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Silicate rock with different granulometry as a potassium source for alfalfa and centrosema crops

Abstract – The objective of this work was to evaluate the application of silicate ultramafic alkaline rock, with different granulometry, as an alternative potassium source on the increase of soil fertility and on the nutritional status and biomass yield of the alfalfa and centrosema crops. The used soil was a Typic Ultisol with 27.4 mg dm^{-3} K and 733 g kg^{-1} clay. The experimental design was completely randomized, in a 4 × 2 + 1 factorial arrangement. The treatments consisted of two granulometries (<0.3 and 0.3–2.0 mm) of alkaline ultramafic rock (4.0% K_2O), four K rates (0, 100, 150, and 300 mg kg^{-1}), and an additional treatment with the application of 150 mg kg^{-1} K in the form of KCl (58% K_2O). Both legumes were grown in a greenhouse and subjected to five successive harvests. In comparison with KCl, the application of silicate rock has the potential to increase K uptake and root and shoot dry weight yield in alfalfa and centrosema. Granulometry does not affect rock use efficiency, and alfalfa presents a better K efficiency recovery in the soil after successive harvests compared with centrosema; the inverse is observed for K use and K uptake efficiencies.

Index terms: *Centrosema pubescens*, *Medicago sativa*, alternative fertilizer, K-use efficiency, potassium fertilization, residual effect.

Rocha silicática com diferentes granulometrias como fonte de potássio para as culturas de alfafa e centrosema

Resumo – O objetivo deste trabalho foi avaliar a aplicação de rocha silicática ultramáfica alcalina com diferentes granulometrias, como fonte alternativa de potássio no aumento da fertilidade do solo e no estado nutricional e na produção de biomassa das cultura de alfafa e centrosema. O solo utilizado foi um Argissolo Amarelo distrófico com 27,4 mg dm^{-3} de K e 733 g kg^{-1} de argila. O delineamento experimental foi inteiramente casualizado, em arranjo fatorial 4 × 2 + 1. Os tratamentos consistiram em duas granulometrias (< 0,3 e 0,3–2,0 mm) da rocha ultramáfica alcalina (4,0% de K_2O), na aplicação de quatro doses de K (0, 100, 150 e 300 mg kg^{-1}) e de um tratamento adicional com a aplicação de 150 mg kg^{-1} de K na forma de KCl (58% de K_2O). Ambas as leguminosas foram cultivadas em casa de vegetação e submetidas a cinco cortes sucessivos. Em comparação ao KCl, a aplicação da rocha silicática apresenta potencial para aumentar a absorção de K e a produção de matéria seca de raízes e da parte aérea da alfafa e da centrosema. A granulometria não altera a eficiência de uso da rocha, e a alfafa apresenta maior eficiência de recuperação de K do solo após cortes sucessivos em comparação à centrosema; o inverso é observado para eficiências de uso e absorção de K.

Termos para indexação: *Centrosema pubescens*, *Medicago sativa*, fertilizante alternativo, eficiência de uso de K, adubação potássica, efeito residual.

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Introduction

Potassium is the second nutrient most absorbed by plants (Marschner, 2012), explaining the importance of potassic fertilizers. About 90% of these fertilizers are imported by Brazil, where 62,5 million hectares are cultivated annually (Boletim de Monitoramento Agrícola…, 2023). The low Brazilian production of potassic fertilizers, mainly of potassium chloride (KCl), is attributed to the small reserves compared with the domestic demand, exacerbating product dependence and significantly increasing crop production costs (Nascimento & Lapido-Loureiro, 2009; Soratto et al., 2021).

To minimize this effect, one of the alternatives is using rocks with reasonable K contents, such as alkali feldspars, feldspathoids, and micas, which occur widely in the country and present potential to be applied in agriculture in the form of salts, thermopotassics, or directly to the soil on a commercial scale (Moreira et al., 2006; Nascimento & Lapido-Loureiro, 2009; Dias et al., 2018). Van Straaten (2006), for example, reported the application in the form of crushed rock over several decades.

Among the rocks studied in agriculture, biotite shale, breccia, carbonatite, phlogopitite, and ultramafic alkaline showed the greatest potential for use (Resende et al., 2006). Of these, biotite schist and phlogopite were the most promising when applied directly to the soil (Castro et al., 2006; Ribeiro et al., 2010). As these materials have a low solubility (Nascimento & Lapido-Loureiro, 2009), a lower particle size may be an alternative to increase their efficiency, since finely-divided materials react faster in the soil than those with coarse particles (Gonçalves et al., 2011). These potassic rocks, due to their variable chemical composition, can also present considerable amounts of calcium oxide (CaO), magnesium oxide (MgO), and silicon oxide (SiO_2), which, in contact with water, has an alkalinizing effect, acting as a soil acidity corrective (Moreira et al., 2006). Therefore, these materials, because of their multi-element composition and slow solubilization capacity, are more appropriate for use in perennial crops and pastures (Leonardos et al., 2000; van Straaten, 2007; Soratto et al., 2021).

In the case of forage legumes, Moreira et al. (2008) found that alfalfa (*Medicago sativa* L.) requires and accumulates a large amount of K, exporting 296 kg ha^{-1} of the nutrient for every 20 Mg of forage. In centrosema (*Centrosema pubescens* Benth.), symptoms of K deficiency are quite common, despite the species originating from tropical regions with soils with a low natural fertility (Rassini & Freitas, 1998). In intercropping pastures, when uptakes are below 8.0 g kg^{-1} in shoot dry weight, growth is limited, causing a decrease in forage quality and yield (Pinkerton et al., 1997).

To evaluate fertilizer use efficiency, studies under controlled conditions in a greenhouse become relevant since factors that can interfere with the results can be isolated, which is not possible in the field (Novais et al., 1991).

The objective of this work was to evaluate the application of silicate ultramafic alkaline rock, with different granulometry, as an alternative K source on the increase of soil fertility and on the nutritional status and biomass yield of the alfalfa and centrosema crops.

Materials and Methods

The soil used in the experiment is an Argissolo Amarelo distroférrico according to the Brazilian soil classification system (Santos et al., 2013), i.e., a Typic Ultisol. It was collected at a 0–0.2 m depth in the countryside in the municipality of São Carlos, in the state of São Paulo, Brazil (21°57'42"S, 47°50'28"W), containing 733 g kg^{-1} clay, 33 g kg^{-1} silt, and 234 g kg^{-1} sand. The soil presents the following chemical properties: 21 g dm^{-3} soil organic matter; pH ($CaCl_2$) 4.3; 4.0 and 27.4 mg dm^{-3} available phosphorus and potassium (resin extractant), respectively; 0.6, 0.2, and 0.7 cmol$_c$ dm^{-3} exchangeable calcium (Ca^{2+}), magnesium (Mg^{2+}), and aluminum (Al^{3+}), respectively (KCl 1.0 mol L^{-1} extractant); 3.7 cmol$_c$ dm^{-3} potential acidity at pH 7.0 (H+Al); and cation exchange capacity of 4.6 cmol$_c$ dm^{-3}.

The alternative source of K fertilizer used in the experiment was an alkaline ultramafic rock from the state of Santa Catarina, Brazil. The rocky material was crushed and subdivided into two granulometry (< 0.3 and 0.3–2.0 mm) by passing through a 0.3 and 2.0 mm sieve. These two grounded and sieved materials were air-dried, homogenized, and stored in the laboratory until use. The chemical characterization of this silicate rock sample presented the following results: 4.0% K_2O, 50% neutralizing power, 13.1% CaO, 17% MgO, 1.4% P_2O_5, 36.2% SiO_2, and pH 8.4.

For the experiment, 'Crioula' alfafa and 'BR 1 (Deodoro)' centrosema were used. For each plant species, a completely randomized design was used, with three replicates, in a $2 \times 4 + 1$ factorial arrangement, consisiting of two fertilizer granulometry (< 0.3 and 0.3–2.0 mm), four K rates (0, 100, 150, and 300 mg kg^{-1}, respectively), and an additional reference treatment, in which 150 mg kg^{-1} K was applied as a KCl solution (58% K_2O).

Soil base saturation was increased through the application of dolomitic limestone (27.1% CaO and 17.5% MgO) to reach 80 and 70% of base saturation for alfalfa and centrosema, respectively, based on the technical recommendations for these forage plant species (Werner et al., 1996). The soil was then fertilized with 200, 50, 0.5, 1.5, 5.0, 5.0, and 5.0 mg kg^{-1} P, S, B, Cu, Fe, Mn, and Zn, respectively, applied as a solution of $Ca(H_2PO_4)_2{\cdot}H_2O$, H_3BO_3, $CuSO_4{\cdot}5H_2O$, $FeSO_4{\cdot}7H_2O$, $MnSO_4{\cdot}H_2O$, and $ZnSO_4{\cdot}7H_2O$. After fertilization and homogenization, the soil was air-dried, and a sample of 5.0 kg was placed into a pot with an internal capacity of 7.0 dm^3, which was considered the experimental unit. The soil was incubated for 30 days, with moisture maintained at 80% water-holding capacity.

Ten seeds of each species were sown per pot. Those of alfalfa were inoculated with strains of *Sinorhizobium meliloti* and the centrosema with *Bradyrhizobium elkanii*, and those of both alfalfa and centrosema were coated with a nutrient solution of 0.01 mg L^{-1} Co and 0.1 mg L^{-1} Mo (Moreira et al., 2011). Between 10 and 14 days after emergence (DAE), thinning was performed, and only five seedlings were kept in each pot. Shoot biomass was harvested five times: first at 90 DAE and then every 30 DAE. Thereafter, the essay was carried out for 210 DAE, maintained at 80% water-holding capacity. After each harvest, plant shoot biomass was dried at 65°C until reaching a constant weight. At the end of the experiment, roots were removed from the pots, rinsed with water on a 0.50 mm sieve until the complete elimination of soil particles, and then dried as previously described. The dried samples of plant tissues were weighed to obtain the following plant variables, expressed in grams per pot: shoot dry weight (SDW) of each harvest, total shoot dry weight of all harvests, root dry weight (RDW), and whole-plant dry weight (SDW + RDW).

Samples of ground plant tissues were subjected to nitric and perchloric acid digestion, followed by the determination of K concentration using flame photometry (Malavolta et al., 1997). Afterwards, K uptake (mg per pot) in shoots (total of all harvests), roots, and the whole plant (K uptake in shoots and roots) was calculated as dry weight × K concentration. The following nutrition efficiency indexes were also determined: K use efficiency (KU_tE), as described in Siddiqi & Glass (1981), using KU_tE (g^2 mg^{-1}) = WP_{DM}^2/WP_K, where WP_{DM} is whole-plant dry matter and WP_K is whole-plant K uptake; K uptake efficiency (KU_pE), adapted from Swiader et al. (1994), by KU_pE (mg g^{-1}) = $WP_K/(R_{DM}{\times}5)$, in which R_{DM} is root dry matter; and K recovery efficiency (KRE), adapted from Greenwood et al. (1989), by KRE (%) = (WP_K from a given treatment with a K fertilization rate - WP_K from the treatment with no K fertilization) [mg per pot]/K rate applied [mg per pot]×100.

The experimental results for each forage species were analyzed individually using GENES statistical packages (Cruz, 2013). For an analysis of the model assumptions, Lilliefors' test for normality and Bartlett's test for homogeneity of variances were carried out. Skewness and kurtosis coefficients were also evaluated. Since all assumptions required for a valid statistical analysis were met, the analysis of variance (ANOVA) was performed. When the ANOVA resulted in a significant p-value ($p \leq 0.05$), the means of quantitative attributes (K rates) were adjusted by linear, quadratic, and the quadratic base of square root models of linear regression. The coefficients of the adjusted models were evaluated using the F-test, at $p \leq 0.001$, $p \leq 0.01$, and $p \leq 0.05$ probability, considering the mean square error of ANOVA of the experiment. Finally, among two or more models with significant coefficients, the one with the higher simple or multiple coefficients of determination (R^2) was chosen. For the qualitative attribute fertilizer granulometry, Tukey's test, at $p > 0.05$, was used for multiple comparisons of the means. Additionally, the 95% confidence interval of the mean was calculated for the reference treatment.

Results and Discussion

SDW, RDW, and K uptake in alfalfa and centrosema were influenced by rock granulometry, K rates, and the granulometry × rates interaction (Table 1 and

Figures 1 and 2). Irrespective of the K rates, the highest SDW yield of the two legumes was obtained in the first harvest, showing a stabilization tendency in the subsequent harvests (Figure 1). Regarding K sources and granulometry, alfalfa was the most responsive to the use of the less soluble ultramafic alkaline source, with an increase of 30.7 and 26.8% between the highest yield and control, compared with that of 14.8 and 24.1% for centrosema at the granulometry of <0.3 and 0.3–2.0 mm, respectively (Figure 3). Despite the increased SDW yield, the values obtained were lower than those using KCl. Ribeiro et al. (2010) also reported an increase in K availability with an increasing amount of rock applied to the studied plants, concluding that, even at similar rates, KCl provided more K than the sources with a lower solubility.

In both alfalfa and centrosema, K uptake was affected by the granulometry × rates interaction, indicating different plant responses in the two granulomety (Table 1 and Figure 2). In the average of the five harvests, regardless of whether the legume was alfalfa or centrosema, K uptake in SDW was only higher in the <0.3 mm particle size at the rate of 300 mg kg^{-1} K. However, this increase in uptake did not increase SDW yield (Figure 1). In their study, Barbosa Filho et al. (2006) evaluated two soils with different clay contents and K uptakes in two periods, finding that the relative efficiency of the granulometric fractions of the silica rocks used as a K source does not present consistent results.

K uptake in SDW varied in the average of the five harvests and two granulometry from 9.9 to 27.7 g kg^{-1}, with a mean of 22.9 g kg^{-1}, in alfalfa and from 5.5 to 14.6 g kg^{-1}, with a mean of 12.1 g kg^{-1}, in centrosema. In alfalfa, the estimated maximum level (EML) was 28.3 mg kg^{-1}, with a maximum estimated rate (MER) of 245 mg kg^{-1} K, according to the regression equation $\hat{y} = 10.246 + 0.147x - 0.0003x^2$ ($R^2 = 0.85$, $p \leq 0.05$), whereas, in centrosema, EML was 13.5 g kg^{-1} and MER was 197.8 mg kg^{-1} K according to the regression equation $\hat{y} = 5.645 + 0.079x - 0.0002x^2$ ($R^2 = 0.86$, $p \leq 0.05$).

The uptakes obtained with KCl at the reference rate of 150 mg kg^{-1} were above 17 and 10.8 g kg^{-1}, possibly due to the lower solubility of the rock in the two used granulometry (Nascimento & Lapido-Loureiro, 2009), resulting in a higher K availability in the soil after five harvests in the two legumes or in the dilution effect caused by a higher SDW yield using the KCl source (Figure 2), as also observed by Marschner (2012). Concerning the sufficiency levels, the MER of K in alfalfa and centrosema was within the range of 20 to 40 g kg^{-1} and of 8.0 to 15 g kg^{-1} considered appropriate by Culot (1986) and Pinkerton et al. (1997), respectively. Castro et al. (2006) and Moreira et al. (2010) also found increases

Table 1. Significance (p-value) of the analysis of variance of the main effects (fertilizer granulometry and potassium rate) of alkaline ultramafic rock and of their interaction in plant variables of alfalfa (*Medicago sativa*) and centrosema (*Centrosema pubescens*) grown in a Typic Ultisol during five shoot-biomass harvests under greenhouse conditions(1).

Source of variation	df(2)	S_{DW-1}	S_{DW-2}	S_{DW-3}	S_{DW-4}	S_{DW-5}	S_{K-1}	S_{K-2}	S_{K-3}	S_{K-4}	S_{K-5}
Alfalfa											
Granulometry (G)	1	0.005	1.000	0.122	0.052	<0.001	0.169	0.027	0.114	0.291	<0.001
K rate (R)	3	0.002	0.008	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
G × R	3	0.001	1.000	<0.001	0.170	<0.001	0.360	<0.001	0.011	0.127	<0.001
Error	16										
CV (%)(3)		6.9	8.2	7.2	6.4	10.0	11.5	12.5	16.7	23.9	10.3
Centrosema											
Granulometry (G)	1	0.002	0.053	0.064	0.017	0.273	0.144	0.280	0.054	1.000	0.006
K rate (R)	3	0.030	0.003	0.006	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
G × R	3	0.236	0.005	0.025	<0.001	0.030	0.289	0.360	<0.001	1.000	0.028
Error	16										
CV (%)(3)		10.8	9.6	5.3	5.6	5.0	19.2	20.8	5.5	15.7	9.7

(1)Plant variables in each of the five harvests: S_{DW-1}, S_{DW-2}, S_{DW-3}, S_{DW-4}, and S_{DW-5}, shoot dry weight; and S_{K-1}, S_{K-2}, S_{K-3}, S_{K-4} and S_{K-5}, shoot K content. (2)df, degrees of freedom. (3)CV, coefficient of variation.

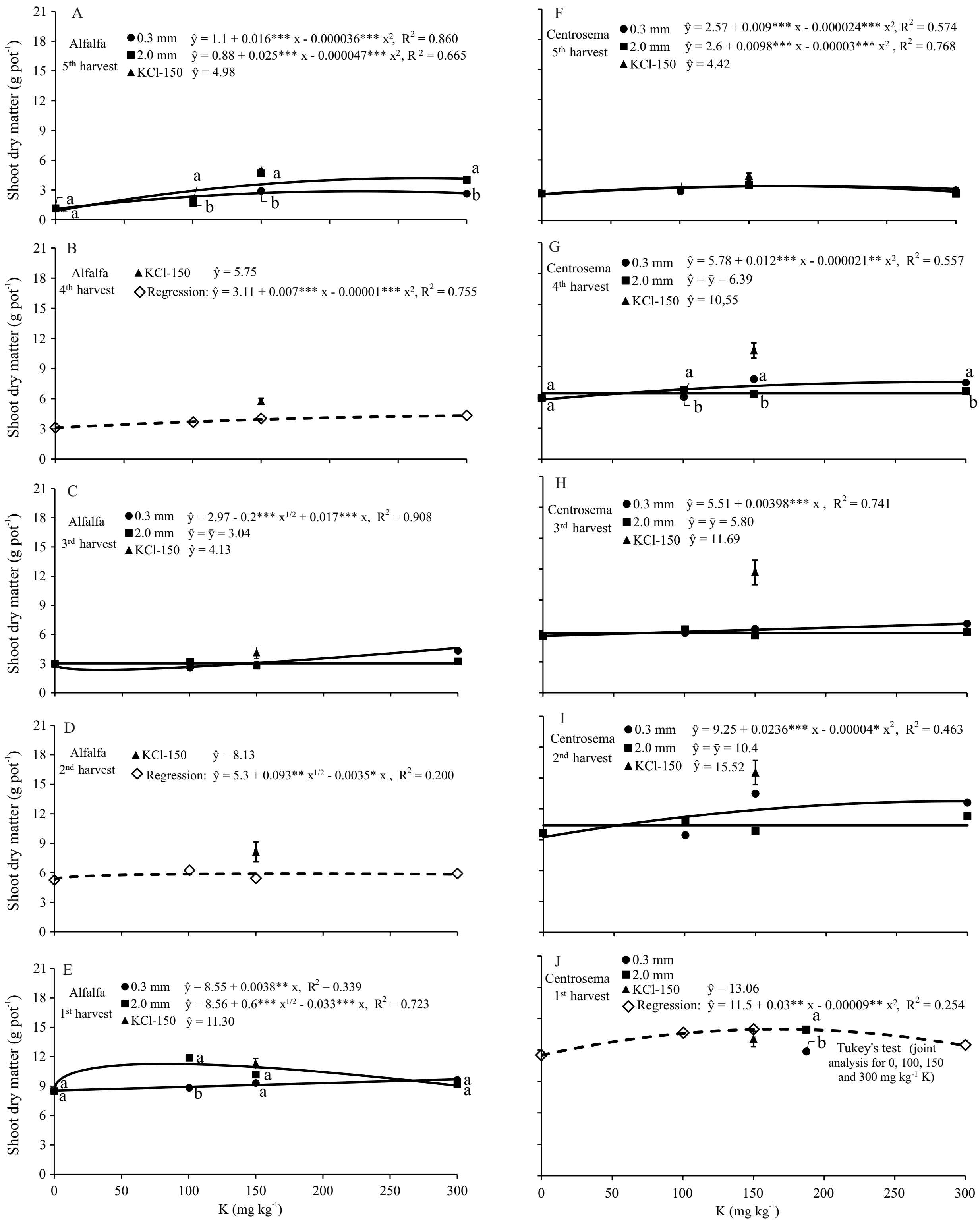

Figure 1. Shoot dry weight in five harvests of alfalfa (*Medicago sativa*) and centrosema (*Centrosema pubescens*) grown in a Typic Ultisol fertilized with four K rates (0, 100, 150, and 300 mg kg^{-1}) from alkaline ultramafic rock. For each K rate, means followed by equal letters do not differ among K fertilization rates by Tukey's test, at 5.0% probability. *, **, and ***Significance of the coefficients of the adjusted models by the F-test, at 5.0, 1.0, and 0.1% probability, respectively. Error bars are the 95% confidence interval for the mean of the reference treatment with 150 mg kg^{-1} KCl.

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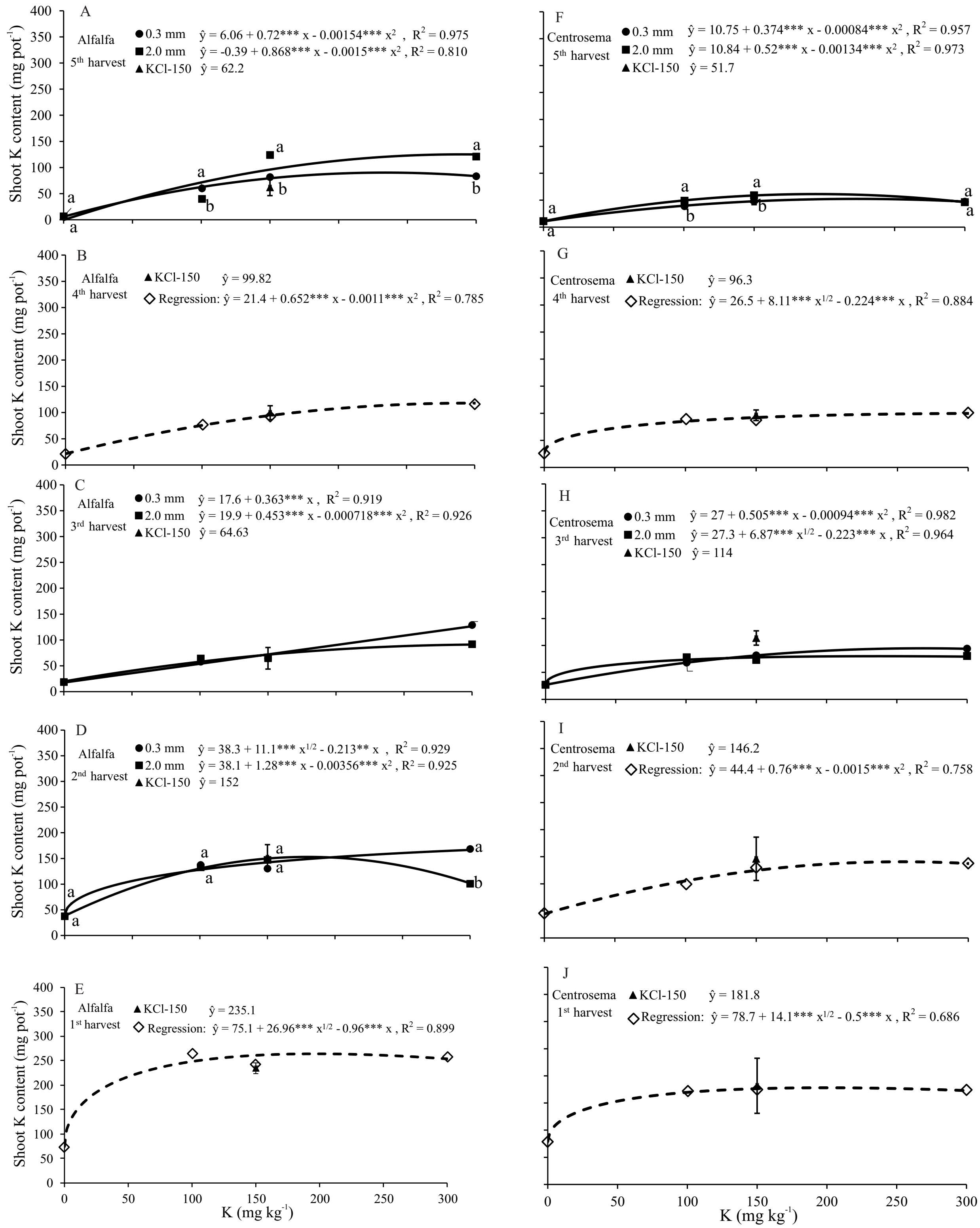

Figure 2. Shoot potassium uptake in five harvests of alfalfa (*Medicago sativa*) and centrosema (*Centrosema pubescens*) grown in a Typic Ultisol fertilized with four K rates (0, 100, 150, and 300 mg kg^{-1}) from alkaline ultramafic rock. For each K rate, means followed by equal letters do not differ among K fertilization rates by Tukey's test, at 5.0% probability. *, **, and ***Significance of the coefficients of the adjusted models by the F-test, at 5.0, 1.0, and 0.1% probability, respectively. Error bars are the 95% confidence interval for the mean of the reference treatment with 150 mg kg^{-1} KCl.

in K uptake in SDW with an increasing amount of silicate rock, while Oliveira et al. (2006) verified that the ultramafic alkaline and biotite schist rocks had the highest rates of residual agronomic efficiency for the SDW yield of soybean [*Glycine max* (L.) Merr.].

K accumulation in SDW in the sum of the five harvests was influenced by K rates, and, in the case of granulometry, differences were observed only in K uptake in centrosema roots (Table 2 and Figure 4). The increment in SDW was 375.3% in alfalfa and 192.2% in centrosema at the rates from 0 to 300 mg kg^{-1} K, varying, respectively, from 157.7 to 721.1 mg per pot and from 188.3 to 547.1 mg per pot in the average of the two granulometry and from 6.6 to 59.7 mg per pot and from 6.6 to 22.3 mg per pot in the roots. Another factor to be considered is the significant and positive correlation verified between RDW yield and K uptake in plant roots (ŷ = 0.119 + 0.223x, r = 0.73, p≤0.05), indicating that a higher uptake of K and its

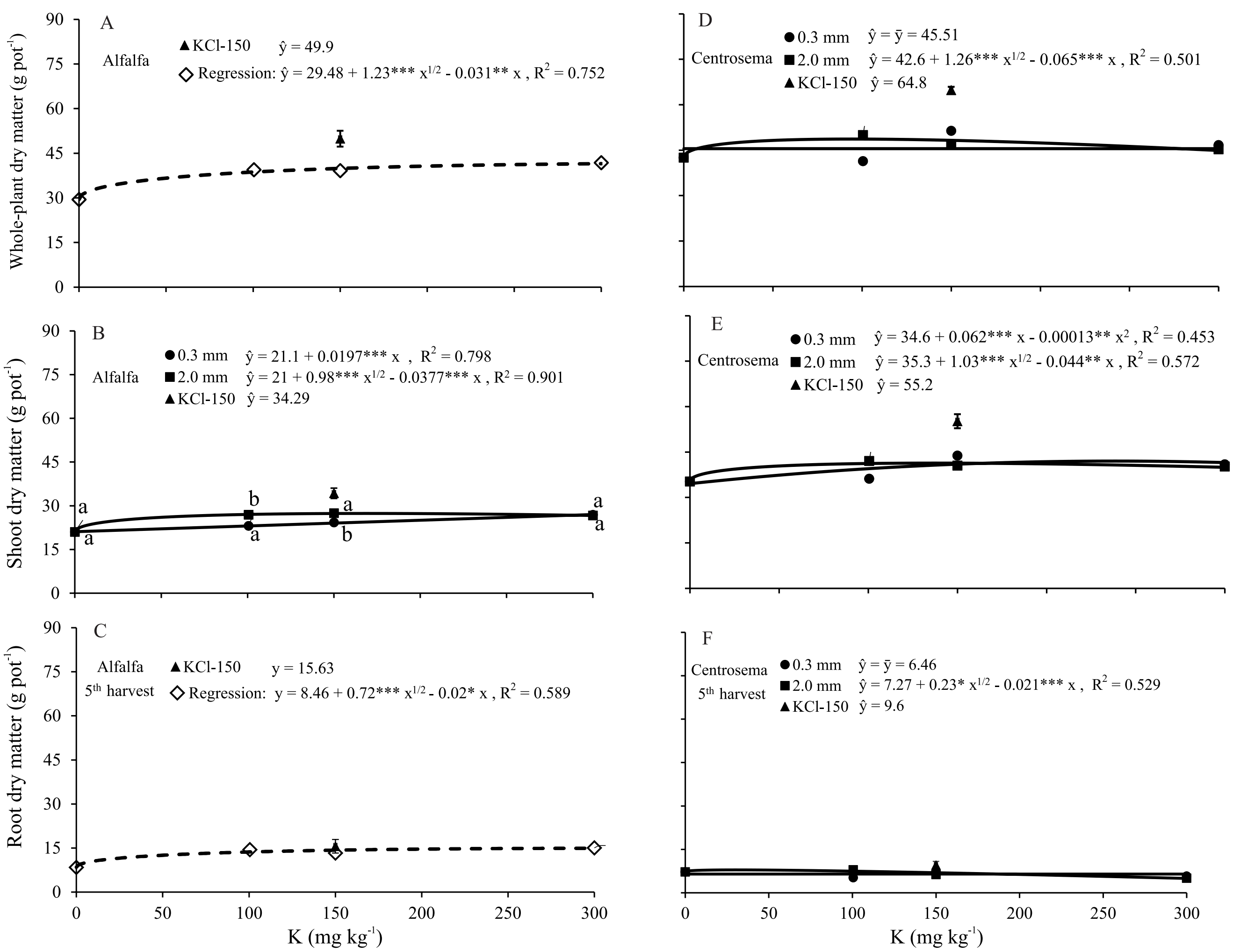

Figure 3. Cumulative whole-plant and shoot dry weight (DW) in five harvests and a single root dry weight in the fifth harvest of alfalfa (*Medicago sativa*) and centrosema (*Centrosema pubescens*) grown in a Typic Ultisol fertilized with four K rates (0, 100, 150, and 300 mg kg^{-1}) from alkaline ultramafic rock. For each K rate, means followed by equal letters do not differ among K fertilization rates by Tukey's test, at 5.0% probability. *, **, and ***Significance of the coefficients of the adjusted models by the F-test, at 5.0, 1.0, and 0.1% probability, respectively. Error bars are the 95% confidence interval for the mean of the reference treatment with KCl 150 mg kg^{-1}.

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availability in the soil increased plant root volume. Regarding KCl, due to the higher demand in SDW (concentration and uptake), at the rate of 150 mg kg^{-1}, alfalfa presented the lowest root K uptake (Figure 4). This result is in alignment with that of Oliveira et al. (2004), who concluded that the lowest number of roots significantly decreased K uptake in SDW and RDW (Figure 4). According to Silberbush & Barber (1983), the root system is the factor that most alters K uptake, that is, the restriction of the root system influences mass flow and diffusion, which are the main transport mechanisms involved in the process of K acquisition by plants (Marschner, 2012).

In the sum of the five harvests, KUtE and KRE were influenced only by K rates (Table 2 and Figure 5). With increasing K rates, KRE ranged from 62.5 to 25% at 50 and 300 mg kg^{-1} K, respectively, in centrosema, which are values lower than those from 93 to 41.1% in alfalfa at the same rates. Moreover, centrosema showed a higher decrease (60%) than alfalfa (55.8%). The highest rate of KRE in alfalfa, regardless of the used K rate, is similar to that obtained by Lloveras et al. (2001) and Moreira et al. (2008), who found that, after N, K is the most required nutrient and that its extractions can reach 1,500 to 1,700 kg ha^{-1} in alfalfa, with a yield of 21.5 Mg ha^{-1} SDW.

The KUtE, for the average of K rates and two rock granulometry, was 76.5% higher in centrosema (Figure 5), i.e., required less K for SDW yield than alfalfa. Comparing the two fertilizer sources within the rate of 150 mg kg^{-1} K at the < 0.3 and 0.3–2.0 mm granulometry, KCl, due to its high solubility (Nascimento & Lapido-Loureiro, 2009), presented the highest KUtE when compared with the silicate rock, with most K adsorbed by clays (van Straaten, 2007). Regarding KUpE, there were K rate effects for both legumes, rock granulometry, and the interaction between these two variables only for centrosema, with a linear effect for 0.3–2.0 mm and a polynomial effect with the tendency of stabilization for 100 mg kg^{-1} K at <0.3 mm. In alfalfa, no interactions were observed between granulometry and K rates, with particle sizes showing the same trend of the highest estimated value of 11.5 mg g^{-1} obtained at 232.1 mg kg^{-1} K (Table 2 and Figure 5).

Among the studied legumes, regardless of the K rates, KUpE was higher in centrosema (Figure 5). KUpE is related to the formation of root hair and morphology, resulting in differences in the efficiency of nutrient uptake between species and, consequently, in the nutritional efficiency of plants (Tomaz et al., 2003). In addition, genetic variability causes a growth or yield difference compared with other species

Table 2. Significance (p-value) of the analysis of variance of the main effects (fertilizer granulometry and K rate) of alkaline ultramafic rock and of their interaction in plant variables of alfalfa (*Medicago sativa*) and centrosema (*Centrosema pubescens*) grown in a Typic Ultisol considering the cumulative shoot biomass of five harvests and a single root biomass collected at the end of the experiment, under greenhouse conditions[(1)].

Source of variation	df[(2)]	R_{DW}	S_{DW}	WP_{DW}	R_K	S_K	WP_K	KU_pE	KU_tE	KRE
Alfalfa										
Granulometry (G)	1	0.209	0.003	1.000	0.007	0.298	1.000	0.135	1.000	1.000
K rate (R)	3	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
G × R	3	0.379	0.014	0.104	0.295	0.071	0.061	0.180	0.182	0.087
Error	16									
CV (%)[(3)]		16.9	4.8	7.2	24.7	7.0	6.4	15.5	10.4	7.0
Centrosema										
Granulometry (G)	1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
K rate (R)	3	0.030	0.001	0.007	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
G × R	3	0.016	0.032	0.005	0.014	0.151	0.125	0.034	0.092	0.058
Error										
CV (%)[(3)]	16	15.3	6.2	5.9	17.7	8.6	8.5	17.1	9.9	13.3

[(1)]Plant variables: R_{DW}, root dry weight; S_{DW}, shoot dry weight; WP_{DW}, whole-plant dry weight; R_K, root K content; S_K, shoot K uptake; WP_K, whole-plant K content; KU_pE, K uptake efficiency; KU_tE, K use efficiency; and KRE, K recovery efficiency. [(2)]df, degrees of freedom. Only for KRE, the df of K rate, granulometry × K rate, and error are 2, 2, and 12, respectively. [(3)]CV, coefficient of variation.

or cultivars under ideal or adverse environmental conditions (Fageria, 1998). Several studies have shown the differential behavior between species regarding K uptake and use (Moreira et al., 2015), highlighting that the nutritional requirements are quite variable between species and that plant yield varies under the same fertilization and soil fertility conditions (Fageria, 1998; Tomaz et al., 2003).

The results obtained in the present study show that in the two granulometry, the ultramafic alkaline rock may be an alternative to KCl, with positive results in the supply of K to the alfalfa and centrosema crops. However, the high logistics costs of both sources, due to their low K concentrations, may limit their use to locations relatively close to their production sites. Despite these results, according to Soratto et al. (2021), increases in the price of soluble K sources may encourage the use of silicate rocks as K fertilizer sources, making them viable for a broader use.

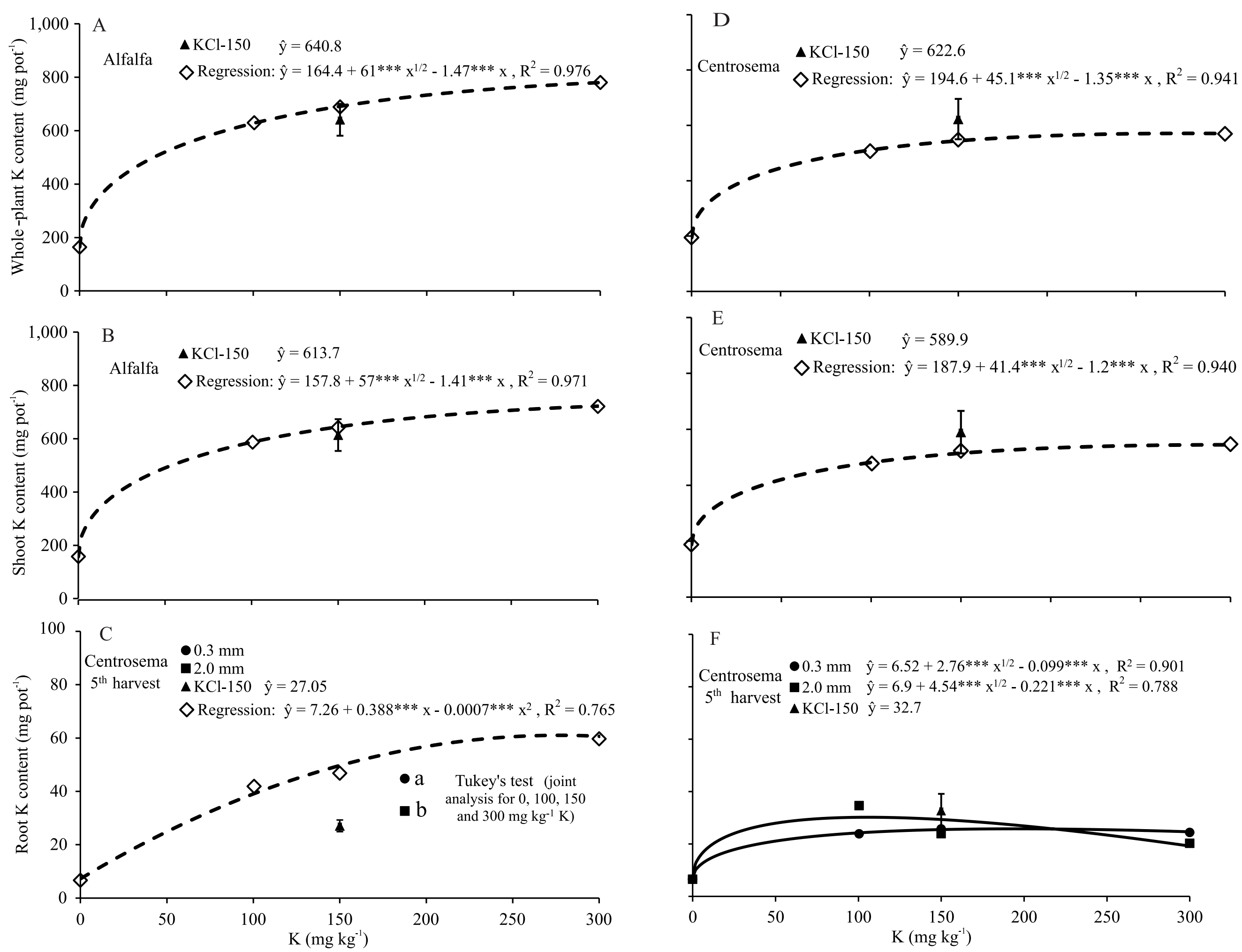

Figure 4. Cumulative whole-plant and shoot potassium uptake in five harvests and a single-root K uptake in the fifth harvest of alfalfa (*Medicago sativa*) and centrosema (*Centrosema pubescens*) grown in a Typic Ultisol fertilized with four K rates (0, 100, 150, and 300 mg kg^{-1}) from alkaline ultramafic rock. For each K rate, means followed by equal letters do not differ among K fertilization rates by Tukey's test, at 5.0% probability. *, **, and ***Significance of the coefficients of the adjusted models by the F-test, at 5.0, 1.0, and 0.1% probability, respectively. Error bars are the 95% confidence interval for the mean of the reference treatment with 150 mg kg^{-1} KCl.

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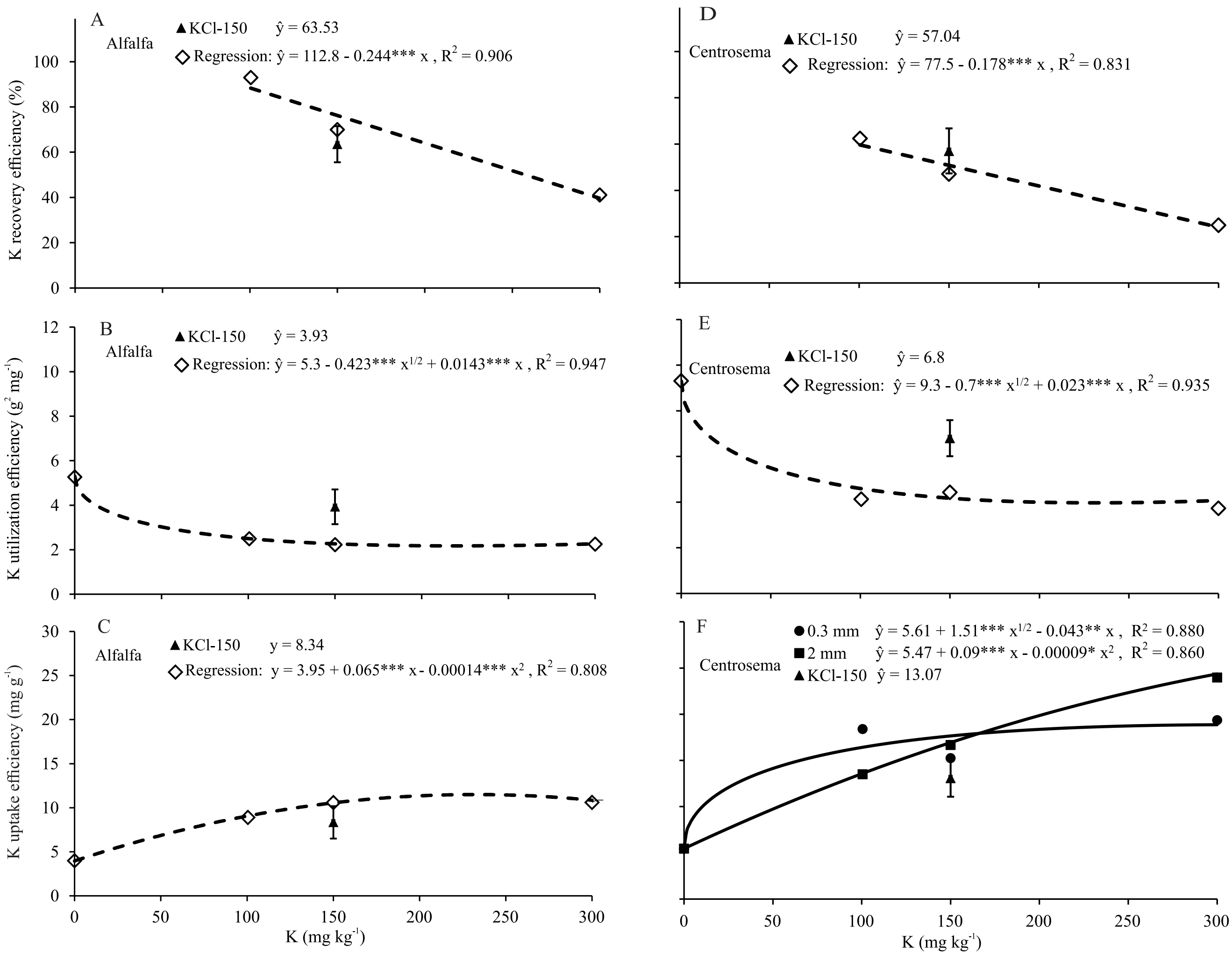

Figure 5. Potassium recovery efficiency (KRE), K utilization efficiency (KUtE), and K uptake efficiency (KUpE) of alfalfa (*Medicago sativa*) and centrosema (*Centrosema pubescens*) grown in a Typic Ultisol fertilized with four K rates (0, 100, 150, and 300 mg kg^{-1}) from alkaline ultramafic rock. For each K rate, means followed by equal letters do not differ among K fertilization rates by Tukey's test, at 5.0% probability. *, **, and ***Significance of the coefficients of the adjusted models by the F-test, at 5.0, 1.0, and 0.1% probability, respectively. Error bars are the 95% confidence interval for the mean of the reference treatment with 150 mg kg^{-1} KCl.

Conclusions

1. Ultramafic alkaline silicate rock has potential to be used as a potassium source for alfalfa (*Medicago sativa*) and centrosema (*Centrosema pubescens*) cultivated under greenhouse conditions.

2. In the studied conditions, the granulometry of the ultramafic alkaline silicate rock does not influence its efficiency as a K fertilizer.

3. Alfalfa is more responsive to the use of the less soluble source of K than centrosema.

4. Alfalfa presents a higher K recovery efficiency of the soil after successive harvests in comparison with centrosema, and the reverse is observed for K use and K uptake efficiencies.

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