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Contribution of non-exchangeable K in soils from Southern Brazil under potassium fertilization and successive cropping[1]

Contribuição do K não-trocável em solos do Sul do Brasil submetidos a adubação potássica e cultivos sucessivos

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ABSTRACT - Intense cropping of plants in pots was used to assess the contribution of non-exchangeable K to plant uptake in different soils of Paraná State, Brazil. Surface samples from nine soil types were fertilized or not with K fertilizer and subjected to six successive cropping (i.e., soybean, pearl millet, wheat, common beans, soybean and maize) under greenhouse conditions. The crops were grown in 8-L pots for 45 days, and at the end of the sixth cropping, the soil was sampled to determination non-exchangeable and exchangeable K. Shoot dry matter yield, K taken up, non-exchangeable pool contribution to K nutrition of plants were also determined. Soils differ in the ability to K supply to the plants in the short to medium term, due to the wide range of parent material and exchangeable K and non-exchangeable K pools. When the soils were not fertilized with K, the successive cropping of plants resulted in a continuous process of depletion of non-exchangeable K and exchangeable K pools; however, this depletion was less pronounced in soils with higher potential buffer capacity of K. Concentrations of non-exchangeable K and exchangeable K were increased with the addition of K fertilizers, indicating the occurrence of K fixation in soil. Non-exchangeable K contribution to K nutrition of plants during the six croppings ranged from 50 to 73% and from 1 to 18%, respectively, without and with K fertilizer addition. These data report the importance of non-exchangeable K pools in the supply of this nutrient to plants in agricultural production systems.

Key words: Successive cropping of plants. Soil potassium budget. Exchangeable K. Potential buffer capacity of K.

RESUMO - Os efeitos dos cultivos sucessivos e da adubação potássica em condições de casa de vegetação na contribuição do K não-trocável para a nutrição das plantas em diferentes solos do Estado do Paraná, Brasil, foram investigados neste estudo. Amostras de nove solos coletadas na camada superficial (0–20 cm) foram submetidas à adição ou não de fertilizante potássico e a seis cultivos sucessivos de plantas (soja, milheto, trigo, feijão, soja e milho). Todas as culturas foram cultivadas em vasos de 8 L por 45 dias e, ao final do sexto cultivo foram coletadas amostras de solos para a deteminação do K trocável e K não-trocável. Foram também determinados a produção de matéria seca da parte aérea, a quantidade de K absorvido, e a contribuição do K não-trocável para a nutrição potássica das plantas. Os solos diferenciaram-se na capacidade de suprir K às plantas a curto e médio prazo, devido à ampla variação do material de origem e dos teores de K trocável e K não-trocável. Quando os solos não foram adubados com K, o cultivo sucessivo de plantas resultou em um processo contínuo de esgotamento das formas de K não-trocável e K trocável, sendo menos acentuado nos solos com maior poder tampão de potássio. Os teores de K não-trocável e K trocável aumentaram com a adição de fertilizantes potássicos, indicando a ocorrência de fixação de K pelo solo. A contribuição do K não-trocável para a nutrição das plantas durante os seis cultivos variou de 50 a 73% e de 1 a 18%, respectivamente, sem e com a adição de fertilizante potássico. Estes resultados reportam a importância das formas de K não-trocável para o suprimento deste nutriente para as plantas nos sistemas de produção agrícolas.

Palavras-chave: Cultivos sucessivos. Balanço de potássio do solo. K trocável. Capacidade tampão de potássio.

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INTRODUCTION

Potassium (K) is a macronutrient needed in large amounts by plants. Soil K includes the solution K, exchangeable K, non-exchangeable K and structural K, and these pools are in equilibrium, following a gradient in which its availability decreases (SPARKS; HUANG, 1985). In tropical soils with predominance of low activity clay minerals as kaolinite and sesquioxides, the solution and exchangeable K are the most important pools of this nutrient in the soil and known as the readily available K pool to plants (SHAIKH *et al*., 2007). However, the available K pool is relatively low (0.1 to 2% of total K) and corresponds to crop demand during only a few years of intense cropping and the release of K from non-exchangeable sources can contribute significantly to plant K nutrition in some soils (ROSOLEM; VICENTINI; STEINER, 2012; SIMONSSON *et al*., 2007). When solution and exchangeable K are reduced to low levels by plant uptake and/or leaching, non-exchangeable K can be released from clay interlayers (BRITZKE *et al*., 2012; ROSOLEM; VICENTINI; STEINER, 2012; SIMONSSON; HILLIER; ÖBORN, 2009). Therefore, for sustainable crop production, the available K must be continually replenished through non-exchangeable and mineral K reserves.

For the appropriate management of K fertilization is important assess the availability of different soil K pools and their influences on K dynamic in the soil profile. This is because the insufficient fertilizer application may lead to depletion of the soil K reserves (ROSOLEM; STEINER, 2017; STEINER *et al*., 2012; KAMINSKI *et al*., 2007). On the other hand, the excessive fertilizer rates may result in low nutrient use efficiency (SHIN, 2014), as well as intensify K losses by erosion and leaching (ROSOLEM; STEINER, 2017; ROSOLEM *et al*., 2010).

The intense cropping and K fertilizer application may affect the relation between soil K pools and its availability, leading to changes in clay mineral composition (BORTOLUZZI *et al*., 2012; FRAGA *et al*., 2009; SIMONSSON; HILLIER; ÖBORN, 2009). Understanding the mechanisms that involve release and fixation of K in soil is important because soils may contain widely variable pools of K that are potentially mobilized by chemical weathering of soil minerals (SIMONSSON; HILLIER; ÖBORN, 2009). In a sandy soil of Rio Grande so Sul, Brazil, Simonete *et al*. (2002) found that non-exchangeable K contribution to K nutrition of plants was 30% of K taken up in a ryegrass-rice cropping system. Fraga *et al*. (2009) found that non-exchangeable K contribution to the K nutrition of rice plants ranged 12 to 72% in the treatments fertilized and non-fertilized with potash fertilizer, respectively. Borkert *et al*. (1997) observed a marked decrease in soil exchangeable K concentration during successive years of soybean crops and reported that it would be necessary to apply at least 80 kg ha^{-1} yr^{-1} of K_2O to maintain soil exchangeable K concentrations and avoid depletion of the soil K reserves.

The contribution of non-exchangeable K to plant-available K^+ can be estimated by intensive cropping of plants in pot (ROSOLEM; VICENTINI; STEINER, 2012; FRAGA *et al*., 2009). However, the understanding of the contribution of these pools of K on plant nutrition for the Paraná soils is still incipient (ALVES *et al*., 2013; MARTINS; MELO; SERRAT, 2004). This study was designed to investigate the effects of potassium fertilization and successive cropping on the mobilization of non-exchangeable K by plants in different soils of Paraná State, Brazil.

MATERIAL AND METHODS

Pot experiments were carried out in a greenhouse at the Western Parana State University in Marechal Cândido Rondon, Paraná, Brazil (24º31’ S, 54º01’ W, and altitude of 420 m) to study the effects of K and successive cropping on soil K dynamics. Surface samples (0-0.20 m) from nine non-cultivated soils were collected in areas under native vegetation or ancient reforestation in the Paraná State, Brazil (Table 1). Soils were classified according to the Brazilian System of Soil Classification (EMBRAPA, 2013) and according to the Keys to USDA Soil Taxonomy (SOIL SURVEY STAFF, 2010). Properties of the soils were determined by adopting standard procedures, and some characteristics are shown in Table 2. Soil pH in water was determined potentiometrically in a 1:2.5 (soil: water) suspension using a combined calomel reference glass electrode and pH meter. Organic matter was quantified by oxidation with potassium dichromate in the presence of sulfuric acid, followed by titration with ammonium Fe(II) sulfate (EMBRAPA, 1997). The amounts of Ca^{2+} and Mg^{2+} were extracted by the 1.0 mol L^{-1} potassium chloride (KCl) solution and determined by atomic absorption spectrophotometry. Exchangeable K was extracted by the 1.0 mol L^{-1} ammonium acetate (CH_3COONH_4) solution buffered to pH 7.0. Exchangeable Al was extracted by 1 mol L^{-1} KCl solution and determined by titration with 0.025 mol L^{-1} NaOH. Cation exchange capacity (CEC) was estimated by the summation method (CEC = Ca + Mg + K). Potential buffer capacity of soils with respect to K (PBC^K) was determined according to the method proposed by Mielniczuk (1978). Particle size analysis was performed by the pipette method (EMBRAPA, 1997), based on decantation speed of different soil particles after dispersion in 0.015 mol L^{-1} $(NaPO_3)_6$. NaO/1 mol L^{-1} NaOH by overnight shaking. The Fe and Al was extracted

Table 1 - Classification, parent material and sampling site of the nine soils used in the experiments

Soil	Brazilian soil classification†	USDA soil taxonomy††	Parent material	Municipality
Ox1	Latossolo Vermelho	Rhodic Acrudox	Basalt(1)	Marechal Cândido Rondon
Ox2	Latossolo Vermelho	Rhodic Hapludox	Shale(2)	Ponta Grossa
Ox3	Latossolo Vermelho-Amarelo	Typic Hapludox	Caiuá sandstone(3)	Umuarama
Ox4	Latossolo Vermelho-Amarelo	Typic Hapludox	Furnas sandstone(4)	Ponta Grossa
Alf1	Nitossolo Vermelho	Typic Hapludalf	Basalt(1)	Marechal Cândido Rondon
Alf2	Nitossolo Vermelho	Typic Hapludalf	Shale(2)	Ponta Grossa
Ult1	Argissolo Vermelho-Amarelo	Arenic Hapludult	Caiuá sandstone(3)	Umuarama
Ult2	Argissolo Vermelho-Amarelo	Arenic Hapludult	Basalt(1)	Mercedes
Ent	Neossolo Regolítico	Typic Usthorthent	Basalt(1)	Marechal Cândido Rondon

† Brazilian soil classification (EMBRAPA, 2013). †† Approximate equivalence to USDA soil taxonomy (SOIL SURVEY STAFF, 2010). (1) Basaltic lava flows. Between two consecutive lava flows, there is usually interbedded sedimentary material - sandstones and siltstones. (2) Shales and siltstones dark gray, very micaceous, laminated, with intercalated sandstones. (3) Continental sedimentary deposits predominantly of sandstone, quartz, feldspar, chalcedony and opaque. (4) White sandstones, micaceous, feldspathic, with kaolinitic matrix and cross bedding with conglomeratic levels.

using a 9 mol L^{-1} H_2SO_4 solution (1:20 soil: solution ratio), and Si was removed with NaOH from the residue of the acid attack. Contents of Fe and Al were determined using flame atomic absorption spectrophotometry and Si was quantified by gravimetry, and expressed in the form of oxides to calculate the weathering index by the molar ratio Ki = (%SiO_2/60)/(%Al_2O_3/102) (EMBRAPA, 1997). Soil total K was determined via wet digestion with concentrated acid [hydrofluoric acid (HF), perchloric acid ($HClO_4$) and nitric acid (HNO_3)] as described by Embrapa (1997).

Lime (CaO 25%, MgO 12% and EEC 96%) was applied before of the experiments to raise base saturation up to 70% for clay soils, 50% for sandy soils and 60% for medium texture soils. The soils were then moistened to reach 70% water retention capacity and incubated for 25 days. Afterwards, 7.5 kg subsamples of each soil were transferred to 8-L plastic pots with sealed bottoms.

In greenhouse conditions, the soils were subjected to six successive cropping of plants: (1^{st}) soybean, (2^{nd}) pearl millet (3^{rd}) wheat, (4^{th}) common beans, (5^{th}) soybean, and (6^{th}) maize and two K fertilization levels [no fertilized or fertilized with potash fertilizer]. The treatments consisted of nine soils and the addition (+K) or not (–K) of potassium fertilizer, arranged in a randomized block design in a factorial design with four replications. Potassium fertilization was carried out before each cropping using potassium chloride (KCl) in amount to raise the soil K saturation up to 6%.

Before crop's sowing, the soils were fertilized with 80 mg kg^{-1} of N as ammonium nitrate, 120 mg kg^{-1} of P as simple superphosphate, 5 mg kg^{-1} of S as calcium sulfate, 5 mg kg^{-1} of Cu as copper sulfate, 5 mg kg^{-1} of Zn zinc sulfate, 1 mg kg^{-1} of Mo as ammonium molybdate and 2 mg kg^{-1} of B as boric acid. At 15 and 30 days after plant emergence were also applied 40 mg kg^{-1} of N as urea solution. Soil water level was kept near the field capacity throughout the experiment by adding deionized water.

All the crops were grown for 45 days, and then the shoot was harvested, oven-dried at 65 ºC for four days, weighed, ground, and determined K concentration as previously described by Malavolta, Vitti and Oliveira (1997). The amount of K taken up by the plants at each harvest (mg pot^{-1}) was calculated considering the nutrient concentration (g kg^{-1}) and dry matter production (g pot^{-1}).

At the end of the 6^{th} cropping, the soil from each pot was sampled, air-dried, ground to pass through a 2.0 mm mesh screen and determined non-exchangeable K and exchangeable K. Exchangeable K was extracted by the 1.0 mol L^{-1} ammonium acetate solution (CH_3COONH_4) buffered to pH 7.0 in a soil:solution ratio of 1:10, and shaken for 15 min on a reciprocating shaker at 120 oscillations min^{-1} and standing overnight (16 h) (SANZONOWICZ; MIELNICZUK, 1985). Non-exchangeable K was obtained by the difference between amount of K extracted with boiling 1.0 mol L^{-1} HNO_3 for 15 minutes in a soil:solution ratio of 1:10 (KNUDSEN; PETERSON; PRATT, 1982), and K extracted with 1.0 mol L^{-1} ammonium acetate solution. In all extracts, K concentration was measured by a flame photometer. The amount of soil exchangeable K, in mg pot^{-1}, was calculated considering their concentration, soil volume in each pot (7.5 L) and soil bulk density of the soils (Table 2).

To calculate the contribution of non-exchangeable K to plant nutrition were considered the (i) amounts of nutrient outputs (extracted by plants) and inputs (fertilizer) from the soil during the six crop cycles, and the (ii) change

Table 2 - Some properties of the soils used in the experiments

Soil	pH	OM	P	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	CEC	V	K_S	PBC^K
		g dm^{-3}	mg dm^{-3}	----------------- cmol$_c$ dm^{-3} -------------------					-------- % -------		
Ox1	4.6	22.7	9.1	0.38	3.1	1.8	0.6	14.9	35	2.6	7.8
Ox2	3.8	21.3	2.2	0.18	2.6	0.6	0.8	14.1	25	1.3	3.5
Ox3	4.9	20.3	15.4	0.16	3.9	2.2	0.2	12.9	64	1.2	4.1
Ox4	4.2	29.4	13.1	0.16	3.0	1.0	0.4	13.1	31	1.2	4.7
Alf1	5.2	32.7	7.6	0.30	5.6	1.9	0.2	15.7	49	1.9	9.2
Alf2	3.9	31.8	9.8	0.21	2.3	0.6	1.1	16.1	19	1.3	5.8
Ult1	5.2	9.1	20.3	0.15	2.1	0.4	0.2	6.4	43	2.3	1.3
Ult2	3.7	30.0	10.7	0.34	6.1	1.7	3.4	16.6	49	2.0	12.8
Ent	5.1	15.7	11.8	0.37	5.9	2.3	0.2	15.3	56	2.4	10.9

Soil	Soil particle size			BD	PD	θ_V	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	Ki	Total K
	Sand	Silt	Clay									
	--------- g kg^{-1} ---------			kg dm^{-3}			---------------- g kg^{-1} ----------------					mg kg^{-1}
Ox1	90	10	900	1.05	2.31	386	234	198	223	394	1.79	1,153
Ox2	90	125	785	0.94	2.33	262	101	97	264	101	0.65	8,562
Ox3	690	60	250	1.21	2.69	314	65	38	75	107	1.47	1,003
Ox4	675	10	315	1.30	2.68	206	41	33	109	44	0.64	1,649
Alf1	240	210	550	1.05	2.44	406	209	169	179	437	1.98	5,362
Alf2	80	140	780	0.92	2.42	450	117	78	220	114	0.90	15,563
Ult1	895	20	85	1.52	2.69	204	18	24	28	67	1.11	547
Ult2	155	145	700	1.09	2.62	318	206	162	197	34	1.78	1,913
Ent	180	185	635	1.11	2.63	420	221	196	153	289	2.46	6,982

OM: Organic matter. CEC: cationic exchange capacity. V: soil base saturation. K_S: percent K saturation of soil. PBC^K: potential buffering capacity of K [in (mmol$_c$ kg^{-1})/(mmol L^{-1})^{½}]. BD: soil bulk density. PD: Particle density. θ_V: soil volumetric moisture content at field capacity. Ki: weathering index.

in the amount of exchangeable K in the soils before and after the sixth successive croppings. Equation 1 was used to estimate the contribution of non-exchangeable K to plant:

$$\Delta K_{\text{Non-ex}} = K_{\text{Total taken up}} - K_{\text{Fertilizer}} - (K_{\text{Soil initial}} - K_{\text{Soil final}}) \quad [1]$$

where, $\Delta K_{\text{Non-ex}}$ is the amount of K taken up by plants from soil non-exchangeable pools during the six successive cropping; $K_{\text{Total taken up}}$ is the amount of K taken up by crops in the six successive croppings; $K_{\text{Fertilizer}}$ is the amount of K applied in the six successive cropping; $K_{\text{Soil initial}}$ is the amount of exchangeable K in the soils before the successive cropping; and $K_{\text{Soil final}}$ is the amount of exchangeable K in the soils at the end of the 6th cropping.

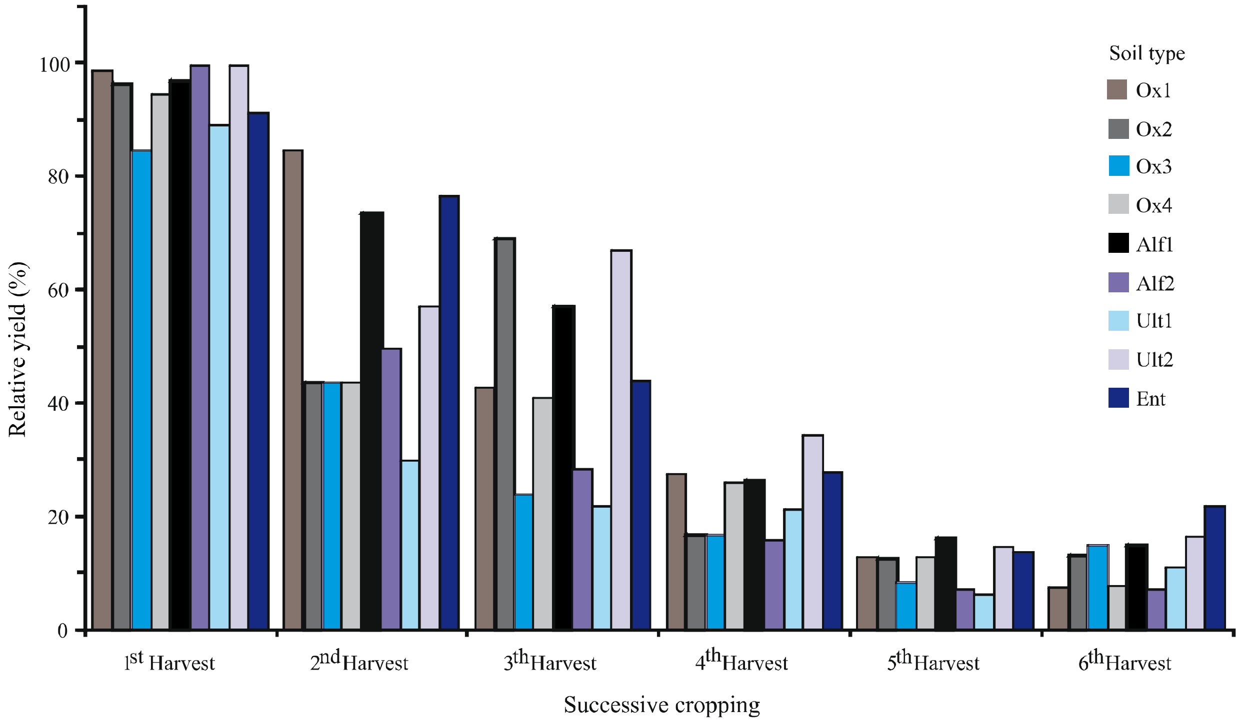
Data were subjected to analysis of variance (F-test, p = 0.05), and the effects of soil type and successive cropping were unfolded for the addition or not of K fertilizer, and the means compared by Scott-Knott test at the 0.05 level of confidence. All analyses were performed using Sisvar 5.3 software for Windows (Statistical Analysis Software, UFLA, Lavras-MG, BRAZIL).

RESULTS AND DISCUSSION

Plant dry matter yield and K uptake

The shoot dry matter yield was affected by the addition of K and soil type in all croppings (Figure 1). For the first cropping, the relative yield of shoot dry matter in the treatment no fertilized with K ranged from 84 to 98% (Figure 1). The slight soybean response (1st cropping) to K fertilization was due the high levels of readily available K (available K ≥ 0.15 cmol$_c$ dm^{-3}) (Table 1). In the second cropping, the relative dry matter yield ranged from 30 to 84%. From the third cropping, the relative dry matter yield was less than 68%, indicating that the initial exchangeable K concentration was able to meet the demand of plants for two croppings. The lower shoot dry matter yield of plants,

Figure 1 - Relative shoot dry matter yield in the treatment no-fertilized (–K) with K compared to treatment fertilized (+K) in the six successive croppings in different Paraná soils



from the third crop without K supply can be attributed to the depletion of readily available K pools with the crop cycles.

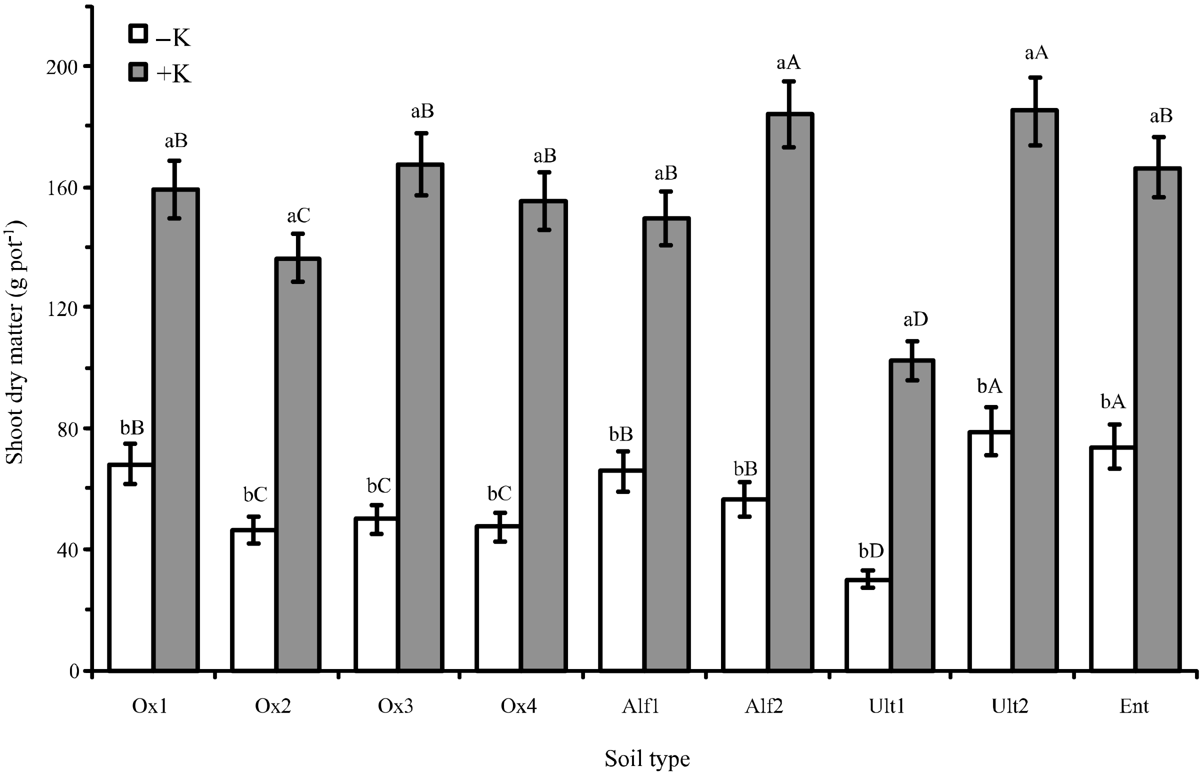
The accumulated shoot dry matter yield of crops, regardless of the addition of K, was different between the soils (Figure 2). These results are due to the wide variation of soil K pools and K-supply potential to plants (Table 1). In general, the higher shoot dry matter yield during six successive croppings was obtained in the Alf2, Ult2 and Ent (Figure 2), regardless of the addition or not of K fertilizer. These results, in part, are due to high levels of readily available K and high PBC^K of these soils (Table 2). On the other hand, the lower dry matter yield obtained in the Ult1 (Figure 2), reflects the lower K availability and lower PBC^K of this soil (Table 1). A soil with a large PBC^K will have a greater capacity to maintain the availability of K for plants. This indicated that soils of high PBC^K have enough K in reserve to replenish used K by plants while those of low PBC^K will only replace used K slowly.

The shoot dry matter yield accumulated in the six successive croppings ranged from 102 to 185 g pot^{-1} (156 g pot^{-1}, on average) and from 30 to 79 g pot^{-1} (57 g pot^{-1}, on average), respectively, with the addition or not of potassium fertilizer (Figure 2). These data indicate that the addition of K resulted in a superiority of 174% on the dry matter yield of crops. These results highlight the importance of proper K fertilization management in tropical soils, once the K reserves in these soils, in general, are not sufficient to meet the demand of plants and achieve high crop yields.

When the soils were fertilized with K, the nutrient concentration in the shoot dry matter of plants in all croppings remained in the range considered adequate for optimal growth and development of plants (data not shown). According to Malavolta, Vitti and Oliveira (1997), the range of K concentrations considered suitable for soybean is 17-25 g kg^{-1}, pearl millet from 15-35 g kg^{-1}, wheat 15-30 g kg^{-1}, common beans 20-25 g kg^{-1} and maize 17-35 g kg^{-1}.

When the soils were not fertilized with K, the K concentration in the shoot dry matter of plants decreases after the second cropping (data not shown), indicating that there was depletion of readily available K pools of soils, as can be seen in Figure 4. After the third cropping, the K concentration in the shoot dry matter was below the optimum range for plant growth in all soils. Potassium concentration after the third cropping ranged from 16.4 to 20.6 g kg^{-1} at the common bean, from 5.6 to 8.8 g kg^{-1} at the soybean, and 4.2 to 17.6 g kg^{-1} at the maize. Symptoms of severe K deficiencies were observed in the last three crops (i.e., common bean, soybean and maize). Potassium deficiency symptoms appeared initially on older leaves

Figure 2 - Total shoot dry matter yield in the six successive croppings in different Parana soils fertilized (+K) and no-fertilized (–K) with K fertilizer. Vertical lines represent the mean standard error (n = 4). Bars represented by the same upper case letters, between the different Parana soils and same lower case letters, for the addition of K fertilizer are not different by Scott-Knott test and F test, respectively, both at the 0.05 level of confidence



as chlorotic spots but soon developed for dark necrotic lesions (dead tissue).

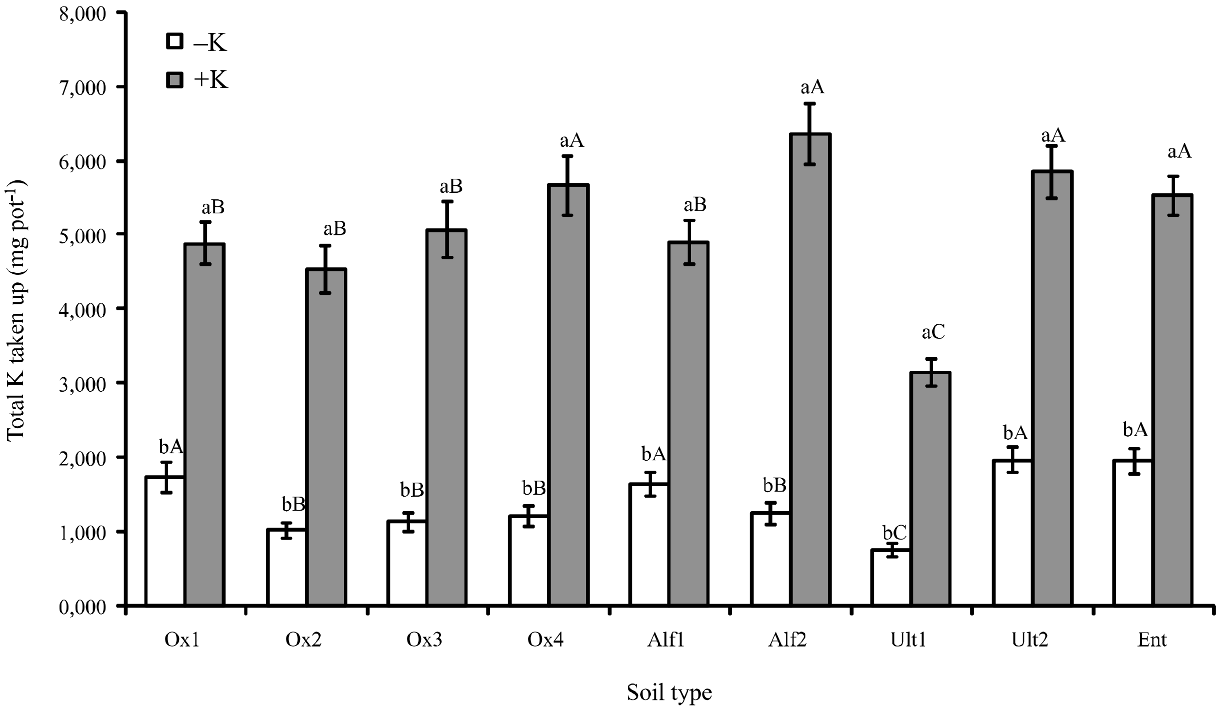
Total amount of K taken up by the plants during the six successive croppings was affected by K fertilizer application (Figure 3). As expected, the K application significantly increased K amount taken up during the six successive croppings in most soils. These increases, however, were dependents of soil type and initial exchangeable K concentration. When the soils were fertilized with K, the highest K amounts taken up by the plants were obtained in the Alf2, Ult2, Ent and Ox4 soils, while the larger amounts of K taken up in the treatment without K were found in the Ult2, Ent, Ox1 and Alf1 soils (Figure 3). On the other hand, the lower K amount taken up by the plants obtained in the Ult1 soil (Figure 3) was due to lower availability and lower PBC^K of this soil (Table 1).

Soil potassium pools and non-exchangeable K contribution

The exchangeable K and non-exchangeable K concentration in the soils were affected by successive cropping and K fertilizer application (Figure 4). Potassium addition significantly increased exchangeable K concentration in the majority of soils, except for the Alf2, Ult2 and Ent (Figure 4A). Initial exchangeable K concentrations ranged from 49 to 147 mg kg^{-1} (102 mg kg^{-1}, on average), and after the sixth cropping these concentrations increased from 102 to 179 mg kg^{-1} (140 mg kg^{-1}, on average), indicating mean increase of 37%. The increase in the exchangeable K concentration of soils was due to the fact of the K fertilization promote greater retention of K in the soil exchange complex (ROSOLEM; VICENTINI; STEINER, 2012).

When the soils were not fertilized with K (–K), the exchangeable K concentration decreases in all the soils (Figure 4A). Before of the croppings, the exchangeable K concentrations ranged from 49 to 147 mg kg^{-1} (102 mg kg^{-1}, on average), and at the end of the sixth cropping these values decreased from 16 to 52 mg kg^{-1} (33 mg kg^{-1}, on average), representing a decrease from the initial mean of 68% (Figure 4A). The highest exchangeable K concentrations observed in Typic Hapludalf (Alf1) (52 mg kg^{-1}) and Arenic Hapludult (Ult2) (48 mg kg^{-1}), especially without the addition

Figure 3 - Total K taken up during the six successive croppings of plants in the different Parana soils fertilized (+K) and no-fertilized (–K) with K fertilizer. Vertical lines represent the mean standard error (n = 4). Bars represented by the same upper case letters, between the different Parana soils and same lower case letters, for the addition of K fertilizer are not different by Scott-Knott test and F test, respectively, both at the 0.05 level of confidence



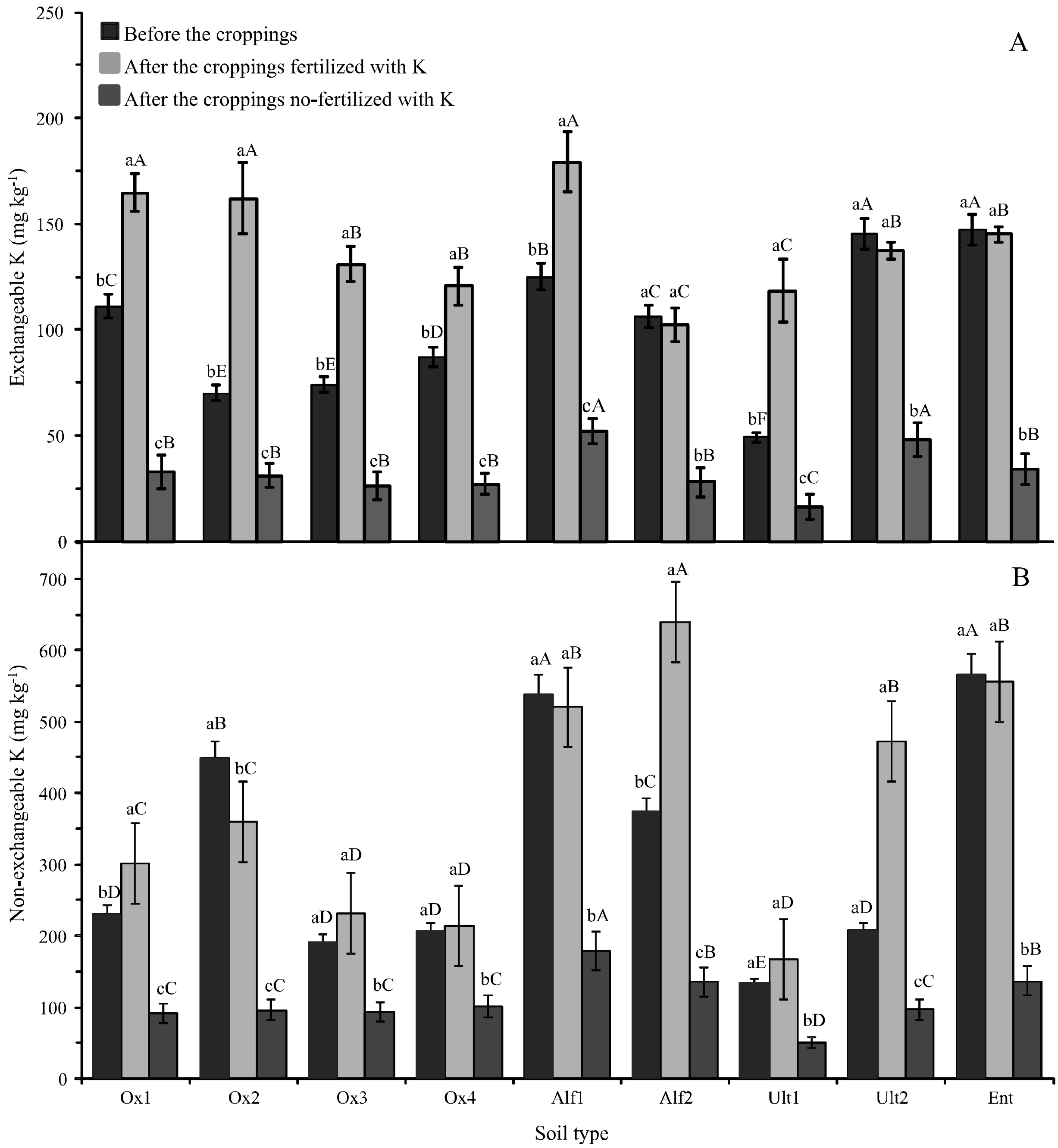
of K fertilizer are associated with higher values of higher PBC^K and CEC of these soils (Table 1). In turn, the lower exchangeable K concentration (16 mg kg^{-1}) observed in Arenic Hapludult (Ult1) is due the lowest PBC^K and CEC of these soil.

Bortoluzzi *et al*. (2005) reported similar results in an experiment conducted for 11 years in an Arenic Hapludult of the State of Rio Grande do Sul, Brazil. These authors found that when the soil was not fertilized with K, the soil available K reduced from 50 mg kg^{-1} in the beginning of experiment to 38 mg kg^{-1} in the first year, and 30 mg kg^{-1} at the end of second year. On the other hand, when the soil was fertilized with K, the soil available K concentrations increased from 50 mg kg^{-1} to 80 and 85 mg kg^{-1}, at the end of first and second year, respectively. After this period, the available K levels in both treatments remained constant around 30 and 90 mg kg$^{-1,}$ respectively, with and without K fertilization. According to these authors, the maintenance of these levels for nearly a decade with intense cropping of K-demanding crops was only ensured by the release of K from weathering of K feldspars and phyllosilicates.

In this study, in general, the exchangeable K concentration of 30 and 140 mg kg^{-1} may be considered the lower and upper limits for the soil K balance in case of exhaustion and excess of K, respectively. The results presented here for the exchangeable K and non-exchangeable K in the soils (Figure 4) confirm the results reported by Bortoluzzi *et al*. (2005), Fraga *et al*. (2009) and Rosolem, Vicentini and Steiner (2012). These authors showed that the non-exchangeable K pool could maintain or even enhance soil exchangeable K reserves in the long term. However, maintaining such a situation in the long term may decrease soil K reserves, compromising the movement of the nutrient into the soil solution and thus also the successful establishment and growth of crops. In long-term experiments conducted by Borkert *et al*. (1997) also observed a decrease in exchangeable K concentration in different soil types during successive years of soybean crop, and found that it would be necessary to apply at least 80 kg ha^{-1} yr^{-1} of K_2O to maintain soil exchangeable K concentrations and avoid depletion of the soil K reserves.

The higher non-exchangeable K concentration in Typic Hapludalf (Alf1) and Typic Usthorthent (Ent) are associated with higher total K levels of these soils (Table 1). When the soils were fertilized with K (+K), there was an increase in the non-exchangeable K concentrations in the Ox1, Alf 2 and Ult2 soils with successive cropping (Figure 4B). This increase in the non-exchangeable K concentration may be because the frequent application of K fertilizers results in changes in soil K minerals, confirming the results reported by Bortoluzzi *et al*. (2005). In a clay soil of the Jaboticabal, São Paulo, Chiba *et al*. (2008) found that the application of 900 kg ha^{-1} yr^{-1} of K_2O resulted in increased of the non-exchangeable K concentration of 40%. In a study conducted for 11 years in an Arenic Hapludult of Santa Maria (RS), Bortoluzzi *et al*. (2005) found increased of non-exchangeable K with the addition of K, reflecting in the increased of micaceous minerals (i.e., illite and illite–smectite interstratified clay), compared to the soil without K fertilization.

Figure 4 - Exchangeable K (A) and non-exchangeable K (B) concentrations in the different Parana soils before and after the successive cropping of plants fertilized (+K) and no-fertilized (–K) with K fertilizer. Vertical lines represent the mean standard error (n = 4). Bars represented by the same upper case letters, between the different Parana soils and same lower case letters, for the addition of K fertilizer are not different by Scott-Knott test and Tukey test, respectively, both at the 0.05 level of confidence



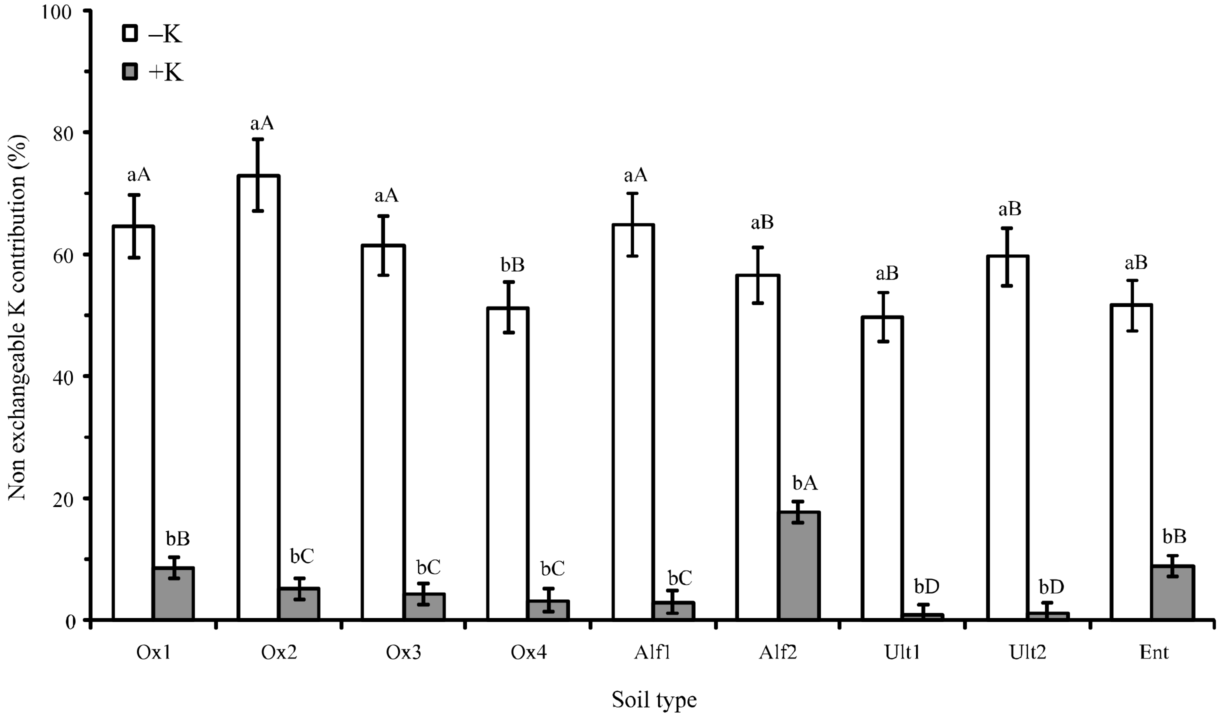
Rosolem, Vicentini and Steiner (2012) showed that the K depletion in soil under intense cropping could occur in both exchangeable and non-exchangeable pools, even when frequent additions of K fertilizers are performed. In this study, similar results were observed only in the Ox2, where the non-exchangeable K concentration decreased from 450 mg kg^{-1} (before cropping) to 360 mg kg^{-1} (at the end of the sixth cropping), representing mean reduction of 20% (Figure 4B).

When the soils were not fertilized with K (–K), the non-exchangeable K concentration decreases in all the soils (Figure 4B), indicating that these non-exchangeable sources contributed to the supply of K to plants. Initial non-exchangeable K concentrations ranged from 134 to 567 mg kg^{-1} (322 mg kg^{-1}, on average), and at the end of the sixth cropping these concentrations decreased from 50 to 179 mg kg^{-1} (109 mg kg^{-1}, on average), representing a decrease from the initial mean of 66%. The depletion of soil non-exchangeable K pools with successive cropping, confirms the results reported by Kaminski *et al.* (2007), who found that the non-exchangeable K concentration at the end of the 5th cropping was reduced in up to 80% in the treatment without K fertilizer.

Fraga *et al*. (2009) showed that the K supply in the short term (1st cropping) was conditioned by the soil exchangeable K, while in the course of successive cropping (2nd and 3rd cropping) this supply was obtained by the release of K from non-exchangeable sources. In fact, when solution K and exchangeable K are reduced to low levels by plant uptake, non-exchangeable K can be released from clay minerals (BORTOLUZZI *et al*., 2005). Non-exchangeable K can be a source available to plants in the medium term.

The K addition and soil type affected the non-exchangeable K contribution to K uptake of plants during the six croppings (Figure 5). When the soils were not fertilized with K (–K), the non-exchangeable K contribution to total K uptake of plants ranged from 50 to 73%. These results report the importance of non-exchangeable K pools in the supply of this nutrient to plants in agricultural production systems. With K fertilization (+K), the non-exchangeable K contribution to total K uptake of plants ranged from 1 to 18% (Figure 5). These results show that even with the application of high rates of K fertilizer the successive croppings also extracted K of non-exchangeable pools. This inference explains the reduction of soil non-exchangeable K concentration after successive croppings (Figure 4B).

Figure 5 - Non-exchangeable K contribution to K uptake of plants during the six successive croppings in the different Paraná soils fertilized (+K) and no-fertilized (–K) with K fertilizer. Vertical lines represent the mean standard error (n = 4). Bars represented by the same upper case letters, between the different Parana soils and same lower case letters, for the addition of K fertilizer are not different by Scott-Knott test and F test, respectively, both at the 0.05 level of confidence



In a sandy soil of Rio Grande do Sul, Brazil, Simonete *et al*. (2002) estimated that, even considering the residual effect of ryegrass K fertilization under continuous ryegrass–rice cropping system, at least 30% of the total K taken up by plants was from the non-exchangeable K pool. In lowland soils of Rio Grande do Sul, Brazil, Fraga *et al*. (2009) found that non-exchangeable K contribution to the K nutrition of rice plants ranged 12 to 72% in the treatments no fertilized and fertilized with K fertilizer, respectively. Exhaustion of K^+ in the soil solution, due to uptake, triggers the desorption of K adsorbed to particles of colloidal size, including K retained by the permanent negative charges of clay minerals, which is considered to be non-exchangeable (BRITZKE *et al*., 2012). The exploitation of K pools initially considered non-exchangeable for plants has been commonly reported in the literature, even in scenarios involving potassium fertilizer application (ROSOLEM; STEINER, 2017; STEINER *et al*., 2012; SIMONSSON; HILLIER; ÖBORN, 2009; GARCIA *et al*., 2008). Rosolem, Vicentini and Steiner (2012) found that when the exchangeable K concentration is less than 50 mg kg^{-1} there is release of K from non-exchangeable sources, and these sources would be responsible for the K nutrition of plants, and the maintenance of appropriate levels of soil exchangeable K.

CONCLUSIONS

1. Soils differ in the ability to K supply to the plants in the short to medium term, due to the wide range of parent material and exchangeable K and non-exchangeable K pools;
2. The initial exchangeable K concentration of soils upper at 0.15 $cmol_c$ dm^{-3} was enough to achieve higher soybean yield at 84% of maximum yield in the first cropping, indicating no need to fertilize with K because the contribution of non-exchangeable K;
3. When the soils were not fertilized with K, the successive cropping of plants resulted in a continuous process of depletion of non-exchangeable K and exchangeable K pools; however, this depletion was less pronounced in soils with higher potential buffer capacity of K;
4. The concentrations of K non-exchangeable and exchangeable K were increased with the addition of potassium fertilizers, indicating the occurrence of K fixation in soil;
5. Non-exchangeable K contribution to K nutrition of plants during the six cropping ranged from 50 to 73% and from 1 to 18%, respectively, without and with K fertilizer addition, reporting the importance of non-exchangeable K pools in the supply of this nutrient to plants in agricultural production systems.

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