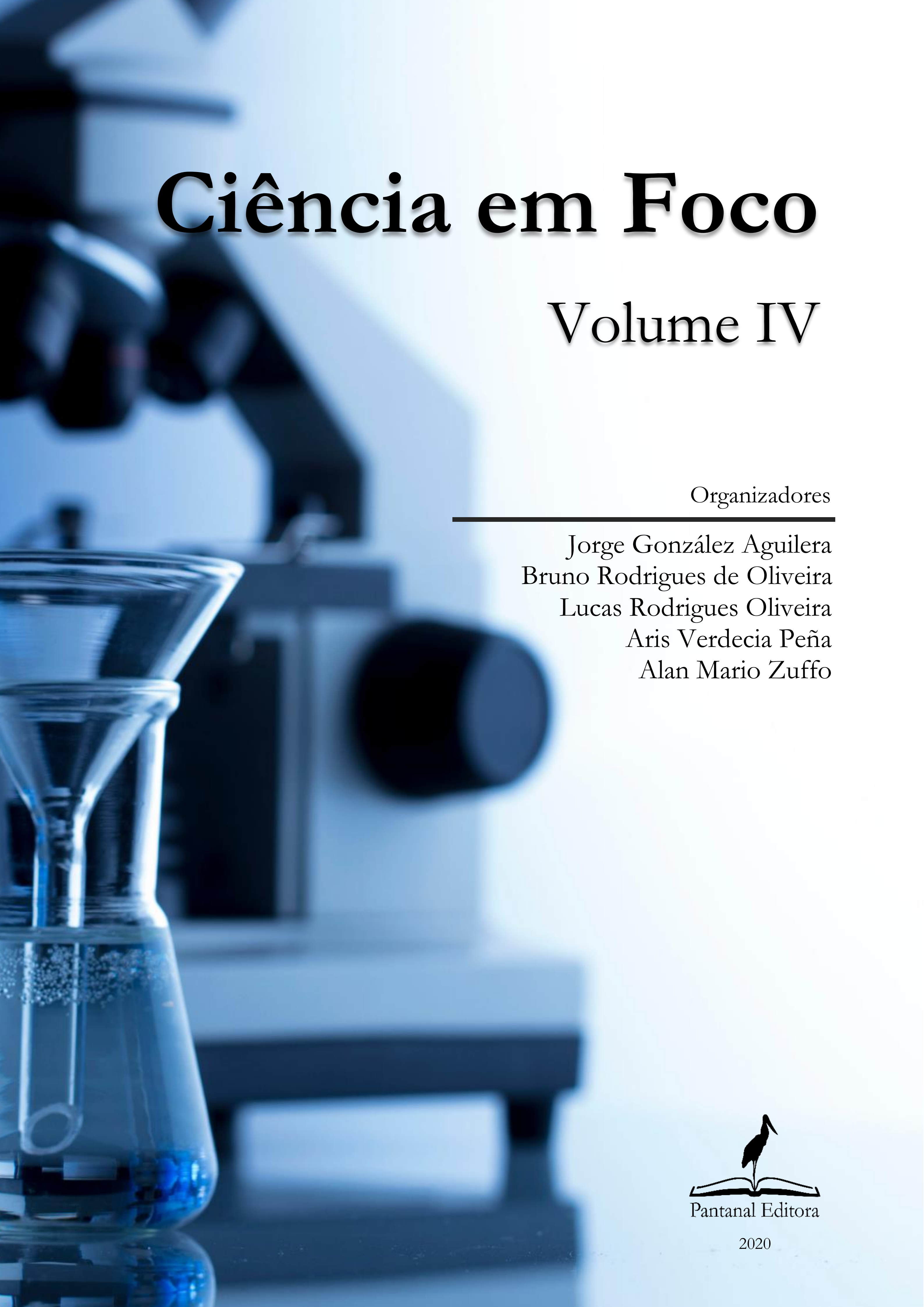

Ciência em Foco

Volume IV

Organizadores

Jorge González Aguilera
Bruno Rodrigues de Oliveira
Lucas Rodrigues Oliveira
Aris Verdecia Peña
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Pantanal Editora

2020

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Organizador(es)

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APRESENTAÇÃO

Neste quarto volume da série “Ciência em Foco” ampliamos as áreas de abrangência das pesquisas relatadas nos 29 capítulos que contemplam esta obra, dentre elas a área de educação, agrárias e alimentos, tendo sempre como centro a divulgação das pesquisas científicas com qualidade e relevância associadas aos problemas atuais no cotidiano de nossos colaboradores.

Relatos na área de educação abordam temas como a inclusão de autistas, desafios do ensino com crianças cegas, tecnologias e métodos de ensino em tempos de pandemia COVID-19, entre outros temas.

A procura dos professionais por novas formas de aproveitar e disponibilizar alimentos a serem elaborados em forma de doces e iogurtes é abordado nesta obra, trazendo desafios e inovações que permitem aumentar ainda mais a disponibilidade de alimentos em regiões menos favorecidas do Brasil.

Temas associados ao manejo das culturas da cana-de-açúcar, cebola, melão, milho, mandioca e café em diferentes regiões do Brasil, são discutidos. A produção de mudas de espécies florestais do cerrado com fins de reflorestamento e seu impacto ambiental, aproveitamento de resíduos de lodos, manejo de sementes amazônicas e a recuperação de áreas degradadas é também elencado.

Todos estes trabalhos visam contribuir no aumento do conhecimento gerado por instituições públicas, melhorando assim, a capacidade de difusão e aplicação de novas ferramentas disponíveis a sociedade.

Aos autores dos diversos capítulos, pela dedicação e esforços sem limites, que viabilizaram esta obra que retrata os recentes avanços científicos e tecnológicos, os agradecimentos dos Organizadores e da Pantanal Editora.

Por fim, esperamos que este livro possa colaborar e estimular aos estudantes e pesquisadores que leem esta obra na constante procura por novas tecnologias e assim, garantir uma difusão de conhecimento simples e ágil para a sociedade.

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Capítulo XXVIII

Mobilization of non-exchangeable K by plants in lowland soils of southern Brazil

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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 (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 soil. The most important component of this dynamics is soil mineralogy, including primary and secondary minerals (Velde et al., 2002; Pernes-Debuyser et al., 2003; Simonsson et al., 2009). The status of different pools of K in soil, their release characteristics and fixation are the other important components of K-dynamics (Simonsson et al., 2009), which in turn are regulated by the soil mineralogical make-up.

Potassium concentration in soil solution and as exchangeable K (readily available pools) is relatively low (0.1 to 2% of total K) and corresponds to crop demand during only a few years of intense cropping (Simonsson et al., 2007; Rosolem et al., 2012; Steiner et al., 2018). 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 (Simonsson et al., 2007; Fraga et al., 2009; Rosolem et al., 2012; Steiner et al., 2012; 2015). Therefore, for sustainable crop production, the available K must be continually replenished through non-exchangeable and mineral K reserves.

In lowland soils, the reducing conditions caused by flooding result 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 Fe^{2+} and Mn^{2+} ions and production of $NH4^+$ ions result in displacement of some of the K^+ ions from the exchange complex to the soil solution. This may lead to greater availability of K

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to rice in flooded 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 minerals. These pools are considered as non-exchangeable and can be an important source of this nutrient to plants (Rosolem et al., 2012; Steiner et al., 2018). Therefore, 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 et al., 2009).

Rosolem et al. (1988) found that when the exchangeable K concentration is less than 60 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. In a sandy soil of Rio Grande do 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 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 the soil K reserves.

The contribution of non-exchangeable K to plant-available K+ can be estimated by intensive cropping of plants in pot (Kaminski et al., 2007; Fraga et al., 2009; Rosolem et al., 2012). However, it is unknown the contribution of these pools of K on plant nutrition in the lowland soils of Paraná, Brazil. This study was designed to investigate 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

Pot experiments were carried out in a greenhouse at the Western Parana State University in Marechal Cândido Rondon, Paraná, Brazil (24° 31' S, 54° 01' 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 (0–0.20 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 origin material (Table 1) and physical and chemical properties (Table 2). Soils were classified according to the Brazilian System of Soil Classification (Embrapa, 2013) and compared with Keys to USDA Soil Taxonomy (Soil Survey Staff, 2010) (Table 1).

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

Soil	Brazilian classification†	USDA soil taxonomy††	Parent material	Municipality
Alf	Haplic Plinthosol	Typic Plinthaqualf	Shale⁽¹⁾	Ponta Grossa
Ert	Haplic Gleysol	Typic Endoaquert	Alluvial sediments	Marechal Cândido Rondon
Ept	Haplic Cambisol	Typic Fragiudept	Furnas sandstone⁽²⁾	Ponta Grossa

† Brazilian soil classification (EMBRAPA, 2013). †† Approximate equivalence to USDA soil taxonomy (Soil Survey Staff, 2010). ⁽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.

Table 2. Some properties (1) of the three lowland soils used in the experiments. Source: The authors.

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

⁽¹⁾ pH in 0.01 mol L^{-1} $CaCl_2$, soil:solution ratio (1:2.5). OM: Organic matter, Walkley-Black method. P and K were extracted by Mehlich-1 solution. Ca, Mg and Al were extracted by 1 mol L^{-1} KCl solution. CEC: cationic exchange capacity was estimated by the summation method (CEC = Ca + Mg + K). V: soil base saturation. K_S: percent K saturation of soil. PBC^K: potential buffering capacity of K [in $(mmol_c\ kg^{-1})/(mmol\ L^{-1})^{½}$] determined as described by Mielniczuk (1978). Particle size analysis was performed by the pipette method (Embrapa, 1997). BD: bulk density measured by the graduated cylinder method (Embrapa, 1997). PD: Particle density (Embrapa, 1997). θ_V: soil volumetric moisture content at field capacity measured as described by Luchese et al. (2001). The Fe and Al contents, associated to the secondary minerals, were extracted with 9 mol L^{-1} H_2SO_4 solution, and Si was removed with NaOH from the residue of the acid attack, and values expressed in the form of oxides (Embrapa, 1997). Ki: weathering index calculated by the molar ratio SiO_2/Al_2O_3. Kr: molar ratio $SiO_2/Al_2O_3+Fe_2O_3$.

Limestone (CaO 25%, MgO 12% and EEC 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. Afterwards, 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 cropping 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 factorial design with four replications. Potassium fertilization was performed with potassium chloride (KCl) in amounts equivalent to raise the soil K saturation up to 6%.

Before sowing of crops, 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. 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 et al., 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 Embrapa (1997). Exchangeable K was extracted by the 1.0 mol L^{-1} ammonium acetate solution (CH_3COONH_4) buffered to pH 7.0 (Sanzonowicz and Mielniczuk, 1985). Non-exchangeable K was obtained by the difference between amount of K extracted with boiling 1.0 mol L^{-1} HNO_3 and K extracted with ammonium acetate solution (Knudsen et al., 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 were considered the (i) amounts of nutrient outputs (extracted by plants) and inputs (fertilizer) from the soil during the six cropping of plants, and the (ii) change in the amount of exchangeable K in the soils before and after the six successive cropping. 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 cropping; $K_{\text{Fertilizer}}$ is the amount of K applied as fertilizer 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 sixth cropping.

Data were subjected to analysis of variance (F-test, p = 0.05), and the effects of soil type and addition of K fertilizer were compared by Tukey test and F test, respectively, both at the 0.05 level of confidence. All analyses were performed using Sisvar 5.3 software for Windows (Statistical Analysis Software, UFLA, Lavras, MG, BRA).

RESULTS AND DISCUSSION

SOIL PROPERTIES

The soils had high levels of readily available K (available K $\geq 0.15\ \text{cmol}_c\ \text{dm}^{-3}$), except for the Typic Endoaquert (Ert) (Table 2). This explains the slight or no response to K fertilizer observed of this soils in the first soybean cropping (Figure 1). Typic Plinthaqualf (Alf) was clay texture (> 400 g kg^{-1} of clay), while Typic Endoaquert (Ert) was silty clay (> 400 g kg^{-1} of clay and > 400 kg^{-1} of silt) and Typic Fragiudept (Ept) was sandy clay loam (200-350 g kg^{-1} of clay) (Table 2). The potential buffer capacity of K (PBC^{K}), which measures the ability of the soil to maintain the intensity of K in the soil solution, varied from 2.1 to 6.7 $(\text{mmol}_c\ \text{kg}^{-1})/(\text{mmol L}^{-1})^{1/2}$ (Table 2). High PBC^{K} values were observed in the Typic Endoaquert (Ert), while Typic Plinthaqualf (Alf) and Typic Fragiudept (Ept) were low (Table 2).

DRY MATTER YIELD AND K UPTAKE

Potassium 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 (1st cropping), especially for the Alf and Ept, was due the high levels of readily available K (available K $\geq 0.15\ \text{cmol}_c\ \text{dm}^{-3}$) (Table 2).

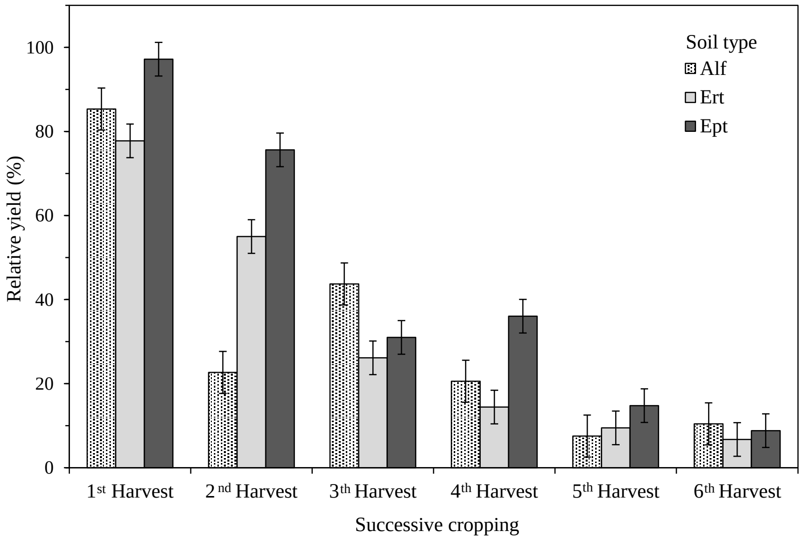

Figure 1. Relative shoot dry matter yield in the treatment no-fertilized (–K) with K compared to treatment fertilized (+K) in the six-successive cropping three lowland soils of Paraná State, Brazil. Vertical lines represent the mean standard error (n = 4). Alf: Typic Plinthaqualf; Ert: Typic Endoaquert; Ept: Typic Fragiudept. Source: The authors.

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 successive cropping.

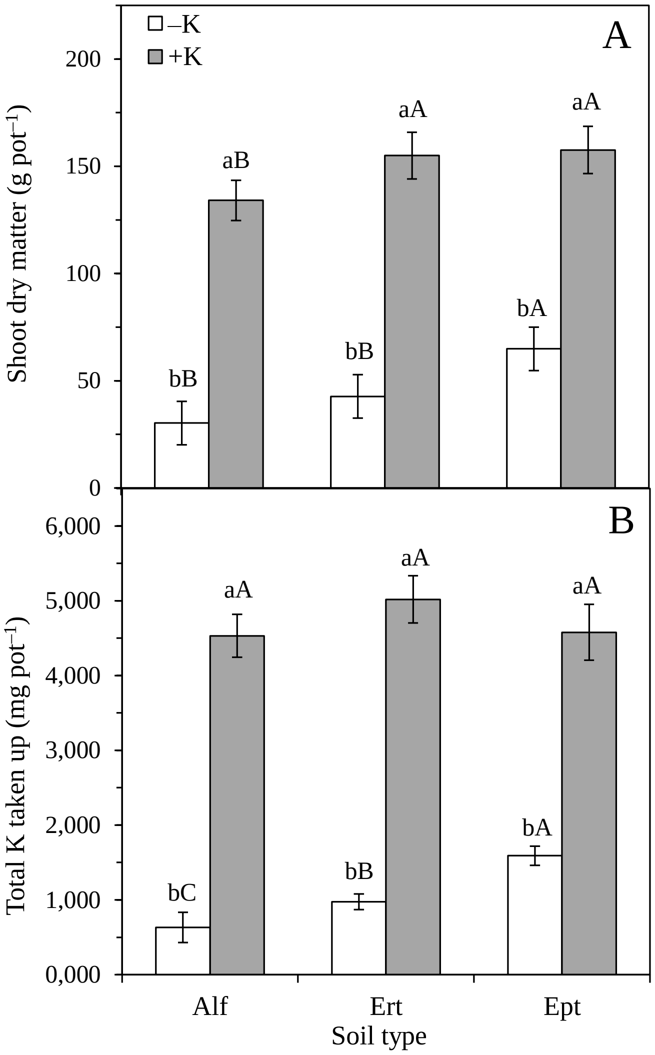

Figure 2. Total shoot dry matter yield – (A) and total K taken up – (B) during the six successive cropping in the three lowland soils of Paraná State, Brazil fertilized (+K) and no-fertilized (–K) with K fertilizer. Vertical lines represent the mean standard error (n = 4). Bars represented by the same upper-case letters, between the different Paraná soils and same lower-case 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. Source: The authors.

The shoot dry matter yield accumulated during six successive cropping 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 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.

The yield of shoot dry matter accumulated in the six cropping 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 indicate that the dry matter yield with 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, as can be seen in Figure 3.

Figure 3. Development of common beans (4th cropping) and maize (6th cropping) in an Typic Plinthaqualf fertilized (+ K) and unfertilized (-K) with potassium fertilizer. Source: The authors.

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 (data not shown). According to Malavolta et al. (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 (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 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 4).

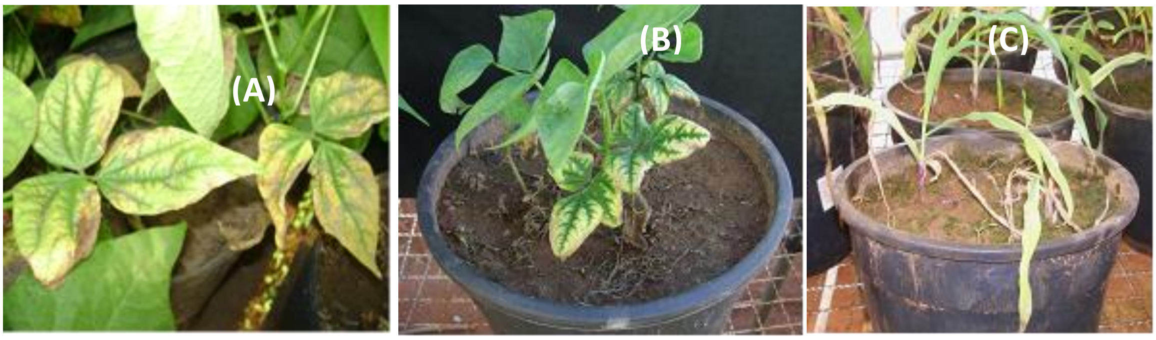

Figure 4. Symptoms of potassium deficiency in leaves of common beans (in A, 4th cropping), in soybeans (in B, 5th cropping) and maize (in C, 6th cropping) grown in an Typic Fragiudept. Source: The authors.

Total amount of K taken up by the plants during the six successive cropping was affected by K fertilizer application and soil type (Figure 3B). As expected, the K application significantly increased K amount taken up during the six successive cropping in all soils. The total amount of K taken up by the plants with 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 3B). These results are due to 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 wide variation between soils (Figure 5). 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 5). The soil structural K constituted 84 to 96% of the total K, and ranged from 1,730 to 7,373 mg kg^{-1} (Figure 5A).

The K content of soil minerals vary with the source of parent material and the degree of weathering (Simonsson et al., 2007). 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, 2000). These results are associated with the presence of mica as natural source of K in its structure. The mineral K reserves of soil are found in the primary minerals such as mica and feldspar, and secondary minerals such as illite, vermiculite and interstratified clay minerals (Sparks et al., 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. (2004) are materials relatively rich in K minerals.

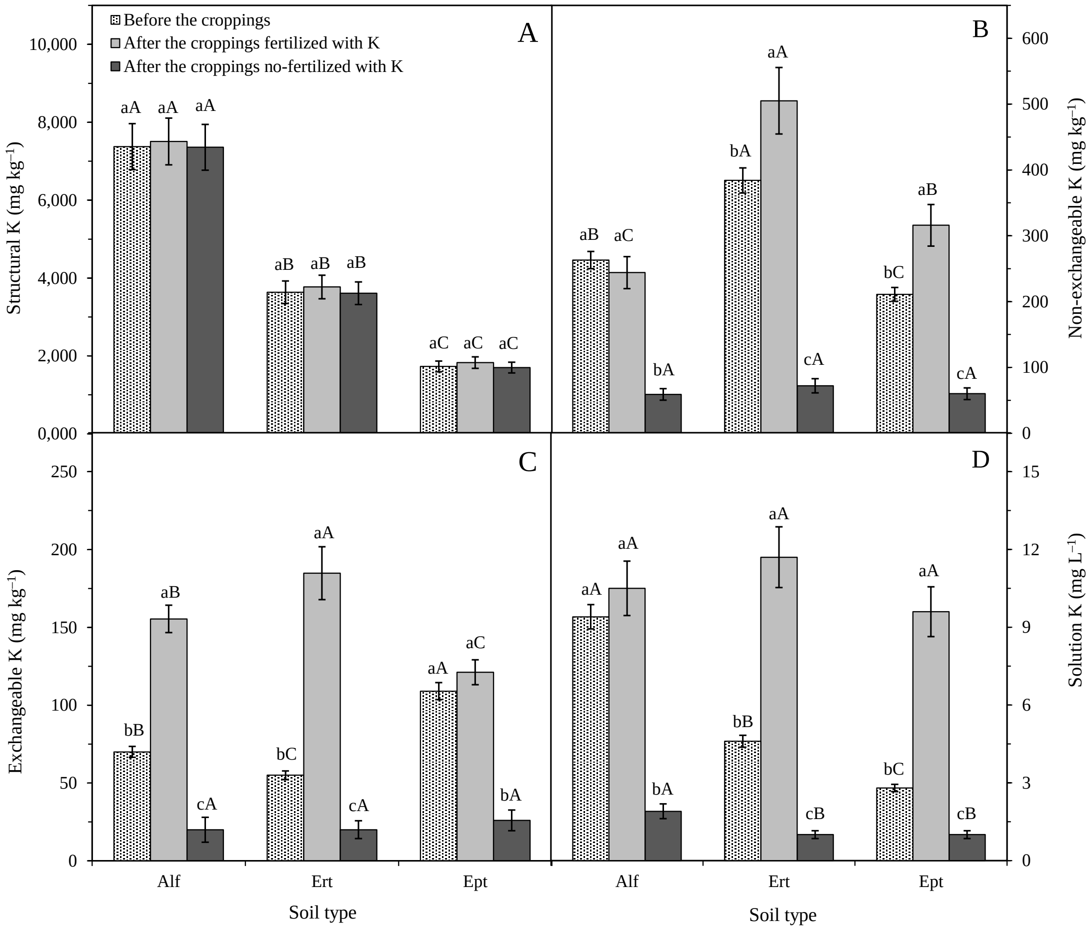

Figure 5. Concentrations of structural K, non-exchangeable K, exchangeable K and solution K in the three lowland soils of Paraná State, Brazil, before and after the sixth successive cropping of plants fertilized (+K) and no-fertilized (–K) with K fertilizer. Vertical lines represent the mean standard error (n = 4). Bars represented by the same upper-case letters, between the different lowland soils and same lower-case letters, for the addition of K fertilizer are not different by Tukey test at the 0.05 level of confidence. Alf: Typic Plinthaqualf; Ert: Typic Endoaquert; Ept: Typic Fragiudept. Source: The authors.

Soil structural K concentration was not affected by successive cropping and addition of K fertilizer (Figure 5A). This indicates that the structural K was not easily released to the plants during the six cropping of plants, confirming the results reported by Kaminski et al. (2007) in soils of southern Brazil.

Non-exchangeable K concentration in the soils were affected by the K fertilizer application (Figure 5B). Potassium addition significantly increased non-exchangeable K concentration in the soils, except for the Alf (Figure 5B). 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 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 (Pernes-Debuyser et al., 2003; 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. According to Pernes-Debuyser et al. (2003), the change of soil K minerals due to 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 5B), 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 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) 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. In fact, 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 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 et al., 2002; Pernes-Debuyser et al., 2003; Bortoluzzi et al., 2005; Rosolem et al., 2012). Hinsinger et al., (1993) observed the formation of vermiculite, in detriment of illite, in the rhizosphere soil of rye grass plants in only 32 days of grown. Under these conditions, the release of K from the illite layers, induced by the action of plant roots, was almost complete. Rosolem et al. (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 5C). The K application significantly increased exchangeable K concentration in the soils, except for the Alf (Figure 5C). 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 mean increase of 97%. 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 et al., 2012). However, these exchangeable K levels is determined by the ability of exchange sites in adsorb 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 in all the soils (Figure 5C). Before of 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 5C). Bortuluzzi 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} 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 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 & 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 6) confirm the results reported by Bortoluzzi et al. (2005), Brunetto et al. (2005), Fraga et al. (2009) and Rosolem et al. (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.

Soil solution K concentration was affected by successive cropping and K fertilizer application (Figure 5D). 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 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 (Figure 6). 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 6).

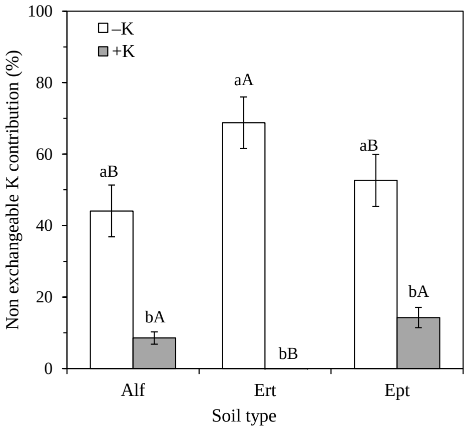

Figure 6. Non-exchangeable K contribution to K uptake of plants during the six successive cropping in the three lowland soils of Paraná State, Brazil, fertilized (+K) and no-fertilized (–K) with K fertilizer. Vertical lines represent the mean standard error (n = 4). Bars represented by the same upper-case letters, between the different lowland soils and same lower-case 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. Source: The authors.

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 potassium fertilizer application (Garcia et al., 2008; Simonsson et al., 2009). Rosolem et al. (2012) found that the non-exchangeable K pools were the main sources of the nutrient for successive cropping of congo grass [*Brachiaria ruziziensis* (Syn. *Urochloa ruziziensis*)]. Rosolem et al. (1988) found that when the exchangeable K concentration is less than 60 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.

FINAL CONSIDERATIONS

The lowland soils from Southern Brazil 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, non-exchangeable, and mineral pools of K. The initial exchangeable K concentration upper at 0.19 $cmol_c$ 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 the contribution of non-exchangeable K. 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. The concentrations of non-exchangeable K and exchangeable K were increased with the addition of K fertilizers, indicating the occurrence of K fixation in soil. The non-exchangeable K contribution to K nutrition of plants during the six cropping ranged from 44 to 69% in the treatments without addition of K fertilizer, reporting the importance of non-exchangeable K pools in the supply of this nutrient to plants in agricultural production systems.

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Toda a nossa ciência, comparada com a realidade, é primitiva e infantil – e, no entanto, é a coisa mais preciosa que temos.

Albert Einstein

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