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Potassium buffering capacity and corrective potassium fertilizer recommendations in soils from Southern Brazil

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ABSTRACT: Soils with low potassium (K) availability require corrective fertilization for grain crops. The recommended rate to increase K availability up to the critical level depends on the soil K buffering capacity (KBC). This study aimed to quantify the KBC and recalculate the rates necessary to reach the K critical level in 23 soils from Southern Brazil. Soil samples were incubated with six K rates, that were thus grouped according to $CEC_{pH7.0}$: below 7.5 $cmol_c$ dm^{-3} (0, 30, 60, 90, 120 and 180 kg K_2O ha^{-1}); from 7.6 to 15 $cmol_c$ dm^{-3} (0, 30, 60, 120, 180 and 240 kg K_2O ha^{-1}) and from 15.1 to 30 $cmol_c$ dm^{-3} (0, 30, 60, 120, 240 and 360 kg K_2O ha^{-1}). The soil test K (STK) was extracted by Mehlich-1 and the fertilizer rates necessary to increase the STK by 1 mg dm^{-3} were quantified. The KBC values were correlated with a suite of soil testing metrics. The relationship between the cation exchange capacity ($CEC_{pH7.0}$) and KBC was modeled, and a linear-plateau equation presented the best fit. The K rates were calculated using the following equation: K rate = (Critical Level - STK) × KBC and were compared with the current rate indicated by the Local Soil Fertility Committee. The K fertilizer rates by KBC were about 2.5 times higher than the values currently indicated, and the largest differences were observed in soils with low STK and high $CEC_{pH7.0}$.

Keywords: potassium fertilization, critical potassium level, rate adjustment, southern Brazil.

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INTRODUCTION

Potassium (K) is an essential nutrient for plants and highly demanded by agricultural species (Firmano et al., 2020). Together with nitrogen (N), it is the nutrient absorbed in greater quantities by plants (Filippi et al., 2021), and when in excess in the soil, plants can use it beyond their need for luxury consumption (Kang et al., 2014; Fornari et al., 2020). Data collected in the meta-analysis by Filippi et al. (2021) show the largest export of K by the most recent soybean cultivars, noting that in most of Brazil, K replacements are below what is necessary. So, with the increased export of nutrients, including K, critical levels could be above the actual requirement of plants, reinforcing the need for constant research to update fertilizer recommendations.

Soils like those from Southern Brazil are highly weathered, presenting commonly high acidity, low base saturation, and, in some cases, low K content (Melo et al., 2001, 2002). Regionally, variability in natural K contents is due to clay content and soil mineralogy, which affect the K richness and K fixation capacity (Zhang et al., 2009; Wang et al., 2017). In addition, inadequate fertilization management where outputs are higher than inputs can lead to K content depletion, negatively impacting crop yields (Firmano et al., 2019; Gatiboni et al., 2020). Thus, for optimal K management, it is important to supply K at adequate levels to meet crop demand (Firmano et al., 2020) and decrease the K transfer potential, especially, by runoff (Ceretta et al., 2010; Wang et al., 2019; Wolka et al., 2021).

Soil K buffering capacity (KBC) can be defined as the amount of K that must be applied to the soil to raise the K content by 1 mg dm^{-3} (soil test K, STK). Generally, these data obtained in tests under controlled conditions, with incubation of K doses and subsequent determination of available levels and evaluation of the mathematical relationship of applied rates versus available levels, in different soils. Soil KBC can be influenced by the mineral content and types of clay fraction and soil organic matter (SOM) content. Clays hold most of the electrical charges in the soil, resulting from the isomorphic substitutions that occurred and/or from variable charges exposed at the edges of the minerals (Strawn, 2021; Pinheiro et al., 2022). In this same sense, SOM has a great contribution to the number of electrical charges dependent on the soil pH, by the deprotonation of the functional groups present in this fraction (Ernani, 2016). Considering different parameters and a set of contrasting and representative soils of the region of interest is fundamental to obtaining correct KBC estimates.

The K critical level can be established according to the crop groups of interest and the $CEC_{pH7.0}$, for the soils from Southern Brazil (CQFS-RS/SC, 2016). For soils that have STK below the critical level, it is recommended to perform corrective fertilization for grain crops, based on the Local Soil Fertility Committee. The corrective fertilization is performed according to STK classes. Soils with STK classified as “very low” (VL), “low” (L) and “medium” (M) can receive the amounts of 120, 60 and 30 kg K_2O ha^{-1}, regardless of the soil’s $CEC_{pH7.0}$ (CQFS-RS/SC, 2016). Based on these values and considering that the critical level are different depending on the soil $CEC_{pH7.0}$, it is possible to estimate the KBC for each group (CQFS-RS/SC, 2016); i) it is necessary to apply from 2.0 to 3.0 (VL), from 1.5 to 3.0 (L), and from 1.6 to 30.0 (M) kg K_2O ha^{-1} to increase the STK 1 mg dm^{-3} in soils with $CEC_{pH7.0}$ ≤7.5 $cmol_c$ dm^{-3}; ii) soils with $CEC_{pH7.0}$ between 7.6 and 15 $cmol_c$ dm^{-3} require from 1.3 to 2.0 (VL), from 1.0 to 2.0 (L), and from 1.0 to 30.0 (M) kg K_2O ha^{-1}; iii) soils with $CEC_{pH7.0}$ between 15.1 and 30 $cmol_c$ dm^{-3} require from 1.0 to 1.5 (VL), from 0.8 to 1.5 (L), and from 0.8 to 30.0 (M) kg K_2O ha^{-1}. Finally, iv) soils with $CEC_{pH7.0}$ >30 $cmol_c$ dm^{-3} require from 0.9 to 1.3 (VL), from 0.7 to 1.3 (L), and from 0.7 to 30.0 (M) kg K_2O ha^{-1} to increase the STK 1 mg dm^{-3}. Regarding the $CEC_{pH7.0}$ classes, we can observe that in soils with $CEC_{pH7.0}$ lower than 7.5 $cmol_c$ dm^{-3} is necessary to apply 2.5 kg K_2O ha^{-1}; soils with $CEC_{pH7.0}$ between 7.6 and 15 is necessary to apply 1.6 kg K_2O ha^{-1}; soils with $CEC_{pH7.0}$ between 15.1 and 30 is necessary to apply 1.2 kg K_2O ha^{-1}; and soils with $CEC_{pH7.0}$ greater than 30 is necessary to apply 1.1 kg K_2O ha^{-1}. Clearly, there are inconsistencies in this recommendation, as there are unjustified variations on the KBC depending on the $CEC_{pH7.0}$ and initial STK. According to the current recommendation, more buffered (higher $CEC_{pH7.0}$) soils need less K to increase KBC, which is quite questionable.

The hypothesis of this study is that the current K_2O rates recommended by the Local Soil Fertility Committee are inadequate to reach the critical level. This study aimed to quantify the KBC and recalculate the rates necessary to reach the critical level in soils from Southern Brazil.

MATERIALS AND METHODS

Soil sampling and characterization

Soil samples were collected in 23 sites, 14 in Santa Catarina State and 9 in Rio Grande do Sul State (Figure 1), both in Southern Brazil. The soil samples were collected from 0.00-0.20 m soil layer. The samplings were carried out adjacent to agricultural sites but without fertilizer application.

The soil samples were oven-dried at 60 °C for 72 hours, ground, and sieved in a 2 mm aperture sieve. Soil acidity was accessed, and when necessary, the soil pH was raised to 6.0, through incubation with dolomitic limestone with 90 % of PRNT, as described by Mumbach et al. (2021). Then, the soils were chemically characterized (Table 1), according to Sparks et al. (1996), and the clay content was determined by the pipette method (Teixeira et al., 2017). Soil test K was extracted by Mehlich-1 (0.0125 mol L^{-1} H_2SO_4 and 0.050 mol L^{-1} HCl), and the K determination was carried out by flame spectrophotometry (DM-62, DIGIMED apparatus). Total organic carbon (TOC) content was determined by spectrophotometry at 645 nm (UV-1800, SHIMADZU) after oxidation by sulfochromic solution ($Na_2Cr_2O_7$ 15 % diluted in concentrated H_2SO_4 5.0 mol L^{-1}). Using methodologies by Thomas (1996), the content of exchangeable Ca and Mg were extracted with KCl 1 mol L^{-1} and analyzed by atomic absorption spectrophotometry. The H+Al was estimated from the SMP index. Finally, the $CEC_{pH7.0}$ (Table 1) was calculated by adding de Ca^{2+}, Mg^{2+}, H+Al, and STK.

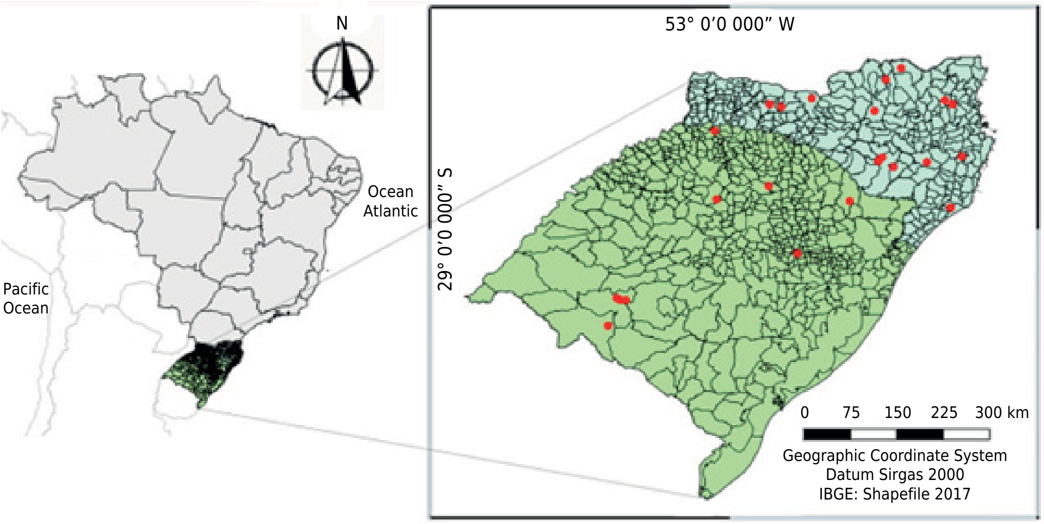


Figure 1. Localization of the 23 sampled soils distributed in the Rio Grande do Sul and Santa Catarina states, Southern Brazil.

Table 1. Classification and characterization of soils samples collected from the 0.00–0.20 m soil layer in the Rio Grande do Sul and Santa Catarina states, Southern Brazil

Soil(1)	Clay(2)	TOC(3)	K(3)	$\text{CEC}_{\text{pH7.0}}$(4)	Ca^{2+}(5)	Mg^{2+}(6)	H+Al(7)	Available K classes(8)
	%	g kg^{-1}	mg dm^{-3}	cmol_c dm^{-3}				
P1	9.7	8.2	41	2.9	0.6	0.8	1.4	Medium
P2	12.1	10.0	52	4.2	1.0	1.1	2.0	Medium
P3	12.2	16.3	40	4.8	1.4	1.6	1.7	Low
P4	18.1	13.4	30	6.7	1.9	2.0	2.8	Low
P5	18.9	9.5	47	7.0	2.3	2.3	2.3	Medium
P6	39.1	10.7	24	7.7	2.5	1.6	3.5	Very Low
P7	24.6	10.8	36	8.2	3.3	1.7	3.1	Low
P8	36.5	5.9	28	8.5	3.4	2.3	2.8	Very Low
P9	12.4	15.3	55	9.4	2.8	3.0	3.5	Low
P10	68.0	14.5	33	10.1	3.9	3.4	2.7	Low
P11	43.3	21.6	51	10.4	3.9	3.7	2.8	Low
P12	34.5	24.8	62	10.8	3.9	4.0	2.7	Medium
P13	35.4	27.0	37	11.1	4.5	4.1	2.3	Low
P14	42.9	21.4	70	11.3	4.5	3.4	3.3	Medium
P15	48.5	39.6	76	11.8	4.0	4.3	3.3	Medium
P16	70.6	12.2	55	11.8	5.1	3.9	2.7	Low
P17	53.9	25.8	54	12.2	4.9	4.3	2.8	Medium
P18	61.7	28.5	41	12.7	5.0	4.8	2.7	Low
P19	34.3	15.9	67	13.0	5.3	4.7	2.7	Medium
P20	58.8	19.2	37	13.1	5.3	4.9	2.8	Low
P21	51.2	22.0	51	13.6	5.7	4.9	2.8	Low
P22	34.5	26.0	46	14.1	5.7	5.4	2.9	Low
P23	66.6	60.5	55	15.5	6.2	5.9	3.2	Low

(1) According to the classification proposed by the FAO (IUSS Working Group WRB, 2015) and by Brazilian Soil Classification System (Santos et al., 2018). P1, P2 and P3: Acrisol/*Argissolo Vermelho*; P4, P19 and P22; Cambisol/*Cambissolo Húmico*; P5, P8 and P12; Acrisol/*Argissolo Vermelho-Amarelo*; P6, P13, P15 and P16: Ferrasol/*Latossolo Vermelho*; P7: Acrisol/*Argissolo Amarelo*; P9: Luvisol/*Luvissolo Háplico*; P10: Ferrasol/*Latossolo Bruno*; P14: Cambisol/*Cambissolo Háplico*; P17, P20 and P21: Nitisol/*Nitossolo Bruno*. The soils designated between P1 and P23 were collected in the cities of Rosário do Sul-RS, Rosário do Sul-RS, Santana do Livramento-RS, Mafra-SC, Sangão-SC, Teotônia-RS, Pomerode-SC, Blumenau-SC, Rosário do Sul-RS, Vargeão-SC, Lages-SC, Rancho Queimado-SC, Passo Fundo-RS, Iraí-RS, Ibirubá-RS, Pinhalzinho-SC, Painel-SC, Major Vieira-SC, Lages-SC, Santa Cecília-SC, Água Doce-SC, Bom Retiro-SC and Vacaria-SC. (2) Clay content determined by the pipette method. (3) Initial Soil Test K (STK). (4) Total organic carbon. (5) Initial calcium content. (6) Initial magnesium content. (7) Potential acidity. (8) Available K classes according CQFS-RS/SC 2016).

Incubation and determination of buffering capacity

In October 2020, the soil samples were incubated with six K rates, from 0 to 360 kg K_2O ha^{-1}, with three replications, under a completely randomized design. Rates were calculated with respect to the $\text{CEC}_{\text{pH7.0}}$, according to CQFS-RS/SC (2016): below 7.5 cmol_c dm^{-3} (0, 30, 60, 90, 120 and 180 kg K_2O ha^{-1}); from 7.6 to 15 cmol_c dm^{-3} (0, 30, 60, 120, 180 and 240 kg K_2O ha^{-1}); and from 15.1 to 30 cmol_c dm^{-3} (0, 30, 60, 120, 240 and 360 kg K_2O ha^{-1}). Potassium rates were applied through a KCl solution; the fertilizer was ground and dissolved in water, with subsequent determination of the K content.

Each experimental unit consisted of 50 g of soil packed in plastic bags. After the K fertilization, the soil samples were homogenized, and the moisture was adjusted to 100 % of the field capacity. The incubation was carried out for 30 days with the plastic bags opened. The moisture of each experimental unit was adjusted weekly by touch, and when necessary, distilled water was slowly added with subsequent homogenization. At the end of the incubation, the samples were oven-dried at 60 °C for 48 hours and sieved in a 2 mm mesh and STK was determined by the Mehlich-1 procedure.

Linear regression was used to describe the relationship between K rates and STK. Potassium buffering capacity was calculated using parameters from the linear regression (Equation 1).

$$KBC = \frac{1}{angular\ coefficient} \qquad \text{Eq. 1}$$

in which: KBC represents the amount of fertilizer (kg K_2O) to raise STK by 1 mg dm^{-3}; and angular coefficient represents the value obtained relating the applied K rates with the available levels in the soil after incubation. Then, KBC values were correlated with soil properties as initial STK, clay content, TOC, $CEC_{pH7.0}$, Ca^{2+}, Mg^{2+} and H+Al.

Corrective fertilization recommendation

The KBC values were used to simulate a recommendation for K corrective fertilization. It was used a set of 333 soil samples obtained from a local soil testing laboratory, Agroveterinary Sciences Center of Santa Catarina State University (CAV/UDESC), in Lages, Southern Brazil. All soils used in the simulation had STK below the critical level for grain crops (CQFS-RS/SC, 2016). The recommendation proposed in this study is based on a methodology used in the Brazilian Cerrado region, adapted from Sousa et al. (2016), according to equation 2.

$$K\ rate\ (kg\ K_2O\ ha^{-1}) = (K_{CL} - STK) \times KBC \qquad \text{Eq. 2}$$

in which: “K rate” represents the amount of K_2O recommended for corrective fertilization to reach the K critical level; “K_{CL}” represents the K critical level (CQFS-RS/SC, 2016) according to the crop groups; “STK” is the initial K value obtained from the soil test reports; and “KBC” is the K buffering capacity in the soil.

The K rate calculated was compared with the amounts of K fertilizer recommended by the Local Soil Fertility Committee (CQFS-RS/SC, 2016) for corrective fertilization. When the soil was classified as “very low”, “low” or “medium”, the Local Soil Fertility Committee recommended 120, 60 and 30 kg K_2O ha^{-1}, respectively, regardless the $CEC_{pH7.0}$.

Statistical analysis

Shapiro-Wilk and Bartlett’s tests were applied to the data obtained during the experiment to evaluate normality and homoscedasticity. After that, the data were subjected to analysis of variance (ANOVA) and, if significant, analyzed through linear regression (K_2O rates and STK). Subsequently, Pearson correlation analysis was performed between KBC and soil properties. Subsequent linear-plateau analysis between KBC and $CEC_{pH7.0}$ were performed. Fertilization recommendations for 333 soil samples were compared using a confidence interval. The SigmaPlot 12.0 and Jamovi 1.6.23.0 software were used for data analysis and graphic production, and the STATISTICA 10.0 software for multiple linear regression. In the equations and figures “*” represent significative at 5 %, “**” significative at 1 % and “***” significative at 0.1 % of error probability.

RESULTS

K buffering capacity

In the 23 soil samples evaluated, the STK increased linearly with the application of K rates (Figure 2) with high significance. Before the incubation, the initial STK varied between 24 to 76 mg dm^{-3} and reached, at the end of the incubation, values between 98 to 163 mg dm^{-3}.

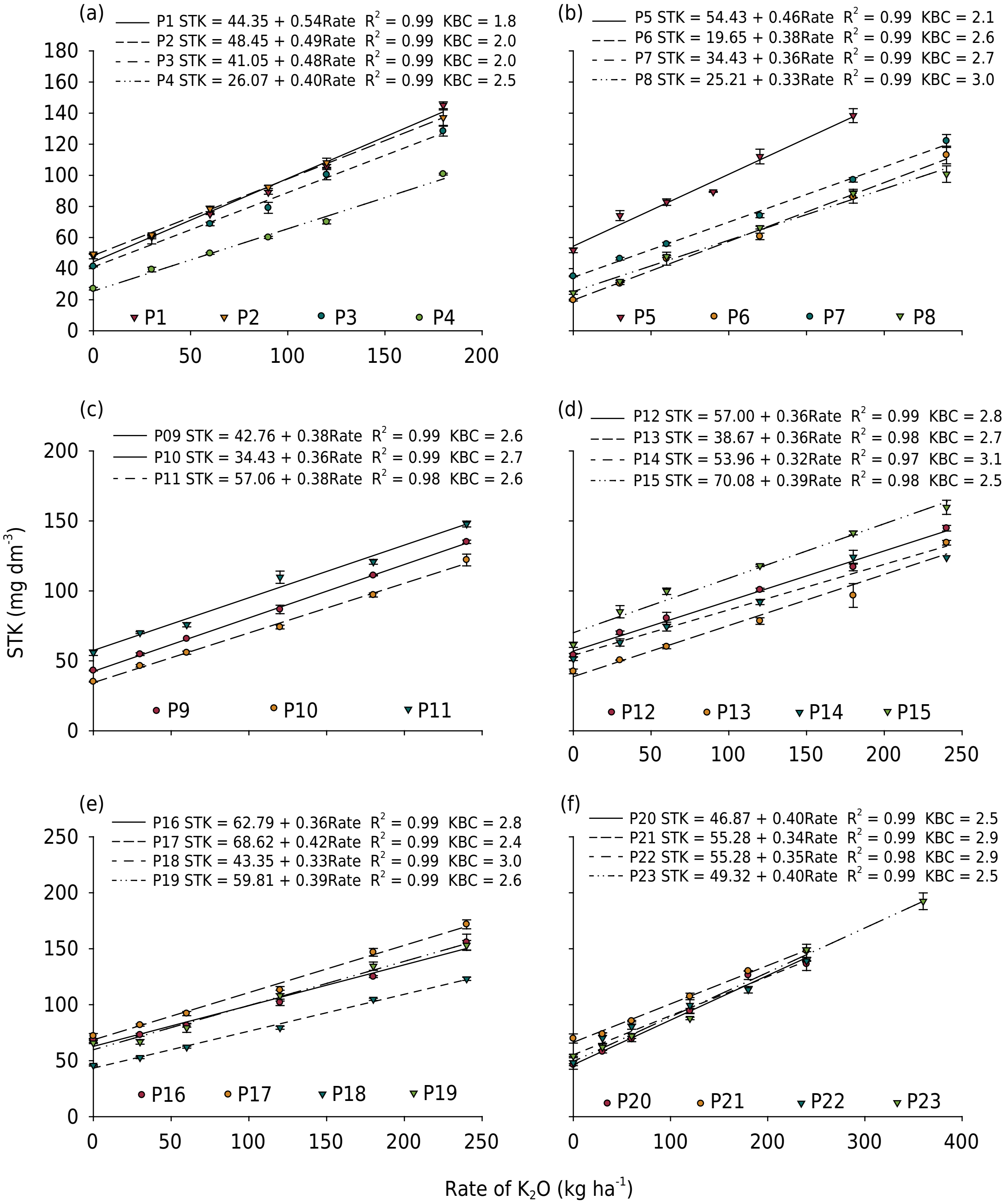


Figure 2. Soil Test Potassium (STK) by Mehlich-1 in 23 soil samples after incubation with rates of K_2O in southern Brazil soils. The soils were arranged in ascending $CEC_{pH7.0}$ order (a: 2.9; 4.2; 4.8; and 6.7 $cmol_c\ dm^{-3}$; b: 7.0; 7.7; 8.2; and 8.5 $cmol_c\ dm^{-3}$; c: 9.4; 10.1; and 10.4 $cmol_c\ dm^{-3}$; d: 10.8; 11.1; 11.3 and 11.8 $cmol_c\ dm^{-3}$; e: 11.8; 12.2; 12.7; and 13.0 $cmol_c\ dm^{-3}$; f: 13.1; 13.6; 14.1, and 15.5 $cmol_c\ dm^{-3}$) and divided equally among six plots to improve the plotted regressions visualization. No criteria related to results or soils with similar characteristics were used.

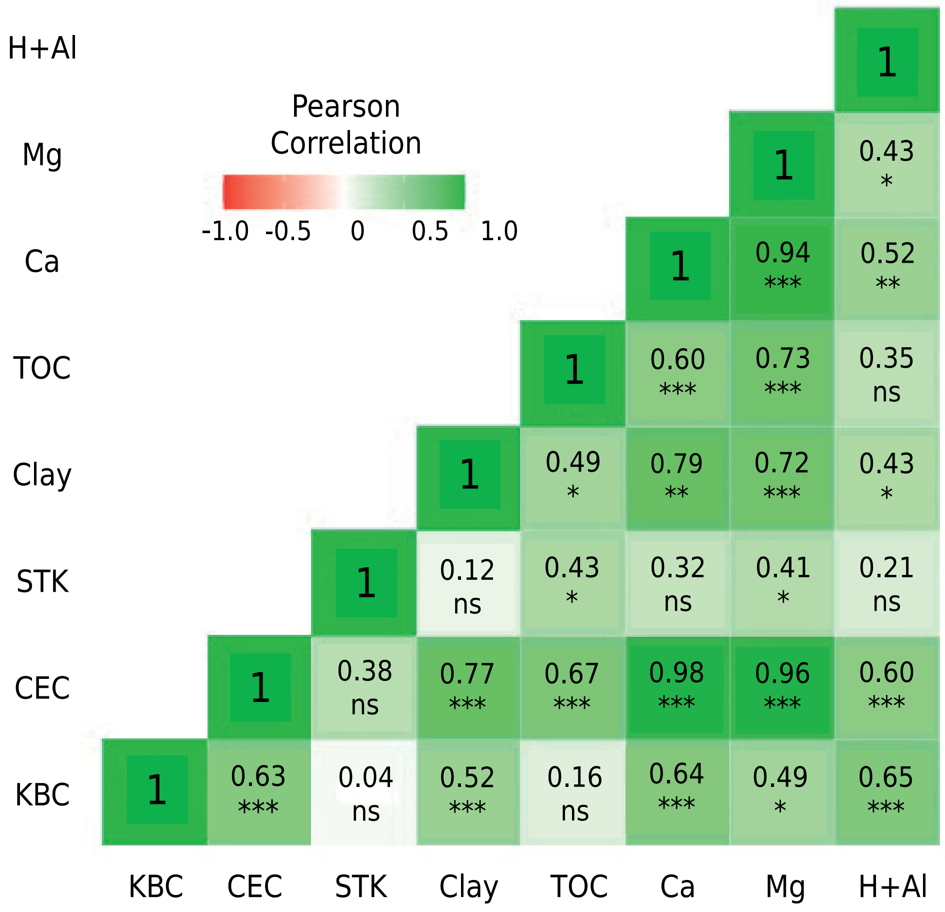
The KBC values obtained through the inverse of the angular coefficients showed little variation, between 1.85 and 3.13 kg K_2O ha^{-1}. Still, considering a soil layer of 0.00–0.20 m, the application of 1 kg of K_2O corresponded to a recovery of 0.41 mg dm^{-3} of K (or KBC 2.4 kg K_2O ha^{-1} for recovery 100 % of the applied K). Thus, slopes greater than 0.41 or KBC lower than 2.4 correspond to recovery values greater than 100 %, where the inverse is true. Thus, we can observe that in soils of the first class of $CEC_{pH7.0}$ (below 7.5 $cmol_c\ dm^{-3}$), the method used for K extraction (Mehlich-1) overestimated the values of STK. In addition, for most of the other soils (16 of the 18, data not shown), there was a recovery of less than 100 %.

The KBC values were correlated significantly with five soil properties: $CEC_{pH7.0}$, clay content, Ca^{2+} and Mg^{2+} contents, and H+Al (Figure 3). However, the KBC was not correlated with STK and TOC. Based on the correlation results, a multiple linear equation was generated using the option “Backward stepwise regression”. The generated equation (Equation 3) integrated the “clay content” and “$CEC_{pH7.0}$” variables, which help to explain the obtained KBC values.

$$KBC = 1.21 + 0.14^{***}\ CEC + 0.036^{***}\ Clay - 0.003^{***}\ CEC \times Clay \qquad R^2 = 0.66 \qquad \text{Eq. 3}$$

in which: “KBC” is the K buffering capacity; “Clay” represents the percentage of clay content; “CEC” represents the $CEC_{pH7.0}$ of the soil in $cmol_c\ dm^{-3}$; and *** means that the equation is significative at 0.1 % of error probability.

This equation presents values calculated with high precision. However, considering that the clay content and the $CEC_{pH7.0}$ correlate significantly with each other, and that the $CEC_{pH7.0}$ is the official parameter used to classify STK by the Local Soil Fertility Committee (CQFS-RS/SC, 2016), it was decided to redo the model using only the $CEC_{pH7.0}$.



	KBC	CEC	STK	Clay	TOC	Ca	Mg	H+Al
H+Al								1
Mg							1	0.43 *
Ca						1	0.94 ***	0.52 **
TOC					1	0.60 ***	0.73 ***	0.35 ns
Clay				1	0.49 *	0.79 **	0.72 ***	0.43 *
STK			1	0.12 ns	0.43 *	0.32 ns	0.41 *	0.21 ns
CEC		1	0.38 ns	0.77 ***	0.67 ***	0.98 ***	0.96 ***	0.60 ***
KBC	1	0.63 ***	0.04 ns	0.52 ***	0.16 ns	0.64 ***	0.49 *	0.65 ***

Figure 3. Pearson correlation values and significance between the variables of 23 soil samples representative of the Rio Grande do Sul and Santa Catarina states. KBC: potassium buffering capacity; CEC: cation exchangeable capacity; STK: soil test potassium; clay: clay content; TOC: total organic carbon; Ca: exchangeable calcium content; Mg: exchangeable magnesium content; H+Al: potential acidity; ns: no significative; * significative at 5 %; ** significative at 1 %; and *** significative at 0.1 %.

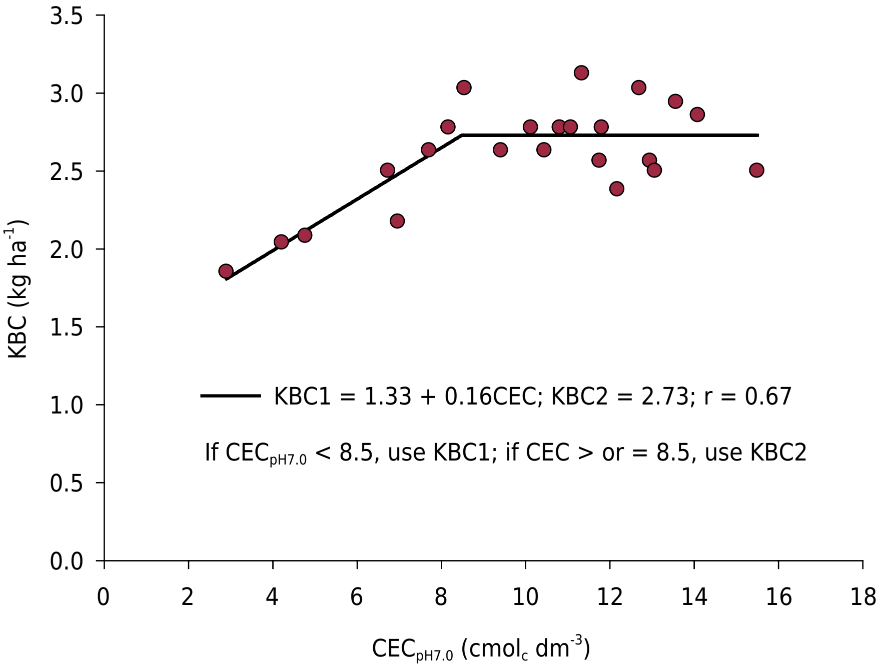


Figure 4. Relationship between potassium buffering capacity (KBC) and the cation exchange capacity (CEC$_{pH7.0}$) of 23 soil samples representative from Rio Grande do Sul and Santa Catarina states, Southern Brazil.

The KBC increased linearly to the CEC$_{pH\ 7.0}$ up to 8.5 cmol$_c$ dm^{-3} (Figure 4). In these soils, increasing the CEC$_{pH7.0}$ by one unit represents an average increase in KBC of 0.16 kg K_2O ha^{-1}. For soils with CEC$_{pH7.0}$ above 8.5 cmol$_c$ dm^{-3}, the KBC values remain unchanged, at 2.73 cmol$_c$ dm^{-3}.

Proposal for adjustment in the recommendation of K corrective fertilization

Simulating K corrective fertilization in the 333 local soil samples, there is a discrepancy between the K rates recommended between the Local Soil Fertility Committee and KBC (Figure 5). Except for the first class of CEC$_{pH7.0}$ (soils with ≤7.5 cmol$_c$ dm^{-3}), all other classes (7.6-15, 15.1-30, and >30 cmol$_c$ dm^{-3}) showed a discrepancy between both recommendation methods.

In soils with CEC$_{pH7.0}$ between 7.6-15 cmol$_c$ dm^{-3}, the recommended rates based on the KBC are 83.6, 101.8 and 103.8 % higher than those recommended by CQFS-RS/SC (2016) for soils with STK classified as “very low” (<30 mg dm^{-3}), “low” (between 31 and 60 mg dm^{-3}) and “medium” (between 61 and 90 mg dm^{-3}), respectively (Figure 5b). In soils from the second class, with CEC$_{pH7.0}$ between 15.1-30 cmol$_c$ dm^{-3}, the recommended rates according to the KBC are 144.3, 218.2 and 29.0 % higher than the currently recommended for soils with STK classified as “very low” (<40 mg dm^{-3}), “low” (between 41 and 80 mg dm^{-3}) and “medium” (between 81 and 120 mg dm^{-3}), respectively (Figure 5c). In soils of the last class, with CEC$_{pH7.0}$ >30 cmol$_c$ dm^{-3}, the recommended rates according to the KBC are 182.9, 298.3 and 147.3 % higher than those recommended by the current recommendation system for soils with STK classified as “very low” (<45 mg dm^{-3}), “low” (between 46 and 90 mg dm^{-3}) and “medium” (between 91 and 135 mg dm^{-3}), respectively (Figure 5d). Generally, when considering the KBC, it is recommended to apply about 2.5 times more K than the current official recommendation.

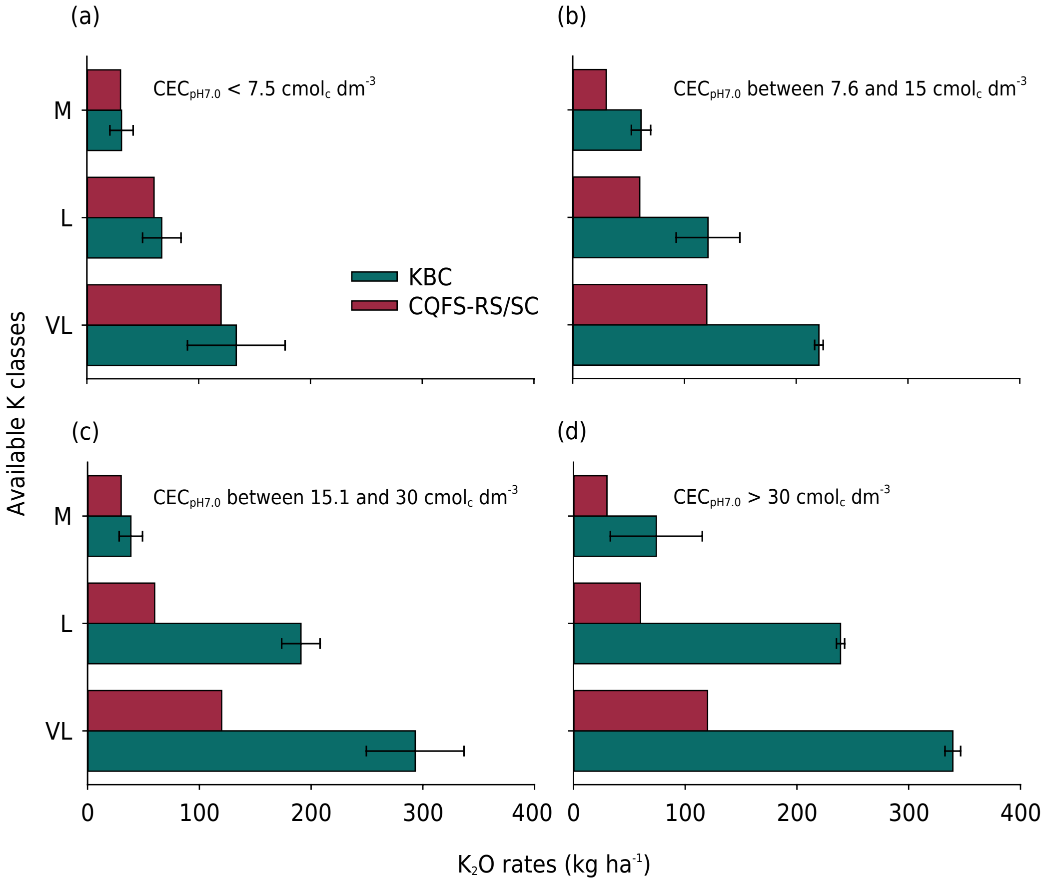


Figure 5. Comparison between the potassium (K) corrective fertilization recommendations between the Local Soil Fertility Committee and using the K buffering capacity (KBC), considering soils with different CEC$_{pH7.0}$. VL: Very Low; L: Low; M: Medium. Soils classified as "very low" had soil test K <20 mg dm^{-3} (a), <30 mg dm^{-3} (b), <40 mg dm^{-3} (c) and <45 mg dm^{-3} (d). Soils classified as "low" had soil test K between 21 and 40 mg dm^{-3} (a), between 31 and 60 mg dm^{-3} (b), between 41 and 80 mg dm^{-3} (c) and between 46 and 90 mg dm^{-3} (d). Finally, soils classified as "medium" had soil test K between 41 and 60 mg dm^{-3} (a), between 61 and 90 mg dm^{-3} (b), between 81 and 120 mg dm^{-3} (c) and between 91 and 135 mg dm^{-3} (d). The horizontal lines at the top of the bars represent the confidence interval ($p<0.05$).

DISCUSSION

K buffering capacity

Application of K fertilizers increases linearly the STK. In soils with low probability of K leaching, as those used in this study, since it is retained in the soil charges mainly by outer-sphere complexes (Strawn, 2021).

The best fit of linear-plateau equation adjusted between the values of KBC and the clay content of the soils (data not shown) highlights that in sandy soils (CEC$_{pH7}$ ≤7.5 cmol$_c$ dm^{-3}) the method recovers more than 100 % of the K applied. Nevertheless, in soils with CEC$_{pH7.0}$ above 7.5 cmol$_c$ dm^{-3} the method generally recovered less than 100 %. It is possible that soils with lower CEC$_{pH7.0}$, due to their low capacity to perform chemical adsorption, are making K available in the system (native K of the soil). On the other hand, adsorption processes (K retention in 2:1 minerals, for example), may make part of the applied K unavailable (or simply undetectable by traditional routine methods) (Moterle et al., 2019). A similar phenomenon occurs with P, where the extraction power of the method depends on the clay content (Mumbach et al., 2020).

Increase in STK is linear (Figure 2), largely due to the non-specific adsorption to the binding sites (Li et al., 2021). That is, regardless of the rate applied, the affinity degree of K to the soil clays remains unchanged. Linear equations were also observed by Wang et al. (2017). Currently, the Local Soil Fertility Community (CQFS-RS/SC, 2016) take into account small variations depending on the initial STK. Thus, these differences should no longer be considered and one single KBC should be adopted.

The change point observed in the figure 4 is related to the relationship between KBC and clay content (data not shown), where the change point is similar, 2.74. In addition, charge numbers in those soils do not increase with clay content (data not shown), then have an exponential relationship, which one tending to maximum value. In practical terms, soils with $CEC_{pH7.0}$ ≤8.5 must have their KBC and, consequently, their recommendation for corrective fertilization varying according to the number of negative electrical loads on the soil (CQFS-RS/SC, 2016; Vieira et al., 2016). In soils with $CEC_{pH7.0}$ >8.5, a single KBC value can be adopted, without compromising the veracity of the recommended amounts of K fertilizers. The occurrence of the non-linear relationship between KBC and $CEC_{pH7.0}$ needs to be better characterized in subsequent studies. It is believed that mineralogical characteristics can explain the different results between the two sets of soil created.

Suggestions for updating the local fertilizer recommendations

Based on the set of 333 soil samples evaluated, the recommendations based on the KBC show that the current recommendations present inconsistencies (Figure 5). The K amounts recommended based on the KBC values were higher than those currently recommended. These differences are greater for soils with lower STK (“low” and “very low” classes) and for soils with higher values of $CEC_{pH7.0}$. The current system recommends three fixed rates, 30, 60 and 120 kg K_2O ha^{-1} for soils classified as “medium”, “low” and “very low”, respectively. These three rates are indicated regardless of the soil $CEC_{pH7.0}$. Based on the results of this study, considering different KBC values and $CEC_{pH7.0}$, it could result in more assertive recommendations. Thus, it is possible to rationalize the use of K fertilizers, reducing the production cost and the potential for contamination, but with adequate plant nutrition (Vieira et al., 2016; Firmano et al., 2019, 2020).

Only the first class of CEC showed no difference between the two current recommendations. To make the current recommendation more practical, we recommend using change point 7.5 $cmol_c$ dm^{-3} instead of 8.5 $cmol_c$ dm^{-3}, since the values are close, plus the 7.5 value already used by the current recommendation system by the Local Soil Fertility Community (CQFS-RS/SC, 2016).

In practical terms, the following procedures can be adopted by technicians and/or farmers. When STK is “very low”, “low”, or “medium”, corrective fertilization is necessary, and the calculated rates can be obtained as follow:

i) if the $CEC_{pH7.0}$ values fall within the first-class proposed by CQFS-RS/SC (2016) (≤7.5 $cmol_c$ dm^{-3}), the KBC must be obtained using the equation “KBC = 1.33 + 0.165CEC”;

ii) if the $CEC_{pH7.0}$ values are >7.5 $cmol_c$ dm^{-3}, the KBC value equal to 2.73 will be used to calculate the K rate;

iii) With the KBC index defined, the K fertilizer rate for corrective fertilization is calculated by the equation [$K\ rate\ (kg\ ha^{-1}) = (K_{CL} - STK) \times KBC$].

On the other hand, it emphasizes the importance of adopting the corrective K fertilization practice with caution. As K binds to soil particles by electrostatic bonds, the unavailability of the nutrient by adsorption processes (for example, common for P), is not a limiting factor. The total correction, considered in this study, involves the incorporation of K in the soil, before the plant cultivation (CQFS–RS/SC, 2016). In many cases, gradual correction, carried out in the seeding line, can be the strategy that guaranties the best cost-benefit ratio. In these cases, the recommendations made in this study may be less assertive, and it is more interesting to follow the current recommendations in the region by the Local Soil Fertility Community.

Regarding the 23 soils incubated in the experiment, the recommended doses of corrective fertilization with current recommendations were able to reach the average level in 20 of them, two at a high level and one remaining at a low level (data not shown). However, with K replacements in maintenance fertilization, soils that remain at insufficient levels are expected to reach the critical level or the medium availability class. It is important to attend the term “plant minimal exchangeable K”, which is the minimal solution K concentration below which plants are unable to take up K (Murrell et al., 2021). This result highlights the effectiveness of the proposed methodology.

It should be noted that the recommendations made in this study are based on soils incubated with $CEC_{pH7.0}$ to 15.5 $cmol_c\ dm^{-3}$, and even considering most of the soils present in the study region, soils with greater than 15 $cmol_c\ dm^{-3}$ can occur in some regions, mainly where there is accumulation of organic matter. With the extrapolation of the results for all $CEC_{pH7.0}$ classes present in the regional guidelines, the recommendations may not be accurate for soils with high $CEC_{pH7.0}$ (15.1 to 30 $cmol_c\ dm^{-3}$ and >30 $cmol_c\ dm^{-3}$). We reinforce the need for more studies in this sense to reach more assertive fertilization recommendations, considering a greater set of soils, both in number and in contrasting characteristics.

Finally, we also emphasize that the total correction of K, accompanied by mechanical soil movement, is not recommended for sandy soils, with $CEC_{pH7.0}$ classified in the first class (≤7.5 $cmol_c\ dm^{-3}$). In these soils, there is a great risk of vertical displacement and K losses by leaching due to the low capacity of the soil to retain the applied nutrient.

CONCLUSION

The current recommendations for corrective K fertilization underestimate 2.5 times the rates required to reach the critical nutrient level in soils with low $CEC_{pH7.0}$ (<15.5 $cmol_c\ dm^{-3}$) and lower the soil test K. Nevertheless, the work does not contain soils with $CEC_{pH7.0}$ greater than 15.5 $cmol_c\ dm^{-3}$, thus we reinforce the necessity for continuous studies in this sense to improve the fertilization recommendations.

The K buffering capacity increases with $CEC_{pH7.0}$ <8.5 $cmol_c\ dm^{-3}$. After that value, the K buffering capacity is constant. In this study, we recommend the use of the equation: [$K\ rate\ (kg\ K_2O\ ha^{-1}) = (K_{CL} - STK) \times KBC$] to calculate the K rate for corrective fertilization. Potassium buffering capacity values must be obtained using the formula: [$KBC: 1.33 + 0.165\ CEC_{pH7.0}$], for soils with $CEC_{pH7.0}$ ≤7.5 $cmol_c\ dm^{-3}$, and, for soils with $CEC_{pH7.0}$ >7.5 $cmol_c\ dm^{-3}$, it should be used the KBC value: 2.73.

APPENDIX A. SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://www.rbcsjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-46-e0220010/1806-9657-rbcs-46-e0220010-suppl01.pdf

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