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Content, extraction and export of nutrients in sugarcane under salinity and leaching fraction

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ABSTRACT: The objective of this study was to evaluate the contents of macronutrients and also chlorine and sodium in the diagnostic leaf, and the extraction and export of macronutrients in sugarcane irrigated with saline water and leaching fractions. The experiment was conducted in a complete randomized design in a 5 x 2 factorial scheme with four replications, corresponding to five levels of water salinity (0.5, 2.0, 3.5, 5.0 and 6.5 dS m^{-1}) and two leaching fractions (L1 = 0 and L2 = 0.17). The treatments were applied 60 days after planting. At 280 days after planting, diagnostic leaves were collected and used to evaluate the nutritional status and the contents of Cl and Na. At 360 days after planting, the sugarcane was harvested and its stalks were separated into tops and leaves. Exposure to water of increasing salinity linearly reduced the N, P, K and Mg contents of the diagnostic leaves and increased their Ca, Cl and Na contents. This effect was minimized by the application of the 0.17 leaching fraction. The extraction of nutrients followed the order K > Ca > N > Mg > S > P. The salinity of the irrigation water had a negative effect on the nutritional status of the plant and on its extraction and export of nutrients; the application of the 0.17 leaching fraction improved the results, except for Ca and S.

Key words: *Saccharum* spp., saline waters, macronutrients

Teor, extração e exportação de nutrientes em cana-de-açúcar sob salinidade e frações de lixiviação

RESUMO: Objetivou-se avaliar o teor dos macronutrientes e também o teor de cloro e sódio, na folha diagnóstico, e a extração e a exportação dos macronutrientes, em cana-de-açúcar irrigada com águas salinas e frações de lixiviação. Utilizou-se delineamento inteiramente casualizado em esquema fatorial 5 x 2, com quatro repetições, cinco níveis de salinidades da água (0,5; 2,0; 3,5; 5,0 e 6,5 dS m^{-1}) e duas frações de lixiviação (L1 = 0 e L2 = 0.17). Os tratamentos foram aplicados aos 60 dias após o plantio. Aos 280 dias após o plantio foram coletadas as folhas-diagnóstico para avaliação do estado nutricional e dos teores de Cl e Na. Aos 360 dias após o plantio realizou-se a colheita separando-se colmos e ponteiro + folhas. A salinidade reduziu linearmente os teores de N, P, K e Mg na folha diagnóstico e elevou os teores de Ca, Cl e Na. Este efeito foi minimizado pela aplicação da fração de lixiviação 0,17. A extração de nutrientes seguiu a seguinte ordem: K > Ca > N > Mg > S > P. A salinidade da água de irrigação influenciou negativamente o estado nutricional, a extração e a exportação de nutrientes pela cultura, sendo que a aplicação da fração de 0,17 proporcionou melhores resultados, exceto para o Ca e o S.

Palavras-chave: *Saccharum* spp., águas salinas, macronutrientes

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Introduction

Brazil is the world's largest producer of sugar and ethanol and has increasingly entered the external market. Among the Brazilian states, São Paulo is the largest producer, and Pernambuco appears in the seventh place (CONAB, 2018).

In Pernambuco state, its production occurs usually in coastal areas where soil salinization problems are commonly observed, due to the intrusion of seawater, which mixes with fresh waters, making them brackish or saline (Lira et al., 2018). The use of these waters for irrigation without proper management causes salinization of the soil. Salinization often leads to nutritional disorders in plants and causes antagonistic relationships among nutrients that affect metabolism and reduce crop yields. According to Schossler et al. (2012) it increases in the NaCl concentration in the soil solution, impair the absorption of K and Ca and interfere with plant physiological functions. Several authors have identified nutritional disorders in plants grown under salinity conditions (Gandonou et al., 2011; Nobre et al., 2013; Silva Júnior et al., 2016).

The use of the leaching fraction is a technique that can minimize the damage caused by saline water in agriculture. In this technique, a quantity of water in excess of the plant requirement is used for irrigation such that a portion of the salts originating from the irrigation water concentrates below the root zone. For effective use of the leaching fraction, it is necessary to study the interactions of salts with crops. Few studies have addressed sugarcane nutrition under conditions of salt stress; moreover, there have been no investigations of the extraction of nutrients under such conditions. Therefore, the objective of this study was to evaluate the contents of macronutrients and also chlorine and sodium in the diagnostic leaf, and the extraction and export of macronutrients in sugarcane irrigated with saline water and leaching fractions.

Material and Methods

The experiment was conducted in drainage lysimeters, in Recife (8° 1' 5" S; 34° 56' 48" W; 6.5 m of altitude). The soil used in the lysimeters came from the 0-0.40 m layer of a Spodosols, whose physical and chemical characteristics were: coarse sand = 640 g kg^{-1}, fine sand = 250 g kg^{-1}, silt = 30 g kg^{-1}, clay = 80 g kg^{-1}, textural class = sand, bulk density = 1.80 Mg m^{-3}, particle density = 2.63 Mg m^{-3}, clay dispersed in water = 0%, flocculation degree = 100%, $moisture_{0.33atm}$ = 0.0302 m^3 m^{-3}, $moisture_{15atm}$ = 0.0134 m^3 m^{-3}, available water = 0.0168 m^3 m^{-3}, organic matter = 20.39 g kg^{-1}, $pH_{(H_2O)}$ = 5, P = 5 mg dm^{-3}, K^+ = 0.02 $cmol_c$ dm^{-3}, Ca^{2+} = 0.30 $cmol_c$ dm^{-3}, Mg^{2+} = 0.40 $cmol_c$ dm^{-3}, Na^+ = 0.11 $cmol_c$ dm^{-3}, Al^{3+} = 0.75 $cmol_c$ dm^{-3}, cation exchange $capacity_{effective}$ = 1.58 $cmol_c$ dm^{-3}, sum of bases = 0.83 $cmol_c$ dm^{-3}.

Soil pH was corrected using dolomitic limestone at a dose of 2 t ha^{-1}, and basal mineral fertilization with N, P and K was performed by applying 20, 200 and 50 kg ha^{-1} of N, P_2O_5 and K_2O, respectively, in the form of urea, single superphosphate and potassium chloride. At 45 days after planting (DAP), topdressing fertilization was performed kg ha^{-1} of N and K_2O, respectively, and, at 104 DAP, a second topdressing with 50 and 80 kg ha^{-1} of N and K_2O, was carried out manually.

Planting was performed on August 2, 2014, using six setts with two buds per lysimeter and in the interrows (borders) with the variety RB 867515.

Treatments consisted in the combination of five levels of electrical conductivity of water (ECw): T1 = 0.5; T2 = 2.0; T3 = 3.5; T4 = 5.0 and T5 = 6.5 dS m^{-1} and two leaching fractions (0 and 0.17). The experimental design was completely randomized, in a 5 x 2 factorial scheme, with four replications, totaling 40 experimental plots, and each one was composed of one drainage lysimeter with a depth of 0.65 m, equidistantly spaced by 1.2 m. The drainage system of each lysimeter remained open all the time, so that the free water percolated or evaporated from the system.

Salinity levels were established by adding NaCl and $CaCl_2$ at molar proportion of 1:1 (Ca:Na), respectively, to the local supply water (EC = 0.5 dS m^{-1}). For the control (T1), only water from the local supply was used, without the addition of salts. In each lysimeter a drip irrigation system was used, with four pressure-compensating drippers, spaced by 0.30 m, with mean flow rate assessed in the field of 4.2 L h^{-1} per dripper.

At 60 DAP, treatments started to be applied and irrigation was daily performed based on ETc, calculated by multiplying the reference evapotranspiration (ETo) by the crop coefficient (kc). ETo was obtained using an automatic weather station (Campbell Scientific, CR1000/CFM100/OS100) situated in the area, which provided the result using the Penman-Monteith equation. The kc used was a dimensionless value corresponding to the phenological stage of the plant, according to the United Nations Food and Agriculture Organization - FAO. On days in which rainfall was equal to or higher than ETc, there was no irrigation. At 285 DAP, the last irrigation was applied.

At the phase of maximum development of the crop (280 DAP) (for the one-and-a-half-year variety), diagnostic leaves (DLs) were collected to evaluate the nutritional status of the plants with respect to the macronutrients, chlorine and sodium. The collection was performed according to the methodology described by Cavalcanti et al. (2008).

The plants were harvested at 360 DAP (July 28, 2015). At the time of harvest, the plants were separated into stems, tops and leaves. The top consisted of the first leaf and leaf +1 (first visible collar); for the leaf component, dried leaves were discarded, and only the green leaves, that is, fully expanded leaves with at least 20% green area, were included. The leaves were counted from the leaf +1, considering leaf + sheath; after removal of the top and leaves, the remainder was considered as the stem.

The stems, top and leaves were weighed, and the stem weight was used to calculate productivity in tonnes of cane per hectare (TCH). For the determination of TCH, the fresh mass obtained in each lysimeter was divided by the area: 1.38 m (the lysimeter length) by 1.20 m (row spacing used in the crop) and multiplied by one hectare. Samples of fresh plant material were ground in an industrial fodder cutting machine; during grinding, the tops and leaves were mixed to form a single sample, and wet subsamples of stem and, top + leaf were collected. Subsequently, the wet sub-samples were subjected to oven drying under forced air circulation at 65 °C.

The samples were processed in mill, and the levels of the macronutrients N, P, K, Ca, Mg and S were quantified. In addition to the extraction and export of these macronutrients, the levels of Cl and N in the diagnostic leaves of the crop were measured according to the methodology proposed by Bezerra Neto & Barreto (2011). The macronutrients extracted from the aerial portions of the plants were calculated by multiplying the dry mass of each component by the concentration of the respective macronutrients in each part (stem and top + leaves). The export of each macronutrient was considered as the amount extracted by the stem of the crop.

The data were subjected to analysis of variance using the F test ($p < 0.05$); when there was significant effects of salinity levels, regression analysis was used; when there was only significance between the leaching fraction, means were compared using the Tukey test ($p < 0.05$).

Results and Discussion

There was effect of the interaction between salinity and leaching fraction on N, K, Ca, Cl and Na leaf contents. In addition, there was isolated effect ($p \leq 0.01$) of the salinity factor on the leaf contents of P and Mg.

There was reduction in leaf N and K contents in response to increased salinity of the water used for irrigation and this decrease was attenuated by the application of the leaching fraction L2 = 0.17 (Figures 1A and B).

Reductions of 7.89 and 7.16% in N and K contents, respectively, for each unit increment of water salinity, were observed when the leaching fraction L1 = 0 was used. However, when the L2 = 0.17 was used, the decreases in the contents of N and K were 3.52 and 5.52%, respectively (Figures 1A and B).

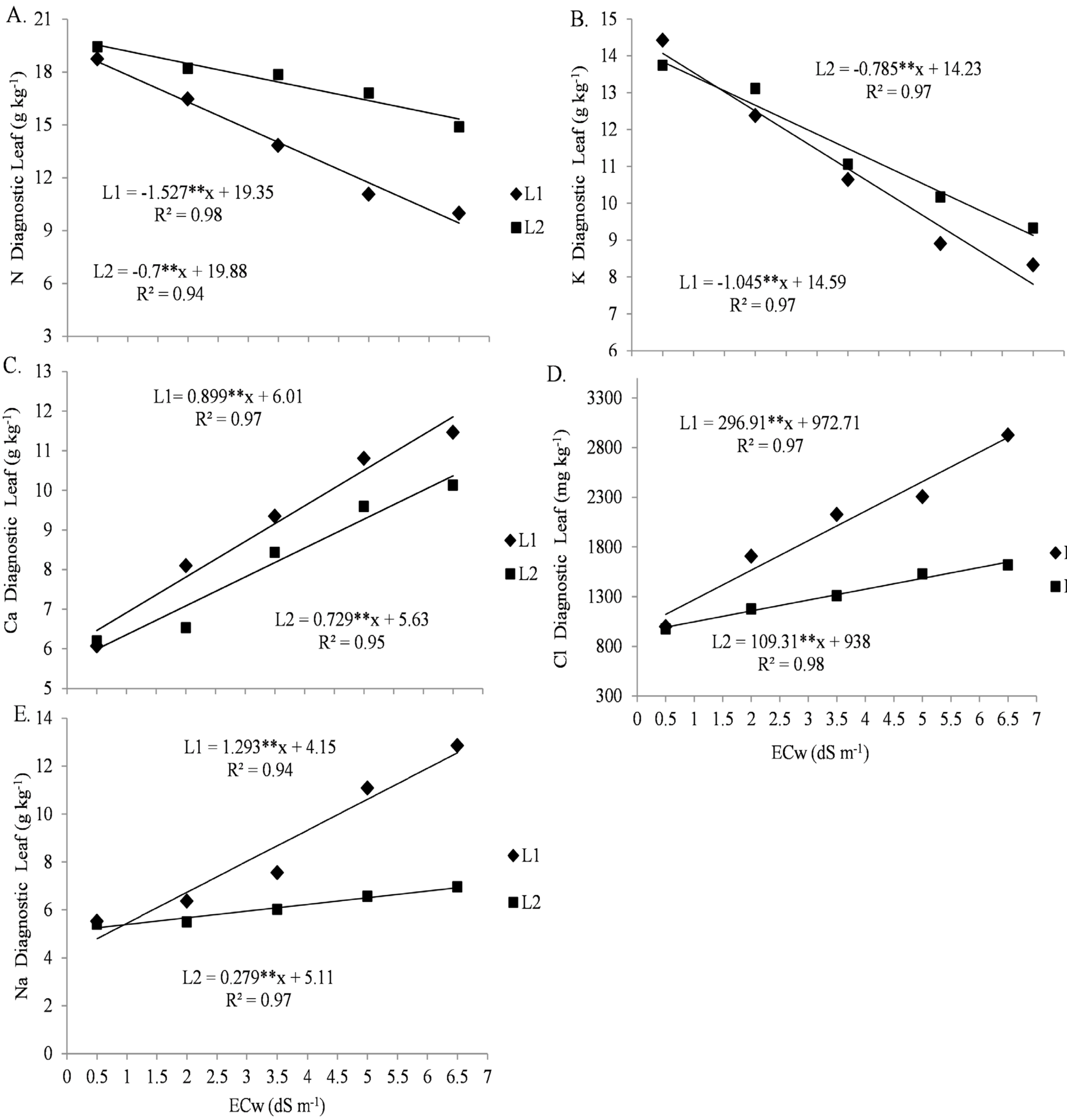

Figure 1. Effect of irrigation water salinity (ECw) and leaching fractions (L1 = 0 and L2 = 0.17) on the nitrogen (N) (A), potassium (K) (B), calcium (Ca) (C), chlorine (Cl) (D) and sodium (Na) (E) contents of diagnostic leaves of sugarcane

There was an increase in the leaf Ca, Cl and Na contents, that is, an increase in the elements that were part of the chemical composition of the irrigating solution (Figures 1C, D and E). The magnitude of the observed increase as a percentage of the per unit increase of ECw was 14.96% for Ca, 30.52% for Cl and 31.16% for Na when the leaching fraction L1 = 0 was used. However, when the leaching fraction L2 = 0.17 was used, the increases relative to ECw were smaller, especially for Cl and Na (12.95% for Ca, 11.65% for Cl and 5.46% for Na).

Table 1 shows the effect of applying the leaching fractions to plots irrigated with water at each of the tested saline levels. It was generally verified that application of the leaching fraction L2 = 0.17 resulted in higher absorption of all macronutrients except calcium and a reduction in the contents of Cl and Na ions in the leaves of the plants.

Salinity is one of the main factors that affect the availability of nutrients to plants; this is due to osmotic effects that restrict water absorption and consequently the absorption of nutrients. It can be observed from Figure 1A that when either of the leaching fractions was applied to the plants, there was a linear decrease in the N content of the diagnostic leaf as water salinity increased. The content of this nutrient remained within the range considered adequate for the crop in the control, and in T2 = 2 dS m^{-1} when the leaching fraction L1 = 0 was used; when the leaching fraction L2 = 0.17 was used, the N content of the leaves was within the normal range for the plant up to T4 = 5 dS m^{-1}, according Cavalcanti et al. (2008).

The decrease in N content as a response to the increased water salinity with either of the two leaching fractions applied may be related to the high concentration of chlorine in the soil solution, since according to Marschner (2012), there is an antagonistic effect between these nutrients.

The appropriate K content in the sugarcane leaves is 12 g kg^{-1} of dry matter (Cavalcanti et al., 2008). The observed negative correlation between K and Na contents in the diagnostic leaf of the crop, which occurred regardless of the leaching fraction applied, is due to the competition between these ions for absorption and for transport across the cytoplasmic membrane. Due to the ionic antagonism between these two elements, the K content of the diagnostic leaves was reduced in the presence of increasing concentrations of Na (Figures 1B and E). According to Deinlein et al. (2014), K is the nutrient that is impaired the most by the ionic antagonism between these two monovalent cations, and the higher the concentration of an element in the soil solution, the more it tends to be absorbed by the plant. In the present experiment, this effect was more pronounced when the leaching fraction L1 = 0 was used.

These results corroborate those obtained by Gandonou et al. (2011), when studying the effect of salt stress on two sugarcane cultivars in Morocco, observed a decrease of K content in the leaves and increases of Na and Cl in both cultivars, with the increase of ECw.

Some researchers (Schossler et al., 2012; Lira et al., 2015) describe that one of the responses of the plant to the application of NaCl is an increase in Na and Cl concentrations and a reduction in K and Ca levels in various plant organs. In the present study, although there was an increase in the Na and Cl contents and a decrease in the K contents of leaves (Figures 1D, E and B), it was verified that, for both leaching fractions applied, there was also an increase in Ca content as a function of increased ECw (Figure 1C). The reason for this finding was that the irrigation water contains a high concentration of Ca, favoring its absorption. It can also be observed in Figure 1C that the increases in Ca in the diagnostic leaves were more accentuated when the leaching fraction L1 = 0 was applied.

The literature indicates that the concentration of Ca in the leaves of sugarcane should be on average 4 g kg^{-1} (Cavalcanti et al., 2008). However, other authors such as Malavolta et al. (1997) stated that the normal range can be as high as 10 g kg^{-1}, depending on the environment and on nutrient availability. In this study, the levels exceeded the ideal range proposed by Malavolta et al. (1997) in irrigation water with ECw of T4 = 5.0 dS m^{-1} and leaching fraction L1 = 0. When leaching fraction L2 = 0.17 was used, the Ca content was outside the normal range only at the highest salinity level (T5 = 6.5 dS m^{-1}) (Malavolta et al., 1997). According to Rengel (1992), when the Na concentration of the cytosol increases, changes in Ca absorption and metabolism occur and Na substitutes Ca, affecting membrane permeability; however, in this study, an increase in both Na and Ca contents in sugarcane leaves was observed.

According to Marschner (2012), Ca at high concentration inhibits the absorption of K and Mg. In this experiment, a significant reduction in Mg content was also observed as a function of the unit increase in water salinity: 7.23% (Figure 2A). Malavolta et al. (1997) stated that the excess of one cation impairs the absorption of the other. In a study using different doses of N and Ca in *Jatropha*, Garrone et al. (2016) also observed that the addition of increasing doses of Ca to irrigation water resulted in a decrease in the plants' absorption of Mg.

Table 1. Mean nitrogen (N), potassium (K), calcium (Ca), sodium (Na) and chlorine (Cl) contents of diagnostic leaves of sugarcane as a function of the leaching fractions applied at each salinity level of irrigation water

Cause of variation	Levels of water electrical conductivity				
	0.5	2.0	3.5	5.0	6.5
	dS m^{-1}				
Leaching fraction	(N) Diagnostic leaf (g kg^{-1})				
L1 = 0	18.73 a	16.45 a	13.83 b	11.05 b	9.98 b
L2 = 0.17	19.43 a	18.20 a	17.85 a	16.80 a	14.8750 a
	(K) Diagnostic leaf (g kg^{-1})				
L1 = 0	14.43 a	12.38 a	10.64 a	8.91 b	8.3250 b
L2 = 0.17	13.74 a	13.11 a	11.06 a	10.17 a	9.3260 a
	(Ca) Diagnostic leaf (g kg^{-1})				
L1 = 0	6.07 a	8.09 a	9.35 a	10.81 a	11.4658 a
L2 = 0.17	6.19 a	6.53 b	8.43 b	9.59 b	10.1318 b
	(Na) Diagnostic leaf (g kg^{-1})				
L1 = 0	5.52 a	5.50 b	7.55 a	11.08 a	12.8565 a
L2 = 0.17	5.40 a	6.36 a	6.01 b	6.55 b	6.9558 b
	(Cl) Diagnostic leaf (mg kg^{-1})				
L1 = 0	997.09 a	1706.13 a	2127.12 a	2304.38 a	2924.7900 a
L2 = 0.17	974.93 a	1174.35 b	1307.29 b	1528.87 b	1617.4975 b

Means followed by the same letters in each column do not differ significantly according to Tukey test at $p \leq 0.05$ probability level

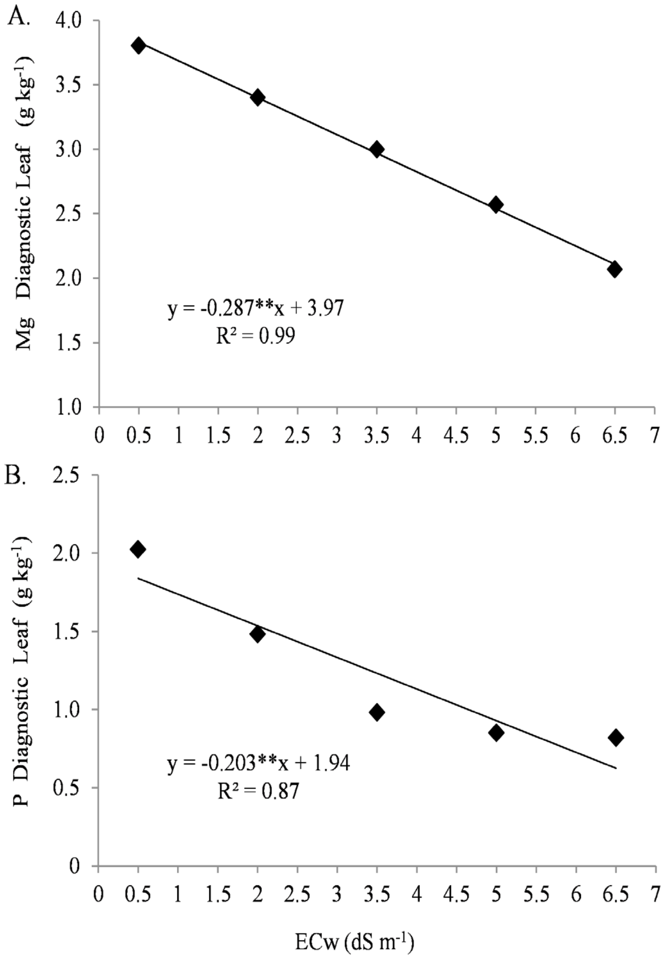

Figure 2. Magnesium (Mg) (A) and phosphorus (P) (B) contents of sugarcane leaves as a function of the salinity of water used in irrigation (ECw)

The Figure 2B shows that increased electrical conductivity of the irrigation water (ECw) resulted in linear reductions in the foliar content of P, equal to 10.46% per unit increase in ECw. High concentrations of chlorine in the soil solution as water salinity increases may decrease the absorption of phosphorus; this is due to the antagonism between these anions (Marschner, 2012).

The determination of the P content in diagnostic leaves indicated that only plants cultivated under control (T1 = 0.5 dS m^{-1}) and T2 = 2.0 dS m^{-1} remained within the range considered adequate for the crop (Figure 2B), which according to Cavalcanti et al. (2008) is about 1.2 g kg^{-1}.

In this experiment, no significant differences caused by any of the evaluated factors were observed for sulfur, probably because no fertilization was done with this element, and because the lysimeters did not allow the expansion of the roots in search of the nutrient.

In general, salinity reduces the activity of ions in solution and alters the absorption and distribution of nutrients in plants. In an analysis of the effects of NaCl and Na_2SO_4 on macronutrients, Cl and Na in *Salvinia auriculata*, Gomes et al. (2011) observed a decrease in N, P, K, Ca and Mg contents in the plants as the concentration of applied salt increased. Analysing the effect of nutrient solutions prepared with NaCl on N, P, K, Ca, Mg, S, Na and Cl contents in the leaves of Chinese cabbage, Lira et al. (2015) also observed reductions for N, K, Ca and Mg.

It is important to mention that reductions in nutrient availability due to salinity also depend on the type of salt, time of exposure and plant species. Cruz et al. (2006), studying yellow passion fruit seedlings during 50 days under saline conditions, observed that the concentrations of Na and Cl in leaf tissue increased as the salinity of the growing medium increased. These authors observed that the contents of macronutrients in the plants were not affected by salinity at this stage of development; only K contents decreased, and S was reduced in the roots.

In the present experiment, the use of a leaching fraction L2 = 0.17 was shown to remove some of the salts from the soil layers in which they were deposited by the plant root system, thereby reducing the nutritional imbalance caused by the salinity of the irrigation water. This finding corroborates the results of Medeiros et al. (2010), who state that, when crops are irrigated with saline water, application of an amount of water that is greater than the one needed by the crop can create a more beneficial environment for plant development.

The applied treatments resulted in differences in the quantities of nutrients extracted and exported by the crop, and the factors independently caused significant effects. When the leaching fraction L2 = 0.17 was used, higher extraction and export of N, P, K and Mg were observed (Table 2).

Analysis of the means obtained in all treatments indicated that the extraction of nutrients followed the order K > Ca > N > Mg > S > P (Table 3). The nutrients present in the stem corresponded to those that were exported. The mean values of N, P, K, Ca, Mg and S as a function of salinity of irrigation water showed that 73, 67, 73, 80, 74 and 65%, respectively, of the absorbed nutrients were exported by sugarcane stems (Table 3).

The values obtained for the export of nutrients depend on the conditions under which the plants are maintained. In the present study for all nutrients examined, export values were higher than those reported by Benett et al. (2013), when studying the same cultivar (RB 867515) using five doses and three sources of manganese as treatments. These authors found maximum exports of N, P, K, Ca, Mg and S of 99, 6.89, 86, 12.52, 12.11 and 11.9 kg ha^{-1}, respectively. These values were attributed to the low productivity of the crop, and the treatment with the highest productivity was the one that received the highest dose of manganese.

The extraction of nutrients by plants varies greatly according to the type of crop, cultivar, cultivation technique

Table 2. Mean extraction and export of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) by sugarcane subjected to different leaching fractions

Cause of variation	N	P	K	Ca	Mg	S
	(kg ha^{-1})					
Leaching fraction	Extraction					
L1 = 0	86.35 b	10.02 b	149.09 b	151.17 a	61.96 b	22.31 a
L2 = 0.17	127.35 a	13.56 a	183.17 a	155.09 a	76.73 a	23.65 a
	Export					
L1 = 0	60.26 b	6.64 b	111.76 b	122.33 a	36.48 b	15.64 a
L2 = 0.17	98.46 a	9.83 a	135.92 a	119.65 a	49.18 a	16.70 a

Means in the same column followed by the same letter do not differ significantly according to Tukey test at p ≤ 0.05 probability level

Table 3. Effect of the salinity of irrigation water (ECw) on the extraction (Extr.) and export (Exp.) of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) in sugarcane

Salinity ($dS\ m^{-1}$)	N		P		K		Ca		Mg		S	
	Extr.	Exp.	Extr.	Exp.	Extr.	Exp.	Extr.	Exp.	Extr.	Exp.	Extr.	Exp.
	$kg\ ha^{-1}$											
0.5	171	122	20	13	222	154	161	129	89	65	30	20
2.0	130	100	15	10	192	140	163	131	66	48	27	19
3.5	98	71	10	7	166	128	166	131	61	47	23	16
5.0	79	60	7	5	141	112	131	117	43	29	18	12
6.5	54	41	6	4	117	85	112	84	32	24	15	10
Mean	106	78	12	8	168	123	147	118	58	43	23	15
CV	18.3	24.3	23.8	32.8	14.9	15.7	17.1	19.9	25.5	32.7	21.3	29.5
Eq. Extr.	y=173.68-19.09**x		y=20.69-2.54**x		y=231.32-18.62**x		$y=154.68+11.74^{**}x-2.5^{**}x^2$		y=90.09-9.06**x		y=32.207-2.63**x	
R^2	0.97		0.94		0.98		0.97		0.98		0.98	
Eq. Exp.	y=126.93-13.59**x		y=13.68-1.55**x		y=162.68-11.09**x		$y=125.24+8.23^{**}x-1.9^{**}x^2$		y=66.08-6.64*x		y=22.458-1.79**x	
R^2	0.98		0.95		0.97		0.99		0.93		0.96	

*,**Indicate significance at $p \le 0.05$ and $p \le 0.01$ probability levels, respectively

and availability of each nutrient. The results of the present experiment yielded almost the same order of extraction by the aerial part observed by Oliveira et al. (2010) (K > Ca > N > Mg > P), when studying 11 varieties of sugarcane, including RB 867515. One difference between their study and the present one was that in the current experiment, sulfur extraction also occurred and was greater than P extraction, that is, in the present work the nutrient extraction order was K > Ca > N > Mg > S > P. However, the amounts of all nutrients extracted by the aerial parts of the plants in this study (Table 3) were smaller than those reported by Oliveira et al. (2010) for the same variety. One reason for this difference may be that the cultivation conditions used by those authors included non-saline full irrigation under field conditions with more plants per linear meter and consequently higher productivity.

Analysis of the results of N extraction by the aerial parts of the crop showed that, when using water with electrical conductivity up to 2.0 $dS\ m^{-1}$ (T2) (Table 3) and when using leaching fraction L2 = 0.17 (Table 2), the results obtained for the extraction of N (130 and 127.352 $kg\ ha^{-1}$, respectively) were higher than the 120 $kg\ ha^{-1}$ N that was incorporated into the soil via fertilizer. This indicates that, in addition to absorbing N from the nitrogen fertilizer applied to the soil (urea), the crop absorbed nitrogen from other sources during its cycle. According to Ambrosano et al. (2005), the main sources of N in sugarcane, other than fertilizers, are the mineralization of organic matter in the soil, fixation of atmospheric N by microorganisms, absorption of ammonia from the atmosphere, uptake of nitrate by the plants' roots from the decomposition of residual straw from previous cultivation cycles.

Evaluating the extraction of N, P and K by the aerial parts of sugarcane, Calheiros et al. (2011) found that the cultivar RB 867515 extracted 226.71, 14.5 and 260.15 $kg\ ha^{-1}$ of these elements, respectively, whereas in the present experiment extraction of these nutrients under the control condition (ECw of T1 = 0.5 $dS\ m^{-1}$) was 171.00, 20.00 and 222.00 $kg\ ha^{-1}$, respectively. In addition, their extraction decreased as the electrical conductivity of the irrigation water increased (Table 3). In a further comparison with the results obtained by Calheiros et al. (2011), greater extraction of P was found in the present experiment at T1 = 0.5 and T2 = 2.0 $dS\ m^{-1}$; this can be attributed to the greater amount of phosphorus applied with the fertilization in this study.

For N and K, however, the lower extraction in this study as compared with that of Calheiros et al. (2011) can be explained by the fact that the present experiment was conducted in lysimeters, which limited the access of the roots to nutrients outside the lysimeter and, consequently, their extraction. In addition, the lower productivity of the plants in the present experiment also resulted in lower extraction of these nutrients. As in the case of N, the application of leaching fraction L2 = 0.17 resulted in higher extraction of P and K compared to the leaching fraction L1 = 0 (Table 2). This can be due to the presence of a greater amount of water in the soil in the former condition, resulting in greater dissolution and leaching of salts in layers farther from the root zone, consequently favoring greater extraction of these essential nutrients.

The quadratic behavior of the data obtained for the extraction of Ca was due to the increase in the salinity of the irrigation water, which included in its chemical composition an increased concentration of calcium and thus provided greater availability of this nutrient to plants. However, increased salinity of the irrigation water also resulted in lower crop productivity (T1 = 114.55; T2 = 110.41; T3 = 100.28; T4 = 92.49 and T5 = 81.73 t of stems ha^{-1}). Thus, even though higher levels of calcium were present in the plant parts, Ca extraction only increased up to T3 = 3.5 $dS\ m^{-1}$. At the two highest salt levels, there was a decrease in Ca extraction due to the lower productivity achieved (Table 3).

The highest extraction of Mg by the aerial parts of the plant was 89 $kg\ ha^{-1}$ when using non-saline water T1 = 0.5 $dS\ m^{-1}$ (Table 3). This result is superior to that found by Tasso Junior et al. (2007), studying five different varieties of sugarcane (80.72 $kg\ ha^{-1}$); however, it is very close to the value of 90 $kg\ ha^{-1}$ reported by Oliveira et al. (2010), on the extraction by the variety RB 867515. In this study, the highest Mg extraction also occurred when the leaching fraction L2 = 0.17 was used (Table 2).

There was a decrease in S extraction and export by the aerial part of the plants as a function of irrigation water salinity (Table 3). The highest percentage of extracted nutrients was exported by the stems, and Ca showed the highest accumulation (Table 3). According to Maathuis (2009), Ca has low mobility in the phloem, preventing its redistribution in the plant and causing it to accumulate to a higher level in stems.

Conclusions

1. Increase in irrigation water salinity reduced the N, P, K and Mg contents of the leaves and increased Ca, Cl and Na contents, and these effects were minimized by the use of the leaching fraction (0.17).

2. The extraction of nutrients by the crop occurred in the following order: K > Ca > N > Mg > S > P.

3. With the exception of Ca, the extraction and export of macronutrients by the crop were negatively affected by increased salinity of the water used for irrigation.

4. The use of the leaching fraction (0.17) resulted in higher extraction and greater export of nutrients by the crop for all macronutrients, except Ca and S.

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