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Potassium fertilisation with humic acid coated KCl in a sandy clay loam tropical soil

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Abstract. Loss of potassium (K) by leaching after potassium chloride (KCl) application is common in light-textured, low cation exchangeable capacity (CEC) soils with predominance of 1 : 1 clay minerals, and is aggravated as soil K concentration increases. Coating of KCl with humic acids may be a strategy to avoid loss and supply K over the plant cycle. The objective of this study was to evaluate the response of maize (*Zea mays*) and soybean (*Glycine max*) to regular KCl and KCl coated with humic acid, as well as K leaching as affected by application of these fertilisers in single or split application to soils with different K levels. Field experiments with maize and soybean were conducted on soil with very low, low, and medium exchangeable K levels, in Botucatu, Brazil. Soybean and maize grain yields were higher with a single application of coated KCl compared with regular KCl, in soil with very low K level; however, when the rate was split, yields were higher with regular KCl. This shows the importance of fertiliser K release synchronisation as the plant develops, avoiding possible K losses by leaching in low CEC soils. Potassium leaching was observed in soil with medium K level. Potassium chloride coated with humic acids is an adequate source of K in low CEC soils with very low K level when applied in a single application at planting, as opposed to regular KCl that must be split. However, the coated fertiliser is not effective for avoiding K leaching in soils that are medium or high in K.

Additional keywords: leonardite, maize, no-till, potassium leaching, slow release fertiliser, soybean.

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Introduction

An expansion of 81 to 147 million ha of global cropland compared with the 2000 baseline is unavoidable to meet the global demand for food in 2030 (Lambin and Meyfroidt 2011). Among the potentially available cropland, extensive areas of tropical, low cation exchangeable capacity (CEC), and low clay content soils can be converted to agriculture. Most of these areas are currently under extensive pastures (Lapola *et al*. 2014). In Brazil alone, ~30 million ha of degraded pastures may be converted into intensive agriculture with low ecological and social cost (Lambin *et al*. 2013), but this will require high fertiliser input.

Potassium chloride (KCl) is the most widely used potassium (K) fertiliser because its K concentrations are high and it is relatively inexpensive. However, potassium fertilisation with KCl can result in K losses by leaching (Rosolem *et al*. 1984), which may account for 70% of the fertiliser applied in tropical sandy soils (Rosolem and Steiner 2017). Potassium leaching after KCl occurs because of its high solubility and low K fixation to low activity clays, and it is higher than after K_2SO_4 application because the companion ion Cl^- is much more mobile in the soil profile than SO_4^{2-} (Rosolem and Nakagawa 2001). The soil and tillage management are determinant factors in K leaching (Calonego and Rosolem 2013). Highly weathered soils with low clay content have low CEC, resulting in higher concentration of K in soil solution after KCl applications and potentially high K loss (Rosolem and Steiner 2017). Furthermore, K losses by leaching are correlated with the soil exchangeable K concentration and rate of K applied (Werle *et al*. 2008; Rosolem *et al*. 2010), which poses additional challenges in bringing light-textured soils into agricultural production.

The K from fertilisers applied to crops may result in soil K fixation, rhizosphere salinisation, and K leaching, depending on the soil and rate applied (Sangoi *et al*. 2009; Rosolem and Steiner 2017). In low CEC, sandy soils it has been recommended to split K application to reduce loss (Rosolem and Steiner 2017). Hence, developing technologies that reduce the need to split KCl rate, decrease costs and loss and increase K use efficiency are of interest. The use of slow or controlled-release K fertilisers is one of the possible strategies to reduce K loss and increase fertiliser K use efficiency (Trenkel 1997). In general, coated fertilisers that provide slow release of nutrients result in increased fertiliser use efficiency and decreased loss by leaching, fixation, or volatilisation (Al-Zahrani 2000). In the case of K, the use of slow-release KCl is expected to decrease soil salinity (Yang *et al*. 2016), K loss by leaching and decrease fixation, optimising K supply to crops over the plant cycle. The most common slow-release K fertiliser is KCl coated with polymers and humic acid. Polymers provide a physical barrier to K diffusion out of the granule. Humic acids, such as leonardite, contain carboxylic groups on the oxidised C surface that have a considerable CEC and decrease the nutrient release rate compared with regular fertilisers (Boehm 1994). Leonardite is naturally oxidised lignite coal, with a high content of humic and fulvic acids (Broughton 1972), and it has a great capacity to bind cations due to the acidic functional groups, mainly carboxylic and phenolic acids (Livens 1991).

Although several studies have focused on slow release fertilisers, very few have been carried out in tropical areas, especially in soils with low CEC and low clay content, in which agricultural expansion is expected to occur. The objective of this work was to evaluate the response of maize and soybean to regular KCl and KCl coated with humic acid, as well as K leaching in soil with different exchangeable K levels.

Materials and methods

Experiments with maize (*Zea mays* L.) and soybean [Glycine max (L.) Merr.] were conducted under no-till, in soil with different K levels, in Botucatu, State of São Paulo, Brazil, 22°50′00″S, 48°25′29″W, and altitude of 806 m. The soil is a deep Rhodic Hapludox (Soil Survey Staff 2014) with 670 g kg^{-1} of sand and 210 g kg^{-1} of clay, with 73–83% kaolinite, 14–18% allophane, and less than 3% gibbsite. Before these experiments, soybean had been cropped for 14 years, with different K rates, in rotation with black oats (*Avena strigosa* Schreb.) and pearl millet (*Pennisetum americanum* (L.) K. Schum.) grown as cover crops during off-season. According to Raij *et al*. (1997), soil analyses showed very low, low, and medium K levels (Table 1), for the plots that had received a total of 0, 1260, and 2100 kg ha^{-1} of K in 14 years respectively. The temperature and rainfall during this study are given in Fig. 1.

Experiment design and treatments

Experiments with maize and soybean were conducted on soil with very low, low, and medium exchangeable K levels. The experimental design for each experiment was a 2 × 2 factorial in randomised complete blocks, with four replications and one control treatment without K application. Each plot (2.25 m × 8 m) consisted of five rows of plants with 0.45 m between rows, for soybean and maize. The treatments consisted of two K fertilisers, regular KCl and KCl coated with humic acid, applied in single dose or split, broadcast on the soil surface. The humic acid coating was prepared from leonardite (lignite coal), a weathered type of oxidised sub-bituminous coal rich in humic substances (Broughton 1972), and applied at 5 kg t^{-1} of KCl. Humic acid coated KCl is openly available to customers (www.heringer.com.br). The single dose was applied right after planting, at 60 and 80 kg K ha^{-1} for soybean and maize respectively, according to official recommendations for high yields (Raij *et al*. 1997). The split rate was distributed in two applications, 50% applied after sowing, and 50% at the recommended growing stage for each crop (Raij *et al*. 1997). In soybean, the second application was 20 days after emergence (DAE), growth stage V3 (Fehr *et al*. 1971), and for maize the second application was 25 DAE, plants with six expanded leaves, V6 (Ritchie and Hanway 1986).

Table 1. Selected chemical characteristics of the soil at 0.0–0.20 m depth sampled on November of 2015, according to K (0, 90 and 150 kg ha^{-1}) applied yearly in a long-term experiment

pH, Soil pH measured in calcium chloride solution; SOM, Soil organic matter; P, K (exchangeable K), Ca, and Mg, extracted with pearl resin; H+Al, potential acidity; Kne (non-exchangeable K), extracted with boiling HNO_3; CEC, cation exchange capacity

K rates (kg ha^{-1})	pH†	SOM (g kg^{-1})	P (mg kg^{-1})	H^{+}Al	Kne	Ke	Ca	Mg	CEC
				(mmol$_c$ dm^{-3})					
0	4.6	18	23	23	0.7	0.4	17	7.1	48
90	4.7	19	31	29	1.5	0.7	16	6.7	52
150	4.7	18	27	25	2.7	1.6	16	6.1	48

Conducting the experiments

Soybean cultivar TMG 7062 IPRO and maize hybrid 2B810PW were planted on 22 October 2015 over black oat residues under no-till. Soybean seeds were inoculated with *Bradyrhizobium japonicum*, and 26 kg ha^{-1} of P was applied as triple superphosphate in the seed furrows. The final soybean population was 312 000 plants ha^{-1}. Maize received 55 kg ha^{-1} P and 26.7 kg ha^{-1} N as monoammonium phosphate, placed in the seed furrows, plus 120 kg ha^{-1} of N side-dressed as ammonium sulfate split in two applications at 15 and 30 DAE. The final population of maize was 65 000 plants ha^{-1}.

Soybean and maize were harvested at 134 and 135 DAE respectively. Grains were harvested in 2.0 m sections of three central rows. Water content was determined and yields were calculated in kg ha^{-1} on a 130 g kg^{-1} wet basis.

Leaf and soil analysis

When soybean was at R2 (Fehr *et al*. 1971), 30 leaves of the third node from the top were collected per plot for foliar diagnosis. In maize, samples were taken by collecting the central third of the leaf opposite and below the ear from 15 plants per plot (Cantarella *et al*. 1997) at tasselling, which corresponds to the VT stage (Ritchie and Hanway 1986). All leaf samples were dried in a forced-air oven at 60°C, ground,

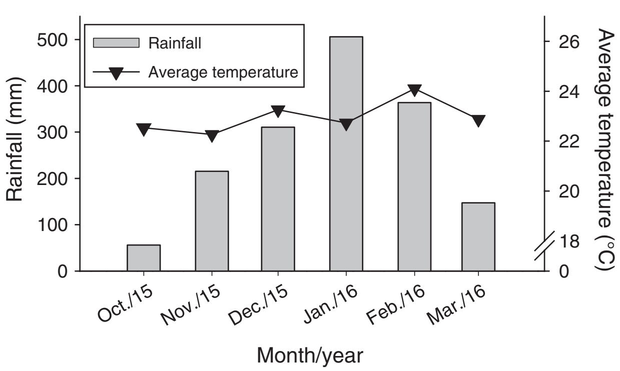

Fig. 1. Monthly rainfall and average temperature recorded during the period that the field experiments were conducted at Botucatu, State of São Paulo, Brazil.

submitted to wet acid digestion, and K concentration was determined using an atomic absorption spectrometer.

Soil samples were collected from the 0.0–0.20 m soil depth before sowing and K application for initial characterisation in October 2015, and from 0.0–0.10, 0.10–0.20, 0.20–0.40, 0.40–0.60, and 0.60–0.80 m depths after harvest in March 2016. Six soil subsamples were randomly taken per plot using a 50-mm inner diameter core sampler and combined into one sample per depth per field replication. The samples were air-dried and passed through a 2-mm sieve for chemical analysis. Soil pH was determined in a 0.01 mol L^{-1} $CaCl_2$ suspension (1 : 2.5 soil/solution), soil organic matter (SOM) was determined according to Walkley and Black (1934), potential acidity at pH 7.0 (H^+Al) and cation exchange capacity (CEC) were determined according to Raij *et al*. (2001). The exchangeable K as well as Ca, Mg, and P concentrations were extracted with ion exchange resin (Raij *et al*. 2001). The K, Ca, and Mg concentrations were determined using an atomic absorption spectrometer, and P concentration was determined using a spectrophotometer.

Statistical analysis

Data from each experiment were subjected to Levene's homogeneity test. Then, ANOVA was performed using a general linear model, considering a 2 × 2 factorial design for each experiment. Means of grain yield, K concentration in leaves and in each soil depth were compared using Tukey's Range Test ($P < 0.05$). The control treatment was not included in ANOVA and Tukey's test. Instead, Dunnett's test ($P < 0.05$) was used to compare means of treatments and the control. All the statistical analyses were performed using SAS software version 9.2.

Results

Leaf K

In the very low K soil, soybean and maize showed K deficiency symptoms in the control treatment. In soybean, there were chlorotic spots and necrosis on the edge of older leaves. This symptom was also observed in new leaves after flowering. Visually, there was extensive flower abortion, higher incidence of green stem, leaf retention, and smaller and deformed pods and grains. In maize, there was tip and marginal chlorosis of older leaves, which progressed to necrosis as the plant developed. Shorter internodes and thinner stems were also observed. Soybean and maize leaf K concentrations were higher with K fertilisation compared with the control in soil with very low K level (Table 2). When fertilisers were applied at single rates soybean leaf K was higher with coated than regular KCl (Table 2), but when the rate was split, regular KCl resulted in higher leaf K. In maize, there was no interaction of the mode of application with K source, and coated KCl and split rate resulted in higher leaf K concentration (Table 2). When K was added, soybean and maize leaf K concentrations were within the range considered adequate, 17 to 25 g kg^{-1} of K in soybean and 17 to 35 g kg^{-1} of K in maize (Malavolta *et al*. 1997).

In the low and medium K soils, K concentrations in soybean leaves were higher with coated KCl than with regular KCl, regardless of the mode of application (Table 2).

Table 2. Average K level in soybean and maize leaves, grown in soil with very low, low, and medium K levels, as a function of K sources (regular and coated KCl) and fertilisation method (single rate and split rate), and a control treatment without K fertilisation

Means followed by the same uppercase letter in rows and lowercase in columns are not significantly different (Tukey, $P < 0.05$); * indicates a significant difference between each treatment and the control treatment (Dunnett, $P < 0.05$)

K sources	Fertilisation method		Average	Control
	Single rate	Split rate		
	K in soybean leaves (g kg^{-1})			
	Very low K soil			
Regular KCl	17.0Bb†*	22.4Aa*	19.7	10.9
Coated KCl	20.2Aa*	19.1Ab*	19.7	
Average	18.6	20.8		
	Low K soil			
Regular KCl	21.1	19.0	20.1b	19.4
Coated KCl	21.5	21.9	21.7a	
Average	21.3	20.5		
	Medium K soil			
Regular KCl	22.4	23.2	22.8b	23.9
Coated KCl	25.3	24.9	25.1a	
Average	23.8	24.1		
	K in maize leaves (g kg^{-1})			
	Very low K soil			
Regular KCl	11.2*	15.0*	13.1b	6.6
Coated KCl	14.8*	17.1*	15.9a	
Average	13.0B	16.1A		
	Low K soil			
Regular KCl	17.9	18.4	18.1	14.7
Coated KCl	17.0	18.6	17.8	
Average	17.4	18.5		
	Medium K soil			
Regular KCl	18.3	21.3	19.8	20.4
Coated KCl	21.5	21.7	21.6	
Average	19.9	21.5		

The K concentration in maize leaves did not respond to K fertilisation in both low and medium K soils (Table 2).

Yield

In soil with very low K level, soybean and maize grain yields were higher with a single application of coated KCl compared with regular KCl (Fig. 2). When the fertiliser application was split, soybean and maize grain yields were higher with regular KCl than with coated KCl (Fig. 2).

In soil with low K, there was no effect of fertilisation, K sources and mode of application in soybean grain yield, which averaged 4 625 kg ha^{-1}. For maize, grain yield in the control treatment was 12 968 kg ha^{-1}, and there was a response when K was used in single application (13 918 kg ha^{-1}), regardless of the K source. When K fertilisation was split, yields were lower (12 228 kg ha^{-1}), regardless of the K fertiliser.

In soils with medium K level, plant response to K fertiliser was not expected, as was the case in the present experiment. There were no differences in soybean or maize grain yields, which averaged 5 248 kg ha^{-1} and 12 271 kg ha^{-1} respectively.

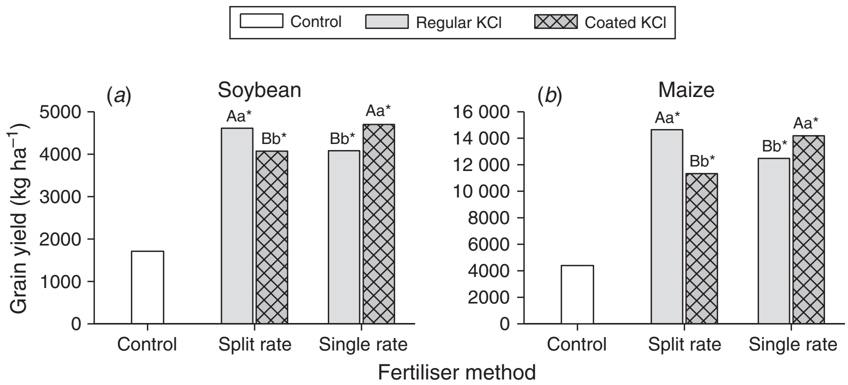

Fig. 2. Soybean (*a*) and maize (*b*) grain yields in soil with very low K level, as affected by K fertilisers (regular and coated KCl) and fertilisation method (single rate and split rate), and a control treatment without K fertilisation. Uppercase letters compare the effect of K sources and lowercase letters compare the effect of K application method (Tukey, $P < 0.05$); * indicates a significant difference between each treatment and the control treatment (Dunnett, $P < 0.05$).

Soil exchangeable K

In the very low K soil, after soybean, K concentration in the uppermost soil layer was higher than in the control due to K fertilisation (Table 3), and when the rate was split, K concentration in the 0.20–0.40 m layer was lower than with single application. In the 0.60–0.80 m layer, K concentration after split application of regular KCl was lower than in the control (Table 3). After maize, K concentration in the soil down to 0.80 m was generally higher than the control, mainly with regular KCl, and split generally resulted in higher soil K compared with single application (Table 3). Below 0.20 m, regular KCl in split form resulted in higher K concentration than coated KCl, showing that K leached deep into the soil profile.

In the low K soil, soybean fertilisation resulted in higher exchangeable K in the uppermost soil layer for both fertilisers, in the 0.10–0.20 m for coated KCl and in the 0.20–0.40 layer for regular KCl (Table 4). In the 0.0–0.10 m layer, soil K was higher with split than single application of coated KCl (Table 4). After maize, split application resulted in higher soil K in the 0–0.10 m layer compared with single application (Table 4). In the 0–0.10, 0.10–0.20, and 0.20–0.40 m layers, the split rate of coated KCl resulted in higher soil K concentration than the control (Table 4).

After soybean in the medium K soil, when the rate was split, coated KCl resulted in higher soil K level than regular KCl, in the 0–0.10 m layer (Table 5). In the 0.10–0.20 m layer the soil K concentration was always higher compared with the control treatment (Table 5). In the layers below 0.20 m, the application of coated KCl resulted in higher soil exchangeable K than regular KCl. In the 0.60–0.80 m layer higher soil K was observed when the rate was split compared with single application (Table 5). After maize, soil K was higher with coated than with regular KCl, and the split application resulted in a higher soil exchangeable K compared with the control in the 0.0–0.10 m layer (Table 5). In the layers from 0.10 to 0.40 m, a higher soil K level was found with the application of regular KCl than with coated KCl (Table 5). From 0.10 to 0.40 m, the soil K was higher than in the control treatment only with regular KCl in single application. All treatments resulted in higher soil exchangeable K in the 0.60–0.80 m layer than the control treatment (Table 5).

Discussion

In the very low K soil, yield was expected to be up to 70%, in low K soil, from 71 to 90%, and in medium K soil, from 91 to 100% of the maximum with adequate fertilisation (Raij *et al.* 1997). Therefore, in the very low K soil without K fertilisation plants showed K deficiency, the leaf K level was low (Table 2) and crops responded to K fertilisation (Fig. 2). The application of K resulted in an increase of ~150% and 200% in soybean and maize yield respectively (Fig. 2). A higher response of maize was observed because soybean is very efficient in taking up K from the soil (Sacramento and Rosolem 1997), and it is able to take up non-exchangeable K (Rosolem *et al.* 1988), which is not the case for maize (Garcia *et al.* 2008). According to Gommers *et al.* (2005), when the plant mechanisms controlling K uptake are efficient, especially at low K concentrations, the strong gradient towards the rhizosphere create a favourable environment for the release of K from non-exchangeable forms. A better K nutrition of soybean was observed in soils with low and medium K levels with the application of coated KCl (Table 2); however, there was no effect of the fertilisers on grain yield. The lack of soybean response in the low K soil can be credited to its high ability to acquire soil K, including non-exchangeable forms (Rosolem *et al.* 1988; Fernandes *et al.* 1993). In these situations, the exchangeable soil K was still lower than 2.0 $mmol_c\ dm^{-3}$, the upper boundary of the medium range (Raij *et al.* 1997), and at least a small yield response to K fertilisation would be possible. However, leaf K also did not increase with K fertilisation, leading to the inference that there was excessive K consumption when coated KCl was applied.

With a single application, coated KCl conferred a better K supply to soybean and maize in soil with very low K levels (Table 2), which resulted in higher grain yields. However, splitting coated KCl resulted in lower soybean and maize leaf K and yields compared with single application, probably due to a lack of synchronism in supplying K throughout the crop

Table 3. Soil exchangeable K after soybean and maize grown in soil with very low K level as affected by depths, K sources (regular and coated KCl) and method of fertiliser application (single rate and split rate), and a control treatment without K fertilisation

Means followed by the same uppercase letter in rows and lowercase in columns are not significantly different (Tukey, $P < 0.05$); * indicates a significant difference between each treatment and the control treatment (Dunnett, $P < 0.05$)

K sources	Fertilisation method		Average	Control
	Single rate	Split rate		
		mmol$_c$ dm^{-3}		
		After soybean		
		0.0–0.10 m		
Regular KCl	0.56Bb*	0.63Aa*	0.60	0.28
Coated KCl	0.64Aa*	0.53Bb*	0.59	
Average	0.60	0.58		
		0.10–0.20 m		
Regular KCl	0.20	0.23	0.22	0.19
Coated KCl	0.21	0.20	0.21	
Average	0.21	0.21		
		0.20–0.40 m		
Regular KCl	0.20	0.16	0.18	0.18
Coated KCl	0.22	0.15	0.19	
Average	0.21A	0.16B		
		0.40–0.60 m		
Regular KCl	0.09	0.12	0.11	0.12
Coated KCl	0.09	0.08	0.09	
Average	0.09	0.10		
		0.60–0.80 m		
Regular KCl	0.06	0.04*	0.05	0.08
Coated KCl	0.06	0.05	0.06	
Average	0.06	0.05		
		After maize 0.0–0.10 m		
Regular KCl	0.48	0.66*	0.57	0.38
Coated KCl	0.48	0.67*	0.58	
Average	0.48B	0.67A		
		0.10–0.20 m		
Regular KCl	0.22	0.37*	0.30	0.16
Coated KCl	0.19	0.25	0.22	
Average	0.21B	0.31A		
		0.20–0.40 m		
Regular KCl	0.18	0.22*	0.20a	0.12
Coated KCl	0.13	0.14	0.14b	
Average	0.16	0.18		
		0.40–0.60 m		
Regular KCl	0.12	0.17*	0.14a	0.06
Coated KCl	0.08	0.13*	0.10b	
Average	0.10B	0.15A		
		0.60–0.80 m		
Regular KCl	0.07	0.13*	0.10a	0.04
Coated KCl	0.05	0.07	0.06b	
Average	0.06B	0.10A		

Table 4. Soil exchangeable K after soybean and maize grown in soil with low K level as affected by depths, K sources (regular and coated KCl) and method of fertiliser application (single rate and split rate), and a control treatment without K fertilisation

Means followed by the same uppercase letter in rows and lowercase in columns are not significantly different (Tukey, $P < 0.05$); * indicates a significant difference between each treatment and the control treatment (Dunnett, $P < 0.05$)

K sources	Fertilisation method		Average	Control
	Single rate	Split rate		
		mmol$_c$ dm^{-3}		
		After soybean		
		0.0–0.10 m		
Regular KCl	0.78Aa*	0.70Ab*	0.74	0.51
Coated KCl	0.71Ba*	0.97Aa*	0.84	
Average	0.74	0.83		
		0.10–0.20 m		
Regular KCl	0.39Aa	0.36Ab	0.38	0.29
Coated KCl	0.28Bb	0.47Aa*	0.38	
Average	0.34	0.42		
		0.20–0.40 m		
Regular KCl	0.30	0.40*	0.35	0.22
Coated KCl	0.30	0.34	0.32	
Average	0.30	0.37		
		0.40–0.60 m		
Regular KCl	0.13	0.13	0.13	0.18
Coated KCl	0.16	0.16	0.16	
Average	0.15	0.15		
		0.60–0.80 m		
Regular KCl	0.09	0.11	0.10	0.10
Coated KCl	0.10	0.10	0.10	
Average	0.10	0.11		
		After maize 0.0–0.10 m		
Regular KCl	0.59	0.75	0.67	0.59
Coated KCl	0.74	0.80*	0.77	
Average	0.67B	0.78A		
		0.10–0.20 m		
Regular KCl	0.38	0.33	0.36	0.31
Coated KCl	0.36	0.46*	0.41	
Average	0.37	0.39		
		0.20–0.40 m		
Regular KCl	0.29*	0.22	0.25	0.17
Coated KCl	0.24	0.27*	0.25	
Average	0.26	0.24		
		0.40–0.60 m		
Regular KCl	0.15	0.13	0.14	0.13
Coated KCl	0.15	0.14	0.14	
Average	0.15	0.14		
		0.60–0.80 m		
Regular KCl	0.12	0.11	0.11	0.10
Coated KCl	0.12	0.09	0.10	
Average	0.12	0.10		

cycle. Yang *et al*. (2016) reported that the polymer used had 3 months of longevity and this could decrease the synchronism to K release and plant uptake. In a study by Oosterhuis and Howard (2008), programmed-release KCl coated with polyolefin resin applied in a single rate at sowing resulted in increased nutrient use efficiency by cotton (*Gossypium hirsutum* L.). When the full rate of regular KCl was applied at planting in our experiment, soybean and maize yields were lower because, in this situation, nutrients could leach below the root zone of the young plants, despite the results of soil analyses (Table 3) showing no indication as to explain these differences.

Due to the high K mobility in low clay, low CEC soils, K application method generally does not interfere in the plant

Table 5. Soil exchangeable K after soybean and maize grown in soil with medium K level as affected by depths, K sources (regular and coated KCl) and method of fertiliser application (single rate and split rate), and a control treatment without K fertilisation

Means followed by the same uppercase letter in rows and lowercase in columns are not significantly different (Tukey, $P<0.05$); * indicates a significant difference between each treatment and the control treatment (Dunnett, $P<0.05$)

K sources	Fertilisation method		Average	Control
	Single rate	Split rate		
		$mmol_c\ dm^{-3}$		
		After soybean		
		0.0–0.10 m		
Regular KCl	1.64Aa*	1.26Ab	1.45	1.22
Coated KCl	1.43Aa	1.88Aa*	1.67	
Average	1.54	1.57		
		0.10–0.20 m		
Regular KCl	0.75*	0.66*	0.71	0.42
Coated KCl	0.70*	0.74*	0.72	
Average	0.73	0.70		
		0.20–0.40 m		
Regular KCl	0.64	0.70	0.67b	0.44
Coated KCl	1.17*	1.00*	1.08a	
Average	0.90	0.85		
		0.40–0.60 m		
Regular KCl	0.34	0.23	0.29b	0.32
Coated KCl	0.76*	0.59*	0.68a	
Average	0.55	0.41		
		0.60–0.80 m		
Regular KCl	0.16	0.20	0.18b	0.23
Coated KCl	0.37*	0.47*	0.42a	
Average	0.27B	0.34A		
		After maize 0.0–0.10 m		
Regular KCl	1.03	1.59*	1.31b	1.11
Coated KCl	1.34	1.70*	1.52a	
Average	1.19B	1.64A		
		0.10–0.20 m		
Regular KCl	1.13*	0.95	1.04a	0.84
Coated KCl	0.87	0.88	0.89b	
Average	1.00	0.92		
		0.20–0.40 m		
Regular KCl	1.11*	0.86	0.99a	0.74
Coated KCl	0.74	0.65	0.70b	
Average	0.93A	0.76B		
		0.40–0.60 m		
Regular KCl	0.62	0.54	0.58	0.45
Coated KCl	0.58	0.59	0.59	
Average	0.60	0.56		
		0.60–0.80 m		
Regular KCl	0.61*	0.44*	0.52	0.22
Coated KCl	0.51*	0.51*	0.51	
Average	0.56	0.48		

use of this nutrient. In addition, broadcast fertilisers result in lower costs and higher operational efficiency than furrow application. In the present study, broadcast coated KCl in single rate was efficient for an adequate K nutrition of soybean and maize. According to Rosolem *et al*. (2010), since KCl is highly soluble, it is prone to leaching in low CEC soils, and it is essential to apply an appropriate amount of K because the excess will be lost.

Although K is a nutrient easily leached in tropical soils, a concentration gradient was observed along the soil profile, decreasing from the surface, which is not uncommon under no-till (Garcia *et al*. 2008). One of the reasons for this K accumulation in the uppermost soil layer is that plant residues left on the soil surface decrease leaching (Rosolem *et al*. 2006). Since more than 80% of K remains in a soluble form in the plant and/or in plant residues after harvest, not strongly bound into carbon chains (Hawkesford *et al*. 2012), it can quickly return to the soil with rains and plant senescence (Rosolem *et al*. 2006).

Higher common bean (*Phaseolus vulgaris* L.) grain yield was observed under the residual effect of K fertilisation with regular KCl and a slow release K fertiliser applied to a preceding maize crop (Rodrigues *et al*. 2013). However, there were no differences in K concentrations in maize, and no impact on soil K as a result of different K sources (Rodrigues *et al*. 2014). In the very low K soil in the present study, exchangeable K at 0–0.10 m depth was higher after harvest in plots with coated KCl than in plots with regular KCl, which could be related to higher K uptake and, consequently, greater cycling of this nutrient by the plants in treatments with coated KCl. The amount of K in plants at harvest is lower than in the phase of maximum accumulation, since much of the K in the shoots is washed out with rainfall (Oltmans and Mallarino 2015). According to Rosolem *et al*. (2003), the amount of K released by rainfall after desiccation of a crop is strongly correlated with the K content of the plants. Thus, the application of coated KCl could result in a greater residual effect than the application of regular KCl. It has to be taken into account that 40 to 50 kg ha^{-1} of K is washed back to the soil from physiological maturity to harvest of soybean and maize (Rosolem *et al*. 2003; Oltmans and Mallarino 2015), and can be found in the soil arable layer in concentrations proportional to the applied K rates.

Potassium movement in the soil profile is related to rainfall and soil K content. The total rainfall during the period of this study was high (Fig. 1), which is common in humid mesothermal climate, and favourable to K leaching. As K binding sites are gradually occupied in soils with low and medium K levels the retention capacity is decreased (Werle *et al*. 2008). Increased K loss with exchangeable K concentration in soil is further aggravated by the low CEC of 1 : 1 clay minerals, low SOM content, and predominance of sandy size particles in the soil in the present study (Sparks and Huang 1985). However, the presence of humic acids results in lower K leaching (Selim *et al*. 2009). In the present study, soil exchangeable K in deeper layers in soil with very low K level was higher after the application of regular KCl than after application of coated KCl, mainly after maize. Possibly the lower concentration of K, and less leaching after application of coated KCl is due to K protection by the humic acid coating, which was also observed by Zhang *et al*. (1998), who reported that the application of protected K can result in higher available K in soils with low K.

Unlike in very low K soil, exchangeable K was higher at harvest in the uppermost soil layer of the low K soil with split coated KCl, which may be related to a lack of synchronism of

K release and plant demand. However, K leaching was not observed in the 0.60–0.80 m soil layer. According to Mielniczuk *et al*. (2005) K leaching depends on K concentration in the soil solution, soil characteristics, and water excess for its displacement to deeper soil layers. Once the K concentration in the soil solution is low in soil with very low and low K levels, K leaching may be reduced. However, the excess K not taken up by plants from the split coated KCl resulted in K leaching in soil with medium K level, which was observed even at the 0.60–0.80 m depth. Therefore, use of coated KCl may result in K leaching as much as regular KCl in soils with a medium K level. Since there were no differences in soybean and maize grain yields with K fertilisation and the control treatment in soil with medium K level, a small K dose of regular or coated KCl should be recommended to avoid K depletion in the long term, and to avoid K losses in light-textured soils.

Conclusion

Coating KCl with humic acid prevents fast release of K to soil solution, without soybean and maize yield loss in light-textured soils that are very low in K. This fertiliser must be applied in a single dose as opposed to regular KCl, which requires split application for high yields in sandy soils with a very low K level. Despite the decreased rate of K release, coating potassium chloride with humic substances does not prevent K leaching in soils with a medium level of exchangeable K.

Conflicts of interest

The authors declare no conflicts of interest.

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