stock difference between the first and third rotations, being, thus, more consistent to compare only the difference of exchangeable Mg stocks (138.0 kg ha^{-1} of Mg from the first to the third rotation) when relating the *Pinus taeda* cultivation.

Despite the low leaf litter content and, consequently, the low stock of accumulated nutrients, this component may be important for the *Pinus taeda* nutrition, justifying its use as a source of nutrients in further cultivations (Batista et al. 2015; Turner et al. 2017). The increased amount of leaf litter under the soil surface may be obtained with, among other practices, proper fertilization (Vogel et al. 2015). However, the importance of leaf litter features a strong relationship with the harvesting system adopted. Systems that allow the permanence of greater contents of vegetable biomass, e.g., without the removal of twigs, will represent a greater stock of nutrients in the soil (Turner and Lambert 2011; Yan et al. 2017). According to Yan et al. (2017), the maintenance of leaves, branches, barks, and roots in the harvest areas can reduce between 44 and 89% the export of nutrients.

Thus, the results of this study show that one should be careful about the replacement of nutrients in soils with forestry use, as the export may compromise the yield of the culture in subsequent cultivations without fertilization. The exchangeable fraction of Ca, Mg, and K were significantly reduced in all soil layers sampled. However, there was also a reduction in the semi-total fraction, of greater recalcitrance. The Ca was the nutrient that suffered the greatest reduction of its semi-total form, this being observed throughout the soil layer sampled, whereas the use of semi-total K occurred until 20-cm deep. On the other hand, the semi-total Mg has suffered no alterations after the third cultivations. Such behavior of cation fractions in the soil influences the potential number of rotations: the Ca, nutrient that suffered a greater reduction in the soil, is also the most limiting one, followed by K and Mg. This limitation of Ca can be due to the greater exportation by the wood since Ca is the cation most exported by *Pinus taeda* (Sixel et al. 2015). The potential number of rotations suffers great influence of the harvesting management adopted: in more conservationist systems, by less removal of nutrients in which only the wood is removed from the system, there is greater recycling of nutrients and, consequently, an increased number of potential cultivations with *Pinus taeda.*

5 Conclusions

Exchangeable cation content and stock are significantly reduced after successive *Pinus* cultivations without fertilization up to 80 cm of soil depth. The semi-total fraction of Ca featured reduced availability and stocks in the soil up to the 80-cm-deep layer, whereas for K this has only occurred in the surface layers—up to 20-cm deep. There was no reduction of semi-total Mg fraction contents and stocks.

The soil capacity to receive new *Pinus* crops without nutrient replenishment via fertilization depends on the type of harvesting. Stocks of K and Mg within the soil after the third successive *Pinus* cultivation may allow new cultures; however, Ca can be a limiting nutrient, especially in systems were cultural remains are removed from the area. Thus, the establishment of new cultivation of *Pinus* without fertilization may have its yield impaired, especially by the Ca availability.

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