ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
v.20, n.11, p.972-977, 2016
Campina Grande, PB, UAEA/UFCG – http://www.agriambi.com.br

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v20n11p972-977

Potassium leaching in different soils as a function of irrigation depths

Walter da C. Mendes[1], José Alves Júnior[2], Paulo C. R. da Cunha[1], Anderson R. da Silva[1], Adão W. P. Evangelista[2] & Derblai Casaroli[2]

[1] Instituto Federal Goiano/Campus Urutaí. Urutaí, GO. E-mail: mendeswalter2@gmail.com (Corresponding author); pcdacunha@hotmail.com; ar.silva@usp.br
[2] Universidade Federal de Goiás/Campus Samambaia/Escola de Agronomia. Goiânia, GO. E-mail: jose.junior@pq.cnpq.br; awpego@bol.com.br; casaroli@agro.ufg.br

Key words:
fertilization
soil texture
nutrient loss
water management

ABSTRACT
Potassium (K) can be easily lost by the leaching process. The objective of this study was to quantify K leaching in clayey and sandy soils under increasing irrigation depths. The experiment was conducted in 2014, in a protected environment, after extraction of undisturbed soil columns, with diameter of 144 mm and height of 300 mm. The columns were arranged in a randomized complete block in a factorial design with three replicates, corresponding to eight treatments: two soil types and four water depths, equivalent to 50, 100, 150 and 200% of the amount of water necessary to bring the soil moisture to field capacity. Potassium chloride, with 58% of K_2O, was used as K source. Water replacement in the columns was performed every three days, for a period of 81 days. After conducting joint analysis of the data according to the factor Time, a second-degree response surface model was fitted and line charts were also used to study the factors Time and Water. After the evaluations, it was found that the higher the applied water depth, the greater the percolated amount of the K^+ ion.

Palavras-chave:
adubação
textura do solo
perda de nutriente
manejo da água

Lixiviação de potássio em diferentes solos em função de lâminas de irrigação

RESUMO
Neste trabalho o objetivo foi quantificar a lixiviação de K em solos argiloso e arenoso sob lâminas crescentes de irrigação. O experimento foi conduzido em 2014, em ambiente protegido, após extração de colunas de solo indeformadas, com diâmetro de 144 mm e altura de 300 mm. As colunas foram arranjadas em um delineamento em blocos completos casualizados em esquema fatorial, com três repetições, constituindo oito tratamentos, sendo dois tipos de solo e quatro lâminas de água equivalentes a 50, 100, 150 e 200% da lâmina de água necessária para levar o solo à umidade na capacidade de campo. Como fonte de K utilizou-se o cloreto de potássio com 58% de K_2O. A reposição da água nas colunas foi realizada a cada três dias, por um período de 81 dias. Após a realização de análise conjunta dos dados de acordo com o fator Tempo, foram ajustados um modelo de superfície de resposta de segundo grau completo e os gráficos de linhas para estudo dos fatores Tempo e Água. Após avaliações concluiu-se que quanto maior a lâmina de água aplicada maior também a quantidade percolada do íon K^+.

Ref. 181-2015 – Received 11 Dec, 2015 • Accepted 19 Sept, 2016 • Published 29 Sept, 2016

Introduction

The intensive use of fertilizers in cultivation systems may result in the leaching of nutrients, a phenomenon that involves a complex interaction between soil hydrology, absorption of water and nutrients by the plants, management practices (Es et al., 2006), dispersive-diffusive movement of the solute in the soil (Ruiz et al., 2010) and capacity of adsorption of ions by the soil (Santos et al., 2002).

The low potential of charges found in most soils of the Cerrado region, associated with the highly soluble sources of potassium (K), may lead to high losses through leaching (Silva et al., 2002). Moraes & Dynia (1992) considered K as the most easily leached cation, due to its displacement to the soil solution and to its percolation, especially in sandy soils.

Soluble ions, from correctives and fertilizers or decomposition of organic matter, are found available to the plants; however, in periods of high rainfall intensity or excessive irrigation, there may be percolation of water in the profile, which favors the downward movement of these ions, considered as one of the main factors of losses of nutrients (Santos et al., 2002).

Thus, when present in the soil solution, K can move in the profile along with the drained water, being leached to depths below the root system of the crops (Oliveira & Villas-Boas, 2008). The movement of K in the soil profile depends mainly on soil texture (Neves et al., 2009), cation exchange capacity (CEC), water regime and on the dose and solubility of the fertilizer (Rosolem et al., 2006).

Therefore, a better management of the nutrients that are essential to the plants is necessary to promote sustainable agriculture (Goulding et al., 2008). One of the methods that can be applied is the use of slow-release fertilizers (Xie et al., 2011).

Given the above, this study aimed to quantify K leaching in clayey and sandy soils under increasing irrigation depths.

Material and Methods

The experiment was carried out from March to August 2014, in a protected environment (greenhouse), at the Federal Institute of Goiás (IF Goiano), Campus of Urutaí, GO, Brazil. The climate of the region, according to Köppen's classification, is Cwa (Humid Subtropical), with dry winter and hot, rainy summer. Two types of soil were used, a clayey soil (dystrophic Red Latosol) and a sandy soil (dystrophic Red-Yellow Latosol) (EMBRAPA, 2006), both from areas managed under direct sowing system. Before the experiment, soil physical and chemical analyses were performed (Table 1).

The soil monoliths, with undisturbed structure, were collected using PVC tubes (diameter = 144 mm; h = 350 mm; thickness = 3 mm) until the depth of 300 mm, using a tractor and a hydraulic jack. The lower part of the tube was sharpened and its walls were lubricated with Vaseline®, to facilitate the collection, and the columns were manually removed from the soil. After collecting the soil, the lower part of the columns was sealed with PVC lids, which had a hole with diameter of 5 mm, where a plastic hose with the same diameter was connected to collect the leachate. In order to avoid the passing of soil particles, a plastic screen was placed on the internal side of the lid. The columns were placed on a wooden support at a height of 0.50 m from the soil surface.

The soil columns remained in a protected environment for 60 days (air-dried) to lose moisture; after this period, the soil contracted, forming a space between the internal wall of the PVC tube and the column, which was sealed with silicone on the upper side to avoid water percolation through preferential flow. Then, deionized water was slowly added to the soils, until saturation, and this condition was maintained for 12 h.

After that, the upper part of the columns was sealed with plastic bags to avoid evaporation and drained by the action of gravity until stabilization, which occurred around 24 h after the beginning of the drainage. When the excess water drained, the plastic bags were removed for the determination of the mass of the columns, to obtain the mass corresponding to the moisture at field capacity, using a scale with precision of 5 g (Filizola - Model CS-15). Then, the columns were maintained losing water through evaporation for three days and, after that, fertilization was performed on soil surface.

Potassium chloride (58% of K_2O), was used as source of K, in amount equivalent to three times the dose normally applied under field conditions in the production of grains (Bertol et al., 2010); according to the authors, the objective is to simulate a high load of the mineral element in solution and, consequently, a maximum leaching potential, by applying on the surface of each column the amount of 521 mg of K_2O, equivalent to 192 kg ha^{-1} of K.

The experimental design was randomized blocks (RBD), in a 2 x 4 factorial scheme, with three replicates in each column, representing one experimental plot. The sources of variation were two types of soil (clayey and sandy) and four percentages of water replacement (50, 100, 150 and 200% of the water depth necessary to bring the soil moisture to field capacity).

A fixed irrigation interval of three days was used and the columns were filled with the different soils and subjected to the water replacement percentages, equivalent to 50, 100, 150 and 200% of the water depth necessary to bring the soil moisture

Table 1. Physical and chemical analyses of the soils

Soil	Layer (m)	pH	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	K	N	OM	Clay	Silt	Sand	Ds
			(cmol$_c$ dm^{-3})				(mg dm^{-3})	(%)					(g cm^{-3})
Clayey[(1)]	0-0.10	5.76	1.05	0.59	0.1	4.95	170	0.06	3.1	45.3	12.2	42.5	1.58
	0.10-0.20	5.55	0.82	0.57	0.1	3.96	60	0.09	2.4	46.3	12.3	41.4	1.71
	0.20-0.30	5.27	0.65	0.36	0.1	3.80	50	0.08	2.0	44.1	14.0	41.9	1.65
Sandy[(2)]	0-0.10	5.99	5.68	1.07	0.0	4.29	90	0.07	2.5	22.1	9.7	68.2	1.47
	0.10-0.20	5.45	2.71	0.75	0.0	4.95	30	0.07	2.2	22.7	9.1	68.2	1.47
	0.20-0.30	5.09	1.33	0.64	0.3	3.63	20	0.04	1.6	24.5	7.4	68.1	1.39

[(1)]Soil of the center pivot area of the IF Goiano - Campus of Urutaí, GO, Brazil (17º 28' 41" S; 48º 11' 35" W; altitude of 823 m); [(2)]Soil of the traditional area of agricultural production in Ipameri-GO, Brazil (17º 40' 53" S; 48º 17' 11" W; altitude of 838 m) to field capacity. These percentages were obtained by the mean difference between the mass at field capacity and the actual mass (moment to perform irrigation) using the columns of the treatments of 100%. Irrigation, manually performed using a syringe, lasted for 81 days.

The volume and concentration of the K ion were evaluated in the leached solution of the different treatments, without filtration or digestion of the solution, by collecting samples of the solution leached from the columns, precisely 24 h after each irrigation. K concentration was obtained using the LAQUAtwin meter of nutrients (Horiba - Model B-731). The amount of K (mg) lost in the columns was calculated by multiplying the concentration (ppm) by the volume of percolated water (liter) after each irrigation.

The leached amounts of K in each one of the percolations were summed and subjected to analysis of variance by the F test; the means were compared by Tukey test and all inferences were made considering a nominal significance level of 0.05.

Then, for the study of the progression of K concentration in the collected effluents as a function of the variation of time and water replacement percentages, equations that best represented the phenomenon were fitted to each type of soil, using the linear regression technique to obtain response surface graphs. The model was selected based on the value of the multiple coefficient of determination (R^2). For the simple analysis of the elements time and water replacement percentages, graphs were elaborated presenting the progression of the leached K concentration over time for each percentage of water replacement, for both soils.

Results and Discussion

Table 2 shows the summary of the analysis of variance for the total leached K. There was significant effect of the interaction between the factors time, water depth and type of soil ($p = 0.005$). Hence, multiple regression models (response surface) were fitted as a function of water depth and time for each type of soil.

According to Table 3, between the types of soil in each treatment with the same water depth, there was significant difference for the treatments with irrigation depths of 150 and 200%; K leaching in the sandy soil for the treatment of 150% was 13.47 times higher in comparison to the clayey soil, and K leaching in the sandy soil for the treatment of 200% was 7.14 times higher in relation to the clayey soil.

Comparing the leached amounts of K in the same type of soil under application of different water depths in relation to the total applied in the column (TAC), the results for the clayey soil show that, in the treatment with 50% water depth, there was no leaching, while only 0.12% of the TAC leached in the treatment of 100%. On the other hand, 3.26% of the TAC leached in the treatment of 150%, while 7.99% of the TAC leached in the treatment of 200%.

Table 3. Cumulative amount of potassium (mg) leached along 81 days in undisturbed columns of clayey and sandy soils, as a function of different irrigation depths

Time (days)	Soil	Water replacement percentages			
		50% [(1)]	100%	150%	200%
81	Clayey	0.00 a [(2)]	0.37 a	10.20 b	25.00 b
81	Sandy	0.00 a	9.73 a	137.43 a	178.53 a

[(1)]50, 100, 150 and 200% represent the % of water applied through irrigation based on the difference of mass of the column irrigated at 100%; [(2)]Means followed by the same letter, in the column, do not differ by Tukey test at 0.05 probability level; F test = 241; CV = 17.54%; LSD = 13.84

Comparing the leached amounts of K for different water depths in sandy soil there was no difference between 50 and 100%, with all other comparations for this type of soil presented significant differences. In the treatment of 50% depth TAC leached was 0% while in treatment of 100, 150 and 200% water depths, TAC leached was 3.11, 43.91 and 57.04%, respectively.

Mendes et al. (2015), studying N-NO_3 leaching below 0.30 m from soil surface, also observed significant losses of the nutrient for water depths equivalent to 150 and 200% of the field capacity, while the losses were equal to 27 and 66% of the total applied at water depths of 150% and to 65 and 72% of the total applied at water depths of 200%, in clayey and sandy soil, respectively.

Extrapolating the values of K leaching of the columns to 1 ha, the leached amounts of K in the clayey soil for the layers below 0.30 m from the surface would be approximately 0.2 kg ha^{-1} for the water depths of 100%, 6.3 kg ha^{-1} for the water depths of 150% and 15.4 kg ha^{-1} for the water depths of 200%. In sandy soil, the amounts of K are equivalent to a leaching of 6.0 kg ha^{-1} for water depths of 100%, 84.4 kg ha^{-1} for water depths of 150% and 109.6 kg ha^{-1} for water depths of 200%.

K leaching in the sandy soil at the irrigation depth of 150% (84.4 kg ha^{-1}) is proportionally similar to that found by Albuquerque et al. (2011), who worked with bell pepper, in Quartzarenic Neosol with sandy texture, with K dose of 120 kg ha^{-1} and water depth of 120% ETc, which caused losses of approximately 60.1 kg ha^{-1}.

According to the fitted second-degree response surface model, presented in the three-dimensional plane (Figure 1), and the regression Eqs. 1 and 2, for the evaluation of the concentration of leached K as a function of the water replacement percentage evaluated from five days after the beginning of the irrigations on, there was expressive effect of the increase in water depths on the amount of leached K. This fact is evident for water depths higher than 100%. Only for the sandy soil, there was a quadratic fit to the data. Differences between the types of soil can be more clearly observed in water depths equal to or higher than 150%, along the entire period of study.

Because of their smoothness, the response surfaces did not show specific or highly localized variations of the data, but the general tendency. In the line graphs, however, it is possible to analyze more precisely the alterations of the data (Figure 2).

Table 2. Summary of the analysis of variance for the total leached K

	Time (T)	Water (W)	Soil (S)	Block/Time	T x W	T x S	W x S	T x W x S	Error
DF	27	3	1	56	81	27	3	81	392
F	1.51	1037.77	197.95	0.73	1.71	1.54	26.20	1.69	--
p-value	0.0486	<0.001	<0.001	0.9209	0.0004	0.0440	<0.001	0.0006	--

The data were transformed to x ^ 0.1, according to the Box-Cox transformation

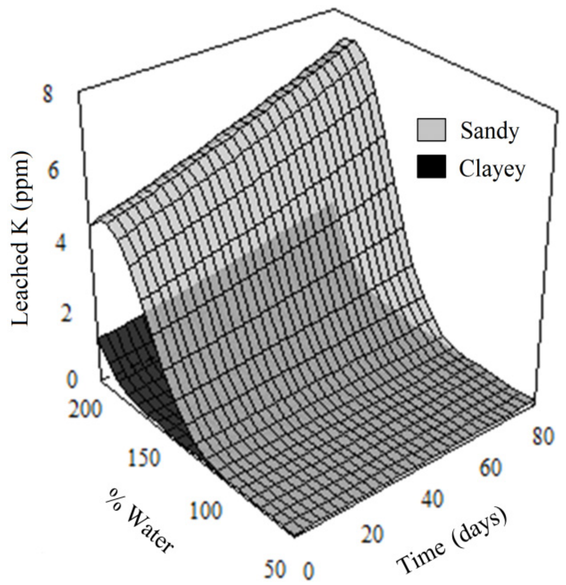

Figure 1. Second-degree response surface model based on the value of the multiple coefficient of determination (R^2)

In the columns with water depths of 100% (Figure 2B), there was collection of leachate in some applications, in both sandy and clayey soils, but always with low values of K; mean cumulative amount in the clayey soil was around 0.12% of the TAC and, in the sandy soil, 3.11% of the TAC. Leaching was not expected to occur in this treatment, but in some columns of this treatment it may have occurred due to a preferential flow of water in the soil profile. According to Eguchi & Hasegawa (2008), water can move along the pathways mainly due to the hydraulic heterogeneity of the soil. According to Morales et al. (2010), the preferential flows in field studies are the rule and not the exception in a wide variety of soils.

In the columns irrigated with water depth of 150% (Figure 2C), the sandy soil in the first irrigations showed K values in the leached solution of approximately 1 mg (0.32% of the TAC), which increase until reaching the highest values around 12 mg (3.83% of the TAC), at about 54 days after the first irrigation (DAFI). After that, there is a reduction along the time, reaching approximately 7 mg (2.24% of the TAC) at 81 DAFI. On the other hand, in clayey soil, there were low values of K in the leached solution in the first half of the experiment, always below 0.5 mg, reaching the highest values around 1 mg (0.32% of the TAC) in the last irrigations.

In the columns under water depths of 200% (Figure 2D), the sandy soil showed K values in the leached solution around 2 mg (0.64% of the TAC) until 15 DAFI, which increased over time, reaching the highest values around 14 mg (4.47% of the TAC) between 30 and 39 DAFI; then, there was a decrease in the values until 60 DAFI, around 4 mg (1.28% of the TAC). This level was maintained approximately until the end of the experiment; in the clayey soil there were K values in the leached solution around 0.5 mg (0.16% of the TAC), which slowly increased and reached, at the end of the experiment, 1.5 mg (0.48% of the TAC).

In the line graphs, it was possible to also visualize the periods characterized by the beginning of the increase in the K^+ ion concentration in the solution leached from the soil columns, especially at the water depths of 150 and 200% (Figure 2C and 2D). In the sandy soil, it occurred around the 18th day (6th irrigation) and 15th day (5th irrigation) and, in the clayey soil, it occurred around the 54th day (18th irrigation) and 30th day (10th irrigation), for the water depths of 150 and 200%, respectively.

These results show that sandy soils tend to show higher K leaching, compared with clayey soils. According to Mielniczuk (1982), for a same amount of total K, there will be less K^+ in the solution in soils with high CEC (clayey soils), which will reflect in lower losses of K through leaching, since this nutrient moves easily, in the vertical direction. In addition, the sandy soil used in this experiment contained more calcium (Ca^{2+}) and magnesium (Mg^{2+}) compared with the clayey soil, which may have contributed even more to the permanence of K in the solution of the sandy soil, due to the preference of soil colloids to retain Ca^{2+} and Mg^{2+}, divalent ions, instead of K^+,

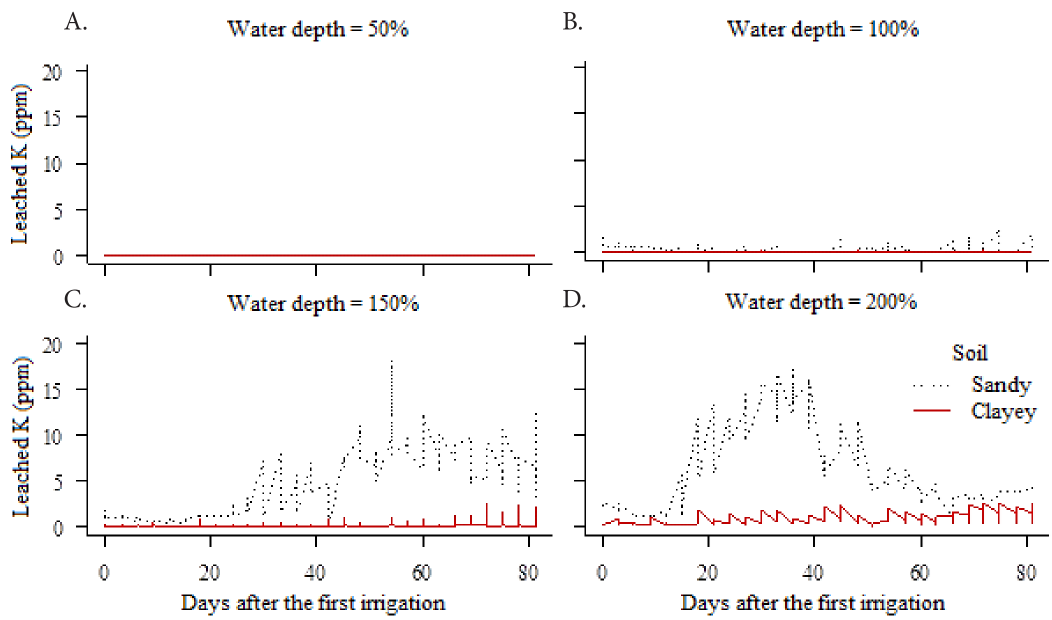

Figure 2. Amount of potassium in the leached effluent as a function of time for the increasing irrigation depths and different types of soil (sandy and clayey)

a monovalent ion. Since K has only valence charge (K^+), it is little adsorbed by soil colloids (Ernani et al., 2007).

In order to obtain a better cost/benefit relationship, it is important the correct management of irrigation and fertilization. Insufficient irrigations, as well as excessive irrigations, result in considerable losses and damages to plants and soils, decreasing the efficiency of use of this technique. The literature reports K losses through leaching on the order of 50 to 70% (Auoada et al., 2008; Wu & Liu, 2008), when it is inadequately applied to the soils (Sousa & Rein, 2009). Therefore, K losses in the soil profile must be monitored, especially in intensive production systems, as those practiced in irrigated areas with large use of inputs, in order to take measures that promote increase in the efficiency of use of the applied K, to allow the management of an economically sustainable production system, with quality products and minimum negative impact to the environment.

Conclusions

1. Increasing irrigation depths influenced the leaching of potassium applied to the soil, and the higher the water depth, the larger the percolated amount of the K^+ ion.

2. When the water replacement percentage was 150% of the depth necessary to bring the soil moisture to field capacity, there were potassium losses of 3.26 and 43.91% of the total applied for the clayey and sandy soils, respectively.

3. The water replacement percentage of 200% of the depth necessary to bring the soil moisture to field capacity caused potassium losses of 7.99 and 57.04% of the total applied, for the clayey and sandy soils, respectively.

Acknowledgments

To the Research Support Foundation of Goiás – FAPEG and to the Coordination for the Improvement of Higher Education Personnel – CAPES, for granting the doctorate scholarship to the first author, Process Nº: 201410267000035.

Literature Cited

Albuquerque, F. S.; Silva, E. F. F.; Souza, A. E. R.; Rolim, M. M. Lixiviação de potássio em um cultivo de pimentão sob lâminas de irrigação e doses de potássio. Revista Caatinga, v.24, p.135-144, 2011.

Auoada, F. A.; Moura, M. R.; Menezes, E. A.; Nogueira, A. R. A.; Mattoso, L. H. C. Síntese de hidrogéis e cinética de liberação de amônio e potássio. Revista Brasileira de Ciência do Solo, v.32, p.1643-1649, 2008. http://dx.doi.org/10.1590/S0100-06832008000400029

Bertol, O. J.; Fey, E.; Favaretto, N.; Lavoranti, O. J.; Rizzi, N. E. Mobilidade de P, Cu e Zn em colunas de solo sob sistema de semeadura direta submetido às adubações mineral e orgânica. Revista Brasileira de Ciência do Solo, v.34, p.1841-1850, 2010. http://dx.doi.org/10.1590/S0100-06832010000600008

Eguchi, S.; Hasegawa, S. Determination and characterization of preferential water flow in unsaturated subsoil of andisol. Soil Science Society of America Journal, v.72, p.320-330, 2008. http://dx.doi.org/10.2136/sssaj2007.0042

EMBRAPA – Empresa Brasileira de Pesquisa Agropecuária. Centro Nacional de Pesquisa de Solos. Sistema brasileiro de classificação de solos. 2.ed. Rio de Janeiro: EMBRAPA, 2006. 306p.

Ernani, P. R.; Bayer, C.; Almeida, J. A.; Cassol, P. C. Mobilidade vertical de cátions influenciada pelo método de aplicação de cloreto de potássio em solos com carga variável. Revista Brasileira de Ciência do Solo, v.31, p.393-402, 2007. http://dx.doi.org/10.1590/S0100-06832007000200022

Es, H. M. van; Sogbedji, J. M.; Schindelbeck, R. R. Effect of manure application timing, crop, and soil type on nitrate leaching. Journal of Environmental Quality, v.35, p.670-679, 2006. http://dx.doi.org/10.2134/jeq2005.0143

Goulding, K.; Jarvis, S.; Whitmore, A. Optimizing nutrient management for farm systems. Philosophical Transactions of the Royal Society, v.363, p.667-680, 2008. http://dx.doi.org/10.1098/rstb.2007.2177

Mendes, W. C.; Alves Júnior, J.; Cunha, P. C. R.; Silva, A. R.; Evangelista, A. W. P.; Casaroli, D. Lixiviação de nitrato em função de lâminas de irrigação em solos argiloso e arenoso. Irriga, v. edição especial, p.47-56, 2015.

Mielniczuk, J. Avaliação da resposta das culturas ao potássio em ensaios de longa duração. A experiência brasileira. In: Simpósio sobre Potássio na Agricultura Brasileira, 1982, Londrina. Anais... Piracicaba: Instituto da Potassa e Fosfato/Instituto Internacional da Potassa, 1982. p.289-303.

Moraes, J. F. V.; Dynia, J. F. Alterações nas características químicas e físico-químicas de um solo Gley Pouco Húmico sob inundação e após a drenagem. Pesquisa Agropecuária Brasileira, v.27, p.223-235, 1992.

Morales, V. L.; Parlange, J. Y.; Steenhuis, T. S. Are preferential flow paths perpetuated by microbial activity in the soil matrix? A review. Journal of Hydrology, v.393, p.29-36, 2010. http://dx.doi.org/10.1016/j.jhydrol.2009.12.048

Neves, L. S.; Ernani, P. R.; Simonete, M. A. Mobilidade de potássio em solos decorrente da adição de doses de cloreto de potássio. Revista Brasileira de Ciência do Solo, v.33, p.25-32, 2009. http://dx.doi.org/10.1590/S0100-06832009000100003

Oliveira, M. V. A. M.; Villas-Boas, R. L. Uniformidade de distribuição do potássio e do nitrogênio em sistema de irrigação por gotejamento. Engenharia Agrícola, v.28, p.95-103, 2008. http://dx.doi.org/10.1590/s0100-69162008000100010

Rosolem, C. A.; Santos, F. P.; Foloni, J. J. S.; Calonego, J. C. Potássio no solo em consequência da adubação sobre a palha de milheto e chuva simulada. Pesquisa Agropecuária Brasileira, v.41, p.1033-1040, 2006. http://dx.doi.org/10.1590/S0100-204X2006000600020

Ruiz, H. A.; Ferreira, P. A.; Rocha, G. C.; Borges Júnior, J. C. F. Transporte de solutos no solo. In: Lier, Q. de J. van (ed.) Física do solo. Viçosa: SBCS, 2010. p.213-240.

Santos, A. B.; Fageria, N. K.; Zimmermann, F. J. P. Atributos químicos do solo afetado pelo manejo da água e do fertilizante potássico na cultura do arroz e irrigado. Revista Brasileira de Engenharia Agrícola e Ambiental, v.6, p.12-16, 2002. http://dx.doi.org/10.1590/S1415-43662002000100003

Silva, T. R. B.; Soratto, R. P.; Ozeki, M.; Arf, O. Manejo da época de aplicação potássica em arroz de terras altas irrigado por aspersão em solo de cerrado. Acta Scientiarum, v.4, p.1455-1460, 2002.

Sousa, D. M. G.; Rein, T. A. Manejo da fertilidade do solo para culturas anuais: Experiências no cerrado. Planaltina: EMBRAPA-CPAC, 2009. 28p. Informações Agronômicas, 126

Wu, L.; Liu, M. Preparation and properties of chitosan-coated NPK compound fertilizer with controlled-release and water-retention. Carbohydrate Polymers, v.72, p.240-247, 2008. http://dx.doi.org/10.1016/j.carbpol.2007.08.020

Xie, L.; Liu, M.; Ni, B.; Zhang, X.; Wang, Y. Slow-release nitrogen and boron fertilizer from a functional superabsorbent formulation based on wheat straw and attapulgite. Chemical Engineering Journal, v.167, p.342-348, 2011. http://dx.doi.org/10.1016/j.cej.2010.12.082