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Effect of potassium rates and application methods in no-till on soil K availability and crop yield

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ABSTRACT: The combination of potassium (K) fertilization with the adoption of no-tillage (NT) increases the concentration gradient of K in the soil, requiring subsurface layers to diagnose fertility. This study aimed to evaluate the effect of K rates applied in band or broadcast on the soil K availability and soybean and wheat yield. The study was established in 2019 on a *Latossolo* (Ferralsol) in the northwest of Rio Grande do Sul State, Brazil, under NT since 2002. Summer soybeans and winter wheat were cultivated from 2020 to 2022, and rates of K (0, 50, 100, 150, and 200 kg ha^{-1}) were applied annually at soybean sowing. Each rate of K was applied in a band at the seeding row or broadcast on the soil surface. Grain yields and the available K content in the soil at different soil layers (0.00-0.05, 0.05-0.10, 0.10-0.15, and 0.15-0.20 m) were evaluated after the soybean harvest in 2020/2021. The K applied remained close to the application site, at the 0.10-0.15 m layer when applied in band and at the 0.00-0.05 m layer when deposited by broadcast. Band application of K can decrease the K gradient and increase soybean and wheat yield when the available K content is below 64 mg dm^{-3} in the 0.10-0.20 m soil layer, coinciding with the critical level adopted in the south of Brazil until 2016. The replacement of K removed by soybean and wheat grains under NT with low soil K availability at 0.10-0.20 m should be band applied in-furrow along the sowing line.

Keywords: band-applied, broadcast, K available, soybean yield, wheat yield.

INTRODUCTION

Soil chemical analysis is very ancient and even predates the publication of Liebig's historical book in 1840 (Boulaine, 1997). In southern Brazil, Mohr (1950) was a pioneer in proposing and conducting methods of soil chemical analysis for the purpose of recommending acidity correctives and fertilizers. From 1960 to 1980, researchers intensified studies on calibrating the response of annual crops to potassium (K) fertilization for soybeans (*Glycine max* (L.) Merrill) and wheat (*Triticum aestivum* L.). In this period, the critical soil test values (CSTV) for K ceased to be determined by geographical region, as established by Mohr (1950), and started to be defined for the main grain crops, as expressed in the next four versions of the Fertilization and Liming Manual (1968, 1968, 1973, and 1976 - Mielniczuk et al., 1969; Volkweiss and Ludwick, 1976). Four more updates were made in the 1980s-1990s (1981, 1987, 1989, and 1995), without changing the diagnostic layer (0.00-0.20 m) and with no significant alterations in the CSTV of K, mainly because the recommendation philosophy was based on K replacement rates.

The expansion of no-tillage (NT) in the 1990s demanded drastic changes in the K fertilization recommendation system, which were expressed in the tenth edition of the Fertilization and Liming Manual for the states of Rio Grande do Sul and Santa Catarina (CQFS-RS/SC, 2004). It was recommended to correct soil acidity to pH 6.0, raise phosphorus (P) and K levels to the critical level, and incorporate lime and fertilizers within the 0.00-0.20 m soil depth during the transition from conventional tillage to NT. Subsequently, the focus shifted to monitoring the 0.00-0.10 m diagnostic layer and keeping a close eye on the 0.10-0.20 m soil layer, especially regarding limestone reapplication. Four critical levels were established for crops based on the cation exchange capacity values at pH 7.0 ($CEC_{pH7.0}$). Since most calibration trials conducted in the states of RS and SC had $CEC_{pH7.0}$ values of 5.1-15 $cmol_c$ kg^{-1}, the critical level of K decreased from 80 to 60 mg kg^{-1} (Borkert et al., 1993; Veduin, 1994; Scherer, 1998; Brunetto et al., 2005). These critical levels remained until 2016 when the most updated version of the Manual (CQFS-RS/SC, 2016) significantly increased the CSTV of K. Nowadays, in soils with $CEC_{pH7.0}$ of 7.6-15.0 $cmol_c$ dm^{-3}, the CSTV for grain crops was raised to 90 mg dm^{-3}, and it increases up to 135 mg dm^{-3} if $CEC_{pH7.0}$ is greater than 30 $cmol_c$ dm^{-3}. Furthermore, there is a recommendation for a maximum rate of K in band-application (67 kg ha^{-1}), but this recommendation does not take into account the row spacing and the difference in depth between fertilizer and seed placement. To our knowledge, only one study reported a negative effect of K fertilization in the sowing line, and it was carried out using washed sand in shallow trays without drainage in a greenhouse (Salton et al., 2002). This, combined with precision agriculture limited to horizontal variability, greatly encouraged the application of K fertilizers on the soil surface. Additionally, the gain in operational performance for sowing crops in large areas due to the elimination of the furrow opener has greatly contributed to the widespread use of broadcast application of K on the soil surface.

Recent studies indicate there is a strong gradient of K in the soil profile under no-tillage (Tiecher et al., 2017; Alves et al., 2019; Almeida et al., 2021; Bellinaso et al., 2021; Ambrosini et al., 2022). This occurs not only in field experiments. Recently, Artuso (2021) evaluated 45 soil profiles from commercial farms in the Brazilian subtropical state of Rio Grande do Sul, in a detailed soil sampling with collection every 0.01 m depth up to 0.10 m, and detected a strong K distribution gradient even within the first 0.10 m. They demonstrated that 87 % of the sampled soils have an excess of K in the 0.00-0.10 m soil layer, reaching up to ten times above the critical level; however, 73 % of the soil samples exhibited a deficiency of K in the 0.10-0.20 m soil layer. This can be attributed to surface broadcasting fertilization practices. Additionally, the continuous adoption of broadcasting fertilization increases K losses through surface runoff (Goulding et al., 2021) and does not achieve the maximum yield potential when compared to bad-applied fertilizer in-furrow (Bordoli and Mallarino, 1998; Fernández and White, 2012).

Potassium gradient raises doubts about the best diagnostic soil layer for assessing K availability status. In some regions of Brazil, such as Cerrado and Paraná State, the diagnostic layer for soil fertility analysis remains 0.00-0.20 m for grain crops, regardless of the soil management system (Sousa and Lobato, 2004; Pauletti et al., 2019). On the other hand, in the states of Santa Catarina and Rio Grande do Sul, in southern Brazil, the diagnostic layer changed from 0.00-0.20 m in conventional tillage to 0.00-0.10 m in NT (CQFS-RS/SC, 2016). The same specification for soil sampling used in southern Brazil occurs in North Carolina, USA (Hardy et al., 2022). However, few studies have been conducted to compare the best diagnostic layer for the NT system (Fernández et al., 2012; Vieira et al., 2013; Bellinaso et al., 2021), especially concerning K fertilization. In soils with high clay content and CEC, K mobility in the soil profile is negligible (Tiecher et al., 2017). In this case, increasing or decreasing the thickness of the diagnostic layer from the surface will only dilute or concentrate the K content, making the diagnosis inaccurate. Therefore, it is necessary to develop studies investigating other possibilities of diagnostic soil layers, such as subsurface soil layers (e.g., 0.10-0.20 m) (Farmaha et al., 2011, 2012; Fernández et al., 2012; Bellinaso et al., 2021).

This study aimed to evaluate the effect of K rates applied in bands in the furrow of sowing row or broadcast on the soil surface on soybean and wheat crop yield and soil K availability. Our findings will provide a crucial foundation to guide the most suitable application method and diagnostic soil layer for K fertilization in no-tillage systems on clayey soils in southern Brazil.

MATERIALS AND METHODS

History of the experimental area

The study was conducted in the northwest of Rio Grande do Sul State, in the municipality of Independência (27° 50′ 43″ S, 54° 13′ 08″ W). The soil is deep and well-drained, with a predominance of kaolinite and the presence of high levels of iron oxides such as hematite and goethite and is classified as *Latossolo Vermelho* (Santos et al., 2013), which corresponds to a Ferralsol (IUSS Working Group WRB, 2022). The climate, according to the Köppen-Geiger classification system, is subtropical, hot, and humid (Cfa) (Alvares et al., 2013). The annual average precipitation and temperature is 2000 mm and 21.4 °C, respectively. During the summer of 2021/2022, the region had a water deficit (Figure 1). The natural biome, mixed ombrophilous forest, was removed to establish agricultural fields in the 1960s, with continuous soil disturbance through plowing and harrowing. In the place of the experimental area from the 1960s until the 2000s, K fertilizers were applied following the official recommendations available during that period. In April 2002, the NT system was adopted in the experimental area, with a preference for cultivating soybean, corn (*Zea mays* L.), and wheat. Fertilization management for crops consisted of applied nitrogen (N), phosphorus (P), and K fertilizers in a band in the seeding row at an approximate depth of 0.10-0.15 m. Soil physical and chemical properties of the experimental area are presented in table 1.

Experimental design and description of soybean and wheat crops

The trial was established in November 2019, using a randomized block design with split-plots, in triplicate. The main plots, measuring 6 by 5 m (30 m²) each, received K at the rates of 0, 50, 100, 150, and 200 kg ha^{-1} as potassium chloride (KCl, 50 % K). Within the split-plots (3 × 5 m - 15 m²), two different application methods were employed, in the band along the sowing line or broadcast on the soil surface. The broadcast application of K was done manually, while the band application was done using a tractor-mounted furrow opener seeder, with the fertilizer deposited at an average depth of 12.5 cm.

From 2019 to 2022, soybeans were cultivated during the summer season, and wheat was cultivated in the winter. Potassium rates were applied once annually, specifically on the sowing date of the summer crop, in the years 2019, 2020, and 2021 (Table 2). Wheat crops were cultivated without supplemental K. Soybean yield data from 2019/2020 is reported in Pesini et al. (2024), where it was found that the treatments did not influence soybean yield, which averaged 4.5 Mg ha^{-1}.

Additional information about sowing time, cultivars, N and P fertilization, as well as evaluations conducted in the soybean and wheat crops are presented in table 2. Nitrogen and P were added according to the recommendations of CQFS-RS/SC (2016), by broadcasting on all plots at sowing. At the wheat tillering stage, N was applied by top-dressing. The spacing between rows for soybean crops was 0.45 m, with a population of 30 plants m^{-2}. The spacing between rows for wheat crops was 0.17 m, with a population of 250 plants m^{-2}. In soybean and wheat crops, seeds were placed at a depth of 3-5 cm.

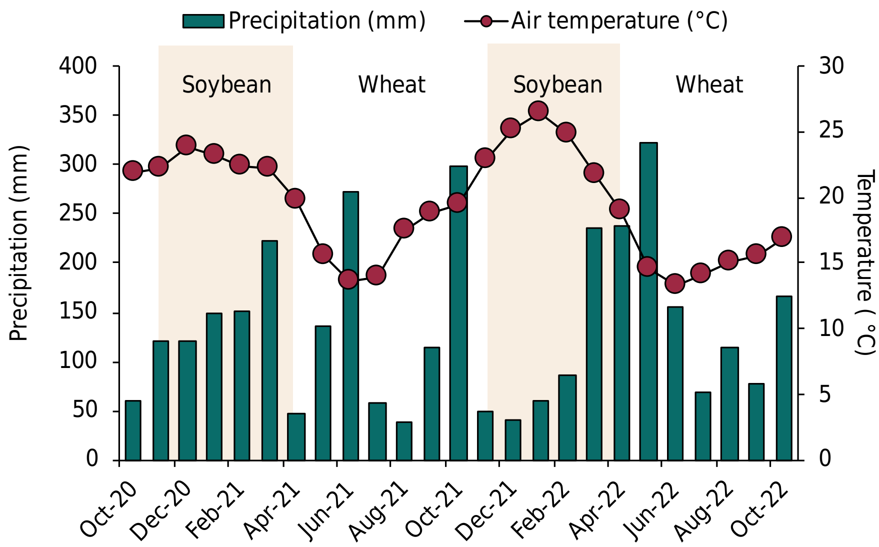

Figure 1. Monthly mean precipitation and temperature (October 2020 - October 2022) in a field trial established in 2019 on a Ferralsol under no-tillage, in Independência, Rio Grande do Sul State, Southern Brazil. Source: INMET, National Institute of Meteorology, Brazil.

Table 1. Main soil properties of the Ferralsol under no-tillage in Southern of Brazil before the establishment of the experiments in 2019

Soil properties	Ferralsol – Independência, RS			
	0.00-0.10 m		0.10-0.20 m	
Clay (g kg^{-1})	617	-	689	-
Silt (g kg^{-1})	49	-	36	-
Sand (g kg^{-1})	334	-	276	-
Available K (mg dm^{-3})(1)	154	High	29	Very low
pH(H_2O) (1:1, v/v)	5.5	-	5.4	-
H+Al (cmol$_c$ dm^{-3})(2)	5.2	-	5.1	-
Available P (mg dm^{-3})(1)	12.0	High	2.7	Very low
Exchangeable Al (cmol$_c$ dm^{-3})(3)	0	-	0	-
Exchangeable Ca (cmol$_c$ dm^{-3})(3)	6.7	High	5.2	High
Exchangeable Mg (cmol$_c$ dm^{-3})(3)	2.9	High	2.2	High
CEC at pH 7.0 (cmol$_c$ dm^{-3})	15.2	High	12.5	Medium
Ca+Mg+K saturation (%)	65	-	60	-
Al saturation (%)	0	-	0	-

(1) Extracted by Mehlich-1 solution. (2) Estimated using SMP solution according to Kaminski et al. (2002). (3) Extracted by NH_4Cl 1.0 mol L^{-1}.

Table 2. Summary of crop rotation in each season, with respective sowing dates, cultivar, and crop evaluations in a Ferralsol under a no-till system in Southern Brazil

Year	Season	Crop	Sowing date	Varieties	N	P	Crop evaluation	K rates treatments				
					Rate							
					kg ha^{-1}			kg ha^{-1}				
2019/2020	S[1]	Soybean	11/20/2019	Pioneer 95R51	-	26	-	0	50	100	150	200
2020	W[2]	-	-	-	70	22	-	-	-	-	-	-
2020/2021	S	Soybean	12/10/2020	Basf 15B70	-	26	Yield; K, Ca e Mg in leaf and grain	0	50	100	150	200
2021	W	Wheat	06/18/2021	BRS Bela Joia	125	26	Yield; K, Ca e Mg in grain	-	-	-	-	-
2021/2022	S	Soybean	11/13/2021	Basf 15B70	-	26	Yield	0	50	100	150	200
2022	W	Wheat	06/13/2022	BRS Bela Joia	125	26	Yield	-	-	-	-	-
Total applied	-	-	-	-	320	152	-	0	150	300	450	600

[1] Summer. [2] Winter.

Soil and plant analysis and crop yield assessment

In March 2021, after soybean cultivation, soil sampling was carried out in the layers of 0.00-0.05, 0.05-0.10, 0.10-0.15, and 0.15-0.20 m. The collection was done using a cutting shovel positioned perpendicular to the seeding row to collect the soil from the row and half of each adjacent interrow. The soil was air-dried, ground, and sieved through a 2 mm mesh. To estimate available K, the Mehlich-1 extractor was used at a soil-to-extractor ratio of 1:10 (v/v). This method is the standard for interpretations and recommendations in CQFS-RS/SC (2016). Potassium was determined by flame photometry.

Soybean grain yields (2020/2021 and 2021/2022 seasons) and wheat grain yield (2021 and 2022 seasons) were evaluated by collecting plants from an area of 3.50 and 1.40 m^2, respectively. Grains were separated from impurities, and subsequently, the yield data was corrected to 130 g kg^{-1} moisture content. Additionally, leaf samples were collected to evaluate the K, Ca, and Mg content in the soybean cropping season 2020/2021. These samples were obtained at the R2 growth stage by collecting the most recently matured trifoliate leaf from one of the top 3 nodes of 10 soybean plants. Moreover, K, Ca, and Mg content in grain samples were also evaluated for soybeans (2020/2021) and wheat (2021). The tissue and grain samples were oven-dried at 65 °C until reaching a constant mass, then they were ground and sieved through a 1 mm mesh. A mass of 1.00 g was digested in 6 mL of 65 % (v/v) HNO_3 and 1 mL of $HClO_4$ (v/v) (Firmano et al., 2020). After digestion, the total content of K, Ca, and Mg was determined by inductively coupled plasma optical emission spectrometry (ICP-OES).

Statistical analysis

Dataset of soybean and wheat yield, content of K, Ca, and Mg in soybean leaves and grains and wheat grains, as well as soil available K, were evaluated separately by crop season. These data were subjected to normality analysis using the Shapiro-Wilk test and variance homogeneity analysis using the Levene test, both at a significance level of 5 %. For normally distributed and homogeneous data, inferential statistical analysis was carried out. For the crop yield data and the nutrient content data in the grains and leaves, a model was used assuming the K rate as the main treatment and the application method as a split-plot. The PSUBDBC function from the AgroR package (Shimizu et al., 2023) in the R software (R Development Core Team, 2023) was used.

For the data on available K in the soil, the soil layer was entered as a split-split-plot. The PSUBSUBDBC function from the AgroR package was used. These two functions performed the analysis of variance (ANOVA) and when significant ($p<0.05$), the means between the application methods and/or soil layers were compared using the Tukey test at $p<0.05$. Data showing variations due to the K rate were fitted with first- and second-degree polynomial regressions.

The quadratic plateau model was used to determine the relationship between the K values from the soil test and the crop yield. This analysis was carried out using the R package soiltestcorr (Correndo et al., 2023). To investigate this relationship, soybean yields in 2020/2021 cultivated before soil collection were used to correlate with available K data in the 0.00-0.10 m layer (average of the 0.00-0.05 and 0.05-0.10 m layers) and 0.10-0.20 m (average of the 0.10-0.15 and 0.15-0.20 m layers). The relative yields were calculated by assigning a value of 100 % to the average of the treatment with the highest yield and for the other treatments based on this reference.

RESULTS

Soybean and wheat grain yield

The increase in crop yields due to K rates occurred in the 2020/2021 soybean cropping season but just with the addition of fertilizer in band-applied, with maximum yield (4.2 Mg ha^{-1}) reached at a rate of 100 kg ha^{-1} (Figure 2a). In the control treatment without K replenishment, the soybean yield was 3.6 Mg ha^{-1}, equivalent to 83 % of yield when the K fertilizer was band-applied. In the treatments with surface application, there was no increase in soybean yield, even with higher rates added. Soybean yield of the 2021/2022 crop season (Figure 2b) was negatively affected by a water deficit from December to March, when the precipitation was 50 % lower compared to the same period of the 2020/2021 cropping season (Figure 1).

Wheat yields in the control treatment, without K replenishment since the beginning of the experiment, were 2.3 and 2.1 Mg ha^{-1} in 2021 and 2022, respectively. These wheat yields were lower than the Brazilian average, 2.8 Mg ha^{-1} in 2021 and 3.4 Mg ha^{-1} in 2022 (Conab, 2023). The increase in wheat yields due to the residual effect of K application in the soybean was <15 % and was significant only for the lower rates (50 and 100 kg ha^{-1}) (Figures 2c and 2d). Better utilization of K was observed when applied in bands, which increased the wheat yield by 12 % compared to the broadcast application in 2021 (Figure 2c). On the other hand, there was no difference in wheat yield between application methods in the 2022 crop (Figure 2d).

Vertical distribution of K in the soil and the relationship with crop yield

Potassium application in the band at a depth of 12.5 cm increased the available K content only in the 0.10-0.15 and 0.15-0.20 m soil layers (Figure 3a). On the other hand, applying K fertilizer on the soil surface more than doubled the available K content in the first centimeters of the soil profile. Available K content in the 0.00-0.05 m layer with surface application was 194 and 435 mg dm^{-3}, while in the 0.05-0.10 m layer, it was 78 and 200 mg dm^{-3} in the control and 200 kg ha^{-1} treatments, respectively (Figure 3b). However, no relationship was observed between the added K and the available K in the soil below 0.10 m depth (Figure 3b). Average K content was 82 and 50 mg dm^{-3} in the 0.10-0.15 and 0.15-0.20 m soil layer, respectively. While there was no relationship between the available K in the 0.00-0.10 m soil layer and relative soybean yield (Figure 4a) soil-available K in the 0.10-0.20 m soil layer was related to relative yield (Figure 4b). The critical value of available K in the 0.10-0.20 m soil layer to achieve 90 % of the relative yield was 64 mg dm^{-3} (Figure 4b).

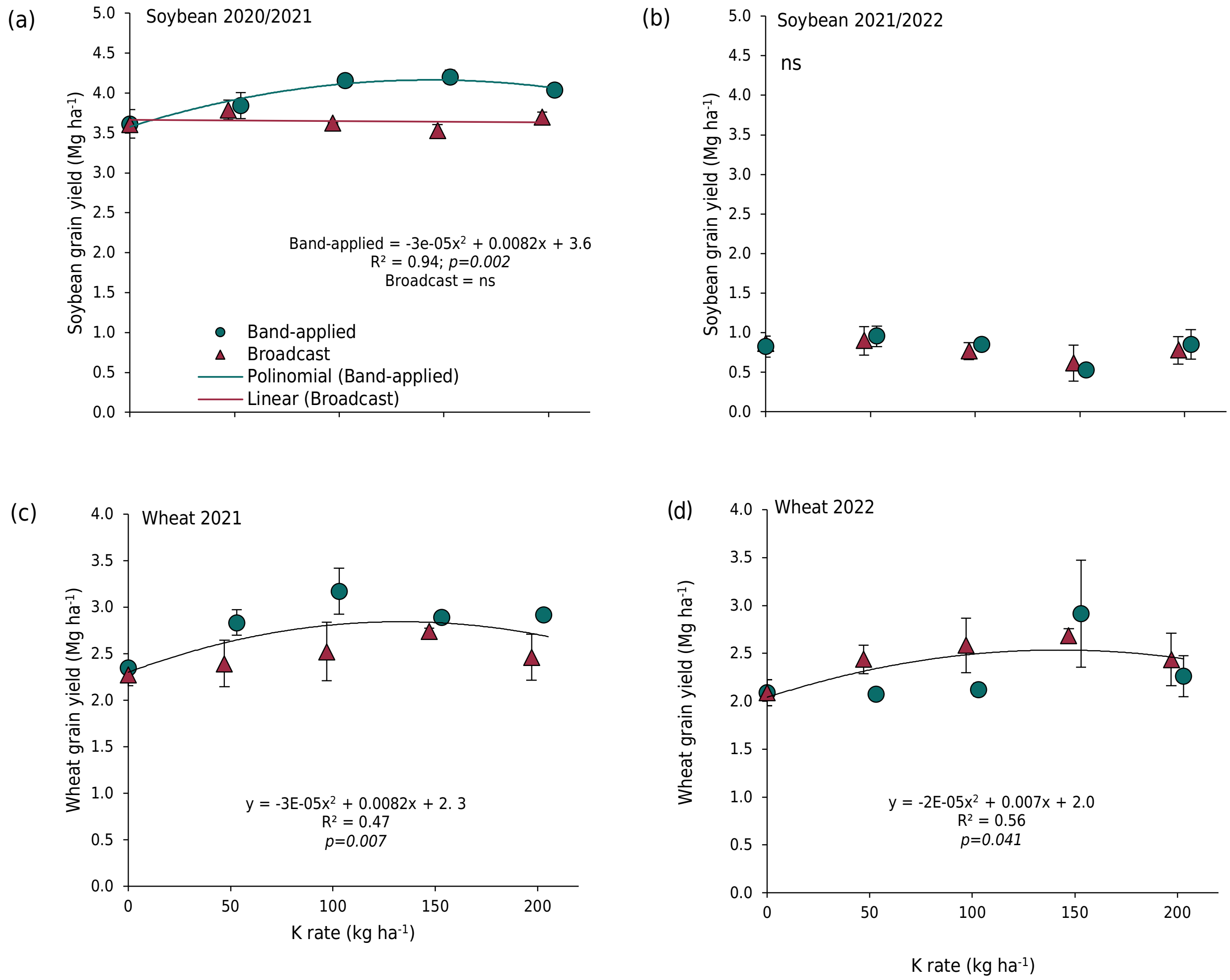

Figure 2. Soybean (a, b) and wheat (c, d) grain yield affected by K rates (0, 50, 100, 150, and 200 kg ha^{-1}) band-applied or broadcast on the soil surface in a Ferrasol under no-tillage in Rio Grande do Sul State, Southern Brazil. ns: non-significant at p<0.05. Regression significant only for Band-applied (a). Application method not significant at p<0.05 (c and d).

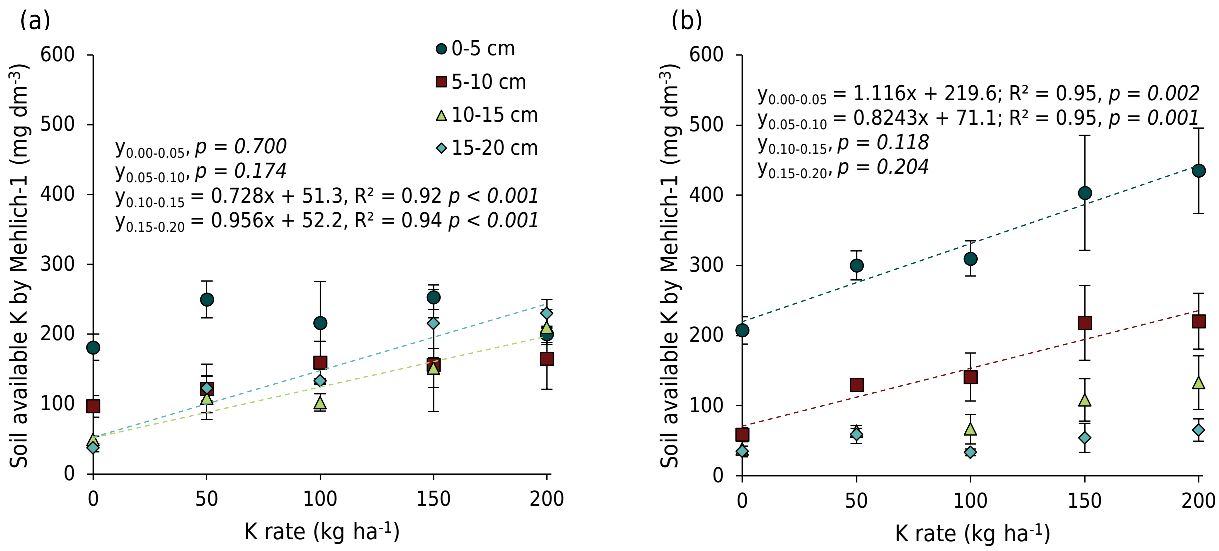

Figure 3. Soil available K in the 0.00-0.05, 0.05-0.10, 0.10-0.15, and 0.15-0.20 m soil layers affected by the K rates (0, 50, 100, 150, and 200 kg ha^{-1}) band-applied (a) or broadcast (b) on the soil surface in a field trial established in a Ferralsol under no-tillage Rio Grande do Sul State, Southern Brazil.

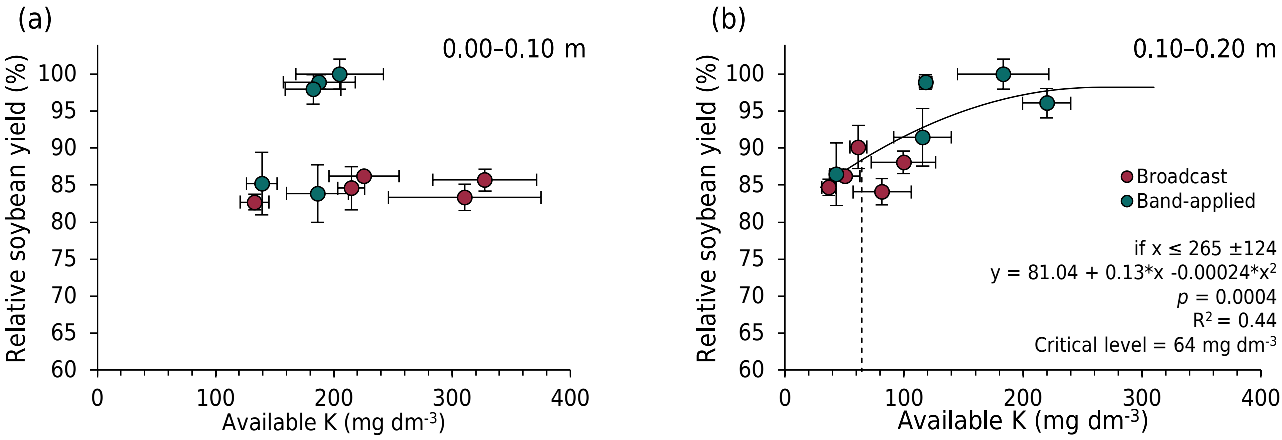

Figure 4. Relationship between the soil available K content extracted by Mehlich-1 in the 0.00-0.10 and 0.10-0.20 m layers and the relative soybean yield in the 2020/2021 crop season as affected by addition of K band-applied or broadcast in a field trial established in a Ferralsol under no-tillage in 2019, in Independência, Rio Grande do Sul State, Southern Brazil.

Application of K at rates close to those exported in soybean (17.6 kg Mg^{-1} - Filippi et al., 2021) and wheat (5 kg Mg^{-1} - CQFS-RS/SC 2016) grain, equivalent to 50-100 kg ha^{-1} yr^{-1} added in a band applied to the soybean seed furrow, increased the K availability above the critical level to a depth of 0.20 m (Figures 5a and 5b). Higher K rates, especially when broadcast on the surface, increased K levels in the first few centimeters (0.00-0.05 m), reaching 403 and 435 mg dm^{-3} at rates of 150 and 200 kg ha^{-1}, respectively.

Magnesium concentration in soybean leaves decreased with K rates above 50 kg ha^{-1} (Figure 6c). On the other hand, the concentration of K and Ca were not altered by K rates (Figures 6a and b). With the surface addition of K, the K concentration in soybean leaves was 12 % higher than treatments with K application in the band (Figure 6a). On the other hand, with the broadcast application, there was a reduction of 27 and 32 % in the Ca and Mg concentrations in soybean leaves, respectively (Figures 6b and 6c). Concentration of K, Ca, and Mg in soybean grains was 11.3, 3.07, and 2.41 g kg^{-1}, respectively. For wheat, the concentration of K, Ca, and Mg was 4.65, 0.45, and 1.54 g kg^{-1}, respectively. The dose and mode of K addition did not influence the nutrient concentrations in grains for both crops.

DISCUSSION

The CSTV value required to achieve 90 % of the maximum yield for soybean for the soil in this study with a CEC of 14 $cmol_c$ dm^{-3} was 64 mg dm^{-3}. This value is half of the currently recommended value by CQFS-RS/SC (2016) (120 mg dm^{-3}) in the 0.00-0.10 m layer. However, the CSTV of 64 mg dm^{-3} of K is similar to the value recommended by CQFS-RS/SC until 2016, which was based on studies by Scherer (1998), Borkert et al. (1993), Veduin (1994), and Brunetto et al. (2005). Therefore, the current K recommendations used in southern Brazil are overestimated. The experimental area used in our study has been cultivated for over 70 years, with the last 20 years under no-till management. The soil in the 0.00-0.10 m layer has adequate Ca, Mg, P, and K levels without Al^{3+} and, therefore, no chemical restrictions on root growth. The soil in the 0.10-0.20 m layer has very low P availability and only one-third of the K content of the upper layer, but it is still very close to the critical level recommended until 2016 by CQFS-RS/SC (2004). Therefore, achieving adequate soybean grain yields was possible even without K replenishment, relying solely on the K adsorbed to the functional groups of the soil solid phase and available for desorption during crop growth (Firmano et al., 2020). In this context, in years when fertilizer prices are extremely high, farmers may choose to stop fertilizing the soil with K. However, this should only be recommended in areas where soil fertility is monitored annually to prevent long-term depletion of K in the soil.

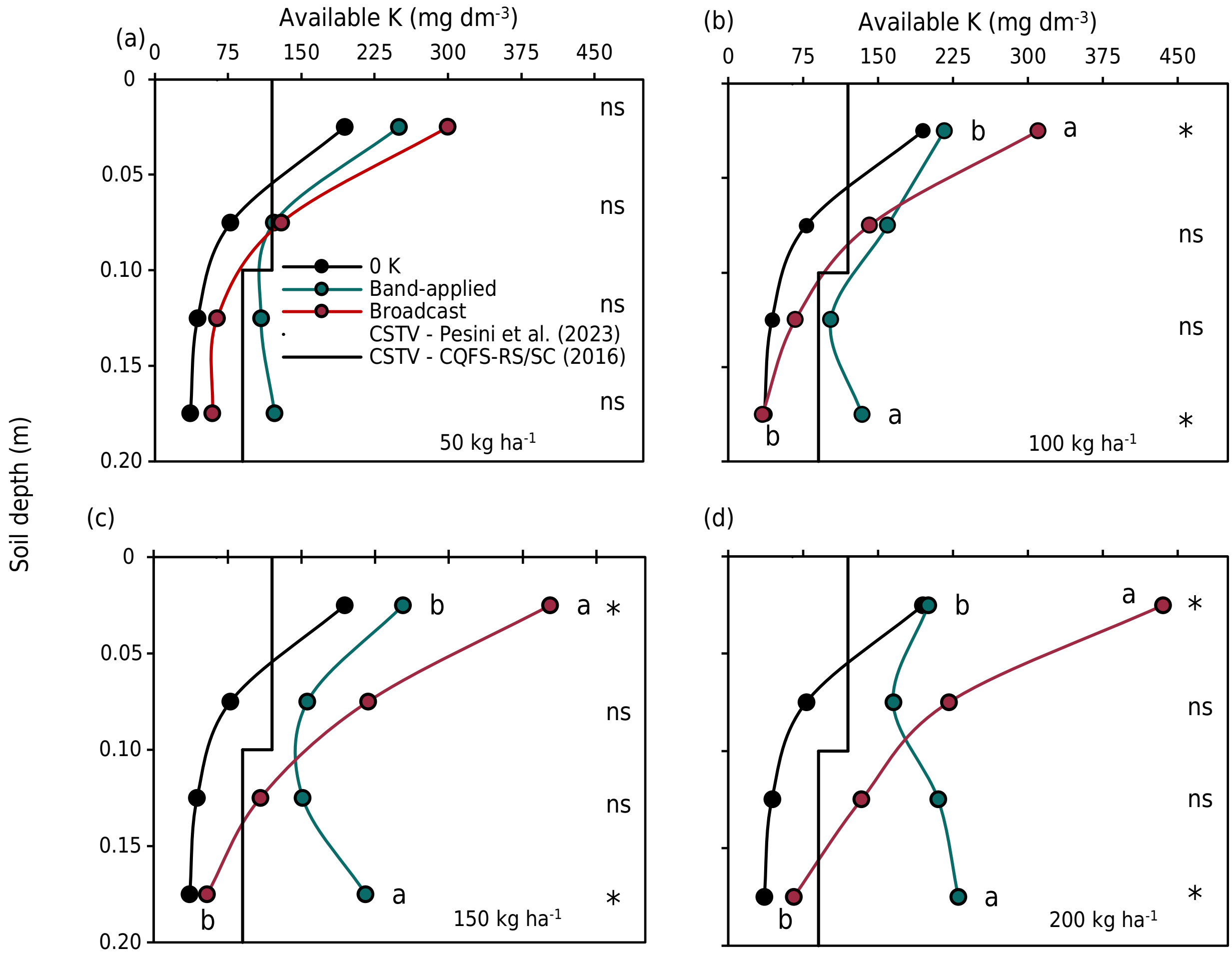

Figure 5. Vertical distribution of soil available K extracted by Mehlich-1 in April 2021 in the treatments receiving the K rates of 0, 50 (a), 100 (b), 150 (c), and 200 kg ha^{-1} of K (d) band-applied or broadcast in the soil surface in a field experiment established in a Ferralsol under no-tillage in 2019, in Independência, Rio Grande do Sul State, Southern Brazil. The black dashed line indicates the CSTV. Means followed by the same lowercase letter in each soil layer comparing the application mode within each K rate are not significantly different by Tukey's test at $p<0.05$.

In the Brazilian and worldwide literature, there are several examples of high soybean yields obtained solely through desorption of stored soil K. For example, Volf et al. (2022) in a tropical Plintossol containing 146 and 43 mg kg^{-1} of available K in the 0.00-0.10 and 0.10-0.20 m layers, respectively, managed under a no-till system, achieved an average soybean yield of 3.34 Mg ha^{-1} without K fertilizer application. This average yield was similar to the treatment that received 83 kg ha^{-1} fertilization broadcast over the previous crop residues. Firmano et al. (2019), in a tropical soil fertilized with K over the long term and with characteristics like those in this study, showed that even after eight years of K deprivation, soybean yields of 3.5 Mg ha^{-1} were achieved. Even with total removal of 450 kg ha^{-1}, these soils still had a plant-available K stock capable of maintaining high yields (Firmano et al., 2019).

In the present case, statistically significant increases in soybean yield were obtained when the K fertilizer was applied in bands (Figure 2a). This is attributed to the placement of the K fertilizer at the 0.10-0.20 m depth where the available K quantity was insufficient for the plants (Figure 5). Fertilization with a rate of 100 kg ha^{-1} of K was sufficient to achieve a maximum of 17 % yield gain in soybeans (4.2 Mg ha^{-1}) compared to treatments with surface fertilization, a rate that is close to the recommended amount to achieve this grain productivity (88 kg ha^{-1} - CQFS-RS/SC, 2016). Out of the 100 kg ha^{-1} of K applied in the 2020/2021 crop, approximately 50 kg ha^{-1} were exported by the soybean grains (considering 4.2 Mg grains and ha^{-1} 11.3 kg Mg^{-1} of grains). Wheat grains removed 13 kg ha^{-1} of K (considering 2.9 Mg grains ha^{-1} and 4.7 kg Mg^{-1} of grains), resulting in a surplus of 37 kg ha^{-1}. This surplus contributes positively to the soil's legacy of K, providing security to farmers and opening possibilities for reducing K fertilization in years of high fertilizer prices.

On the other hand, the application of K fertilizer on the surface after soybean seeding, even at rates of 100 and 200 kg ha^{-1}, did not increase grain yield. This indicates that there is no scientific justification to replace the exported K through fertilizer distribution on the soil surface when there is a large K gradient in the soil profile since doing so further accentuates this gradient. In subtropical soils, such as the one in this study, the soil has a natural nutrient concentration gradient due to the low mobilization of elements to deeper layers and their deposition on the surface through crop residues. This pattern is maintained and even intensified with the cultivation of annual crops, especially if the K exported by the harvest is replenished through surface addition (Figure 5). The higher content of available K in the first few centimeters of soil shows that the rate and amount of K that migrates deeper in the soil profile are lower than the accumulation on the soil surface through straw decomposition. Other examples of K biocycling, especially by soil cover crops, include Tiecher et al. (2017), who showed that the cultivation of oats as a cover plant for 23 years increased the availability of K above the critical level in the most superficial soil layers compared to fallow soil.

In this way, surface fertilization is not justified, as the soil below 0.10 m depth does not have sufficient K quantities to express maximum crop yield. Additionally, the diffusion of K from the dissolution of KCl granules is limited to a few centimeters from the center of the granule (Samal et al., 2010). Therefore, the volume of soil that will be enriched by desorbed K content depends basically on the amount of K remaining in the soil solution compared to the amount of solution outside the diffusion zone and on the soil moisture content (Kuchenbuch et al., 1986; Almeida et al., 2021). Consequently, the distribution of added K on the soil surface or within the profile does not depend solely on the water flow in the soil profile. On the contrary, it fundamentally depends on the number of surface complexes formed and the adsorption energy (Du et al., 2004). Similarly, the amount of K absorbed by plants also depends on the diffusion of K from the soil solution towards the rhizosphere and the volume of soil in contact with the roots. Thus, with homogeneous available K content in the soil profile, deeper and more branched root systems are more likely to achieve maximum crop yield.

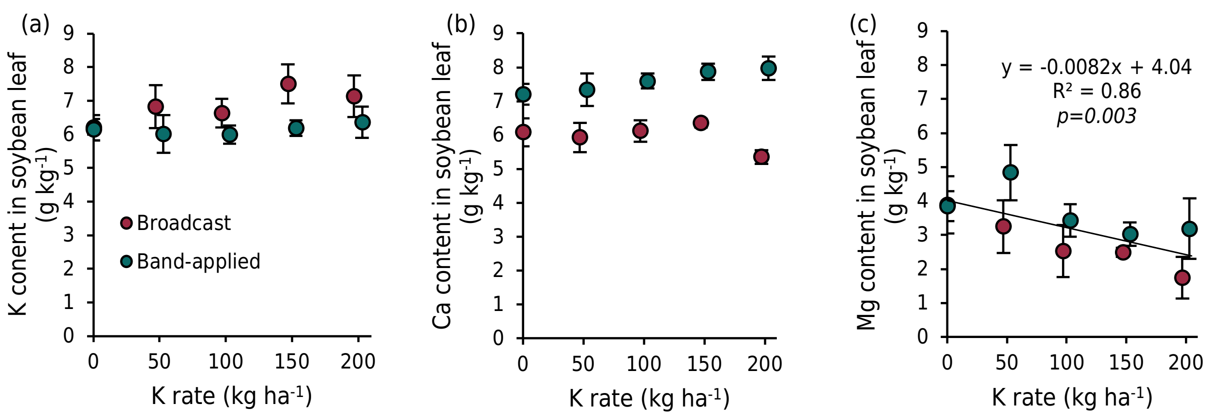

Figure 6. Soybean leaf content of K (a), Ca (b), and Mg (c) in 2020/2021 after the addition of K rates (0, 50, 100, 150, and 200 kg ha^{-1}) band-applied or broadcast in a field experiment established in a Ferralsol under no-tillage in 2019, in Independência, Rio Grande do Sul state, Southern Brazil.

In a scenario with a strong K gradient in the soil profile where the soil below the 0.10 m depth is deficient in K, applying K fertilizer solely at depth below the seeds is recommended via the band-applied method. Surface fertilizer application only represents additional costs for farmers and increases the risk of transfer of K from the system to surface water sources through surface runoff. According to the recommendations of CQFS-RS/SC (2016), the critical K level is the same in no-till and conventional tillage systems; the difference lies in soil sampling depths of 0.00-0.10 and 0.00-0.20 m, respectively. Therefore, increasing or decreasing the sampling depth in no-till only concentrates or dilutes the available K. For a proper assessment of K availability, soil sampling should be performed in stratified layers, such as 0.00-0.10 and 0.10-0.20 m. Moreover, K fertilization, aiming to increase crop yield, should be added where there is low K availability.

Reduction in Ca and Mg concentrations in soybean leaves with the broadcast application of K may have resulted from the competition of these cations with K for plant uptake. High concentrations of K can competitively inhibit the absorption of Ca and Mg (Firmano et al., 2020). With the increase in soil K concentration provided by fertilization, the absorption of this nutrient is favored due to its monovalence, which promotes a lower degree of hydration and results in a faster absorption rate compared to divalent Ca and Mg. This led to a linear reduction in Mg concentration in the leaves with increased K dose. However, the decrease in Ca and Mg concentrations in plant tissues during the reproductive period does not necessarily cause yield loss. This effect can occur more frequently in highly weathered tropical and subtropical soils that receive successive K fertilization, especially when K is broadcast on the soil surface. In this scenario, future studies should consider this approach by further exploring the dynamics of nutrients and their influence on crop yields in different K fertilization management systems.

CONCLUSIONS

Potassium fertilization in the band-applied method (approximately 12.5 cm deep) resulted in increased soybean and wheat yields due to the elevation of K availability in the 0.10-0.20 m soil layer, which is the layer with lower K availability. In this layer, the CSTV for K to achieve 90 % of the relative soybean yield was 64 mg dm^{-3}, indicating that the current CSTV for K in southern Brazil is overestimated. On the other hand, surface broadcasting of K only increases available K in the 0.00-0.05 and 0.05-0.10 m layers, which already have high K availability due to the gradual formation of the K concentration gradient over time, resulting from no-tillage and the low mobility of K in the soil. Our results demonstrate that K movement is negligible in clayey soils (i.e., 650 g kg^{-1} clay and CEC of 14 $cmol_c$ dm^{-3}). Therefore, the diagnosis of K availability in long-term no-till Ferralsols should be carried out in stratified layers, such as 0.00-0.10 and 0.10-0.20 m.

DATA AVAILABILITY

The data will be provided upon request.

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