Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission – Soil Fertility and Plant Nutrition

Potassium distribution in soil profiles under no-tillage system

Deonilce Retka Artuso[1], Diovane Freire Moterle[2], Danilo Rheinheimer dos Santos[1] and Tales Tiecher[3]*

[1] Universidade Federal de Santa Maria, Departamento de Solos, Programa de Pós-Graduação em Ciência do Solo, Santa Maria, Rio Grande do Sul, Brasil.
[2] Instituto Federal de Educação, Ciência e Tecnologia do Rio Grande do Sul, Bento Gonçalves, Rio Grande do Sul, Brasil.
[3] Universidade Federal do Rio Grande do Sul, Departamento de Solos, Porto Alegre, Rio Grande do Sul, Brasil.

ABSTRACT: Potassium (K) vertical mobility in soils has often been overestimated and used as a rationale for recommending the broadcast application of this nutrient in fertility management programs, especially in soils with low cation exchange capacity (CEC). This study aimed to evaluate the vertical distribution of K in two land uses: areas with natural vegetation and crop fields managed under no-tillage (NT) fertilized with K. For this purpose, 49 soil profiles from the Brazilian subtropical state of Rio Grande do Sul were sampled, comprising 45 profiles from areas under NT management and four profiles from sites with natural vegetation. Soil samples were collected in 19 very thin layers: 1 cm layer in the first 10 cm, 2.5 cm layer from 10 to 25 cm, and 5 cm layer from 25 to 40 cm. Sampling sites were then grouped according to their CEC, categorized as < 7.5, 7.6-15.0, and 15.1-30.0 $cmol_c\ dm^{-3}$. Both crop fields and natural fields exhibit a similar vertical gradient model, characterized by a strong accumulation of K in the soil within the uppermost centimeters. This gradient is notably enhanced by the addition of K fertilizers, leading to a substantial portion of K becoming inaccessible to the root system. The optimal level of available K for the topsoil soils was found within an average range of 4 to 12.5 cm of soil depth. Consequently, K fertilization resulted in two main outcomes: (i) an excess of K in the upper soil layers, which increases the potential for K loss through surface erosion and runoff, and (ii) a limited migration of K towards the deeper soil layers until reaching the root growth zone. There is an urgent need to: (a) reaffirm the official recommendations of public agencies that the replacement of K exported by crops should be carried out in the furrow, along the sowing line, and as deep as possible; and (b) reconsider the diagnostic soil layer for assessing the status of K availability in soils under NT management.

Keywords: available potassium, vertical potassium distribution, potassium movement.

*** Corresponding author:**
E-mail: tales.tiecher@ufrgs.br

Received: October 23, 2023

Approved: April 11, 2024

How to cite: Artuso DR, Moterle DF, Santos DR, Tiecher T. Potassium distribution in soil profiles under no-tillage system. Rev Bras Cienc Solo. 2024;48:e0230125.
https://doi.org/10.36783/18069657rbcs20230125

Editors: José Miguel Reichert and Edicarlos Damacena Souza.

INTRODUCTION

Potassium (K) fertilization plays a pivotal role in ensuring robust crop growth in strongly weathered soil. The increasing demand for food, fiber, and energy is driving up the global consumption of K fertilizers (USGS, 2021). In 2020, the world consumption of K fertilizers was estimated at 34.4 million Mg of K (USGS, 2021). Brazil ranks as the second-largest consumer of this fertilizer, accounting for 15.3 % of the global demand (MME, 2019). However, the Brazilian reserves of K are estimated at only 1.9 million Mg, while global reserves are estimated at 210 billion Mg of K (USGS, 2021).

Conventional agricultural practices, such as annual soil disturbance through tillage, typically homogenize the distribution of available nutrients up to a depth of 0.20-0.30 m (Tshuma et al., 2021), which can be advantageous for plant root systems. However, this practice also leads to several detrimental effects, including soil erosion, loss of nutrient and organic matter, and selective loss of clay mineral (Cogo et al., 2003; Panachuki et al., 2011; Tiecher et al., 2017, 2020). In contrast, the no-tillage system (NT) involves fertilizers being either banded near the seed during planting or, more commonly, broadcasted on the soil surface (Lopes and Guilherme, 2000; Derpsch et al., 2010). Over time, NT results in accumulation and enrichment of P and K in the soil surface (Rheinheimer and Anghinoni, 2001; Moreno et al., 2006; Ernani et al., 2007; Ferreira et al., 2009; Kaminski et al., 2010; Rheinheimer et al., 2019; Oliveira et al., 2022). This nutrient accumulation primarily occurs within the first few centimeters of soil, posing a high risk for transfer to water bodies via surface runoff (Bertol et al., 2007; Santos et al., 2020), leading to economic losses for farmers (on-site effects) (Bertol et al., 2011) and water pollution (of-site effects) (Bortoluzzi et al., 2013; Tiecher et al., 2022).

From an agronomic perspective, broadcast fertilization is typically assumed to facilitate nutrient migration to the crop root system. However, certain ions, such as $H_2PO_4^-$/HPO_4^{-2}, K^+, Zn^{2+}, and Cu^{2+}, tend to form high-affinity complexes with the solid surface of the soil, thereby limiting their availability and downward movement. Moreover, ion migration relies on water percolation, but the amount of these nutrients migrating in the soil profile is often minimal and insufficient to meet crop demands. In natural biomes, there are instances of negative rates of nutrient migration within the soil profile, as plant uptake from deeper soil layers surpasses downward nutrient movement, resulting in K accumulation in the upper few centimeters of the soil profile (Bortoluzzi et al., 2005). Beyond that, K distribution within the soil profile can be influenced by several soil parameters, including mineralogy (Hinsinger et al., 1992; Bortoluzzi et al., 2005; Barré et al., 2008; Firmano et al., 2020), cation exchange capacity (CEC), liming, clay content, cropping system (Ambrosini et al., 2022), and the applied K rate (Hinsinger et al., 1992; Raheb and Heidari, 2012). Bortoluzzi et al. (2006) proposed a mathematical model, utilizing multiple linear regression, to estimate the CEC and the contribution of permanent charges and pH-dependent charges (pH, clay, and organic matter content) in subtropical soils. They found soil organic matter contributed approximately 54, 45, and 39 % of CEC at pH 7 in the Ap1a, Ap1b, and Ap2 horizons, respectively, decreasing to only 14.1 % in the B horizon. Consequently, within soil sub-layers of the A horizon, where there is little variation in clay content and type, the CEC decreases along the soil profile, leading to a reduction in the capacity to store bioavailable K.

Potassium is present in the soil in two main compartments that are in equilibrium: the soil solution and adsorbed to the solid phase of the soil. Plants absorb K in its ionic form (K^+) from the soil solution, with diffusion being the main transfer process responsible for the movement of K^+ from the soil solution to the cell membranes of the roots (Barber, 1995; Simonsson et al., 2007). Potassium application must be close to the root system for optimal uptake. Excessive K rate application increases soil K levels, in chemical forms that are less or more available to plants, such as labile K and non-exchangeable K. Non-exchangeable K form promotes occlusion within the interlayers of 2:1 clay mineral (Moterle et al., 2016, 2019). Additionally, the labile fraction increases, resulting in luxury absorption by plants and potentially enhancing K migration into the soil profile (Bell et al., 2021). Potassium balance in the NT system consists of the total amount of K inputs through fertilization minus system losses (K exported by crops and K adsorbed by 2:1 clay minerals). This balance significantly influences K distribution in the soil profile, and K migration is primarily determined by the soil's chemical K status rather than pedogenic factors like clay migration into the profile (Bortoluzzi et al., 2008). In subtropical soils containing 2:1 clay mineral, K accumulation in the topsoil surface at the expense of migration into deeper layers is even more typical (Bell et al., 2021). However, the prevalent practice of broadcast K fertilization in NT raises concerns, as the superficial accumulation of K may not align with crop root system distribution, potentially decreasing crop yields and causing economic and environmental damage.

We hypothesized when K is applied to the topsoil in the NT, it causes the accumulation of K in the superficial layers, while the subsequent K migration in the soil profile is an overestimated process. Broadcast fertilization of K in the NT lacks scientific justification and may result in economic damage to the country's agribusiness due to reduced crop productivity. This study aims to evaluate the distribution of K in contrasted soil profiles from NT that received K broadcast fertilizer.

MATERIALS AND METHODS

This study was carried out using soil samples collected in the southern region of Brazil, in the state of Rio Grande do Sul. Sampling sites primarily consisted of cropfields (n = 45) cultivated with annual crops under NT system (Figure 1), with a few additional sites sampled in areas under natural vegetation (NV) serving as reference backgrounds (n = 4). Sampling covered two traditional soybean-growing regions under NT (Middle plateau region and Missões region) and two regions where grain crops have recently expanded, also under NT (Cental depression region and Serra Gaúcha region). Cropfields sites were selected randomly on commercial farms, with permission obtained from farmers whenever possible. Four NV sites were chosen in areas adjacent to the crop field sites, one in each region, as indicated in figure 1. Environmental characteristics of the sampling sites are detailed in table 1.

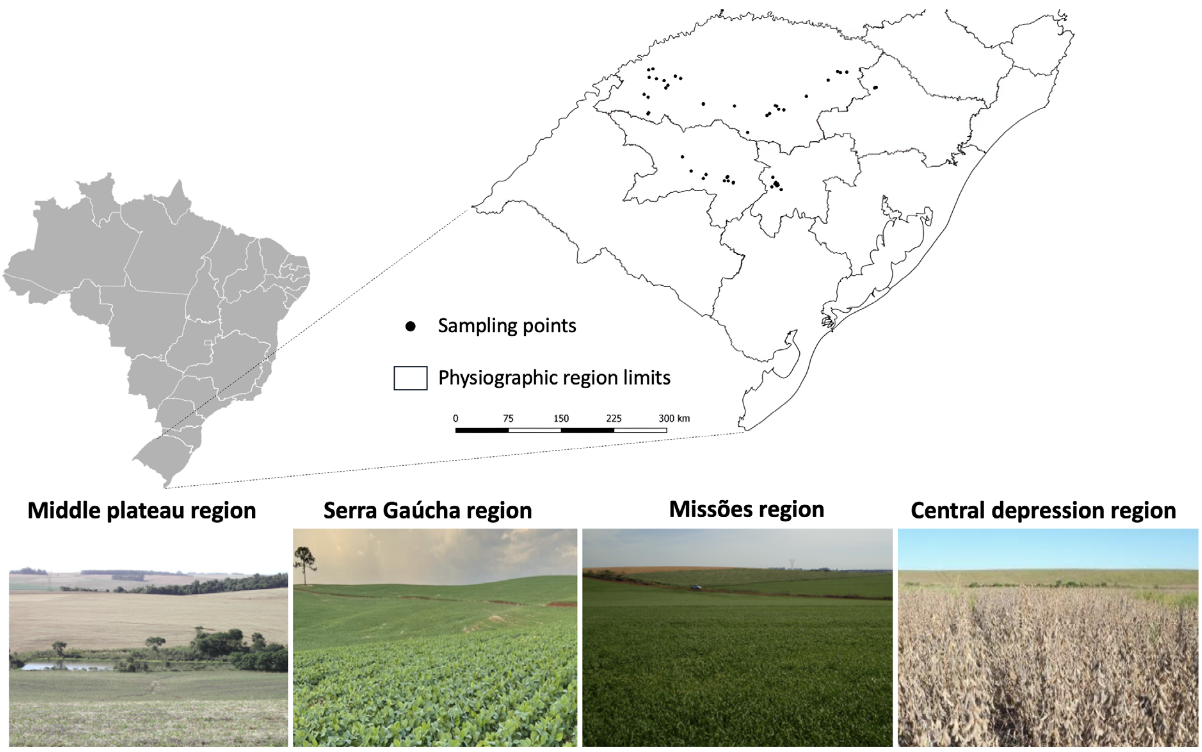

Figure 1. Sampling sites in the state of Rio Grande do Sul, Brazil, and the typical landscapes of the physiographic regions sampled.

Table 1. Environmental and pedogenic characterization of soil sampling sites in Southern Brazil, state of Rio Grande do Sul

Feature[1,2,3]	Missões region	Middle plateau region	Central depression region	Serra Gaúcha region
Climate	Cfa	Cfa	Cfa	Cfb
Average annual temperature (°C)	21	21	21	19
Average annual precipitation (mm)	1250	1450	1450	1650
Geology	Basalt - Group São Bento	Basalt - Group São Bento	Sedimentary sandstones - Rosário do Sul	Dacite/Basalt - Group São Bento
Soil classification	Ferralsols (Latossolos)	Ferralsols (Latossolos)	Ultisols (Argissolos)	Ferralsols (Latossolos)

(1) Pessoa (2017). (2) Scherer et al. (2000). (3) Streck et al. (2018).

According to farmer records, the 45 sites sampled in cropfields have been managed under NT system for 4 to 31 years. These fields receive K fertilizer either in the sowing line or broadcast on the soil surface. These sites were classified based on the average CEC in the 0.00-0.40 m soil layer. Annual amount of K added varied between 50 and 120 kg ha^{-1}, in accordance with regional fertilization guidelines (CQFS-RS/SC, 2016). Of the 45 cropfield sites sampled, only two were planted with corn in the summer season; while the remaining were all planted with soybeans. Additionally, in 12 of these sites, farmers practiced a soybean/corn succession. During the fall/winter season, most areas were left fallow or reseeded with ryegrass + oats; 18 were cultivated with wheat; two were sporadically cultivated with canola; and two with barley. In 33 fields, fertilizers were routinely applied to the sowing line below the seeds. Twelve fields received annual surface applications of K, and in 11 of these, farmers broadcasted applications of NPK. Farmers preferred to remain anonymous regarding the fertilizer application method used in two sites.

Due to potential inaccuracies in the information provided by farmers and the limited sample size to represent each factor (K application method – broadcast or banding, time using NT, crop rotation, annual K rate), we have opted not to address these aspects in our study. Additionally, other factors such as different soil types and mineralogy could confound these comparisons. While discussing these differences may be appealing, we lack an experimental design or sufficient sampling representation to make such comparisons reliably. However, these aspects could certainly be explored in future studies. Therefore, we have focused our study on conveying a single clear and robust message that we can motivate future research and provide insights into the dynamics of potassium (K) in Brazilian soils: there is a significant stratification of K in depth in soils cultivated under no-tillage, regardless of soil cation exchange capacity (CEC).

Soil samples were taken from 19 layers within the soil profile (horizon A): 0-1, 1-2, 2-3, 3-4, 4-5, 5-6, 6-7, 7-8, 8-9, 9-10, 10-12.5, 12.5-15, 15-17.5, 17.5-20, 20-22.5, 22.5-25, 25-30, 30-35, and 35-40 cm. A trench of 0.40 m in width and 0.60 m in depth was opened across the seeding line to obtain these samples. Soil samples were dried in a forced circulation oven at 55 °C until a constant mass was achieved. After drying, soil samples were ground in a mechanical mill. Subsequently, the soil was sieved through a 2 mm mesh sieve and placed in a hermetically sealed flask for analysis.

Soil samples underwent to several chemical determinations, such as: active acidity (pH in water - ratio 1:1 (v/v)); potential acidity - estimated using the equation proposed by Kaminski et al. (2001) [$H^0 + Al^{3+} = e^{10.665-1.1483*TSM}/10$] and adopted by CQFS-RS/SC (2016); TSM index was measured by Toledo et al. (2012) method; and exchangeable Ca^{2+}, Mg^{2+}, and Al^{3+} extracted by KCl 1.0 mol L^{-1} (soil: extractant ratio 1:25; Tedesco et al., 1995). Exchangeable Al was determined by titration with 0.0125 mol L^{-1} NaOH solution, while Ca^{2+} and Mg^{2+} were determined using atomic absorption spectrophotometry. Cation exchange capacity at pH 7.0 ($CEC_{pH7.0}$) was calculated as the sum of $H^0 + Al^{3+} + Ca^{2+} + Mg^{2+} + K^+$.

Soil available K content was extracted using Mehlich-1 solution [(HCl 0.05 mol L^{-1} and H_2SO_4 0.0125 mol L^{-1} – Mehlich (1953)]. Briefly, 3.00 dm^3 of soil was transferred to a snap-cap with a screw cap, and 30 mL of Mehlich-1 extractant solution was added. Containers were closed and stirred for 5 min. Afterward, the containers were uncapped and left to stand for 16 h. Then 10 mL of the supernatant was pipetted off, and the K content was measured using emission spectrophotometry.

Descriptive statistics were conducted to determine the mean values and the confidence intervals (95 %) for the K contents extracted by Mehlich-1. The data was segregated into three CEC classes: <7.5, 7.6-15.0, and 15.1-30.0 $cmol_c$ dm^{-3}. Soil critical level of K for these classes are 60, 90, and 120 mg dm^{-3}, respectively, for annual crops, based on the regional guidelines provided by the CQFS-RS/SC (2016). Subsequently, the available K data was classified into availability classes.

RESULTS AND DISCUSSION

Vertical distribution of available K

All sampled soil profiles, both in cropfields under NT and under natural vegetation, regardless of soil CEC, exhibited a pronounced gradient of available K with depth (Figures 3a, 3c, and 3e). These findings contrast with some reports suggesting potential K percolation in subtropical soils (Neves et al., 2009). If a chemical element exhibits high vertical mobility in the soil, potentially leading to loss through percolation, two scenarios for its vertical distribution can be expected: (i) homogeneous distribution, characterized by a uniform nutrient distribution throughout the soil profile, typically resulting in concentrations close to zero as observed in nitrate concentration assessments (Ernani et al., 2002) or chlorine studies (Liu et al., 2021); or (ii) accumulation with depth, in which the chemical element is distributed throughout the soil profile with increasing accumulation as the sampled depth increases, as observed for sulfate (Eckert et al., 2023; Costa et al., 2022). However, neither of the two possibilities was found in the present study; on the contrary, the vertical distribution of available K in the studied soil profiles is inverse to the intense percolation process, even with highly contrasting physical and chemical characteristics, as indicated by the CEC of the studied soils varying from 4.6 to 30.0 $cmol_c$ dm^{-3} (Figure 2). Moreover, the substantial K accumulation in the uppermost centimeters of soil (Figure 3) suggests a high risk of nutrient loss due to erosion and surface runoff. Indeed, the few existing experiments that concretely evaluate K losses from the system clearly demonstrate that K losses through percolation are negligible compared to losses through surface runoff, even in sandy soils with low CEC. For instance, the five-year monitoring of K losses in a Ultisol with 170 g kg^{-1} clay, 9.6 $cmol_c$ dm^{-3} of CEC, and a very gentle slope (4 %) showed only 0.3-0.7 % of the total applied K was lost through leaching (below 0.60 m depth) (Girotto et al., 2013), while losses through surface runoff ranged between 9 and 17 % of the total K applied (Ceretta et al., 2010).

Some recent studies also demonstrate this vertical gradient of K availability in the soil, but typically, they utilize much thicker soil layers, such as 0.05 or 0.10 m (Calegari et al., 2013; Tiecher et al., 2017; Almeida et al., 2021). Our study took it a step further and showed there is stratification of the soil available K, even in the top 0.05 or 0.10 m layers. Available K content is at its highest in the first centimeter, demonstrating it is an element with exceptionally poor mobility in subtropical soils (Figure 3). Only two soils demonstrated different behavior, where the maximum available K content was found in the layer between 2 and 4 cm deep (Figures 3c and 3e), and these are precisely soil profiles where fertilization is done in the furrow of the sowing line. Nevertheless, most soils that had fertilization in the furrow displayed their highest levels of available K in the top 0–1 cm of soil, highlighting the significant role that plants play in K cycling. Plants uptake the nutrient from the entire soil profile explored by the root system, store it in

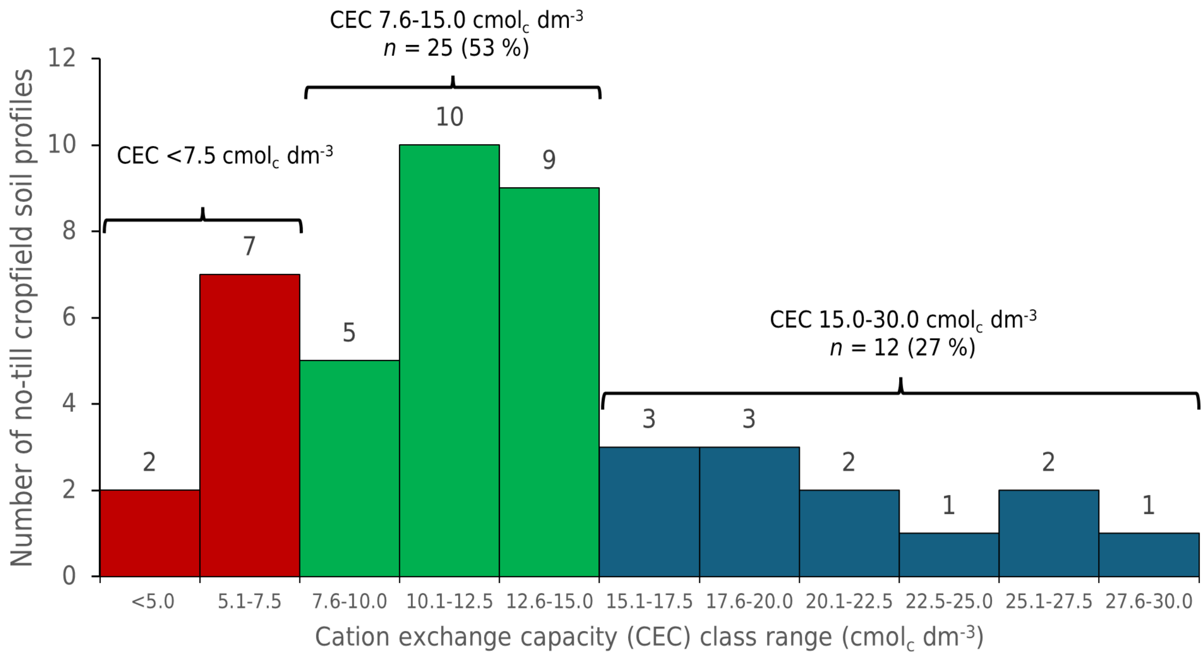

Figure 2. Distribution of no-till cropfield soil profiles according to the cation exchange capacity (CEC) range for the 0.00-0.20 m soil layer.

their aboveground biomass, and later, as there is no soil disturbance and incorporation of plant residues, K accumulates in the top few centimeters of soil (Costa et al., 2009; Figure 3). Because of the high capacity of plants to cycle K and the superficial addition of K fertilizers during crop fertilization, the natural gradient of K distribution in the profile inexorably worsens, keeping most of this nutrient out of reach for the roots.

Vertical distribution pattern of soil-available K in the reference areas (under native vegetation) already demonstrates negligible K migration in the profile, with a negative balance (i.e., migration is lower than plant uptake in depth and accumulation on the surface), a behavior that is accentuated in NT cropfields (Figures 3d and 3f). However, due to K fertilization, the cultivated areas consistently exhibited a higher available K content than the native areas in the first 0.10 m of soil (Figures 3d and 3f). Even so, the available K content in the soil in the 0.00-0.10 m layer in native vegetation areas was above the critical level established for grain crops under NT.

In areas cultivated under NT, the influence of the CEC value on the vertical distribution of K (Figure 3g) is noticeable, especially in the first centimeters. Soils with CEC <7.5 cmol$_c$ dm^{-3} exhibit lower K contents and a more drastic decrease in K content than soils with CEC >7.6 cmol$_c$ dm^{-3} up to approximately 0.20 m deep. Although some soil profiles with CEC between 15.1-30.0 cmol$_c$ dm^{-3} display more discrepant K contents, the 95 % confidence interval for K content throughout the soil profile is similar to those soils with CEC between 7.6- 15.0 cmol$_c$ dm^{-3} (Figure 3g). This behavior may be attributed to the similar K buffering capacity of soils with CEC higher than 7.6 cmol$_c$ dm^{-3}. Despite the official fertilization guidelines in South Brazil (CQFS-RS/SC, 2016) separating these soils into different CEC classes, recent research by Souza Junior et al. (2022), using 23 soils from the states of Santa Catarina and Rio Grande do Sul, demonstrates the K buffer capacity increases linearly with increasing CEC up to 8.5 cmol$_c$ dm^{-3}, but remains constant for soils with CEC ranging from 8.5-15.5 cmol$_c$ dm^{-3}. These findings combined with our results, underscore the need for future studies evaluating the K buffering capacity in soils with CEC greater than 15.0 cmol$_c$ dm^{-3}.

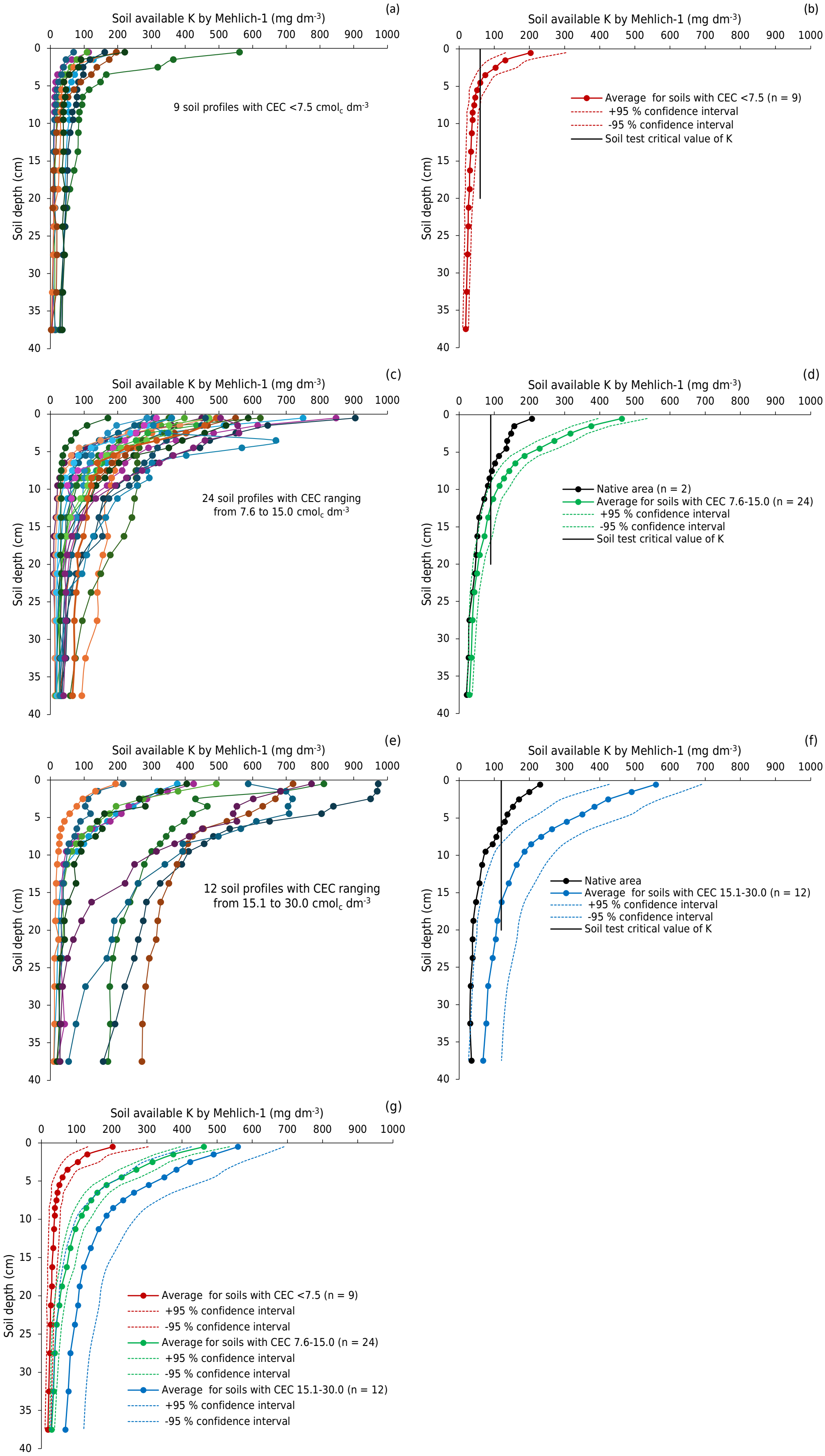

Figure 3. Vertical distribution of soil-available K content extracted with Mehlich-1 in soils with CEC <7.5 $cmol_c\ dm^{-3}$ (a, b), soils with CEC between 7.6-15.0 $cmol_c\ dm^{-3}$ (c, d), soils with CEC between 15.1-30.0 $cmol_c\ dm^{-3}$ (e, f), and mean distribution of soil-available K and 95 % confidence interval in no-till cropfields sites with different CEC classes (g). For the CEC class <7.5 $cmol_c\ dm^{-3}$, it could not sample soil under natural vegetation.

Decrease in available K content at depth cannot be attributed to a lower soil CEC at depth (Figure 4). While it is true that deeper soil layers generally contain less organic matter, which contributes to CEC, other factors also play significant roles. In some soils, there might be an increase in clay content with depth, along with less weathered minerals with higher CEC. This led to similar or slightly smaller CEC values over the first 0.40 m, and, in some cases, even an increase in CEC with increasing depth (Figure 4). Therefore, as the saturation of K in the CEC tends to decrease with depth, this indicates the decrease in K content at depth is not directly proportional to changes in soil CEC.

Availability of K in depth

Soil K availability can be evaluated based on critical levels established in calibration studies for predefined diagnostic soil layers. Current guidelines for the states of Santa Catarina and Rio Grande do Sul in southern Brazil establish the following critical levels of K in soil extracted with Mehlich-1 for grain production: 60, 90, and 120 mg dm^{-3}, for soils with CEC <7.5, 7.6-15.0, and 15.1-30.0 $cmol_c$ dm^{-3}, respectively (CQFS-RS/SC, 2016). These critical levels are established for the 0.00-0.10 m layer for NT, and for the 0.00-0.20 m layer for conventional cultivation systems or for the implementation of NT system. In areas under NT, it is possible to use these critical levels also to monitor whether the 0.10-0.20 m soil layer remains above these reference values. Therefore, the soil-available K contents will be compared for each layer individually and considering the possible diagnostic layers according to CQFS-RS/SC (2016).

In soils with CEC <7.5 $cmol_c$ dm^{-3}, only in the 0.00-0.04 m soil layer (or in the 0.00-0.03 m layer when considering the 95 % confidence interval) exhibited an available K content above the threshold level when comparing soil layers individually (Figure 3b). For soils with CEC between 7.6-15.0 $cmol_c$ dm^{-3}, the available K content was above the critical level up to 12.5 cm deep (or up to 9 cm deep when considering the 95 % confidence interval) (Figure 3d). For soils with CEC between 15.1-30.0 $cmol_c$ dm^{-3}, the available K content was above the critical level up to 17.5 cm deep (or up to 8 cm deep when considering the 95 % confidence interval) (Figure 3f).

When considering the diagnostic layers, it is noted that the soil in the 0.00-0.10 m layer, 87 % of the sampling sites in NT cropfields have a K content above the critical level (Figure 5d). For soils with CEC between 7.6-15.0 $cmol_c$ dm^{-3}, this percentage reaches 96 % (Figure 5b). A similar trend occurs when evaluating the 0.00-0.20 m layer. However, as the gradient of availability in depth is very strong, there is dilution due to lower K contents in the subsurface soil (i.e., 0.10-0.20 m). Therefore, only 66 % of sampling sites in NT cropfields had K content above the critical level (Figure 5d). On the other hand, considering only the 0.10-0.20 m layer, only 27 % of sampling sites in NT cropfields showed K content above the critical level. This percentage is even lower for soils with CEC <7.5 $cmol_c$ dm^{-3}, which was only 11 % (Figure 5a).

Depletion of available K reserves in the deeper soil layers (0.10-0.40 m) and the enrichment in the superficial layers (up to 0.05-0.10 m) indicate a mismatch between the site of the fertilizer application in NT and the distribution pattern of the crop root system. This highlights the need to implement strategies for redistributing K within the soil profile. During crop seasons, the first centimeters of soil are precisely the first to lose moisture, resulting in decreased diffusion of K present in the soil solution to the cell membranes of the roots. Consequently, even if the soil has high or very high availability of K in the superficial diagnostic layers, it may not adequately meet the crop's needs. Furthermore, acidity in deeper layers under NT further hinders root growth and access to K in depth (Tiecher et al., 2023). Studies have indicated crop yields are associated with a higher concentration of nutrients in deeper soil layers or a better distribution of nutrients in the soil profile (Nora et al., 2014; Corassa et al., 2018). This behavior has been observed for phosphorus as well (Bellinaso et al., 2021). These findings underscore the urgent need to develop recommendations that consider the accelerated stratification of K in

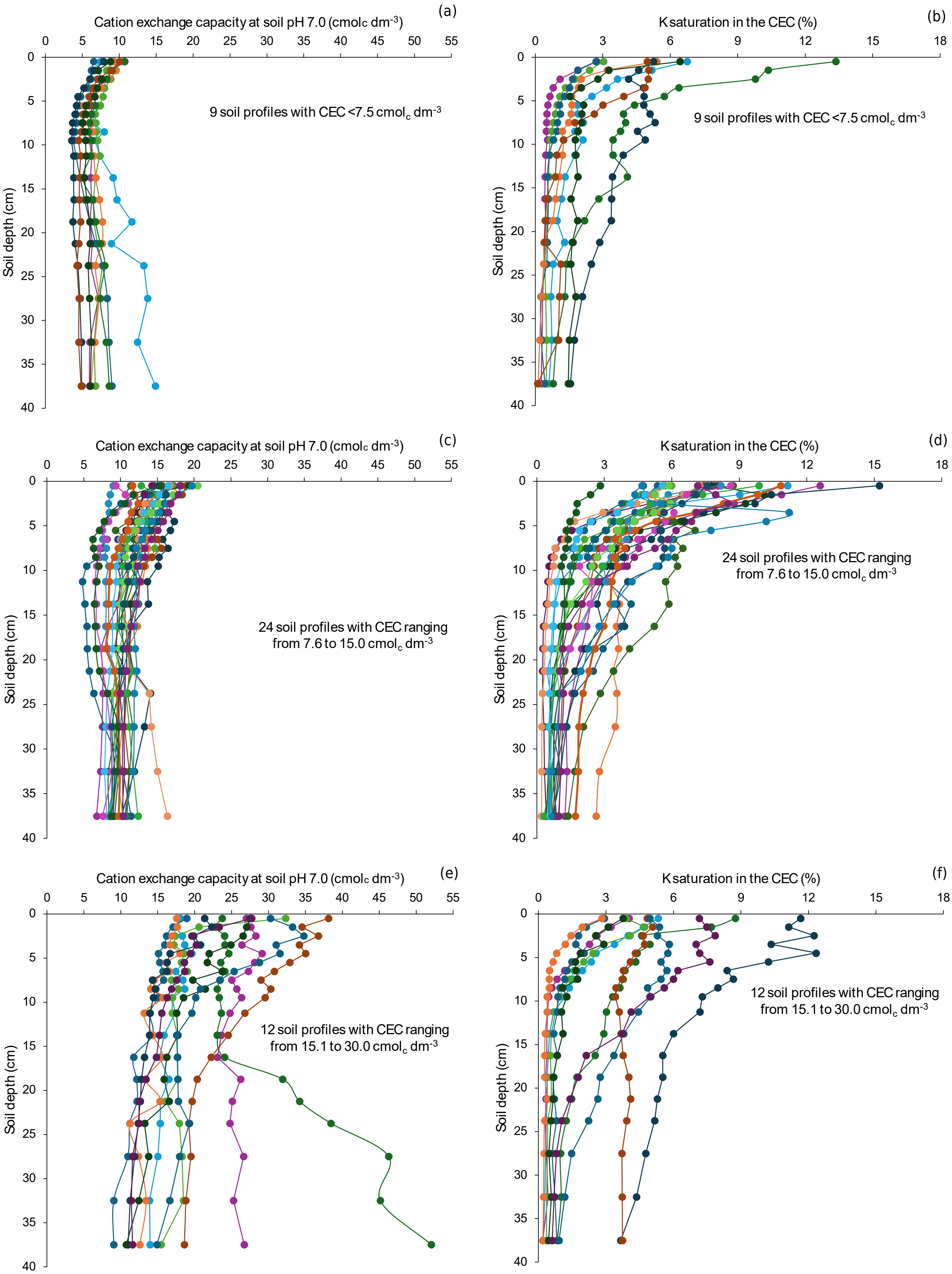

Figure 4. Vertical distribution of cation exchange capacity (CEC) at soil pH 7.0 and K saturation in the CEC for soils with <7.5 $cmol_c$ dm^{-3} (a, b), soils with CEC between 7.6-15.0 $cmol_c$ dm^{-3} (c, d), and soils with CEC between 15.1-30.0 $cmol_c$ dm^{-3} (e, f).

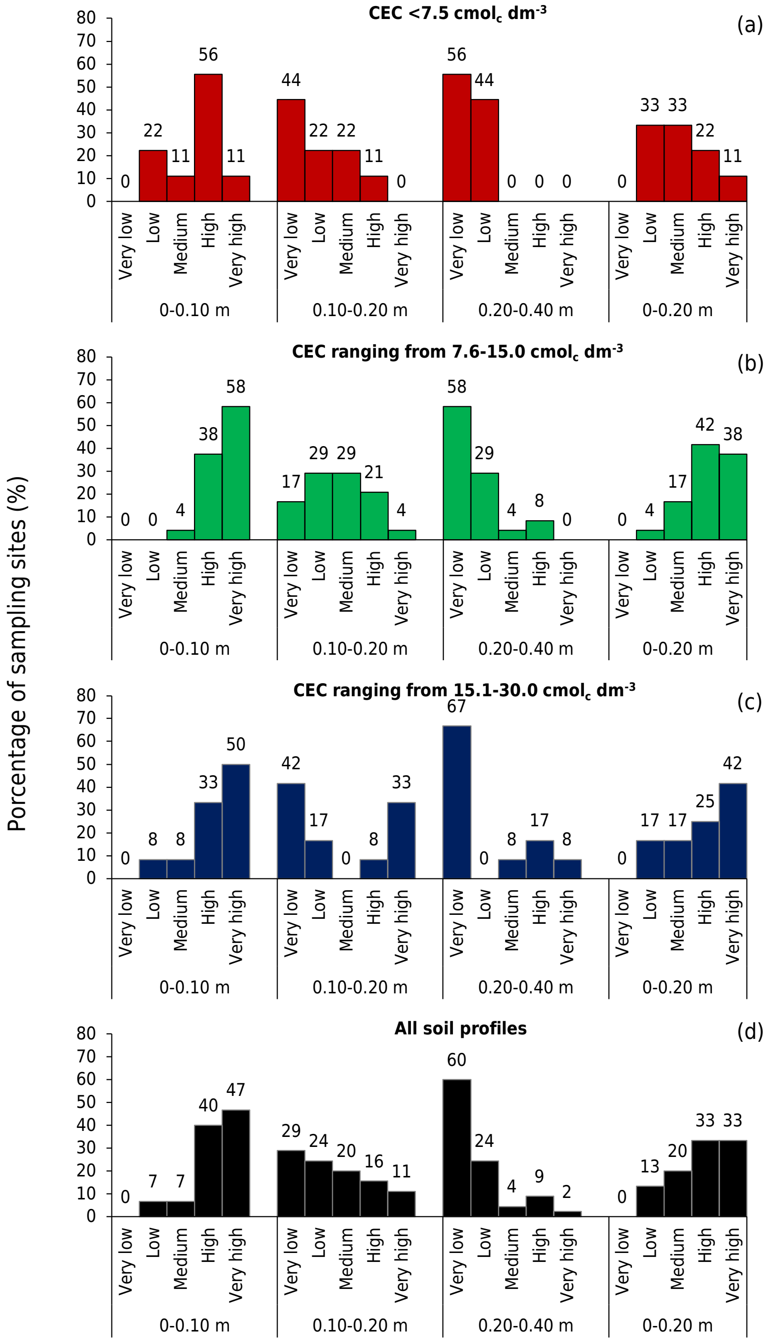

Figure 5. Interpretation of soil-available K content in the 0.00-0.10, 0.10-0.20, 0.20-0.40, and 0.00-0.20 m layer of no-till cropfields in Southern Brazil, for soils with CEC <7.5 cmol$_c$ dm^{-3} (a), 7.6-15.0 cmol$_c$ dm^{-3} (b), 15.1-30.0 cmol$_c$ dm^{-3} (c), and for the entire set of soils sampled (d). Interpretation according to the CQFS-RS/SC (2016) guidelines.

the soil profile of NT cropfields, including diagnostic subsurface layers, to better infer the real accessibility of K by plants. Furthermore, it is crucial to reduce K use in surface broadcasting and promote fertilizer use in the furrow and in-depth to increase K use efficiency and mitigate potential losses due to erosion and surface runoff.

This study offers valuable insights into the complex dynamics of K availability in subtropical soils managed under NT and native vegetation. Vertical distribution pattern of K, characterized by significant accumulation in superficial layers and depletion in deeper layers, highlights the discrepancy between fertilization practices and the actual requirements of plants. The pronounced stratification of K, especially in the top few centimeters of soil, poses a considerable challenge in ensuring crops have adequate access to this nutrient throughout their growth cycle. The disparity between the K availability in the superficial diagnostic layers and the plant requirement highlights the urgency of revising fertilization strategies. Our findings emphasize the urgency of developing management guidelines that consider the pronounced K stratification in the soil profile, including subsurface diagnostic layers, to accurately assess K accessibility by plants in NT systems. Furthermore, it is imperative to reduce indiscriminate K application on the soil surface and promote deep fertilizer application in the seeding line. This approach aims to increase the K utilization efficiency and mitigate potential losses through erosion and surface runoff.

To support new interpretations of K availability and refine recommendations for dosages and methods of K application, conducting new K calibration studies is essential. These studies should involve corrections of soil K levels for different volumes or soil layers to ensure accuracy in K assessments. Moreover, future investigations on the vertical distribution of K should expand to other regions, such as the tropical region of Brazil, particularly focusing on the Center-West and the region encompassing the states of Maranhão, Tocantins, Piauí, and Bahia. Additionally, increasing the sampling density is crucial to facilitate comparisons among various land use histories in areas under NT. Factors such as application methods, annual doses of K, and the duration of direct planting adoption should be considered. Furthermore, exploring the diversity of soil types and mineralogy across different regions will provide valuable insights into the variability of K dynamics in Brazilian soils. These comprehensive studies will contribute significantly to advancing our understanding of K management practices and optimizing agricultural productivity and K use efficiency in Brazil.

CONCLUSION

Application of fertilizers containing K, particularly when distributed over surface residues, exacerbates the natural model of a decreasing gradient of bioavailable K in the soil profile. Soils with cation exchange capacity (CEC) lower than 7.5 $cmol_c\ dm^{-3}$ exhibit lower K contents and a more pronounced decrease in K content in soil profile (>0.20 m) compared to soils with CEC greater than 7.6 $cmol_c\ dm^{-3}$. The optimal level of available K for topsoil soils was found within an average range of 4 to 12.5 cm of soil depth. Consequently, K fertilization resulted in three main outcomes: (i) an excess of K in the upper soil layers, which increases the potential for K loss through surface erosion and runoff, (ii) limited migration of K towards the deeper soil layers until reaching the root growth zone, and (iii) a suggestion to consider changing the diagnostic soil layer for estimating the status of K availability in soils under NT.

AUTHOR CONTRIBUTIONS

Conceptualization: Danilo Rheinheimer dos Santos (lead).

Data curation: Danilo Rheinheimer dos Santos (equal), Deonilce Retka Artuso (equal) and Tales Tiecher (equal).

Formal analysis: Deonilce Retka Artuso (lead).

Funding acquisition: Danilo Rheinheimer dos Santos (lead).

Investigation: Danilo Rheinheimer dos Santos (equal) and Deonilce Retka Artuso (equal).

Methodology: Danilo Rheinheimer dos Santos (equal) and Deonilce Retka Artuso (equal).

Project administration: Danilo Rheinheimer dos Santos (lead).

Resources: Danilo Rheinheimer dos Santos (lead).

Supervision: Danilo Rheinheimer dos Santos (equal), Deonilce Retka Artuso (equal), Diovane Freire Moterle (equal) and Tales Tiecher (equal).

Validation: Diovane Freire Moterle (equal) and Tales Tiecher (equal).

Visualization: Danilo Rheinheimer dos Santos (equal), Diovane Freire Moterle (equal) and Tales Tiecher (equal).

Writing – original draft: Danilo Rheinheimer dos Santos (equal), Deonilce Retka Artuso (lead) and Tales Tiecher (equal).

Writing – review & editing: Danilo Rheinheimer dos Santos (equal), Diovane Freire Moterle (equal) and Tales Tiecher (lead).

REFERENCES

Almeida TF, Carvalho JK, Reid E, Martins AP, Bissani CA, Bortoluzzi EC, Brunetto G, Anghinoni I, Carvalho PCF, Tiecher T. Forms and balance of soil potassium from a long-term integrated crop-livestock system in a subtropical Oxisol. Soil Till Res. 2021;207:104864. https://doi.org/10.1016/j.still.2020.104864

Ambrosini VG, Almeida JL, Araújo EA, Alves LA, Filippi D, Flores JPM, Fostim ML, Fontoura SMV, Bortoluzzi EC, Bayer C, Tiecher T. Effect of diversified cropping systems on crop yield, legacy, and budget of potassium in a subtropical Oxisol. Field Crops Res. 2022;275:108342. https://doi.org/10.1016/j.fcr.2021.108342

Barber SA. Soil nutrient bioavailability: A mechanistic approach. 2nd ed. New York: John Wiley; 1995.

Barré P, Velde B, Fontaine C, Catel N, Abbadie L. Which 2:1 clay minerals are involved in the soil potassium reservoir? Insights from potassium addition or removal experiments on three temperate grassland soil clay assemblage. Geoderma. 2008;146:216-23. https://doi.org/10.1016/j.geoderma.2008.05.022

Bell MJ, Ransom MD, Thompson ML, Hinsinger P, Florence AM, Moody PW, Guppy CN. Considering soil potassium pools with dissimilar plant availability. In: Murrell TS, Mikkelsen RL, Sulewski G, Norton R, Thompson ML, editors. Improving potassium recommendations for agricultural crops. Switzerland: Springer; 2021. p. 163-90.

Bellinaso RJ, Tiecher T, Vargas J, Rheinheimer DS. Crop yields in no-tillage are severely limited by low availability of P and high acidity of the soil in depth. Soil Res. 2021;60:33-49. https://doi.org/10.1071/SR21021

Bertol OJ, Rizzi NE, Bertol I, Roloff G. Perdas de solo e água e qualidade do escoamento superficial associadas à erosão entre sulcos em área cultivada sob semeadura direta e submetida as adubações mineral e orgânica. Rev Bras Cienc Solo. 2007;31:781-92. https://doi.org/10.1590/S0100-06832007000400018

Bertol OJ, Rizzi NE, Fey E, Lana MC. Perda de nutrientes via escoamento superficial no sistema plantio direto sob adubação mineral e orgânica. Cienc Rural. 2011;41:1914-20. https://doi.org/10.1590/S0103-84782011005000135

Bortoluzzi EC, Pernes M, Tessier D. Mineralogia de partículas envolvidas na formação de gradiente textural em um Argissolo subtropical. Rev Bras Cienc Solo. 2008;32:997-1007. https://doi.org/10.1590/S0100-06832008000300009

Bortoluzzi EC, Santos DR, Kaminski J, Gatiboni LC, Tessier D. Alterações na mineralogia de um Argissolo do Rio Grande do Sul submetido à fertilização potássica. Rev Bras Cienc Solo. 2005;29:327-35. https://doi.org/10.1590/S0100-06832005000300002

Bortoluzzi EC, Santos DR, Santanna M, Caner L. Mineralogy and nutrient desorption of suspended sediments during a storm event. J Soils Sediments. 2013;13:1093-105. https://doi.org/10.1007/s11368-013-0692-4

Bortoluzzi EC, Tessier D, Rheinheimer DS, Julien JL. The cation exchange capacity of a sandy soil in southern Brazil: An estimation of permanent charge and pH-dependent charges. Eur J Soil Sci. 2006;57:356-64. https://doi.org/10.1111/j.1365-2389.2005.00746.x

Calegari A, Tiecher T, Hargrove WL, Ralisch R, Tessier D, Tourdonnet S, Guimarães MF, Rheinheimer DS. Long-term effect of different soil management systems and winter crops on soil acidity and vertical distribution of nutrients in a Brazilian Oxisol. Soil Till Res. 2013;133:32-9. https://doi.org/10.1016/j.still.2013.05.009

Ceretta CA, Girotto E, Brunetto G, Lourenzi CR, Vieira RCB. Nutrient transfer by runoff under no tillage in a soil treated with successive applications of pig slurry. Agr Ecosyst Environ. 2010;139:689-99. https://doi.org/10.1016/j.agee.2010.10.016

Cogo NP, Levien R, Schwarz RA. Perdas de solo e água por erosão hídrica influenciadas por métodos de preparo, classes de declive e níveis de fertilidade do solo. Rev Bras Cienc Solo. 2003;27:743-53. https://doi.org/10.1590/S0100-06832003000400019

Comissão de Química e Fertilidade do Solo - CQFS-RS/SC. Manual de calagem e adubação para os Estados do Rio Grande do Sul e de Santa Catarina. 11. ed. Porto Alegre: Sociedade Brasileira de Ciência do Solo - Núcleo Regional Sul; 2016.

Corassa GM, Santi AL, Silva VR, Baron FA, Reimche GB, Fioresi D, Della Flora DP. Soil chemical attributes restricting grain yield in Oxisols under no-tillage system. Pesq Agropec Bras. 2018;53:1203-12. https://doi.org/10.1590/S0100-204X2018001100002

Costa SEVGA, Souza ED, Anghinoni I, Flores JPC, Andriguetti MH. Distribuição de potássio e de raízes no solo ecrescimento de milho em sistemas de manejo do solo e da adubação em longo prazo. Rev Bras Cienc Solo. 2009;3:1291-301. https://www.researchgate.net/publication/250033918

Costa RF, Firmano RF, Colzato M, Crusciol CAC, Alleoni LRF. Sulfur speciation in a tropical soil amended with lime and phosphogypsum under long-term no-tillage system. Geoderma. 2022;406:115461. https://doi.org/10.1016/j.geoderma.2021.115461

Derpsch R, FriedrichT, Kassam A, Li H. Current status of adoption of no-till farming in the world and some of its main benefits. Int J Agric Biol Eng. 2010;3:1-25. https://doi.org/10.3965/j.issn.1934-6344.2010.01.0-0

Eckert DJ, Martins AP, Vian AL, Pesini G, Alves LA, Flores JPF, Filippi D, Tiecher TL, Fink JR, Bredemeier C, Coser TR, Guterres DB, Ambrosini VG, Horowitz N, Tiecher T. Single superphosphate replacing agricultural gypsum: short-term effect on grain yield and soil chemical properties in subtropical soils under no-tillage. Arch Agron Soil Sci. 2023;69:1973-89. https://doi.org/10.1080/03650340.2022.2129618

Ernani PR, Sangoi L, Rampazzo C. Lixiviação e imobilização de nitrogênio num Nitossolo como variáveis da forma de aplicação da uréia e da palha de aveia. Rev Bras Cienc Solo. 2002;226:993-1000. https://doi.org/10.1590/S0100-06832002000400017

Ernani PR, Bayer C, Almeida JA, Cassol PC. Mobilidade vertical de cátions influenciada pelo método de aplicação de cloreto de potássio em solos com carga variável. Rev Bras Cienc Solo. 2007;31:393-402. https://doi.org/10.1590/S0100-06832007000200022

Ferreira EVO, Anghinoni I, Carvalho PCF, Costa SEVGA, Cao EG. Concentração do potássio do solo em sistema de integração lavoura-pecuária em plantio direto submetido a intensidades de pastejo. Rev Bras Cienc Solo. 2009;33:1675-84. https://doi.org/10.1590/S0100-06832009000600016

Firmano RF, Melo VF, Montes CR, Oliveira AJ, Castro C, Alleoni LRF. Potassium reserves in the clay fraction of a tropical soil fertilized for three decades. Clay Clay Miner. 2020;68:237-49. https://doi.org/10.1007/s42860-020-00078-6

Girotto E, Ceretta CA, Lourenzi CR, Lorensini F, Tiecher TL, Vieira RCB, Trentin G, Basso CJ, Brunetto G. Nutrient transfers by leaching in a no-tillage system through soil treated with repeated pig slurry applications. Nutr Cycl Agroecosys. 2013;95:115-31. https://doi.org/10.1007/s10705-013-9552-2

Hinsinger P, Jaillard B, Dufey JE. Rapid weathering of a trioctahedral mica by the roots of ryegrass. Soil Sci Soc Am J. 1992;56:977-82. https://doi.org/10.2136/sssaj1992.03615995005600030049x

Kaminski J, Moterle DF, Rheinheimer DS, Gatiboni LC, Brunetto G. Potassium availability in Hapludalf soil under long-term fertilization. Rev Bras Cienc Solo. 2010;34:49-57. https://doi.org/10.1590/S0100-06832010000300020

Kaminski J, Rheinheimer DS, Bartz HR. Proposta de nova equação para determinação do valor de H+Al pelo uso do índice SMP em solos do RS e SC. ANAIS: Reunião Anual da ROLAS, 23. Frederico Westphalen (RS); 2001.

Lopes AS, Guilherme RLG. Uso eficiente de fertilizantes e corretivos agrícolas: Aspectos agronômicos. 3. ed rev ampl. São Paulo: Associação Nacional para a Difusão de Adubos; 2000. (Boletim técnico, 04).

Liu X, Hu C, Zhu Z, Riaz M, Liu X, Dong Z, Liu Y, Wu S, Tan Z, Tan Q. Migration of chlorine in plant–soil–leaching system and its effects on the yield and fruit quality of sweet orange. Front Plant Sci. 2021:12;744843. https://doi.org/10.3389/fpls.2021.744843

Mehlich A. Determination of P, Ca, Mg, K, Na and NH_4 by North Carolina soil testing laboratories. Raleigh: University of North Carolina; 1953.

Ministério de Minas e Energia - MME. Anuário estatístico: Setor transformação não metálicos. Brasília, DF: Secretaria de Geologia, Mineração e Transformação Mineral; 2019.

Moreno F, Murillo JM, Pelegrín F, Giróna F. Long-term impact of conservation tillage on stratification ratio of soil organic carbon and loss of total and active $CaCO_3$. Soil Till Res. 2006;85:86-93. https://doi.org/10.1016/j.still.2004.12.001

Moterle DF, Bortoluzzi EC, Kaminski J, Rheinheimer DS, Caner L. Does Ferralsol clay mineralogy maintain potassium long-term supply to plants? Rev Bras Cienc Solo. 2019;43:e0180166. https://doi.org/10.1590/18069657rbcs20180166

Moterle DF, Kaminski J, Rheinheimer DS, Caner L, Bortoluzzi EC. Impact of potassium fertilization and potassium uptake by plants on soil clay mineral assemblage in South Brazil. Plant Soil. 2016;406:157-72. https://doi.org/10.1007/s11104-016-2862-9

Neves LS, Ernani PR, Simonete MA. Mobilidade de potássio em solos decorrente da adição de doses de cloreto de potássio. Rev Bras Cienc Solo. 2009;33:25-32. https://doi.org/10.1590/S0100-06832009000100003

Nora D, Amado TJC, Bortolotto RP, Ferreira AO, Reichardt K, Santi AL. Subsoil chemical amelioration and crop yields under continuous long-term no-till in a subtropical Oxisol. Afr J Agric Res. 2014;9:3338-49. https://doi.org/10.5897/AJAR2013.8283

Oliveira LEZ, Nunes RS, Figueiredo CC, Rein TA. Spatial distribution of soil phosphorus fractions in a clayey Oxisol submitted to long-term phosphate fertilization strategies. Geoderma. 2022;418:115847. https://doi.org/10.1016/j.geoderma.2022.115847

Panachuki E, Bertol I, Sobrinho TA, Oliveira PT, Rodrigues DBB. Perdas de solo e de água e infiltração de água em Latossolo Vermelho sob sistemas de manejo. Rev Bras Cienc Solo. 2011;35:1777-85. https://doi.org/10.1590/S0100-06832011000500032

Pessoa ML. Clima do RS. In: Atlas Fundação de Economia e Estatística - FEE. Porto Alegre: FEE; 2017 [cited 2020 Aug 10]. Avaiable from: http://atlas.fee.tche.br/rio-grande-do-sul/socioambiental/clima.

Raheb A, Heidar A. Effects of clay mineralogy and physico-chemical properties on potassium availability under soil aquic conditions. J Soil Sci Plant Nutr. 2012;12:747-61. https://doi.org/10.4067/S0718-95162012005000029

Rheinheimer DS, Anghinoni I. Distribuição do fósforo inorgânico em sistemas de manejo de solo. Pesq Agropec Bras. 2001;36:151-60. https://doi.org/10.1590/S0100-204X2001000100019

Rheinheimer DS, Fornari MR, Bastos MC, Fernandes G, Santanna MA, Calegari A, Canalli LBS, Caner L, Labanowski J, Tiecher T. Phosphorus distribution after three decades of different soil management and cover crops in subtropical region. Soil Till Res. 2019;192:33-41. https://doi.org/10.1016/j.still.2019.04.018

Santos DR, Schaefer GL, Pellegrini A, Alvarez JWR, Caner L, Bortoluzzi EC. Weirs control phosphorus transfer in agricultural watersheds. Wat Air Soil Poll. 2020;231:486. https://doi.org/10.1007/s11270-020-04833-2

Scherer CMS, Faccini UF, Lavina EL. Arcabouço estratigráfico do Mesozóico da Bacia do Paraná. In: Holz M, De Ros LF, editors. Geologia do Rio Grande do Sul. Porto Alegre: CIGO/UFRGS; 2000. p. 335-54.

Simonsson M, Andersson S, Andrist-Rangel Y, Hillier S, Mattsson L, Öborn I. Potassium release and fixation as a function of fertilizer application rate and soil parent material. Geoderma. 2007;140:188-98. https://doi.org/10.1016/j.geoderma.2007.04.002

Souza Junior AA, Mumbach GL, Almeida E, Grando DL, Gatiboni LC, Brunetto G, Ernani PR. Potassium buffering capacity and corrective potassium fertilizer recommendations in soils from Southern Brazil. Rev Bras Cienc Solo. 2022;46:e0220010. https://doi.org/10.36783/18069657rbcs20220010

Streck EV, Kämpf N, Dalmolin RSD, Klamt E, Nasicmento PC, Giasson E, Pinto LFS. Solos do Rio Grande do Sul. 3. ed., Porto Alegre: Emater/RS-Ascar, 2018; 252 p.

Tedesco MJ, Gianello C, Bissani CA, Bohnen H, Volkweiss SJ. Análises de solo, plantas e outros materiais. 2. ed. Porto Alegre: Universidade Federal do Rio Grande do Sul; 1995. (Boletim técnico, 5).

Tiecher T, Calegari A, Caner L, Rheinheimer DS. Soil fertility and nutrient budget after 23 years of different soil tillage systems and winter cover crops in a subtropical Oxisol. Geoderma. 2017;308:78-85. https://doi.org/10.1016/j.geoderma.2017.08.028

Tiecher T, Fontoura SMV, Ambrosini VG, Araújo EA, Alves LA, Bayer C, Gatiboni LC. Soil phosphorus forms and fertilizer use efficiency are affected by tillage and soil acidity management. Geoderma. 2023;435:116495. https://doi.org/10.1016/j.geoderma.2023.116495

Tiecher T, Gubiani E, Santanna MA, Veloso MG, Calegari A, Canalli LBS, Finckh MR, Caner L, Rheinheimer DS. Effect of 26-years of soil tillage systems and winter cover crops on C and N stocks in a Southern Brazilian Oxisol. Rev Bras Cienc Solo. 2020;44:e0200029. https://doi.org/10.36783/18069657rbcs20200029

Tiecher T, Ramon R, Andrade LA, Camargo FAO, Evrard O, Minella JPG, Laceby PL, Bortoluzzi EC, Merten GH, Rheinheimer DS, Walling D, Barros CAP. Tributary contributions to sediment deposited in the Jacuí Delta, Southern Brazil. J Great Lakes Res. 2022;48:669-85. https://doi.org/10.1016/j.jglr.2022.02.006

Toledo JA, Kaminski J, Santanna MA, Rheinheimer DS. Tampão Santa Maria (TSM) como alternativa ao tampão SMP para medição da acidez potencial de solos ácidos. Rev Bras Cienc Solo. 2012;36:427-35. https://doi.org/10.1590/S0100-06832012000200012

Tshuma F, Rayns F, Labuschagne J, Bennett J, Swanepoel PA. Effects of long-term (42 years) tillage sequence on soil chemical characteristics in a dryland farming system. Soil Till Res. 2021;212:105064. https://doi.org/10.1016/j.still.2021.105064

United States Geological Survey - USGS. Mineral Commodity Summaries 2021. United States: Geological Survey; 2021. https://doi.org/10.3133/mcs2021