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Potassium, Calcium, and Magnesium Distribution in an Oxisol under Long-Term Potassium-Fertilized Apple Orchard

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Abstract: Most Brazilian soils do not possess sufficient concentrations of available potassium (K) to produce maximum apple yield. Potassium distribution was evaluated with a depth profile of a Humic Xanthic Hapludox receiving K fertilization in an apple orchard, cv. Gala/MM106, at Vacaria, Rio Grande do Sul, Brazil. Treatments consisted of four rates of annual maintenance K fertilization. After 12 years of cultivation, soil was sampled in eight depth increments. Potassium, calcium (Ca), and magnesium (Mg) contents were extracted by Mehlich I, ion-exchange resin, and ammonium acetate pH 7.0. Long-term application of K fertilizer resulted in K accumulation mainly in the 0- to 30-cm surface layer, with low K mobilization to deeper layers. Increasing rates of K fertilizer did not affect soil Mg concentration but induced a lower Ca concentration extracted by Mehlich I, especially in the 0- to 20-cm layer. The estimated K_2O rate for maximum apple yield was 86.5 kg/ha/year.

Keywords: *Malus domestica*, potassium, potassium fertilization, profile of the soil

INTRODUCTION

Potassium (K) is probably the second-most important nutrient for maximum apple fruit yield and quality, being surpassed in some situations by nitrogen

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(N) and in others by calcium (Ca). Its function in the plant is regulation of cell turgor (stomata opening and closure), carbohydrate transportation, respiration, and fruit quality, among others (Marschner 1995). Even though it is very mobile in plants, its leaf concentration remains almost stable during the summer, and decreases at the beginning of fruit formation. At the end of each growing season, K migrates to the leaves.

Potassium is a highly available nutrient in most soils of southern Brazil, where the majority of apple orchards are established. The high K content is attributed to the parent material and to the fact that, with few exceptions, soils are relatively young (Suzuki 1986). Nevertheless, without appropriate fertilization management, the content of available K in the soil could quickly decrease (Suzuki and Basso 1997).

Accumulation of exchangeable K in the soil as a function of successive applications of K fertilizer for several growing seasons has been reported by Findley (1973), Souza et al. (1979), Garz et al. (1993), and Venkatesh-Bharadwaj et al. (1994). Usually, long-term K application increases the concentration of exchangeable K, mainly in the surface layer of the soil, without a proportional increase in deeper layers (Malhi et al. 2003).

Interactions of K with Ca and magnesium (Mg) may occur either when plants are cropped under low soil Ca and Mg concentrations or when they are species with a high K demand (Usherwood 1982). Accumulation of exchangeable K in the soil will likely affect Ca and Mg availability in the surface and subsurface layers, mainly in areas receiving high K rates. Conditions where continuous K application does not result in high K accumulation in the soil are not likely to influence the relationship between K and the other cations. Conversely, K distribution may vary along the soil profile, depending on the soil type. Under the conditions of our field experiment in an apple orchard, the object of the present work, the accumulation of high exchangeable K concentration in the 0- to 20-cm soil layer might have affected the relationships between this nutrient and the other cations in the soil with depth. It is possible that high K concentrations in this layer have also affected the concentration of this nutrient in deeper soil layers, consequently altering the relationships with the other soil cations. The objective of this study was to evaluate K, Ca, and Mg distribution along the profile of an Oxisol that supported an apple orchard fertilized with K for 12 years.

MATERIALS AND METHODS

This study was conducted using soil samples collected from a field experiment involving K fertilization in an apple orchard, carried out since 1990 on a Humic Xanthic Hapludox, at Vacaria, Rio Grande do Sul, Brazil (28° 30′ S, 50° 42′ W, and 955 m above sea level). This soil contains clay and CEC concentrations of 590 g kg^{-1} and 170 $mmol_c$ dm^{-3} in the 0- to 10-cm layer, 630 g kg^{-1} and 158 $mmol_c$ dm^{-3}in the 10- to 40-cm layer, and 730 g kg^{-1} and 131 $mmol_c$

dm^{-3}in the 40- to 60-cm layer, respectively (Brazil Ministéro da Agricultura 1973). Initial soil K concentration, extracted by Mehlich-I solution (0.05 M $HCl + 0.0125$ M H_2SO_4), was 45 mg dm^{-3}. Gala/MM106 nursery trees were planted at a spacing of 2.5 × 5.0 m. Treatments were three annual K fertilization rates, 50, 100, and 150 kg/ha of K_2O, and the control, in a completely randomized block experimental design, with four replications.

After 12 years of cultivation, soil sampling was performed at the drip line of the tree canopy (tree height varying from 2.0 to 2.5 m), with a Dutch-type soil auger, during the vegetative growth period of the apple tree (stage H—fall of the petals). Soil was sampled at eight depths (0–2.5, 2.5–5, 5–10, 10–20, 20–30, 30–40, 40–50, and 50–60 cm). Samples were air dried, ground, passed through a 2-mm-screen sieve, and stored for the analysis. Fruit yield of the corresponding growing season was also measured in the 12-year-old apple orchard. Soil K, Ca, and Mg were extracted by Mehlich I, which is the extractant for K in the Rio Grande do Sul state (Mielniczuk, Ludwig, and Bohen 1969); by the ion-exchange resin, used in São Paulo state (Raij and Quaggio 2001); and by 1 M ammonium acetate pH 7.0, considered a reference for exchangeable K (Pratt 1965). Potassium was determined by flame photometry, and both Ca and Mg were determined by atomic absorption spectrophotometry.

Data were subjected to analyses of variance and regression analysis. The magnitude of the determination coefficients (at 5%) and the appropriate description of the chemical and biological phenomena were adopted as a criterion for choosing the statistical model.

RESULTS AND DISCUSSION

Distribution of the Soil K Contents and Fruit Yield

Long-term K fertilization promoted high K accumulation in the surface horizon at the highest rates of K fertilizer (Figure 1). Potassium concentrations were 34, 21, and 45 $mmol_c\ dm^{-3}$ for Mehlich I, ion-exchange resin, and ammonium acetate pH 7.0, respectively. Concentrations greater than 3.1 $mmol_c\ dm^{-3}$, extracted by Mehlich I, are considered high according to the Soil Fertility Commission of the Rio Grande do Sul and Santa Catarina states (Comissão de Fertilidade do Solo 1995). These high K concentrations in the surface horizons where the highest rates of potassium fertilizer when applied are consequence of annual fertilization during the 12 years when the experiment was carried out.

Depending on the extractants, differences in available K concentrations were found and were related to the extractant mode of action. Acid extractants induce not only ion exchange but also H^+ ion adsorption by the soil, blocking a negative charge and thus releasing cations to the soil solution. On the other hand, resin allows the results of the chemical analyses to represent the characteristics of the soil that regulate K diffusion and estimates K

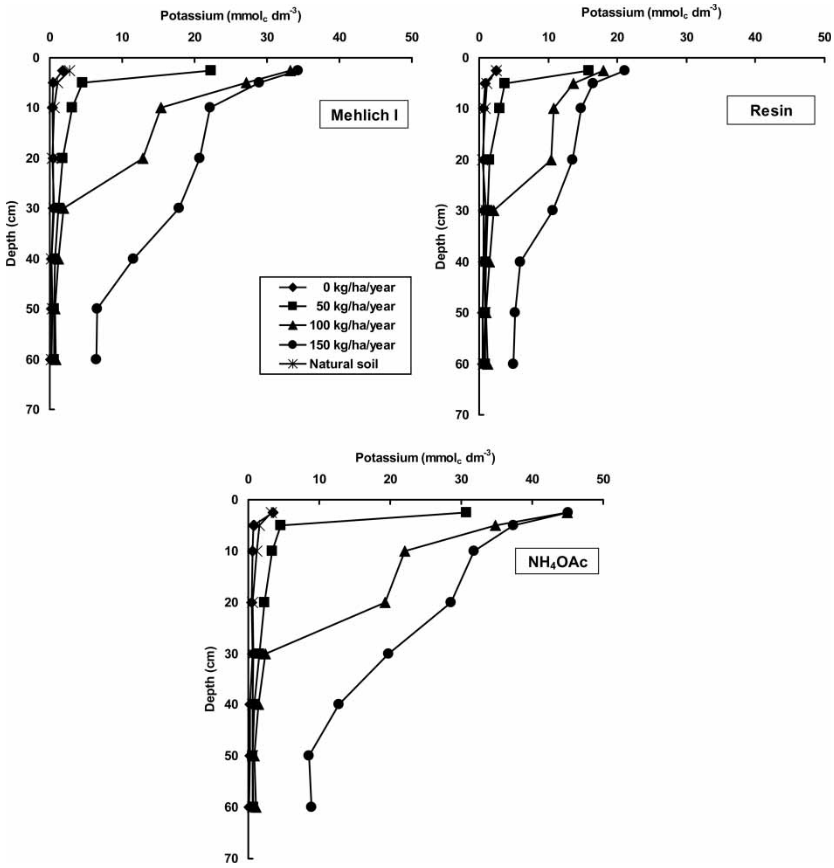

Figure 1. Distribution of K concentrations obtained by Mehlich I, ion-exchange resin, and ammonium acetate at pH 7.0 along the profile of a Humic Xanthic Hapludox, cultivated with apple tree for 12 years, submitted to four rates of K fertilization (0, 50, 100, 150 kg/ha/year of K_2O) and in the natural condition (with neither cultivation nor potassium fertilization).

concentration in the soil solution, which is directly related to K mass flow to the plant-root system.

In the absence of K fertilization, results were similar to those obtained for an uncropped area, even with apple tree cultivation for several years. Average concentrations were considered as critical limits for Rio Grande do Sul and Santa Catarina crop conditions (Comissão de Fertilidade do Solo 1995).

Regardless of the extraction method, K concentrations decreased gradually to the 40-cm depth at the highest K fertilizer rates (100 and 150 kg ha^{-1} of K_2O), whereas its concentration decreased abruptly below the 0- to 2.5-cm layer at the lower rate (50 kg/ha/year of K_2O) (Figure 1).

Souza et al. (1979) observed K accumulation in the surface layer of an Oxisol under "Cerrado" (Savannah), and K movement down to 60 and 90 cm, after applying 250 and 500 kg ha^{-1} of K_2O, respectively.

Soil exchangeable K accumulation due to long-term application of K fertilizer was reported by Garz et al. (1993) in a 40-year field experiment in Germany. There were differences in K concentration in soils fertilized with 52, 102, and 210 kg ha^{-1} of K_2O. Exchangeable K decreased in the absence of K fertilization, whereas its application avoided soil K deficiency (Findley 1973; Venkatesh-Bharadwaj et al. 1994).

The high accumulation of K in the surface soil layer during 12 years of long-term application of K fertilizer can be attributed to the high soil CEC and soil clay content, as well as to the dolomitic lime applied when the orchard was planted (10.7 t ha^{-1}), which may have prevented an intense leaching of this element. In the region where this experiment was carried out, the annual rainfall ranges between 1,200 and 1,600 mm, which might promote excessive K leaching in sandy soils with low CEC. Cation leaching, particularly K, is influenced by CEC, which is associated with soil pH and with Ca and Mg concentrations (Raij and Camargo 1973). The reduction in K losses after liming increases basic cation retention due to the release of pH dependent negative charges (Quaggio, Dechen, and van Raij 1982). It is also probable that the 2:1-type clay present in this soil might have favored K fixation on stronger adsorption sites, as noticed by Suzuki (1986), thus preventing its leaching. High 1:1-type clay content promotes intense K loss due to nonselective K adsorption, in contrast to the 2:1 clay that strongly binds great amounts of K (Mengel and Kirkby 2001).

Extractable K obtained by Mehlich I, resin, and ammonium acetate increased in depths greater than 30 cm only after the application of the highest rate (150 kg/ha/year) of K_2O. This result can be explained by the leaching of the element down the soil profile, due to the high concentrations of K in the surface layer (Figure 1). At the other K rates, the characteristics of the soil and the low K concentrations in the surface layer did not allow leaching of the element. Considering that for apple trees, the proportion of fine roots (thickness less than 1 mm) responsible for most of the absorption of water and nutrients is 74% in the 0- to 30-cm soil layer (Hoffmann and Bernardi, 2004), the distribution of K in the soil due to fertilization was sufficient for the nutrient supply required by the plants.

In deeper layers, at the rates of 50 and 100 kg/ha/year of K_2O, K concentrations were close to those of the uncropped soil. Similar results were described by Malhi et al. (2003), who evaluated the effect of annual applications of two rates of N (as ammonium nitrate) for 30 years and of K (potassium chloride) for 14 years to forage plants. After the application of 46 kg ha^{-1} of K, not only was the decrease in the concentration of exchangeable K corrected as a result of K fertilization, but there was also an increase in exchangeable K concentration, mainly in the 10- to 15-cm layer. At the 30-cm depth, there was no proportional increase, even with high concentrations in the surface layer of the soil.

In the 0- to 2.5-cm layer, soil K concentrations were affected by rates of K fertilization, following a quadratic model, and reached close to 30, 23, and 45 mmol$_c$ dm^{-3} for Mehlich I, ion-exchange resin, and ammonium acetate at pH 7.0, respectively (Figure 2). From 2.5 to 20 cm, K concentrations increased linearly with the applied rates. At less than 20 cm, K concentrations

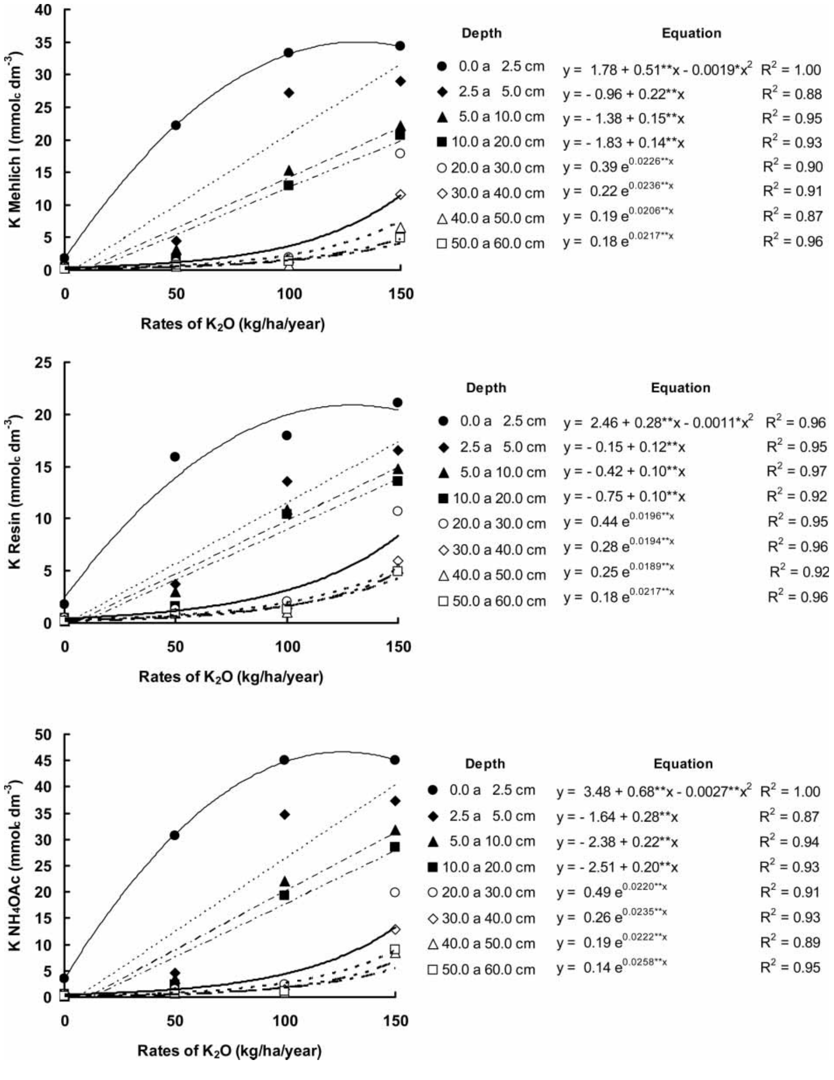

Figure 2. Relationship between K concentrations obtained by Mehlich I, ion-exchange resin, and ammonium acetate at pH 7.0, as a function of rates of K fertilization (0, 50, 100, 150 kg/ha/year of K$_2$O), along the profile of a Humic Xanthic Hapludox, cultivated with apple tree for 12 years.

increased in the soil, mainly the highest rates, following an exponential model, with higher increments from the 100 kg/ha/year K_2O rate. In general, regardless of the extracting method, K concentrations in all the studied depths were positively correlated with K_2O rate, showing higher accumulation of K in the 0- to 5.0-cm depth.

Fruit yield in the 12th harvest after planting (time of evaluation of the soil K distribution) was positively correlated ($P < 0.01$) with the applied K rate (Figure 3). Maximum fruit yield, estimated by a quadratic model, occurred at 86.5 kg/ha/year of applied K_2O. At the 100 kg/ha/year K_2O rate, there was a reduction in yield, which was probably due to a nutritional imbalance in the plants caused by the high K concentrations in the soil. In a field experiment carried out from 1992 to 1999 with Fuji apple on a humic Xanthic Hapludox, Ernani, Dias, and Flores (2002) showed that the sufficient average K rate to maintain maximum fruit yield (varying from 73 to 120 t ha^{-1}) was about 200 kg ha^{-1} of K_2O. However, only 70 kg ha^{-1} of K_2O were necessary to maintain the exchangeable K in the soil. In a study with Fuji cultivar and K rates, Nava et al. (2000) observed maximum yield (40 t ha^{-1}) at an application rate of 120 kg $ha^{-1}K_2O$ in the second year of the study. Estimated rates for maximum yield obtained by these authors were higher than those of this study, probably due to fewer fertilizer rates, as well as larger yield, which probably resulted in smaller accumulation of the nutrient in the soil during the study period and largest uptake of the nutrient by the fruits.

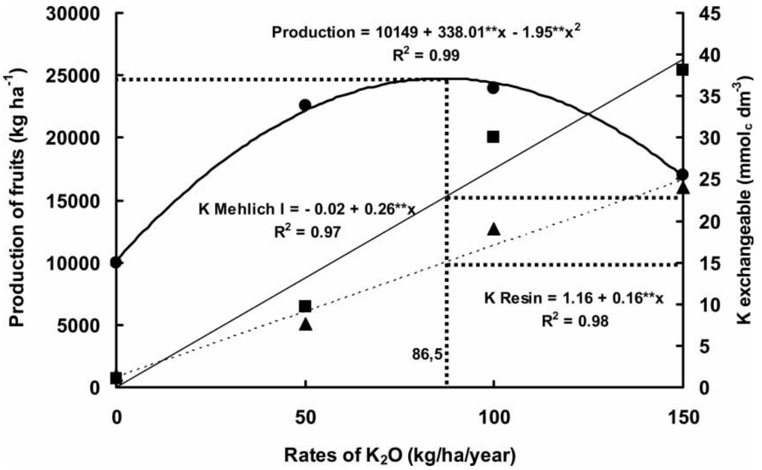

Figure 3. Relationship between apple fruit yield (•), concentrations of K by Mehlich I (■), and K by ion-exchange resin (▲) in the layer 0–20 cm deep, and rates of K fertilization (0, 50, 100, 150 kg/ha/year of K_2O), at the 12th year after planting.

The concentrations of soil K extracted by Mehlich I and ion-exchange resin from the 0- to 20-cm layer (considering the average of the values obtained in the layers from 0 to 2.5, 2.5 to 5, 5 to 10, and 10 to 20 cm) increased linearly with the applied fertilizer rates (Figure 3). At maximum fruit yield, soil K concentrations estimated by the model were 22.5 and 14.9 $\text{mmol}_c\,\text{dm}^{-3}$ for Mehlich I and ion-exchange resin, respectively. Taking into account the fertilizer recommendation for apple in RGS and SC states (Commissão de Fertilidade do Solo 1995), soils with 3.1 $\text{mmol}_c\,\text{dm}^{-3}$ of K would contain an adequate nutrient supply. However, in this study, this concentration in the soil was reached with the application of 12 kg/ha/year of K_2O. Nevertheless, the estimated yield for this condition was only 14 t ha^{-1}, much lower than the maximum yield obtained in this experiment (approximately 25 t ha^{-1}). For an apple crop, where long-term applications of K fertilization occur, it is plausible to state that there is no leaching of the element from a soil like the one in this experiment. So, the amount of potassium required to obtain maximum yield seems to be higher than the current recommended rate for this soil.

Content Distribution of Calcium and Magnesium in the Soil

There was a higher Ca accumulation in the upper soil layers (0–30 cm) compared with the deeper layers in the profile. Values of 120, 65, and 70 $\text{mmol}_c\,\text{dm}^{-3}$ for Mehlich I, ion-exchange resin, and ammonium acetate at pH 7.0, respectively, were observed with lower K rates. This result might be explained by the effect of liming prior to orchard planting (Figure 4). In deeper layers (30–60 cm), Ca concentrations decreased abruptly to about 20, 10, and 15 $\text{mmol}_c\,\text{dm}^{-3}$ using the same extractants.

A similar trend was observed for Mg concentrations. In the upper soil layers (0 to 30 cm), values were 50, 40, and 50 $\text{mmol}_c\,\text{dm}^{-3}$ for Mehlich I, ion-exchange resin, and ammonium acetate at pH 7.0, respectively, whereas in deeper soil layers (30–60 cm) these concentrations were 10, 5, and 10 $\text{mmol}_c\,\text{dm}^{-3}$, respectively. The lower Mg concentrations obtained by the ion exchange resin were probably related to the mode of action of the extractant, which is sensitive to the processes that control nutrient availability in the soil and is more dependent on the soil characteristics (Raij, Quaggio, and Silva 1986).

Calcium and Mg concentrations extracted by ion-exchange resin and by ammonium acetate at pH 7.0 were not affected by K application rate. In the 0- to 20-cm layer, Ca concentrations extracted by Mehlich I decreased with the application of high rates of K fertilizer (Figure 5). With the high K fertilizer rates, soil Ca concentrations were lower than those observed in the uncropped soil, which may be attributed to the competition between Ca and K for exchange sites, because K, when present in high concentrations in the soil, displaces other cations from adsorption sites.

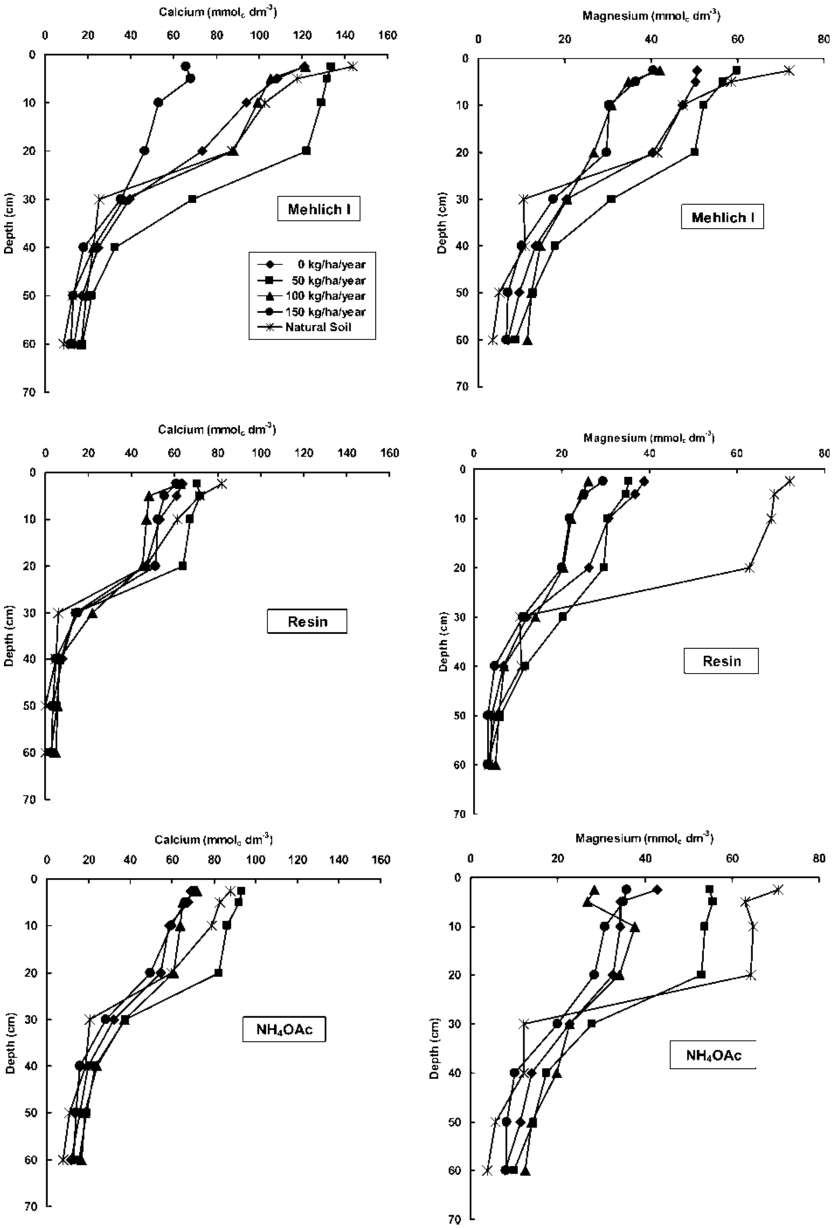

Figure 4. Distribution of Ca and Mg concentrations, extracted by Mehlich I, ion-exchange resin, and ammonium acetate at pH 7.0, along the profile of a Humic Xanthic Hapludox, cultivated with apple tree for 12 years, submitted to K fertilization (0, 50, 100, 150 kg/ha/year of K_2O) and in the natural condition (with neither cultivation nor potassium fertilization).

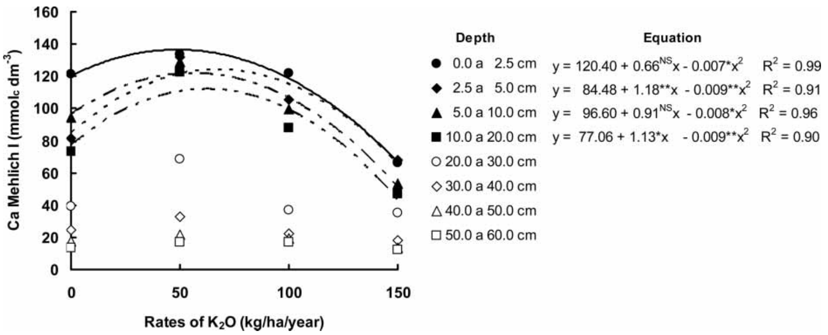

Figure 5. Relationship between Ca concentrations extracted by Mehlich I and rates of K fertilization (0, 50, 100, 150 kg/ha/year of K_2O), along the profile of a Humic Xanthic Hapludox, cultivated with apple tree for 12 years.

CONCLUSIONS

Long-term application of K fertilizers promoted K accumulation, mainly in the upper layers (0 to 30 cm), with little nutrient movement toward the deeper layers. Increasing rates of the K fertilizer did not affect soil Mg concentration but reduced soil Ca concentrations extracted by Mehlich I, mainly in the top layer (0 to 20 cm). The estimated rate to obtain the maximum apple fruit yield was 86.5 kg/ha/year of K_2O.

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