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POTASSIUM SUPPLYING CAPACITY OF SOME LOWLAND SOILS UNDER POTASSIUM FERTILIZATION AND SUCCESSIVE CROPPINGS

CAPACIDADE DE SUPRIMENTO DE POTÁSSIO DE ALGUNS SOLOS DE VÁRZEA SUBMETIDOS A ADUBAÇÃO POTÁSSICA E CULTIVOS SUCESSIVOS

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ABSTRACT: The effects of intense cropping and potassium fertilization on potassium (K) dynamics and non-exchangeable K release from three lowland soils of Paraná State, Brazil, were investigated in this study. Samples of three lowland soils were fertilized or not with K and subjected to six successive croppings (soybeans, pearl millet, wheat, common beans, soybeans, and maize). The crops were grown in 8-L pots for 45 days, and at the end of the sixth cropping, the soil from each pot was sampled to the determination of soil K pools. The lowland soils differ in the ability to K supply to the plants in the short to medium term due to the wide range of origin material and the concentration of K in solution, exchangeable K, non-exchangeable K, and structural K. When the soils were not fertilized with K, the successive cropping resulted in continuous depletion process of non-exchangeable and exchangeable K; however, this depletion was less pronounced in soils with a higher potential buffer capacity of K. Non-exchangeable and exchangeable K concentrations were increased with the addition of K fertilizer, indicating the occurrence of K fixation in soil. The non-exchangeable K contribution to K nutrition of plants ranged from 44 to 69% in the treatments without the addition of K fertilizer, reporting the importance of non-exchangeable K pools in the supply of this nutrient to plants in agricultural production systems.

KEYWORDS: Exchangeable K. Intense cropping. Non-exchangeable K. Soil potassium budget.

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 (BARBER, 1995). The existence of these various pools of soil K and its incessant transformation from one pool into another as well as the gain and losses generate a dynamic system in the soil. The most important component of this dynamics is soil mineralogy, including primary and secondary minerals (VELDE; PECK, 2002; SIMONSSON; HILLIER; ÖBORN, 2009). The [illegible] characteristics and fixation are the other important components of K-dynamics (BILIAS; BARBAYIANNIS, 2018; STEINER; LANA, 2018), which in turn are regulated by the soil mineralogical makeup.

Potassium concentration in soil solution and as exchangeable K (readily available pools) is relatively low (0.1 to 2.0% of total K) and corresponds to crop demand during only a few years of intense cropping (ROSOLEM; VICENTINI; STEINER, 2012; STEINER et al., 2015). When solution K and exchangeable K are reduced to low levels by plant uptake and/or leaching, non-exchangeable K can be released from clay interlayers and contribute significantly to plant K nutrition in some soils (ROSOLEM; VICENTINI; STEINER 2012; VIEIRA et al., 2016; BILIAS; BARBAYIANNIS, 2018). Therefore, for sustainable crop production, the available K must be continually replenished through non-exchangeable and mineral K reserves.

Soybean cultivation in lowland areas, where irrigated rice cultivation predominates, has increased in recent decades. However, this production environment differs from traditional soybean cultivation areas by presenting [illegible]w natural drainage, subject to excess moisture at some time during soybean development. In lowland soils, the reducing conditions caused by flooding resulting in a larger fraction of the K^+ ions being displaced from the exchange complex into the soil solution (BARBER, 1995). The release of a relatively large amount of iron (Fe^{2+}) and manganese (Mn^{2+}) ions and production of ammonium (NH_4^+) ions result in the displacement of some of the K^+ ions from the exchange complex to the soil solution. This may lead to greater availability of K to rice in flooded

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soils, as reported by Fraga et al. (2009). This increased diffusion rate of K in the soil may result in the contribution from the structural K of feldspars and micas, and K retained in the interlayer of some 2:1 clay mineral. These pools are considered as non-exchangeable and can be an important source of this nutrient to plants (ROSOLEM; VICENTINI; STEINER, 2012; STEINER; LANA, 2018). Therefore, understanding the mechanisms that involve release and fixation of K in the 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).

Rosolem, Machado, and Ribeiro (1988) found that when the exchangeable K concentration is less than 60 mg kg^{-1} there is the 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. In upland soils of Paraná, Brazil, Steiner and Lana (2018) reported that non-exchangeable K contribution to K nutrition of plants was up to 73% of K taken up in a successive cropping system. In lowland soils of Rio Grande do Sul, Brazil, Fraga et al. (2009) concluded 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, 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 this nutrient soil reserves.

The contribution of non-exchangeable K to plant-available K^+ can be estimated by intensive cropping of plants in the pot (FRAGA et al., 2009; ROSOLEM; VICENTINI; STEINER, 2012; STEINER; LANA, 2018). However, it is unknown the contribution of these pools of K on plant nutrition in the lowland soils of Paraná, Brazil. In this sense, this study aimed to evaluate the effects of intensive cropping and potassium fertilization on K dynamics and non-exchangeable K release from three lowland soils of Paraná State, Brazil.

MATERIAL AND METHODS

Pots experiments were carried out in greenhouse conditions in Marechal Cândido Rondon, Paraná, Brazil (24º31' S, 54º01' W, and altitude of 420 m) to study the effects of intense cropping and K fertilization on K dynamics and non-exchangeable K release in lowland soils of Southern Brazil.

Surface samples (0.00–0.20 m) from three lowland soils of Paraná State, Brazil (designated Alf, Ert, and Ept) were collected in areas under native vegetation or ancient reforestation in the Paraná State, Brazil. These soils were selected by presenting a wide variation in the original material (Table 1). Soils were classified according to the Brazilian System of Soil Classification (SANTOS et al., 2018) and compared with Keys to USDA Soil Taxonomy (SOIL SURVEY STAFF, 2014) (Table 1).

Table 1. Classification, parent material and sampling site of the three lowland soils used in the experiments.

Soil	Brazilian soil classification†	USDA soil taxonomy††	Parent material	Municipality
Alf	Plintossolo Háplico	Typic Plinthaqualf	Shale⁽¹⁾	Ponta Grossa
Ert	Gleissolo Háplico	Typic Endoaquert	Alluvial sediments	Marechal Cândido Rondon
Ept	Cambissolo Háplico	Typic Fragiudept	Furnas sandstone⁽²⁾	Ponta Grossa

† Brazilian soil classification (SANTOS et al., 2018). †† Approximate equivalence to USDA soil taxonomy (Soil Survey Staff, 2014); (1) Shales and siltstones dark gray, very micaceous, laminated, with intercalated sandstones; (2) White sandstones, micaceous, feldspathic, with kaolinitic matrix and cross-bedding with conglomeratic levels.

The physical and chemical properties of the soils were determined by adopting standard procedures (TEIXEIRA et al., 2017), and some characteristics are shown in Table 2. Soil pH in water was measured potentiometrically in a 1:2.5 (soil:water) suspension using a combined calomel reference glass electrode. Organic matter was quantified by oxidation with potassium dichromate in the presence of sulfuric acid, followed by titration with ammonium Fe(II) sulfate. P and K were extracted by the Mehlich-1 solution (HCl 0.05 mol L^{-1} + H_2SO_4 0.0125 mol L^{-1}) in a soil:solution ratio of 1:10, with 5 min of stirring time in a horizontal shaker at 120 oscillations per minute and settling for 16 h. Ca and Mg were extracted by 1 mol L^{-1} KCl solution in a soil:solution ratio of 1:10, with shaken for 15 min on a reciprocating shaker at 120 oscillations per minute and standing overnight (16 h) and determined by atomic absorption spectrophotometry. Exchangeable Al was extracted

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by 1 mol L^{-1} KCl solution and determined by titration with 0.025 mol L^{-1} ammonium hydroxide. Cationic exchange capacity (CEC) was estimated by the summation method (CEC = Ca + Mg + K + H + Al). The particle size analysis was performed by the pipette method, based on the 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 bulk density measured by the graduated cylinder method. The Fe and Al contents, associated with the secondary minerals, were extracted 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 = $(\%SiO_2/60)/(\%Al_2O_3/102)$.

Table 2. Some physicochemical properties of the three lowland 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}	---------------------			------ % ------		
Alf	3.8	31.2	3.1	0.19	1.2	0.4	1.2	14.2	12	1.3	2.1
Ert	3.6	20.7	2.8	0.12	4.4	1.4	3.5	17.5	34	0.7	6.7
Ept	5.2	16.2	9.5	0.26	2.8	1.2	0.1	9.8	41	2.6	3.6

Soil	Soil particle size			BD	PD	θ_V	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	Ki	Kr
	Sand	Silt	Clay									
	--------	g kg^{-1}	------	kg dm^{-3}			------------------	g kg^{-1}	-----------------			
Alf	215	170	615	0.94	2.65	250	114	103	289	120	0.67	0.55
Ert	110	440	450	1.16	2.43	256	161	66	83	345	3.29	2.19
Ept	755	10	235	1.21	2.62	254	43	25	137	49	0.54	0.48

OM: Organic matter. CEC: cationic exchange capacity. V: soil base saturation. K_S: K saturation of the soil. PBC^K: potential buffering capacity of K [in $(mmol_c\ kg^{-1})/(mmol\ L^{-1})^{½}$]. BD: bulk density. PD: Particle density. θ_V: soil volumetric moisture content at field capacity. Ki: weathering index. Kr: molar ratio $SiO_2/Al_2O_3+Fe_2O_3$.

Limestone [CaO = 25%, MgO = 12%, and CCE (calcium carbonate equivalent) = 96%] was applied before of the experiments to raise soil base saturation up to 70%. The soils were then moistened to reach 70% water retention capacity and incubated for 25 days. Afterward, 7.5 dm^3 subsamples of each soil were transferred to 8-L plastic pots with sealed bottoms.

In greenhouse conditions, the soils were subjected to six successive croppings of plants: (1st) soybean, (2nd) pearl millet (3rd) wheat, (4th) common beans, (5th) soybean, and (6th) maize and two K fertilization levels [no fertilized or fertilized with potash fertilizer]. The treatments consisted of three soils and the addition (+K) or not (–K) of potassium fertilizer, arranged in a randomized block design in a 3 × 2 factorial scheme with four replications. Potassium fertilization was performed with potassium chloride (KCl = 60% of K_2O) in amounts equivalent to raise the soil K saturation to 6%.

Before sowing of crops, the soils were fertilized with 80 mg kg^{-1} of nitrogen (N) as ammonium nitrate, 120 mg kg^{-1} of phosphorus (P) as simple superphosphate, 5 mg kg^{-1} of sulfur (S) as calcium sulfate, 5 mg kg^{-1} of copper (Cu) as copper sulfate, 5 mg kg^{-1} of zinc (Zn) as zinc sulfate, 1 mg kg^{-1} of molybdenum (Mo) as ammonium molybdate and 2 mg kg^{-1} of boron (B) as boric acid. At 15 and 30 days after plant emergence was also applied 40 mg kg^{-1} of N as urea solution. Soils were maintained at a water potential near field capacity throughout the experiment by adding deionized water.

All the crops were grown for 45 days, and then the shoot of plants was harvested, oven-dried at 65 ºC for four days, weighed, ground, and subjected to determination of 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 6th cropping, the soil from each pot was sampled, air-dried, ground to pass through a 2.0 mm mesh screen. 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 Teixeira et al. (2017). Exchangeable K was extracted by the 1.0 mol L^{-1} ammonium acetate solution (CH_3COONH_4) buffered to pH 7.0 (SANZONOWICZ; MIELNICZUK, 1985). Non-exchangeable K was obtained by the difference between the amount of K extracted with boiling 1.0 mol L^{-1} HNO_3 and K extracted with ammonium acetate solution (KNUDSEN; PETERSON; PRATT, 1982). Solution K was obtained after equilibration with 1.0 mmol L^{-1} $SrCl_2$ solution in a soil: solution ratio of 1:10 for 30 minutes as described by Mielniczuk (1978). In all extracts, K concentration was measured by a flame photometer. The amount of soil 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 was considered the (i) amounts of nutrient outputs (extracted by plants) and inputs (fertilizer) from the soil during the six plant croppings, and the (ii) change in the amount of exchangeable K in the soils before and after the six successive croppings. Equation 1 proposed by Steiner and Lana (2018) was used to estimate the contribution of non-exchangeable K to plants:

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

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 as fertilizer in the six successive croppings; $K_{\text{Soil initial}}$ 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 sixth cropping.

Data were subjected to analysis of variance (F-test, p = 0.05), and the effects of soil type and the addition of K fertilizer were compared by Tukey test and F test, respectively, both at the 0.05 level of confidence, considering a factorial arrangement, with four replications. All analyses were performed using Sisvar 5.6 software for Windows (Statistical Analysis Software, UFLA, Lavras, MG, BRA) (FERREIRA, 2014).

RESULTS AND DISCUSSION

The results of the analysis of variance showed significant effects ($p<0.05$) for the main effects of K fertilizer addition and soil types, as well as for interaction on all the traits measured (Table 3). The significant interaction between the main effects of K addition and soil types indicates that the crop response and soil K dynamics have different behavior in lowland soils of Paraná State, Brazil.

Table 3. Summary of the analysis of variance for the shoot dry matter (SDM), K uptake, structural K, non-exchangeable K ($_{NE}K$), exchangeable K ($_{E}K$), solution K, and non-exchangeable K contribution ($_{NE}KC$) for the effects of potassium addition and soil types

Causes of variation	Probability > F						
	SDM	K uptake	structural K	$_{NE}K$	$_{E}K$	solution K	$_{NE}KC$
Bloks	0.893	0.457	0.534	0.587	0.341	0.217	0.547
K addition (K)	<0.000	<0.000	<0.000	<0.000	<0.000	<0.000	<0.000
Soil (S)	<0.000	<0.000	<0.000	<0.000	<0.000	<0.000	<0.000
K × S	<0.000	0.038	<0.000	<0.000	<0.000	0.003	<0.000
CV (%)	6.52	9.17	11.37	12.71	11.32	15.27	6.11

Dry matter yield and K uptake

The K supply potential to the plants was different between soils (Figure 1), due to the wide range of parent material and exchangeable K concentration of soils (Table 2). The relative dry matter yield in the first cropping of treatment no fertilized with K ranged from 78 to 97% (Figure 1). The high dry matter yield of soybean (1^{st} cropping), especially for the Alf and Ept, was due to the high levels of readily available K (available K ≥ 0.15 $cmol_c$ dm^{-3}) (Table 2). In the second cropping, the relative dry matter yield ranged from 23 to 76% (Figure 1). From the third cropping, the relative dry matter yield was less than 44%. These data indicate that the initial exchangeable K concentration was able to meet the demand of plants only the first cropping. The lower shoot dry matter yield of plants, from the second crop without K supply can be attributed to the depletion of readily available K pools with the course of successive cropping.

The shoot dry matter yield accumulated during six successive croppings was affected by the addition of K and soil type (Figure 2A). In general, the highest yield of shoot dry matter was obtained in the Ert and Ept, regardless of the addition or not of K fertilizer. These results are due to the high PBC^K of these soils (Table 2). A soil with a large PBC^K will have a greater capacity to maintain the activity of K in the soil solution. This indicated that soils of high PBC^K have enough K in reserve to replenish used K by crops while those of low PBC^K will only replace used K slowly. Thus, the release of K will be rapid and slow accordingly. It then implies that soils with high PBC^K will be able to maintain solution K intensity against plant depletion for longer periods while those of low values will have low capacity to maintain the activity of K in the solution and hence frequent fertilization.

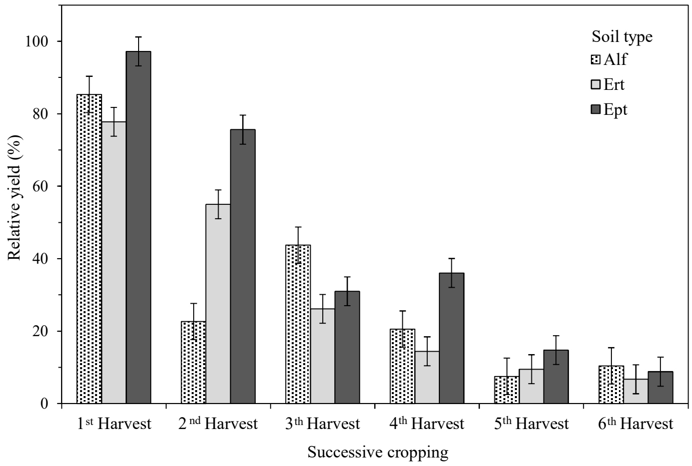

Figure 1. Relative shoot dry matter yield of treatments non-fertilized with K during the six-successive croppings in the three lowland soils of Paraná State, Brazil. Vertical lines represent the mean standard error. Alf: Typic Plinthaqualf; Ert: Typic Endoaquert; Ept: Typic Fragiudept.

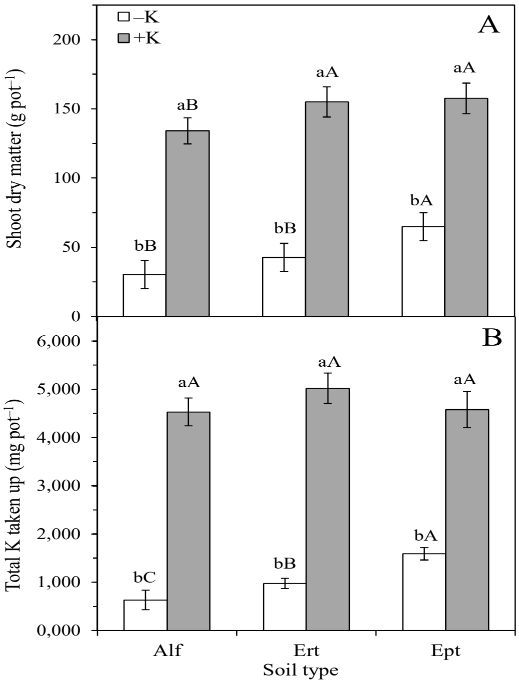

Figure 2. Total shoot dry matter yield – (A) and total K taken up – (B) during the six successive croppings in the three lowland soils of Paraná State, Brazil fertilized (+K) and no-fertilized (–K) with K fertilizer. Vertical lines represent the mean standard error. Bars represented by the same uppercase letters, between the different Paraná soils and the same lowercase letters, for the addition of K fertilizer, are not different by Tukey test and F test, respectively, both at the 0.05 level of confidence. Alf: Typic Plinthaqualf; Ert: Typic Endoaquert; Ept: Typic Fragiudept.

The yield of shoot dry matter accumulated in the six croppings ranged from 134 to 158 g pot^{-1} (149 g pot^{-1}, on average) and from 30 to 65 g pot^{-1} (46 g pot^{-1}, on average), respectively, with the addition or not of potassium fertilizer (Figure 2A). These data indicated that the dry matter yield with the addition of K was 224% higher when compared to treatment no fertilized with K. This demonstrates the importance of K fertilization in tropical lowland soils, once the K reserves of 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 K concentration in the shoot dry matter of plants in all cropping remained in the range considered adequate for optimal growth and development of plants (from 19 to 36 g kg^{-1} of K). 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}. However, in the treatments not fertilized with K, the K concentration in the shoot dry matter of plants decreases after the second cropping (< 20 g kg^{-1} of K), indicating that there was depletion of readily available K pools of soils, as can be seen in Figure 3. 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 18.2 to 19.8 g kg^{-1} at the common bean, from 5.6 to 6.3 g kg^{-1} at the soybean, and 7.7 to 15.2 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 as chlorotic spots but soon developed for dark necrotic lesions (dead tissue).

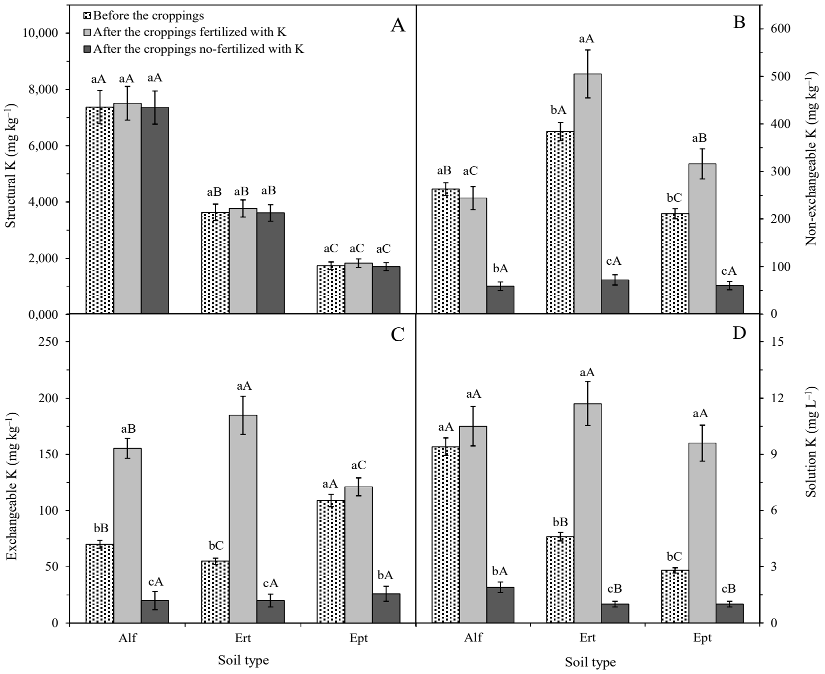

Figure 3. Concentrations of structural K, non-exchangeable K, exchangeable K and solution K in the three lowland soils of Paraná State, Brazil, before and after the sixth successive cropping of plants fertilized (+K) and no-fertilized (–K) with K fertilizer. Vertical lines represent the mean standard error. Bars represented by the same uppercase letters, between the different lowland soils and the same lowercase letters, for the addition of K fertilizer, are not different by the Tukey test at the 0.05 level of confidence. Alf: Typic Plinthaqualf; Ert: Typic Endoaquert; Ept: Typic Fragiudept.

The total amount of K taken up by the plants during the six successive croppings was affected by K fertilizer application and soil type (Figure 2B). As expected, the K application significantly increased K amount taken up during the six successive croppings in all soils. The total amount of K taken up by the plants with the addition of K (4,710 mg pot^{-1}, on average) was 342% higher when compared to treatment no fertilized with K (1,065 mg pot^{-1}, on average). When the soils were not fertilized with K, the higher K amount taken up by the plants was obtained in the Ept (Figure 2B). These results are due to the high levels of readily available K of this soil (Table 1). On the other hand, the lower K amount taken up by the plants obtained in the Alf was due to lower availability and lower PBC^{K} of this soil (Table 1).

Soil potassium pools

Potassium supply capacity to plants in the short and medium-term had a wide variation between soils (Figure 3). Potassium supply potential of soils is conceived to include K supplied from solution K, exchangeable K, and non-exchangeable K pools. The order of abundance of the K pools in the soils is structural K > non-exchangeable K > exchangeable K > solution K (Figure 3). The soil structural K constituted 84 to 96% of the total K and ranged from 1,730 to 7,373 mg kg^{-1} (Figure 3A).

The K content of soil minerals varies with the source of parent material and the degree of weathering (STEINER; LANA, 2018). Higher structural K concentration was observed in the Typic Plinthaqualf (Alf) derived from the Ponta Grossa Formation sediments composed of very micaceous shale's (Table 1). The pellitic sedimentary rocks (shales) can contain up to 30,000 mg kg^{-1} of K (SPARKS; HUANG, 1985). These results are associated with the presence of mica as a natural source of K in its structure. The mineral K reserves of soil are found in primary minerals such as mica and feldspar, and secondary minerals such as illite, vermiculite and interstratified clay minerals (SPARKS; HUANG, 1985). Silva et al. (2000) also found the highest values of total K in soils derived from pellitic rocks, which according to Melo et al. (2005) are materials relatively rich in K mineral.

Soil structural K concentration was not affected by successive cropping and the addition of K fertilizer (Figure 3A). This indicates that the structural K was not easily released to the plants during the six croppings of plants, confirming the results reported by Steiner and Lana (2018) in upland soils of southern Brazil.

Non-exchangeable K concentration in the soils was affected by the K fertilizer application (Figure 3B). Potassium addition significantly increased non-exchangeable K concentration in the soils, except for the Alf (Figure 3B). Initial non-exchangeable K concentrations ranged from 211 to 384 mg kg^{-1} (286 mg kg^{-1}, on average), and after the sixth cropping, these concentrations increased from 244 to 505 mg kg^{-1} (355 mg kg^{-1}, on average), indicating a mean increase of 24%. This increase in the non-exchangeable K concentration may be because the frequent application of K fertilizers results in changes in soil K minerals (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 increased 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. According to Steiner and Lana (2018), the change of soil K minerals due to the weathering process can be minimized with the addition of K fertilizers.

When the soils were not fertilized with K (–K), the non-exchangeable K concentration decreases in all the soils (Figure 3B), indicating that these non-exchangeable sources contributed to the supply of K to plants. Initial non-exchangeable K concentrations ranged from 211 to 384 mg kg^{-1} (286 mg kg^{-1}, on average), and at the end of the sixth cropping, these concentrations decreased from 59 to 72 mg kg^{-1} (64 mg kg^{-1}, on average), representing a decrease from the initial mean of 78%. The depletion of soil non-exchangeable K pools with successive cropping, confirms the results reported by Steiner and Lana (2018) in upland soils of Southern Brazil, who found that the non-exchangeable K at the end of the 6th cropping was reduced in up to 68% in the treatment without K fertilizer.

Fraga et al. (2009) reported that the K supply in the short term (1st cropping) was conditioned by the soil exchangeable K concentration, while in the course of successive cropping (2nd and 3rd cropping) this supply was obtained by the release of K from non-exchangeable sources. Indeed, when solution K and exchangeable K are reduced to low levels by plant uptake, non-exchangeable K can be released from clay interlayers (BORTOLUZZI et al., 2005). Non-exchangeable K can be a source available to plants in the medium term. However, the release rate of K from the non-exchangeable pool is influenced by particle size and chemical and mineralogical composition of the soil (MELO et al., 2005).

The intense cropping and/or K fertilizer application may affect the soil K dynamic, leading to changes in clay mineral composition (VELDE; PECK 2002; BORTOLUZZI et al., 2005; ROSOLEM; VICENTINI; STEINER, 2012). Hinsinger and Jaillard (1993) observed the formation of vermiculite, in detriment of illite, in the rhizosphere soil of ryegrass plants in only 32 days of growing. Under these conditions, the release of K from the illite layers, induced by the action of plant roots, was almost complete. 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.

Soil exchangeable K concentration was affected by successive cropping and K fertilizer application (Figure 3C). The K application significantly increased exchangeable K concentration in the soils, except for the Alf (Figure 3C). These increases, however, were dependents of soil type and initial exchangeable K concentration. Initial exchangeable K concentrations ranged from 55 to 109 mg kg^{-1} (78 mg kg^{-1}, on average), and at the end of the sixth cropping, these concentrations increased from 121 to 185 mg kg^{-1} (154 mg kg^{-1}, on average), indicating a mean increase of 97%. The increase in the exchangeable K concentration of soils was due to the fact the K fertilization promotes greater retention of K in the soil exchange complex (ROSOLEM; VICENTINI; STEINER, 2012; STEINER; LANA, 2018). However, these exchangeable K levels are determined by the ability of exchange sites in adsorbing K ion, where its increase is only possible by the increase in the number of such sites.

When the soils were not fertilized with K (–K), the exchangeable K concentration decreases (Figure 3C). Before the cropping, the exchangeable K concentrations ranged from 55 to 109 mg kg^{-1} (78 mg kg^{-1}, on average), and at the end of the sixth cropping, these values decreased from 20 to 26 mg kg^{-1} (22 mg kg^{-1}, on average), representing a decrease from the initial mean of 72% (Figure 3C). 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 verified that when the soil was not fertilized with K, the soil available K reduced from 50 mg kg^{-1} at the beginning of the experiment to 38 mg kg^{-1} in the first year, and 30 mg kg^{-1} at the end of the 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 the 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 general, in this study, the exchangeable K concentration of 22 and 150 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. According to Velde and Peck (2002), these limits are determined mainly by the mineralogy of soils. The results presented here for the exchangeable K and non-exchangeable K in the soils (Figure 4) confirmed the results reported by Fraga et al. (2009), Vieira et al. (2016) 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, Borkert et al. (1997) also observed a decrease in exchangeable K concentration in different soil types during successive years of the 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.

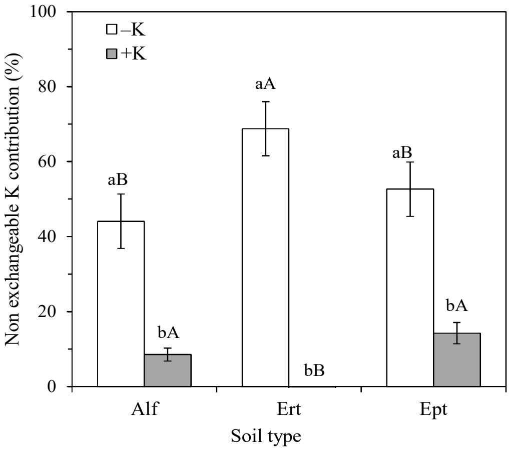

Figure 4. Non-exchangeable K contribution to K uptake of plants during the six successive croppings in the three lowland soils of Paraná State, Brazil, fertilized (+K) and no-fertilized (–K) with K fertilizer. Vertical lines represent the mean standard error. Bars represented by the same uppercase letters, between the different lowland soils and the same lowercase letters, for the addition of K fertilizer, are not different by Tukey test and F test, respectively, both at the 0.05 level of confidence. Alf: Typic Plinthaqualf; Ert: Typic Endoaquert; Ept: Typic Fragiudept.

Soil solution K concentration was affected by successive cropping and K fertilizer application (Figure 3D). The addition of K fertilizer resulted in significant increases in solution K concentration in the soils, except for the Alf. These increases, however, were dependents of soil type and initial exchangeable K concentration. Initial solution K concentration ranged from 2.8 to 9.4 mg L^{-1} (5.6 mg L^{-1}, on average), and at the end of the sixth cropping, these concentrations increased from 9.6 to 11.6 mg L^{-1} (10.6 mg L^{-1}, on average), indicating a mean increase of 89%. In turn, when the soils were not fertilized with K (–K), the initial solution K concentration ranged from 2.8 to 9.4 mg L^{-1} (5.6 mg L^{-1}, on average), and at the end of the sixth cropping these values decreased from 1.0 to 1.9 mg L^{-1} (1.2 mg L^{-1}, on average), representing a decrease from the initial mean of 78%. These results indicate that has reached a balance between pools of solution K and exchangeable K with a minimum of soluble K in the soil-plant system.

Non-exchangeable K contribution

The K addition and soil type affected the non-exchangeable K contribution to K uptake of plants during the six cropping's (Figure 4). When the soils were not fertilized with K (–K), the non-exchangeable K contribution to total K uptake of plants ranged from 44 to 69%. 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 was 9 and 14% for the Alf and Ept. These results show that even with the application of high rates of K fertilizer the successive cropping also extracted K of non-exchangeable pools. However, for the Ert there was no non-exchangeable K contribution to total K uptake of plants during the cropping (Figure 4).

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. The exploitation of K pools initially considered non-exchangeable for plants has been commonly reported in the literature, even in scenarios involving K fertilizer application (VIEIRA et al., 2016; STEINER; LANA, 2018). Rosolem, Vicentini, and Steiner (2012) found that the non-exchangeable K pools were the main sources of the nutrient for successive cropping of ruzigrass [*Urochloa ruziziensis* (Syn. *Brachiaria ruziziensis*)]. Rosolem, Machado and Ribeiro (1988) found that when the exchangeable K concentration is less than 60 mg kg^{-1} there was the 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

The initial exchangeable K concentration upper at 0.19 $cmol_c$ dm^{-3} (or 74 mg dm^{-3}) in the Typic Plinthaqualf (Alf) and Typic Fragiudept (Ept) was enough to achieve higher soybean yield at 85% of maximum yield in the first cropping, indicating no need to fertilize with K because of the contribution of non-exchangeable K.

When the soils were not fertilized with K, the successive cropping of plants resulted in a continuous depletion process of non-exchangeable K and exchangeable K pools. However, this depletion was less pronounced in soils with a higher potential buffer capacity of K.

The concentrations of non-exchangeable K and exchangeable K were increased with the addition of K fertilizers, indicating the occurrence of K fixation in lowland soils.

The non-exchangeable K contribution to K nutrition of plants during the six-cropping ranged from 44 to 69% in the treatments without the addition of K fertilizer, reporting the importance of non-exchangeable K pools in the supply of this nutrient to plants in agricultural production systems.

RESUMO: Os efeitos dos cultivos sucessivos e da adubação potássica na dinâmica de potássio (K) do solo e na mobilização do K não-trocável para às plantas em três solos de varzea do Estado do Paraná, Brasil, foram investigados neste estudo. Amostras dos três solos de várzea foram submetidas à adição ou não de fertilizante potássico e a seis cultivos sucessivos de plantas (soja, milheto, trigo, feijão, soja e milho). 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 das diferentes formas de K do solo. Os solos de vázea diferenciaram-se na capacidade

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de suprir K às plantas a curto e médio prazo, devido à ampla variação do material de origem e dos teores de K na solução, K trocável, K não-trocável e K estrutural. 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 acentuada 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 44 a 69% no tratamento sem adição de fertilizante potássico. Estes resultados reportam a importância das formas de K não-trocável para o suprimento deste nutriente às plantas nos sistemas de produção agrícolas.

PALAVRAS-CHAVE: K trocável. Cultivos intensivos. K não-trocável. Balanço de potássio do solo.

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