

NITRATE AND POTASSIUM DYNAMICS IN PROFILES OF SOILS CULTIVATED WITH FERTIGATED SUGARCANE CROPS¹

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ABSTRACT - The objective of this study was to evaluate the distribution of NO_3^- and K^+ in the profile of soils cultivated with sugarcane crops, after application of different nitrogen (N) and potassium (K_2O) rates via subsurface drip fertigation, in Teresina, PI, Brazil. The experiment was conducted at the experimental area of Embrapa Meio-Norte, using a randomized block design with four replications. The treatments were arranged in split plots, with N+ K_2O rates (60+120, 180+120, 120+60, 120+180, and 120+120 kg ha^{-1} of N + K_2O , respectively) in the plots, and soil layers (0.0-0.2, 0.2-0.4, and 0.4-0.6 m), for quantification of NO_3^- and K^+ concentrations in the soil, in the subplots. The soil of the experimental area was a Typic Hapludult of sandy-loam texture. The distribution of nitrate (NO_3^-) and potassium (K^+) in the soil layers after the N+ K_2O applications were evaluated. The NO_3^- and K^+ concentrations in soils under sugarcane crops in the plant crop cycle is higher at the beginning and at the end of the cycle, respectively. The NO_3^- and K^+ concentrations in the soil solution are dependent on the evaluation time, soil layer, and N and K_2O rates applied via fertigation. The highest concentrations of NO_3^- (264 mg L^{-1}) and K^+ (377 ppm) were found in the 0.0-0.2 m soil layer. No leaching of NO_3^- or K^+ to deepest soil layers (>0.4 m) was found.

Keywords: Nutrient. Depth. Ionic concentration.

DINÂMICA DE NITRATO E POTÁSSIO EM PERFIL DE SOLO CULTIVADO COM CANA-DE-AÇÚCAR FERTIRRIGADA

RESUMO - Objetivou-se, nesse estudo, avaliar a distribuição de NO_3^- e K^+ no perfil do solo cultivado com cana-de-açúcar em resposta a doses de nitrogênio (N) e potássio (K_2O) aplicados via fertirrigação por gotejamento subsuperficial na microrregião de Teresina-PI. O experimento foi conduzido na área experimental da Embrapa Meio-Norte, Teresina – PI. Usou-se o delineamento experimental de blocos ao acaso, com quatro repetições. Os tratamentos foram arranjados em parcelas subdivididas, com as doses de N e K_2O , nas parcelas, e as profundidades de quantificação das concentrações de NO_3^- e K^+ , nas subparcelas. O solo da área experimental é um Argissolo Vermelho Amarelo distrófico, textura franco-arenosa. Avaliou-se a distribuição de nitrato (NO_3^-) e potássio (K^+), nas camadas de 0 – 0,2; 0,2 – 0,4 e 0,4 – 0,6 m, em resposta a aplicação de cinco doses de N e de K_2O (60+120; 180+120; 120+60; 120+180 e 120+120 kg ha^{-1} de N e K_2O , respectivamente). A distribuição da concentração de NO_3^- no cultivo de cana-de-açúcar, ciclo de cana planta, ocorre de forma mais intensa no início do ciclo, enquanto que a do K^+ ao final do ciclo. As concentrações de NO_3^- e K^+ na solução do solo são condicionadas às épocas de avaliação, profundidades e doses de N e K_2O aplicadas via fertirrigação. As maiores concentrações de NO_3^- (264 mg L^{-1}) e K^+ (377 ppm) apresentaram-se na profundidade 0,0-0,2 m. Não houve lixiviação de NO_3^- e K^+ para a camada mais profunda do solo (>0,4 m).

Palavras-chave: Nutriente. Profundidade. Concentração iônica.

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INTRODUCTION

The use of traditional soil fertilization for sugarcane crops is common due to its practicality and lower technical requirement, which may lead to disordered applications. This practice is characterized by applications of high fertilizer rates at low frequencies, causing risk of nutrient leaching to areas with no root systems, especially nitrate (NO_3^-) and potassium (K^+) (VITTI et al., 2005). Intensive and often disordered fertilizations with insufficient and unbalanced nutrients generate economic losses and aggravate possible environmental impacts, which is not in agreement with the principles of agronomic science (FREITAS et al., 2007).

Thus, the use of fertigation is recommended; this system allows a better control of the distribution of nutrients throughout the sugarcane cycle. Nutrient uptake by plants, such as sugarcane, is limited by soil, temperature, solar radiation, and precipitation (OLIVEIRA et al., 2011). The Brazilian northeastern coast presents rainfall concentrated within four months, thus, hindering the crops' productive capacity and the plants' efficiency in absorbing available soil water and nutrients (SANTOS et al., 2009).

K^+ is the most exported nutrient by sugarcane, reaching extraction of approximately 55% only by the culms (ROSSETTO et al., 2008). Oliveira et al. (2010) evaluated the exportation of nitrogen (N) in sugarcane crops and found that this nutrient was one of the most exported, reaching extraction of 51% by the culms.

The N supply to sugarcane should be monitored considering its use by the plant, and nutrient loss through several processes, including nitrification. Silva et al. (2006) evaluated the N balance for N-fertilizer recommendation and found large loss of ammonium because of the lack of rainfall after application and the high temperatures during fertilization, which reduced mineral N contents, nitrification, and, thus, the N availability to the sugarcane crop.

Part of the NO_3^- leachate to layers below 0.2 m is possibly partially absorbed by sugarcane plants, considering that a significant part of their root system can reach deep soil layers. According to Silva-Olaya, Cerre and Cerre (2017), 61% of the root biomass of sugarcane plants is in the 0.0-0.02 cm soil layer, and Camargo et al. (2017) found that the effective depth of the sugarcane root system is at 0.6 m. This context denotes the need for studies regarding the distribution of NO_3^- and K^+ in different layers of the soil profile after application of N and K fertilizers.

Losses of NO_3^- in the soil profile should be monitored, especially in intensive production systems with high use of nitrogen fertilizers, for the planning of measures that increase the use efficiency

of the applied N focused on the management of an economically sustainable production system, with quality products and a minimal negative environmental impact (MENDES et al., 2015). NO_3^- leaching increases depending on soil physical properties and use of intensive farming practices and high amount of water for irrigation (ANDRADE et al., 2009).

K^+ leaching is common because of rainfall events (ROSOLEM et al., 2003); this loss is due to its high solubility, which may result in unsatisfactory crop yields.

Therefore, the objective of this study was to evaluate the distribution of NO_3^- and K^+ in the profile of soils cultivated with sugarcane crops, after applications of different nitrogen (N) and potassium (K_2O) rates via subsurface drip fertigation, in Teresina, PI, Brazil.

MATERIAL AND METHODS

The experiment was conducted at the experimental area of the Brazilian Agricultural Research Corporation (Embrapa Meio-Norte), in Teresina, PI, Brazil ($5^{\circ}5'21''\text{S}$, $42^{\circ}48'6''\text{W}$, and altitude of 72 m). The region presents average air temperature of 27.6°C and annual average rainfall of 1,349 mm. The climate of the region is C1sA'a', according to the Thornthwaite and Mather climate classification, characterized as dry sub-humid, megathermal, with moderate water surplus in the summer and a concentration of the potential evapotranspiration (32.2%) from September to November (BASTOS; ANDRADE JÚNIOR, 2014).

A randomized block experimental design with four replications was used to evaluate the distribution of NO_3^- and K^+ in the soil profile. The treatments were arranged in split plots, with N+ K_2O rates in the plots, and soil layers in the subplots.

The sugarcane variety RB 92579 (plant crop cycle) was used. This variety is recommended for irrigated crops and covers an expressive area in the Teresina microregion. The planting was done on June 06, 2014, using double-row spacing (0.5 m between plant rows and 2.0 m between double rows), and 15 buds per linear meter. The soil was prepared with one plowing and one harrowing.

A subsurface drip irrigation system was used, with two meters between drip lines, drippers spaced 0.6 m apart, flow rate of 2.3 L h^{-1} , and pressure of 200 kPa; the drip lines were buried 0.25 m deep in the center of the double rows.

The soil of the experimental area was classified as a Typic Hapludult (Argissolo Vermelho Amarelo distrófico) of a sandy-loam texture (MELO; ANDRADE JÚNIOR; PESSOA, 2014). The chemical and physical-hydrological properties of the 0.0-0.2, 0.2-0.4, and 0.4-0.6 soil layers are presented in Table 1.

Table 1. Chemical and physical-hydrological characterization of the soil the experimental area.

Parameters	Soil layer (m)		
	0.0-0.2	0.2-0.4	0.4-0.6
Chemical attributes			
pH H ₂ O	5.76	5.22	5.28
OM (g kg ⁻¹)	13.88	7.64	6.46
P (mg dm ⁻³)	16.21	13.56	12.77
H+Al (cmol _c dm ⁻³)	3.30	3.85	4.73
Al (cmol _c dm ⁻³)	0.07	0.95	1.27
Ca (cmol _c dm ⁻³)	1.21	0.38	0.42
Mg (cmol _c dm ⁻³)	0.69	0.11	0.10
K (cmol _c dm ⁻³)	0.23	0.07	0.12
Na (cmol _c dm ⁻³)	0.02	0.02	0.04
CEC (cmol _c dm ⁻³)	5.43	4.40	5.37
Sum of bases	2.15	0.58	0.68
Base saturation (%)	39.59	13.18	12.63
Physical-hydrological attributes			
Density (mg m ⁻³)	1.434	1.603	1.577
Sand (g kg ⁻¹)	610	626	573
Silt (g kg ⁻¹)	279	225	246
Clay (g kg ⁻¹)	112	149	181
FC (m ³ m ⁻³)	0.245	0.245	0.268
PWP (m ³ m ⁻³)	0.06	0.08	0.12

Soil samples collected before the lime application; CEC = cation exchange capacity; FC = field capacity (6 kPa); PWP = permanent wilting point (1,500 kPa).

Based on studies about soil fertilization for sugarcane crops (ANDRADE JÚNIOR et al., 2010; COELHO et al., 2014; FLORES et al., 2012; JORIS, 2015), five treatments were established, composed of N (urea) + K₂O (potassium chloride) at rates of 60+120 (T1); 180+120 (T2); 120+60 (T3); 120+180 (T4), and 120+120 (T5) kg ha⁻¹.

Fertigation with N and K₂O started on August 04, 2014 (60 days after planting) and lasted six months (August 2014 to January 2015); it was applied once a week, totaling 24 applications throughout the sugarcane crop cycle. The application of the treatments throughout the crop cycle was divided according to the distribution presented in table 2.

Table 2. Monthly applications (%) of N and K₂O rates throughout the sugarcane crop cycle.

Month/Year	N	K ₂ O
Aug/2014	15%	10%
Sep/2014	20%	15%
Oct/2014	25%	20%
Nov/2014	20%	25%
Dec/2014	15%	20%
Jan/2015	5%	10%

30% of the recommended K₂O rate was applied directly to the soil at planting.

Based on the soil chemical analysis, 2 Mg ha⁻¹ of lime (total neutralizing power of 90%) was applied at 90 days before planting. The P₂O₅ was applied at a rate of 100 kg ha⁻¹—30% at planting (triple superphosphate), and 70% via fertigation (monoammonium phosphate) distributed monthly. The micronutrients applied were boric acid (4.5 kg ha⁻¹), zinc oxide (7 kg ha⁻¹), copper oxide (6 kg ha⁻¹), manganese oxide (11 kg ha⁻¹), and sodium molybdate (1 kg ha⁻¹); they were applied via fertigation split in six applications during the crop cycle.

The N and K₂O rates were applied using a hydraulic injector (positive displacement pump).

The fertigation flow to the plots was turned on and off by hydraulic registers installed at the beginning of the row of each experimental plot to control the irrigation depths and N and K₂O rates.

The irrigation depth was established based on crop evapotranspiration (ET_c), using the reference evapotranspiration (ET_o) estimated by the Penman-Monteith method, based on daily climatic data from an automatic weather station installed at the site (Embrapa Meio-Norte) and on crop coefficients of sugarcane established for the region (ANDRADE JÚNIOR et al., 2017). The irrigation application frequency was three times a week (Mondays, Wednesdays, and Fridays).

The plots were 60 m² and consisted of three 10-meter double rows. The area of the plot evaluated for NO₃⁻ and K⁺ concentration in the soil solution consisted of two plant rows, from where the soil samples were taken for analysis. Simple soil samples (~0.5 kg) were collected at 6 different times (105, 122, 194, 227, 276, and 326 days after planting - DAP) in each replication and soil depth (0.0-0.2, 0.2-0.4, and 0.4-0.6 m), using a Dutch auger at 0.2 m from the dripper line, totaling 360 samples. This sampling method was used to collect soil samples from both the sugarcane root system region and near the region where the fertilizers were applied.

The soil samples were, then, disaggregated and passed through a 2-mm mesh sieve to reduce the size of the soil particles. The disaggregated soil samples were subjected to a saturated paste preparation, following the methodology of Richards (1954). A sub-sample of 0.25 kg was taken from each sample and placed in a 0.5 L beaker. Then, 100 mL of distilled water was slowly added with the aid of a wash bottle, always homogenizing the soil with a stainless-steel spatula until the paste became saturated.

The soil solution extracts were, then, removed from the saturated paste using a filter paper placed on a porcelain Büchner funnel coupled to a beaker, which was set to a pressure of -80 kPa generated by a vacuum pump. A 15-mL aliquot of the solution extract was taken from each sub-sample and placed in 50-mL capped glass containers for subsequent determination of NO₃⁻ and K⁺ ion concentrations, which was made according to the Kjeldahl (NO₃⁻) and photometry (K⁺) methods (SILVA et al., 2010).

The results regarding the dynamics of the NO₃⁻ and K⁺ ions in the soil profile were subjected to analysis of variance, and the means were compared by the Tukey's test ($p > 0.05$). Statistical analyses were done using the SAS 14.1 program (SAS INSTITUTE, 2016).

RESULTS AND DISCUSSION

The cumulative monthly data of ET_c, applied irrigation depth (ID), rainfall (R), and sum of ID and R throughout the experimental period are presented in Figure 1.

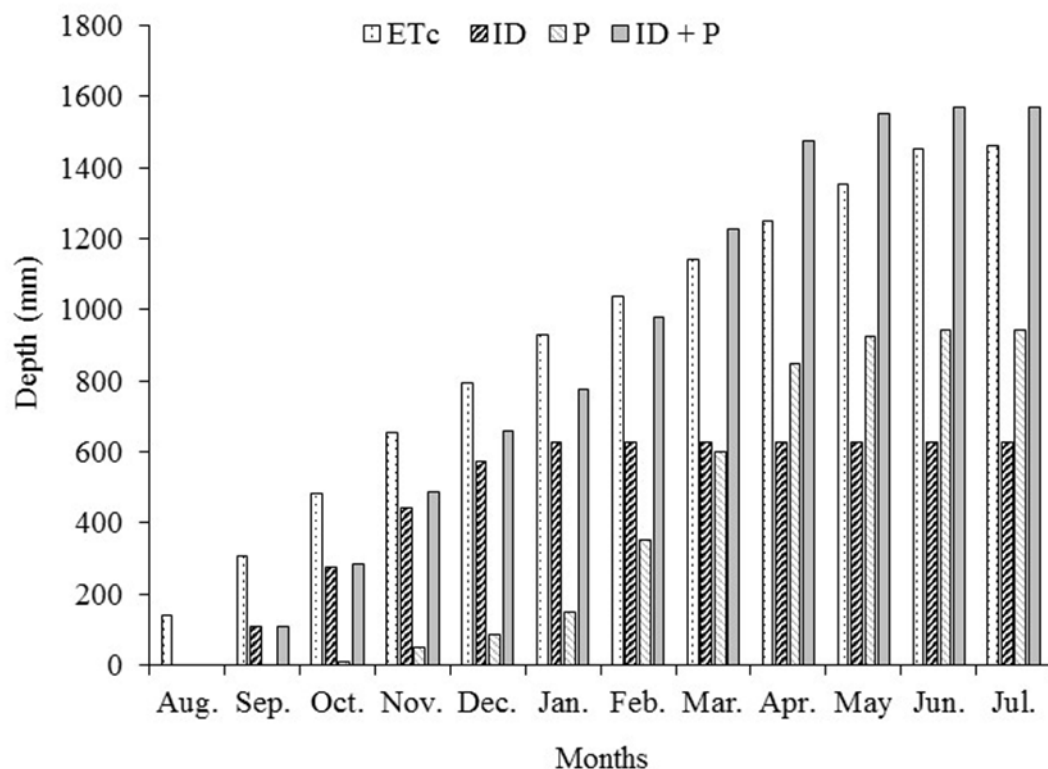


Figure 1. Cumulative monthly data of ET_c, applied irrigation depth (ID), precipitation (P), and sum of ID and P throughout the experimental period.

The sugarcane water requirement was fully met by the application of ID+R during the experiment period. The total ID used was 657.0 mm and the total rainfall measured was 849.2 mm, totaling 1,506.2 mm. The water requirement of sugarcane plants is 1,500 to 2,500 mm (MARIN,

2019), which must be evenly distributed during their vegetative development (BRASIL, 2016); and the amount of water needed for the maximum production potential of the crop is 1,200 to 1,300 mm (DOORENBOS; KASSAM, 2000). Therefore, this was not a limiting factor for the expression of

the crop productive potential under the conditions of the present experiment.

The analysis of variance for the NO_3^- concentrations over the three soil layers and six

sampling times throughout the sugarcane cycle, after application of different N rates via subsurface drip fertigation, is shown in Table 3.

Table 3. Analysis of variance for nitrate (NO_3^-) concentration (mg L^{-1}) in three soil layers collected at six different times (days after planting - DAP) during the sugarcane crop cycle.

Source of variation	DF	105 DAP	122 DAP	194 DAP
Block	3	2113.91**	690.19**	1414.75**
Treatments (T)	4	3652.47**	2797.81**	2274.44**
Error (a)	12	1366.31**	334.00**	742.58**
Soil layer (L)	2	8662.48**	2622.05**	5616.68**
T*L	8	659.53**	1923.75**	612.64**
Error (b)	30	38.63	95.77	38.10
CV (a) %	---	15.34	15.34	26.09
CV (b) %	---	16.84	24.65	17.74

Source of variation	DF	227 DAP	276 DAP	326 DAP
Block	3	1550.20 ^{ns}	1143.50*	13781.84**
Treatments (T)	4	24858.20**	1429.68**	24113.61**
Error (a)	12	8447.86**	3403.60**	10178.96**
Soil layer(L)	2	18907.34**	10505.76**	13069.83*
T*L	8	1310.52*	704.46*	5078.70*
Error (b)	30	549.66	197.21	1913.41
CV (a) %	---	14.96	45.99	18.60
CV (b) %	---	27.22	33.21	24.20

DAP = days after planting; DF = degrees of freedom; CV = coefficient of variation; ns = not significant ($p > 0.05$), * = significant at $0.05 \geq p > 0.01$, ** = significant at $p \leq 0.01$.

The interaction between treatments and soil layers was significant ($p < 0.05$) for NO_3^- concentrations in all evaluated sampling times, indicating that NO_3^- concentration varied in the soil layers in each sampling time depending on the N rates applied.

The highest NO_3^- concentrations in the 0.0-0.2 m soil layer (Table 4) were found at 227 DAP (culm growth stage), despite the reduction from 25% to 20% in the rates of N applied during this period (Table 2). The highest NO_3^- concentration was found at 326 DAP (maturation stage and harvest), denoting that sugarcane extracted less NO_3^- from the soil during this period, since the N demand of sugarcane plant decreases significantly in this stage (PENATTI, 2013). Joris (2015) evaluated NO_3^- concentrations in different layers of soils cultivated with sugarcane crops, after application of different N rates, and found increases in NO_3^- concentration in the 0.1-0.2 m soil layer as the sampling time increased, which was confirmed by the results obtained in the present study.

Regarding the 0.0-0.2 m soil layer, when the plants were at 105 DAP (establishment stage), higher NO_3^- concentrations were found in the treatments T2 ($180 \text{ kg ha}^{-1} \text{ N} + 120 \text{ kg ha}^{-1} \text{ K}_2\text{O}$) and T4 ($120 \text{ kg ha}^{-1} \text{ N} + 180 \text{ kg ha}^{-1} \text{ K}_2\text{O}$). Similar result was found at 194 DAP (tillering stage), when the treatments received the highest percentage of N rates. However, these higher NO_3^- concentrations in T2 and T4 were not constant throughout the sugarcane crop cycle,

due to lower nitrogen uptake by the crop at initial vegetative stages. Joris (2015) evaluated applications of different N rates on sugarcane crops to evaluate NO_3^- concentrations in the soil profile and found similar results: the application of the highest N rates (180 kg ha^{-1}) did not result in the highest NO_3^- concentrations (16 mg kg^{-1}), which was reached with application of lower N rates (120 kg ha^{-1}). Considering the 0.0-0.2 m soil layer, significantly higher NO_3^- concentration was found only for the treatment T4, when the plants were at 194 DAP; whereas at 227 DAP, higher NO_3^- concentrations were found for T4 and T5 (120 kg ha^{-1} of N + 120 kg ha^{-1} of K_2O).

Regarding the 0.2-0.4 m soil layer, the NO_3^- concentrations found from 105 DAP to 194 DAP were lower than those found in the 0.0-0.2 m. This result was due to the root system development and performance in this soil layer at 122 DAP (sugarcane establishment stage) and to the higher initial nutrient consumption of the plants during this period. The NO_3^- concentration in this layer increased from 227 DAP (culm growth stage), presenting the highest values at the last evaluation (326 DAP). Coelho et al. (2014) evaluated NO_3^- concentrations in the soil profile of fertigated soils and found similar results; they reported increases in mean NO_3^- concentrations in the soil solution at the 0.0-0.30 m layer from the beginning of the crop cycle, which lasted for 11 months.

Table 4. Nitrate (NO_3^-) concentrations (mg L^{-1}) in the 0.0-0.2, 0.2-0.4, and 0.4-0.6 m soil layers after application of different N rates, evaluated at six sampling times (days after planting - DAP).

Treatments N+K ₂ O (kg ha ⁻¹)	105 DAP	122 DAP	194 DAP	227 DAP	276 DAP	326 DAP
0.0-0.2 m soil layer						
60+120	50 b	39 b	52 b	63 b	75 a	195 a
180+20	83 a	40 b	57 b	92 b	71 a	199 a
120+60	55 b	80 a	40 b	63 b	57 a	208 a
120+80	88 a	66 a	74 a	170 a	62 a	184 a
120+120	18 c	39 b	46 b	147 a	77 a	264 a
0.2-0.4 m soil layer						
60+120	32 b	22 b	7 b	74 b	40 a	134 b
180+20	47 a	37 b	64 a	64 b	36 a	160 b
120+60	36 b	78 a	22 b	74 b	32 a	183 b
120+80	55 a	19 b	22 b	115 b	36 a	109 b
120+120	28 b	17 b	21 b	177 a	14 a	258 a
0.4-0.6 m soil layer						
60+120	27 a	44 b	6 b	20 b	44 a	66 b
180+20	27 a	7 c	48 a	8 b	57 a	207 a
120+60	35 a	20 bc	15 b	20 b	17 a	131 b
120+80	23 a	71 a	23 b	100 a	13 a	180 a
120+120	14 b	16 c	24 b	106 a	2 a	232 a

Means followed by different letters in the columns are different by the Tukey's test at 5% probability.

The NO_3^- concentrations found in treatments T1 (60 kg ha⁻¹ N + 120 kg ha⁻¹ K₂O) and T2 were significantly different at 194 DAP, presenting the lowest and highest NO_3^- concentrations, respectively. These treatments received the lowest and highest N rates, respectively, in this period, which explains the differences in NO_3^- concentrations. The highest NO_3^- concentrations in the 0.2-0.4 m soil layer were found at 326 DAP; despite the reduction in N rates applied in this period, the values were higher because of the greater rainfall volumes occurring during this period and decreases in N consumption by the sugarcane plants (FRANCO et al., 2008), resulting in more available NO_3^- in the soil solution.

Regarding the 0.4-0.6 m soil layer, the NO_3^- concentrations were higher at 326 DAP, which was a similar result to those found for the 0.0-0.2 e 0.2-0.4 m. Studies on NO_3^- quantification at the end of the crop cycle of sugarcane crops under conventional management conditions (without constant soil coverage) showed that the contribution of nitrogen fertilizers to the total N absorbed by sugarcane is low (10% to 16%) at this final stage (GAVA et al., 2001; TRIVELIN; VICTORIA; RODRIGUES, 1995; FRANCO et al., 2008). A higher N consumption at initial crop stages and a lower NO_3^- concentration in the soil were confirmed at 122 DAP, when the treatment T2 (highest N rate) resulted in the lowest NO_3^- concentrations. However, at 194 DAP, T2 presented higher NO_3^- concentrations in the soil than T3, T4, and T5. The plants were over half of their cycle at 194 DAP, with decreasing demand for N; thus, the results are in agreement with those of Franco et al. (2011), who evaluated the ¹⁵N use

efficiency by sugarcane ratoon crop and found that after fertilization, at 30-60 DAP (initial stage of the crop cycle), the sugarcane plants absorbed practically all N accumulated during the whole crop cycle.

Higher NO_3^- concentrations were expected in the 0.4-0.6 m soil layer because of the leaching process. However, no significant difference in NO_3^- concentrations was found when compared to the other evaluated layers. This denotes the efficiency of the fertigation and subsurface irrigation system. The results confirm those found by Gil et al. (2008), who reported that subsurface drip irrigation presents high uniformity of water application, reducing the percolation of NO_3^- .

Despite the proportionally lower nutrient rates applied, the highest NO_3^- concentrations in the three evaluated soil layers were found in the last evaluation times. Franco et al. (2011) evaluated N fertilization in sugarcane and found higher N extraction at the beginning of crop cycle, usually up to 90 days, due to a subsequent decrease in the crop N demand.

Coelho et al. (2014) evaluated mean NO_3^- concentrations in profiles of fertigated soils and found increases throughout 11 months in depths of 0.3 and 06 m, with no differences between these soil depths. Contrastingly, significant different NO_3^- concentrations was found in the present study for the evaluated soil layers (0.0-0.2, 0.2-0.4, and 0.4-0.6 m).

Oliveira et al. (2001) evaluated the effect of the application of different N rates on the leaching of NO_3^- in an Oxisol (Latossolo Amarelo) cultivated

with sugarcane crops and found differences in NO_3^- concentrations in the soil solution at depths of 0.3, 0.6, and 0.9 m according to the treatments and sampling times, and found increases in NO_3^- contents in all evaluated soil layers as the N rates applied was increased, which is in agreement with the results found in the present study. These results denote the proportionality between N application and NO_3^- concentrations; as in the evaluation at 197 DAP, when the treatment T2 received the highest N rate and presented the highest NO_3^- concentrations in the 0.2-0.4 m (63.9 mg L^{-1}) and 0.4-0.6 m (47.68 mg L^{-1}) soil layers (Table 4).

According to Oliveira et al. (2001), differences in NO_3^- concentrations over time and soil depths can be attributed to rainwater percolation. The sum of the rainfall depths recorded and the irrigation depths applied was higher ($1,500.02 \text{ mm}$) in June (Figure 1).

The analysis of variance for K^+ concentrations in the soil layers at the six sampling times throughout the sugarcane crop cycle is shown in Table 5. This analysis showed significant difference between treatments and soil layers in all evaluation times, showing that the soil depth is also a significant factor for K^+ distribution.

Table 5. Summary of analysis of variance for potassium (ppm) in three soil layers, evaluated at six sampling times (days after planting - DAP) throughout the sugarcane crop.

Source of variation	DF	105 DAP	122 DAP	194 DAP
Block	3	216.84*	17367.68**	5581.00**
Treatments (T)	4	502.11**	86090.43**	6598.48**
Error (a)	12	146.59**	16944.58**	1446.38**
Soil layers (L)	2	2708.36**	1581.43**	6736.81**
T*L	8	198.75**	10690.65**	1090.86**
Error (b)	30	49.15	222.86	183.20**
CV (a) %	---	14.96	9.44	16.07
CV (b) %	---	26.00	27.43	17.15
Source of variation	DF	227 DAP	276 DAP	326 DAP
Block	3	551.54*	71.32*	84.37*
Treatments (T)	4	241.02 ^{ns}	50.86**	123.50**
Error (a)	12	400.09*	34.43**	60.23**
Soil layers(L)	2	3143.00**	32.57**	161.08**
T*L	8	100.11**	2.09 ^{ns}	15.80 ^{ns}
Error (b)	30	130.11	3.28	7.40
CV (a) %	---	18.52	26.86	19.10
CV (b) %	---	31.69	24.82	20.09

n.s = not significant ($p > 0.05$), * = significant at $0.05 \geq p > 0.01$, ** = significant at $p \leq 0.01$; DF = degrees of freedom; CV = coefficient of variation.

The interaction between treatments and soil layers was significant ($p < 0.05$) at 105, 122, 194, and 227 DAP, indicating variations in K^+ concentrations throughout the soil profile in each sampling time according to the K_2O rates.

The treatment T4 had the highest K_2O rate and presented the highest K^+ concentrations in the 0.0-0.2 m layer in four of the six evaluation times (Table 6). The significantly different K^+ concentrations denote their proportional response to K_2O application, mainly considering the K^+ increases in the soil solution between 105 and 122 DAP (sprouting and establishment stages). Flores et al. (2012) evaluated the K^+ distribution in soils under sugarcane crops and found similar results, with K_2O applications affecting the K^+ concentration in the soil solution of the surface layer the K^+ concentration in the soil solution increased in the 0.0-0.2 m layer as the K_2O rates were increased.

Increases in the K^+ concentrations in the soil surface layer as the K_2O rates are increased were

expected; the loss of K^+ by leaching is small in clayey soils with high cation exchange capacity (CEC) (MIELNICZUK, 1982).

T2 presented a high K^+ concentration (377 ppm) in the 0.0-0.2 m soil layer at 122 DAP. This result can be explained by the higher K_2O rate applied at 105 and 122 DAP (sprouting and establishment stages). Moreover, this soil layer presented almost 2-fold the K^+ concentration ($0.23 \text{ cmolc dm}^{-3}$) when compared to the 0.4-0.6 m layer ($0.12 \text{ cmolc dm}^{-3}$), and more than 3-fold that of the 0.2-0.4 m layer ($0.7 \text{ cmolc dm}^{-3}$) (Table 1). The experimental error may have affected this result, considering the number of samples collected (60 per evaluation time).

The highest K^+ concentrations were found at the first evaluation times (105, 122, and 194 DAP) and the lowest at the last ones (227, 276, 326 DAP) in all evaluated soil layers. Thus, the K^+ consumption in the early stages of the sugarcane crop cycle is lower than in the final stages. Vitti et

al. (2005) recommended K_2O fertilization at higher rates before the sugarcane crop canopy closure because of its high consumption at final stages, as

observed in the last evaluations for all soil layers, with decreases in K^+ concentrations due to the higher consumption of K^+ by the sugarcane plants.

Table 6. Potassium concentration (ppm) in the 0.0-0.2, 0.2-0.4, and 0.4-0.6 m soil layers after application of different K_2O rates, evaluated at six sampling times (days after planting - DAP).

Treatments N+K ₂ O (kg ha ⁻¹)	105 DAP	122 DAP	194 DAP	227 DAP	276 DAP	326 DAP
0.0-0.2 m soil layer						
60+120	32 b	51 b	129 a	38 a	6 a	12 a
180+20	47 a	377 a	69 b	53 a	8 a	17 a
120+60	36 b	103 b	65 b	39 a	9 a	20 a
120+80	55 a	140 b	139 a	51 a	10 a	22 a
120+120	28 b	150 b	94 b	58 a	9 a	11 a
0.2-0.4 m soil layer						
60+120	27 a	45 b	83 a	32 a	4 a	10 a
180+20	27 a	248 a	55 b	40 a	5 a	11 a
120+60	35 a	126 a	85 a	32 a	6 a	17 a
120+80	23 a	166 a	100 a	42 a	10 a	12 a
120+120	13 a	155 a	50 b	40 a	8 a	10 a
0.4-0.6 m soil layer						
60+120	8 a	42 b	93 a	23 a	3 a	10 a
180+20	18 a	229 a	32 b	27 a	6 a	11 a
120+60	21 a	228 a	70 a	23 a	6 a	14 a
120+80	21 a	151 a	74 a	24 a	10 a	14 a
120+120	13 a	160 a	46 a	18 a	7 a	8 a

Means followed by different letters in the columns are different by the Tukey's test at 5% probability.

The treatment T4, which received the highest K_2O rate, presented the highest K^+ concentrations in the 0.2-0.4 m soil layer in three of the six evaluation times, showing a proportionality between K^+ concentrations and K_2O rates applied. Similar results were found by Rossetto et al. (2004) in an experiment also in a Typic Hapludult (Argissolo Vermelho), showing that the application of K_2O -based fertilizers increased the K^+ concentration in the soil solution.

Higher K^+ concentrations were expected in the 0.4-0.6 m layer (Table 6) when compared to the other evaluated layers, which would characterize the leaching process, mainly when considering the rainfall events occurred. The highest K^+ concentrations in the 0.4-0.6 m soil layer was found at 122 DAP (establishment stage), which corresponds to less than half of the sugarcane cycle; similar results were found for the other soil layers evaluated in the present study.

CONCLUSIONS

The NO_3^- concentration in soils under sugarcane crops in the plant crop cycle is higher at the beginning of the crop cycle, whereas the K^+ concentration is higher at the end of the crop cycle. The NO_3^- and K^+ concentrations in the soil solution are dependent on the evaluation time, soil layer, and N and K_2O rates applied via fertigation.

The highest NO_3^- concentration (264 mg L⁻¹) was found in the 0.0-0.2 soil layer at 236 days after planting (DAP), corresponding to the harvest time. The highest K^+ concentration (377 ppm) was found in the 0.0-0.2 soil layer at 122 DAP, corresponding to the crop establishment stage. No NO_3^- and K^+ leaching to deep soil layers (>0.4 m) was found; similar concentrations were found for these ions in the three evaluated soil layers, denoting the good efficiency of fertilizer application via fertigation for sugarcane crops.

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