CATION DYNAMICS IN SOILS WITH DIFFERENT SALINITY LEVELS GROWING IRRIGATED RICE [1]

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SUMMARY

Salinity levels in soils of the Outer Coastal Plain of Rio Grande do Sul, Brazil, can be high, due to excess of Na in the irrigation water, evapotranspiration and soil development from marine sediments. The cultivation of irrigated rice could be an alternative, since ion uptake as well as leaching by the establishment of a water layer could mitigate the effects of soil salinity. This study aimed to evaluate the dynamics of basic cations in the solution of Albaqualf soils with different salinity levels growing irrigated rice. The plow layer contained exchangeable Na percentages (ESP) of 5.6, 9.0, 21.2 and 32.7 %. The plant stand, dry matter, Na, K and Ca + Mg uptake at full flowering and grain yield were evaluated. The levels of Na, K, Ca + Mg and electrical conductivity (EC) in the soil solution were also measured weekly during the rice cycle at four soil depths, in the water layer and irrigation water. The Na, K and Ca + Mg uptake by rice at full flowering was used to estimate ion depletion from the layer under root influence. Soil salinity induced a reduction in the rice stand, especially in the soil with ESP of 32.7 %, resulting in lower cation uptake and very low yield at that site. As observed in the water layer and irrigation water, the Na, K, Ca + Mg and EC levels in the soil solution decreased with time at depths of 5, 10 and 20 cm, regardless of the original soil salinity, showing that cation dynamics in the plow layer was determined by leaching and root uptake, rather than by the effect of evapoconcentration of basic cations in the soil surface layer.

Index terms: exchangeable sodium percentage, potassium, calcium, magnesium, electrical conductivity.

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RESUMO: *DINÂMICA DE CÁTIONS EM SOLOS COM DIFERENTES NÍVEIS DE SALINIDADE, SOB CULTIVO DE ARROZ IRRIGADO*

Solos da Planície Costeira Externa do Rio Grande do Sul podem conter altos níveis de salinidade, devido à utilização de água para irrigação com excesso de Na, à evapotranspiração e à gênese dos solos originários de sedimentos marinhos. O cultivo do arroz irrigado pode ser uma alternativa na mitigação da salinidade do solo, tanto pela absorção de íons quanto pela lixiviação ocasionada pelo estabelecimento de uma lâmina de água. Este trabalho teve o objetivo de avaliar a dinâmica de cátions básicos na solução de solos com diferentes níveis de salinidade sob cultivo de arroz irrigado. O experimento foi conduzido em diferentes áreas com Planossolo Háplico, com percentagens de saturação de Na (PST) da camada de 0–20 cm de 5,6; 9,0; 21,2; e 32,7 %. Avaliaram-se o estande de plantas, a massa seca da parte aérea, a absorção de Na, K, Ca + Mg no florescimento pleno e o rendimento de grãos. Os teores de Na, K, Ca + Mg e a condutividade elétrica (CE) na solução do solo em quatro profundidades, na lâmina de água e na água de irrigação, foram mensurados semanalmente ao longo do ciclo do arroz irrigado. A absorção de Na, K e Ca + Mg pela cultura no florescimento pleno foi utilizada para estimação da retirada de íons da camada sob influência das raízes. A salinidade do solo causou redução do estande de plantas de arroz, sobretudo no solo com PST de 32,7 %, o que se refletiu em menor absorção de cátions e produtividade ínfima nesse local. Assim como observado na lâmina de água e na água de irrigação, os teores de Na, K, Ca + Mg e a CE da solução do solo nas profundidades de 5, 10 e 20 cm diminuíram com o desenvolvimento da cultura, independentemente da salinidade original do solo, demonstrando que a dinâmica de cátions na camada arável é determinada pela lixiviação e absorção radicular, em detrimento do efeito da evapoconcentração de bases na camada superficial do solo.

Termos de indexação: percentagem de saturação por sódio, potássio, cálcio, magnésio, condutividade elétrica.

INTRODUCTION

In Rio Grande do Sul, Brazil, rice is grown in six different regions in the Southern half of the State, called Fronteira Oeste, Campanha, Depressão Central, zona Sul and Planícies Costeiras Interna and Externa (here Outer and Inner Coastal Plain). The yield varies regionally, although the applied technology levels are basically the same. On the Outer Coastal Plain, for example, yields are lower compared to other regions, and, in the 2008/09 growing season, the average yield was 6.8 Mg ha^{-1} in an area of 128,760 ha, but 7.8 Mg ha^{-1} in an area exceeding 310,000 ha in Fronteira Oeste (IRGA, 2009). The discrepancies observed between some regions may be attributed to the different soil types (Streck et al., 2008), variation in solar radiation (Mota, 1995; Custódio, 2007) and region-specific stress, such as soil and water salinity. In this context, the lagoon Laguna dos Patos is highly important, because of its connection to the Atlantic Ocean. Laguna dos Patos is the main irrigation source for rice crops in the coastal plains. As a result, the soils can be threatened by salt deposition at incompatible levels for rice cultivation.

Aside from the salts in irrigation water, soil salinization in Rio Grande do Sul can have other causes. On the Outer Coastal Plain, the soil is constantly evolving as a result of marine and fluvio-lacustrine sedimentation. These sediments, which may be more or less permeable, favor the groundwater flow, providing a reaction zone where the freshwater from the Laguna dos Patos and the salt water from the sea flow together (Charette & Sholkovitz, 2006). The brackish water level in the soil profile moves in response to the seasonal water level of the Laguna dos Patos and the hydraulic gradient of groundwater (Niencheski et al., 2007). At sites where the groundwater is nearer the surface and depending on the evaporation, salts can rise up to the plow layer.

Rice cultivation could be a viable alternative of reducing soil salinity, provided that good quality water is applied to the crop. Although rice responds sensitively to salinity in the seedling stage, with plant stand reduction, and in the reproductive stage, with spikelet sterility (Ehrler, 1960; Zeng & Shannon, 2000), the establishment of a water layer favors salt leaching, especially Na, throughout the soil profile (Ponnamperuma, 1981). Moreover, the proper crop uptake favors the removal of other salts from the system, since irrigated rice is highly demanding in K, Ca and Mg (Machado, 1983; Slaton et al., 2004). Although the soil characteristics determine the intensity of changes in the solution, the presence of plants influences the process, either by nutrient uptake, or by modifications in the rhizosphere, mainly by oxygen flow in the aerenchyma and Fe^{3+} precipitation in the roots (Silva et al., 2003). Grattan et al. (2002), Boivin et al. (2002) and Schoenfeld et al. (2007) reported an increase in salinity in the surface layer to a depth of 10 cm, as an effect of evapoconcentration. Several factors may affect these dynamics, e.g., soil texture, CEC, soil porosity and depth of the impermeable layer, as well as the experimental environment. Therefore, the question arises whether rice cultivation can potentially increase or decrease soil salinity levels in the regions of the state where the problem had already been reported.

This study aimed to monitor the influence of irrigated rice cultivation on the dynamics of basic cations and electrical conductivity in soils with different salinity levels in the Outer Coastal Plain of Rio Grande do Sul, Brazil.

MATERIAL AND METHODS

The study was carried out on the Fazenda Cavalhada, in Mostardas, in the rice region called Outer Coastal Plain (OCP), Rio Grande do Sul, Brazil. On the property, Albaqualf is the predominant soil type (Streck et al., 2008) and rice has been grown for the past 80 years.

Soils with different salinity levels in the plow layer were selected. Salinity was expressed as the percentage of exchangeable Na percentage, according to the equation: ESP (%) = $[(Na + / CEC_{pH\ 7.0})] \times 100$. The sampling sites were selected based on the previous analysis of eight cropping areas, with and without history of salinity symptoms in rice plants, characterized by low tillering and high spikelet sterility (Ehrler, 1960). At these sites, soil samples were taken from stratified layers of 0–5, 5–10, 10–20 and 20–40 cm in an area of 40 m^2. Ten sub-samples were taken to form one composite sample per layer per site. From these, four sites were selected with different ESP in the 0–20 cm layer (Table 1). Two areas were chosen representing the extremes, one area with intermediate ESP and one with high ESP. The ESP in the 0–20 cm layer of the selected sites was 5.6 % (Casamento) where no salinity damage had been reported, 9.0 % (Cavalhada), with a history of uneven germination, but without spikelet sterility; 21.2 % (Banhado), uneven germination and problems with spikelet sterility, and 32.7 % (Sinval), sparse rice germination, high spikelet sterility and very low productivity.

The rice variety IRGA 417 was grown at three sites: Cavalhada, Banhado and Sinval. In Casamento, to a better control of red rice infestation, it was used the variety IRGA 422 Clearfield®, which is an immediate parental of IRGA 417 (Lopes et al., 1993) from which it was derived in five backcrosses and therefore has 97 % of the traits of IRGA 417. Sowing dates were November 1 (Cavalhada), November 8 (Banhado and Sinval) and November 17, 2008 (Casamento).

The chemical attributes and clay content of soils (Tedesco et al., 1995) are shown in table 1. No basal fertilization was applied, since the P levels were very high at the four sites (SOSBAI, 2007) and K, a study object, was not applied so as not to interfere with the interpretation of results. Only urea topdressing

Table 1. Chemical atributes of different sites and layers of the soils used in the experiment

Site	Layer	pH H_2O	Clay	Organic matter	Exchangeable cation						CEC	ESP[(3)]	EC
					P[(1)]	K[(2)]	Na[(2)]	Ca[(2)]	Mg[(2)]	H + Al			
	cm	1:1	g kg^{-1}		mg dm^{-3}		cmol$_c$ dm^{-3}					%	dS m^{-1}
Casamento	0– 5	4.4	140	24	34	70	0.40	2.50	1.40	4.67	9.2	4.4	2.23
	5– 10	4.6	140	22	37	51	0.41	2.51	1.45	4.54	9.0	4.6	1.61
	10– 20	4.9	140	15	28	23	0.51	2.16	1.47	3.57	7.8	6.6	1.46
	20– 40	5.6	160	8.6	8.1	51	0.88	2.58	2.81	2.72	9.1	9.7	1.63
Cavalhada	0– 5	4.6	150	18	36	81	0.40	1.81	1.50	2.53	6.5	6.2	2.01
	5– 10	4.6	150	15	39	43	0.47	1.63	1.50	3.27	7.0	6.8	1.53
	10– 20	5.7	130	11	70	62	0.87	2.03	2.42	2.14	7.6	11.4	1.86
	20– 40	7.1	150	6.5	15	137	2.50	3.06	4.38	1.45	11.7	21.2	2.82
Banhado	0– 5	4.9	140	19	31	90	1.58	2.03	1.80	2.56	8.2	19.1	6.34
	5– 10	5.2	160	19	34	82	1.35	2.01	1.68	2.28	7.5	18.0	5.82
	10– 20	6.3	160	9.5	20	82	1.80	2.07	1.79	1.63	7.5	23.8	5.40
	20 40	6 5	160	3.5	9.7	82	2.53	2.23	2.36	1.32	8.7	29.3	4.98
Sinval	0– 5	5.1	130	14	47	152	5.04	1.77	3.41	2.51	13.1	38.5	15.54
	5– 10	5.6	120	14	45	148	3.63	2.20	3.12	2.29	11.6	31.3	9.03
	10– 20	6.3	130	10	26	160	3.30	2.34	3.01	1.93	11.0	30.4	6.87
	20– 40	7.0	140	4.8	11	183	3.66	2.08	3.18	1.40	10.8	33.6	6.41

(1) Mehlich-1 method. (2) Ammonium acetate extractant, 1.0 mol L^{-1}. (3) Exchangeable sodium percentage.

(120 kg ha^{-1} N) was applied at the four sites prior to irrigation, in V4. Two sources of good water quality were used: the Lagoa do Casamento (Cavalhada and Casamento) and Lagoa dos Gateados (Banhado and Sinval). A water level of about 10 cm was maintained in the paddy fields until grain harvest. The experiments were performed in 12 m^2 plots (4 x 3 m) with a spacing of 0.5 m between plots and three replications. A rain gauge was installed at the headquarters of the Fazenda Cavalhada, approximately equidistant from the four experimental areas. The rainfall during the trial, in November and December 2008; and January and February 2009, is shown in table 2, which also contains the rainfall data of the automatic weather station of the National Institute of Meteorology (INMET) of the same period. The maximum average rainfall in Mostardas was presented for comparison, which is also valid for the experimental areas, based on isohyets on basic climate maps (averages of 30 years) as well as average rainfall (11 years) in Tramandaí. Mostardas and Tramandaí are 84 and 63 km away from the headquarters of the Fazenda Cavalhada, respectively.

Prior to irrigation in the experimental paddy fields, soil solution collectors were installed at depths of 5, 10, 20, and 40 cm. The equipment consisted of a plastic hose (diameter 5 mm), connected to a collector PVC tube (diameter 25 mm, length 40 mm), covered with nylon mesh at the ends. At the end of the hose surface, approximately 40 mL solution per depth was extracted with 60 mL syringes (Silva et al., 2003). The aliquots were immediately placed in plastic tubes with a vacuum cap. Sampling began on the seventh day after irrigation started (7 DIS) until 91 DIS, in weekly intervals between collections. The water layer and irrigation water were also sampled, until 84 DIS, when irrigation was interrupted. The electrical conductivity (EC) of the samples was measured about four hours after sampling. Then the aliquots were acidified for later analysis of Na, K, Ca, and Mg.

The stand of each site was evaluated when the plants reached V4. The number of plants in two 1 m-long rows was counted. To assess dry matter, plant shoots were collected in 1 m segments, at full flowering (FF), 77 DIS. The plants were dried in a forced-air oven for 72 h to determine dry matter and the Na, K, Ca and Mg shoot levels, as well as ion uptake. Grain was harvested from an area of 5 m^2 (2 x 2.5 m) per plot. The material was processed in a stationary thresher and the grain cleaned by sieving, weighed and the grain mass corrected to 13 % moisture.

The data of the soil solution, water layer and irrigation water were subjected to regression analysis. The best-fitting polynomial equations were used. The significance of the regression coefficients was presented at 10, 5 and 1 %, together with the coefficients of determination. To determine the ion balance in the soil solution, as a function of plant uptake, the ion concentrations of the soil solution 7 DIS was subtracted from the ion concentration 77 DIS, when full flowering coincided at the four sites. The average ion concentrations at depths of 5, 10 and 20 cm were used, since about 90 % of the rice roots are concentrated in the 0–20 cm layer (Lopes et al., 1994; Teo et al., 1995; Abichequer, 2004). Based on the values of the ionic balance in the soil solution between 7 and 77 DIS and of the ion uptake 77 DIS, the ion leaching loss was determined by the difference between these properties.

Table 2. Total rainfall of November and December 2008 and January and February 2009 on the Fazenda Cavalhada and Mostardas (1) and mean monthly rainfall in Mostardas (2) and Tramandaí (3)

Site	November	December	January	February
	mm			
Cavalhada	24.5	109	106.5	182
Mostardas (1)	16	61	120	146
Mostardas (2)	up 60	up 80	up 100	up 100
Tramandaí (3)	86	97	95.5	113.2

(1) Data provided by the 8th District of Meteorology, National Institute of Meteorology - INMET, from measurements at the automatic station located at Mostardas city, in the months of November and December 2008 and January and February 2009. (2) Data based on basic climate isohyetal maps. Normal period 1931 - 1960 (IPAGRO, 1989). (3) Average monthly rainfall. Normal period 1961 - 1972 (IPAGRO, 1979).

RESULTS AND DISCUSSION

Plant stand, dry biomass at full flowering and grain yield

In relation to the salinity levels evaluated, plant establishment was best in Cavalhada, where the plant stand was higher than in Casamento (Table 3), with lowest levels of soil salinity (Table 1). This may be explained by the later sowing date in Casamento (November 17, 2008), when soil moisture conditions were unfavorable, unlike the situation in Cavalhada (November 1, 2008), Banhado and Sinval (November 8, 2008). The reduced establishment in Banhado and, especially, in Sinval may be attributed to the higher soil salinity at these sites than in Casamento and Cavalhada (Table 1). Several studies (Oster et al., 1984; Shannon et al., 1998; Grattan et al., 2002) reported a decrease in plant stand, proportional to the salinity level in soil as well as irrigation water and soil solution.

The dry matter yield at full flowering was highest exactly at the lowest salinity level (Table 3). However, the higher yield in Banhado, at an ESP of 21.2 %, compared to Cavalhada, where the ESP was 9.0 %, was not expected. Similarly to observations related to the establishment, much less dry matter was produced in Sinval than at the other locations (Table 3), in response to the higher soil salinity (Table 1). Data related to grain yield are best related to the soil salinity levels; the highest yield was obtained in Casamento and the lowest in Sinval (Table 3). At the lowest salinity levels, productivity was very similar, but in Banhado, although the plant stand was consistent with high yield (Counce et al., 1989), grain productivity was more than 1.0 Mg ha^{-1} lower, compared to data observed in Casamento and Cavalhada, which may reflect the ESP at that site (Table 1), above the critical level of 20 % established for rice (Fairhurst et al., 2007).

Ion dynamics in soil solution and plant uptake

The Na contents in the soil solution (Figure 1), similarly to the dry soil contents (Table 1), increased with the soil salinity level and depth. In general, soil solution contents decreased with the crop growth, except in Banhado (Figure 1c) at depths of 5 cm and 20 cm, where the Na content remained relatively stable, with fluctuations over the rice cycle. This reduction in Na concentration over time was also observed in the water layer (Figure 2a), which was also directly influenced by the soil salinity level (Table 1), since the irrigation water quality (Figure 2b) was good (maximum Na levels around 0.3 $cmol_c$ L^{-1}). The Na levels in the water layer decreased more intensely at the locations with initially higher soil contents (Table 1) and became similar at the end of the rice cycle. The Na contents in the water layer (Figure 2a) followed the same trend as in the soil solution (Figure 1), demonstrating an equilibrium relationship, determined by the interface between the soil surface and water layer. The incidence of regular rainfall throughout the study period, mainly in December 2008 and January and February 2009, when rainfall was above average (Table 2), may have caused the decrease, due to dilution effect of Na in irrigation water at all sites but Cavalhada (Figure 2b).

Table 3. Stand, dry matter and irrigated rice yield, grown on soils with different salinity levels

Site	Stand[(1)]	Dry mass [(2)]	Yield
	plants m^{-2}	——— t ha^{-1} ———	
Casamento	303	18.8	8.30
Cavalhada	361	14.8	8.15
Banhado	259	16.7	6.97
Sinval	10	5.9	1.72

[(1)] At V4 growth stage (Counce et al., 2000). [(2)] At full flowering.

The physical action of roots increases permeability and hydraulic conductivity in the soil, facilitating Na leaching, which, together with the uptake of these ions by rice, may have contributed to the decrease during the rice cycle (McNeal et al., 1966), since a partial replacement of K by Na may occur at the uptake sites of rice roots (Castilhos et al., 1999). Additionally, the high biological activity in the roots increases CO_2 concentration in the rhizosphere and, together with the dissolution of native soil carbonates, may have moved part of the Na present at the root exchange sites, facilitating their output from the soil layer influenced by the rhizosphere (Chhabra & Abrol, 1977). Due to its high hydrated ionic radius, Na is a cation easily leached by the water flow.

The difference between Na levels in the soil solution 7 DIS and 77 DIS was similar in Casamento, Cavalhada and Banhado (Table 4). The uptake of this ion, however, was quite different at these three sites and highest in Banhado (Table 4). The lowest uptake in Cavalhada can be partially explained by the lowest dry matter yield at full flowering. Despite this discrepancy in Na uptake, the difference between the ionic balance and Na uptake was positive and similar, indicating that at these three sites, 55–68 mg L^{-1} Na was lost through leaching, without even taking a possible contribution of Na from the non-exchangeable fraction to the soil solution into account. In Sinval, the Na content reached 520 mg L^{-1}. The highest leaching at that site may have been stimulated by the low Na uptake (Table 4), due to the low stand and dry matter yield (Table 3), and the high soil salinity (Table 1).

At a depth of 40 cm, the Na content in the soil solution did not have standard performance at the sites evaluated, because, over time, Na content increased in Casamento (Figure 1a) and Banhado (Figure 1c) and decreased in Sinval (Figure 1d). In Casamento and Banhado, the increased levels in deeper layers may have been due to a rise of the brackish water level or to Na leaching (Table 4), originated from the surface horizons. In the case of Sinval, the decrease in Na at all depths may be due to leaching of this ion to deeper layers, which can occur if the impermeable layer, a common feature of Albaqualfs, is located at a greater depth.

As no K fertilizer was added to the soil, the initial levels (7 DIS) of this nutrient in the soil solution (Figure 3) must result from an equilibrium state between the cations of the soil (Table 1), since the plants were still undeveloped. In this situation, the K content of the soil solution at different sites and depths, relates to the Na content, which, due to mass action, causes K displacement from exchange sites in the soil. However, throughout the rice cycle, the K concentration in the soil solution (Figure 3) decreased at all locations and depths. The K content in the water layer (Figure 4a) followed the same trend as observed in the 5–20 cm layer, in Casamento,

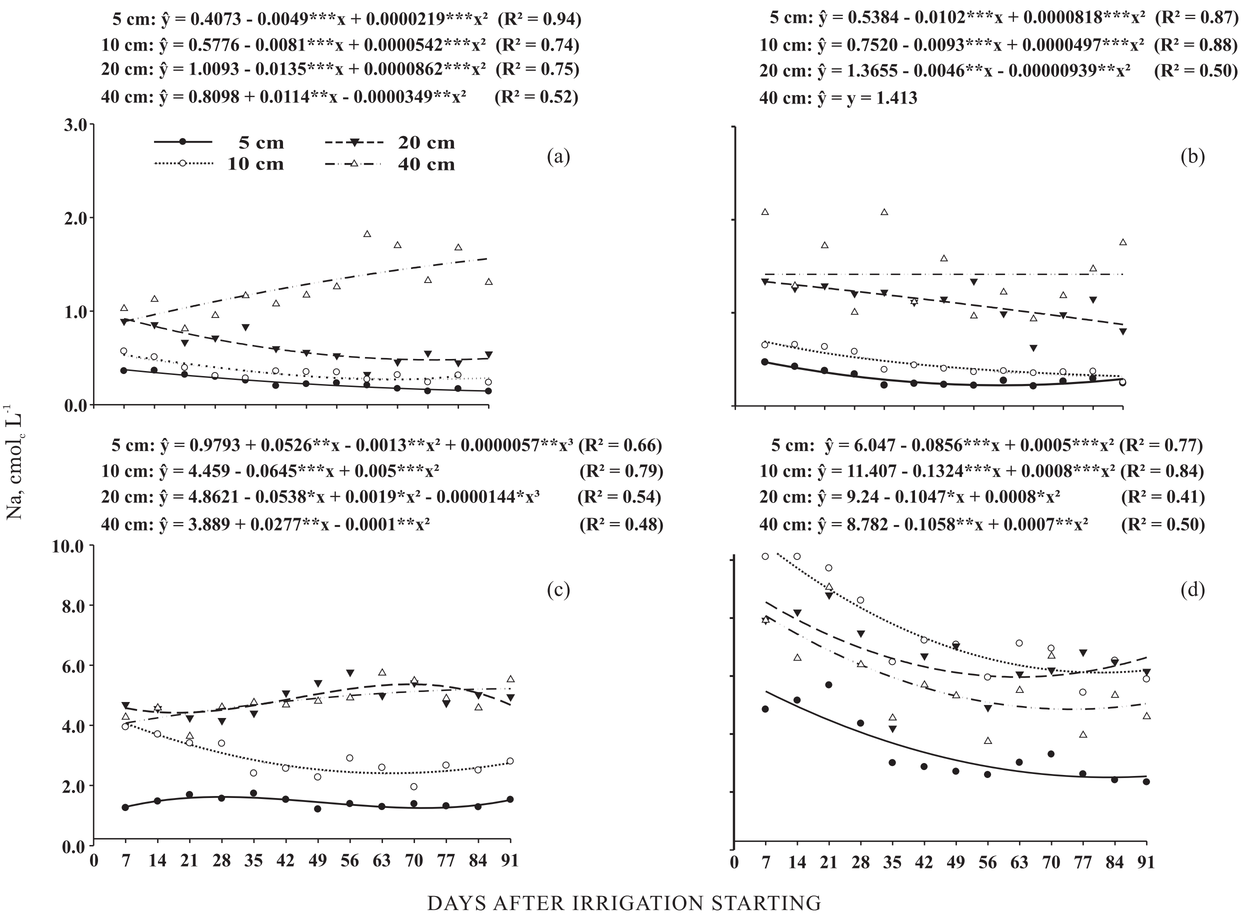

Figure 1. Sodium concentration in the soil solution at different depths and salinity levels: Casamento (a) Cavalhada (b) Banhado (c) Sinval (d). *, **, *: significant at 10, 5 and 1 %, by the F-test, respectively.**

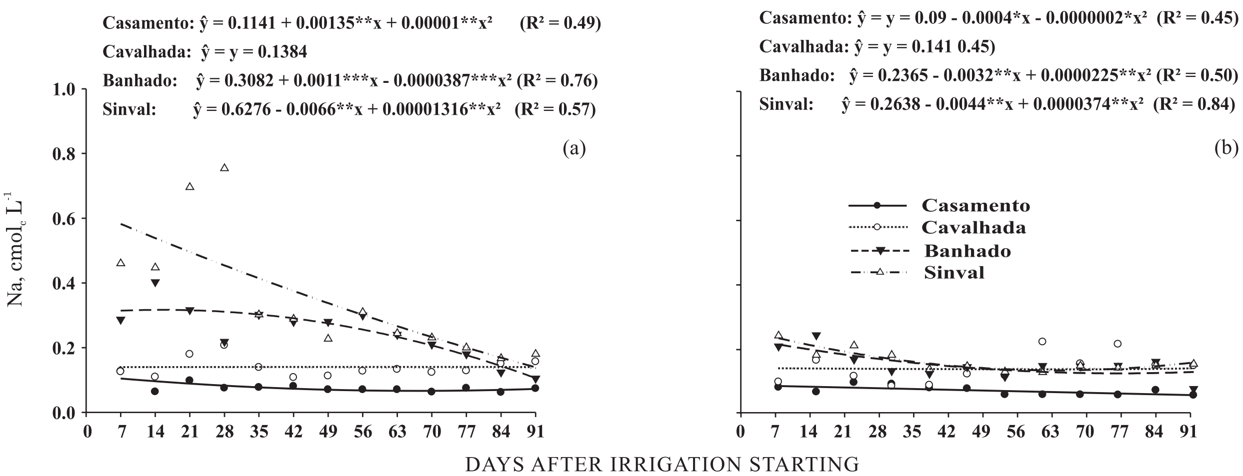

Figure 2. Sodium concentration in the water layer (a) and irrigation water (b), at the different sites. *, **, *: significant at 10, 5 and 1 %, by the F-test, respectively.**

Cavalhada and Banhado (Figure 3a-c), decreasing during the vegetative and part of the reproductive stage and increasing at physiological maturity. This increase cannot be attributed to the contribution of K through irrigation water, in which K values were lowest exactly at the end of the rice cycle (Figure 4b). Potassium is not part of the structure of organic compounds (Marschner, 1995), thus it is rapidly

Table 4. Ion concentration in the soil solution, cation uptake at full flowering and difference between ion concentration in the soil solution and ion uptake by irrigated rice, grown on soils with different salinity levels

Site	Sol [7 DIS - 77 DIS][(1)]	Uptake	Δ[(2)]
	mg L^{-1}	mg dm^{-2}	mg L^{-1}
		Na	
Casamento	70.4	5.43	65.0
Cavalhada	69.9	1.78	68.1
Banhado	64.4	9.32	55.1
Sinval	524	3.25	520
		K	
Casamento	11.2	343	-331
Cavalhada	22.8	247	-225
Banhado	64.8	239	-174
Sinval	43.5	74.2	-30.7
		Ca + Mg	
Casamento	27.8	102	-74.0
Cavalhada	28.7	59.2	-30.5
Banhado	442	55.9	386
Sinval	399	16.5	383

(1) Ionic balance in the soil solution by the difference in concentration measured at seven days after flooding and 77 days after flooding. (2) Difference between the ionic balance in the soil solution and the ionic uptake by rice plants.

recycled after leaf senescence. Costa et al. (2009) observed K accumulation in the vicinity of maize plants and a proportional decrease of K concentration with increasing distance from the sowing line, a behavior known as "K washing" (Klepker & Anghinoni, 1995). Thus, the element may have drained from the rice tissues and deposited in the water layer. This can be proved by the dynamics of this nutrient at the site with the highest salinity level (Sinval - Figure 4a), where there was very little development of plants (Table 3). In this case, there was a slight increase in K content in the water layer from 84 DIS (Figure 4a). The increase of K in the water layer can also be attributed to increased levels in the solution at the end of the cycle (Figure 3), due to the equilibrium of the water layer and the soil solution.

However, an increase of K concentration in the soil solution was expected in the first weeks, because of the biochemical changes caused by flooding. After irrigation, oxygen is rapidly consumed and the anaerobic microorganisms use oxidised soil compounds as electron acceptors, including nitrate and iron and Mn oxides (Ponnamperuma, 1972). The soil solution composition would therefore change by an increase of Fe^{2+}, Mn^{2+} and NH_4^+ levels, causing a displacement of other cations to the solution, such as K (DeDatta, 1983), increasing the plant availability and leaching losses, which are significantly higher when the rice fields are continuously flooded (Santos et al., 2002). The presence of plants, however, appeared to prevent this phenomenon, since K depletion was more pronounced at a depth of 20 cm from after the second sampling, 14 DIS (Figure 3). Similar results were observed by Silva et al. (2003), who studied the dynamics of cations of an Albaqualf and a Gley soil, with and without rice plants, and found a K decrease in the 0–10 cm layer, caused by root uptake.

The apex of K depletion in the soil solution, regardless of the original content in the soil, which was highly variable (Table 1), occurred between 49 and 84 DIS, when K levels increased slightly (Figure 3). In that period, minimum values were null for several weeks in the root growth layer (0–10 cm) in Casamento (Figure 3a), Cavalhada (Figure 3b) and Banhado (Figure 3c), where rice establishment was not as severely affected (Table 3).

The difference in the amount of K between 7 and 77 DIS and the K uptake by plants was negative at all sites (Table 4), indicating a contribution of non-exchangeable K to plant nutrition, especially in areas with higher growth (Casamento, Cavalhada and Banhado - Table 3). Despite the tiny plant stand in Sinval, K uptake was also sufficient to contribute with non-exchangeable K forms (Table 4). Higher plants have extremely efficient mechanisms to take up K, even at low concentrations in the soil solution (Gommers et al., 2005). This generates a gradient toward the roots, creating a favorable environment for the release of non-exchangeable K forms, causing a permanent buffering of exchangeable and non-exchangeable K forms, adsorbed with both low and high bond energy in the clay interlayers, or in primary minerals (Kaminski et al., 2007). Castilhos & Meurer (2002) and Fraga et al. (2009) demonstrated the contribution of non-exchangeable K forms to nutrition of rice grown in pots with different soil types. The change of exchangeable to non-exchangeable K may be rapid (Rosolem et al., 2006), especially when the K concentration in the soil solution is very low. However, the peak of K uptake by rice takes place from the panicle differentiation, i.e., about 35 to 40 days after the beginning of flooding in early-maturing cultivars, and drops dramatically after full flowering (Lopes et al., 1994). Consequently, it would be expected here that K levels in the soil solution would increase as of 77 DIS, when the plants' avidity for nutrients decreases, which occurred only 84 DIS, a period that coincides with the senescence phase of rice leaves (Ookawa et al., 2003) and with rainfall (Table 2), which allowed "K washing" from leaves.

Negative values for the difference between the K amount in the soil solution in the 20 cm layer, and K uptake by plants hinders K leaching in these soils, contrary to what was observed with Na (Table 4). However, the decrease in K concentration at all sites at a depth of 40 cm (Figure 3), therefore out of reach of most roots, suggests that there may have been K leaching. The data reported by Beltrame et al. (1991) confirm this interpretation; the authors observed cumulative K losses of 65.5 kg ha^{-1} in the 20–30 cm

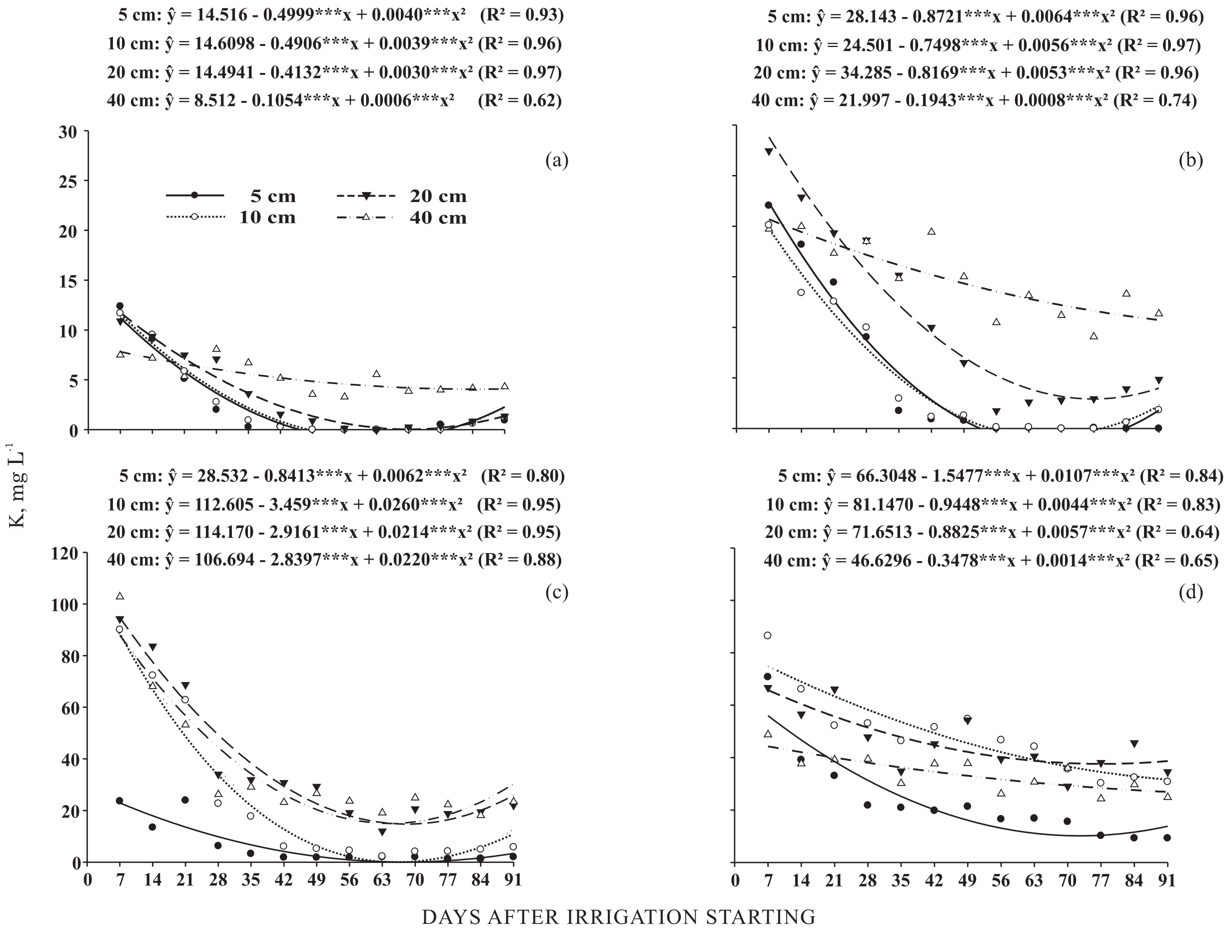

Figure 3. Potassium concentration in the soil solution at different depths and salinity levels: Casamento (a) Cavalhada (b) Banhado (c) Sinval (d). *, **, *: significant at 10, 5 and 1 %, by the F-test, respectively.**

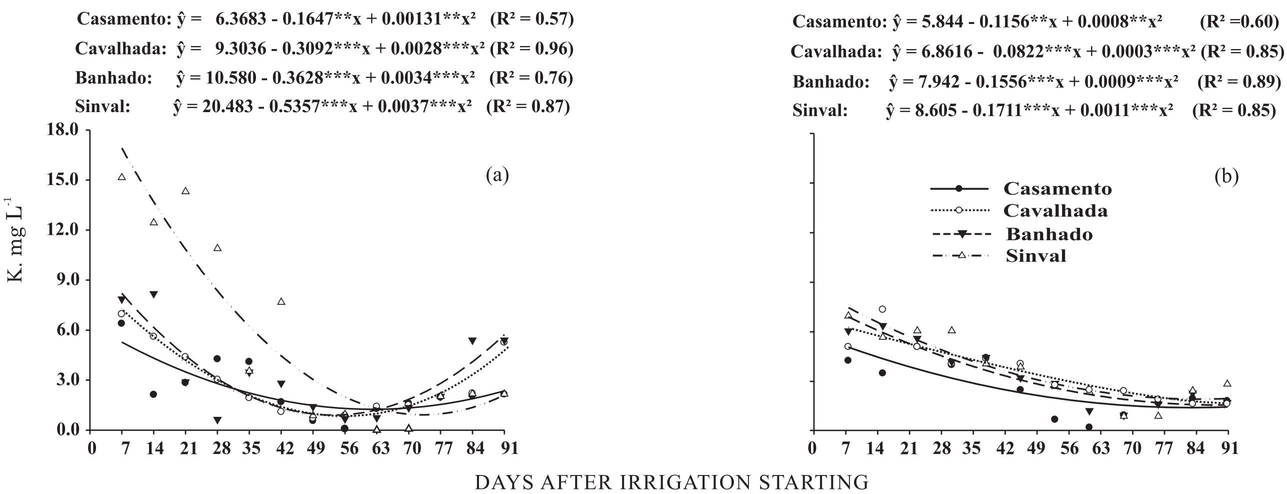

Figure 4. Potassium concentration in the water layer (a) and irrigation water (b), at the different sites. *, **, *: significant at 10, 5 and 1%, by the F-test, respectively.**

layer over a period of 63 days after flooding, in an Albaqualf with similar characteristics to the soils in this study.

The initial Ca + Mg levels in the soil solution (Figure 5), similar to K (Figure 3), are a result of the equilibrium between cations, especially of Na, the main determinant of the salinity degree in the soils used in this study (Table 1). The same was observed with the cation contents during the crop cycle, with a decrease in the soil solution at all sites, especially in the soil layer to 20 cm under rhizosphere influence, where a slight increase was observed at the end of the rice cycle at the sites with lowest salinity: Casamento (Figure 5a) and Cavalhada (Figure 5b). These effects were also observed in the water layer (Figure 6a) and were not related to irrigation water (Figure 6b), in which nutrient contents were similarly low and unchanged throughout the rice cycle.

At the two sites with lowest soil salinity (Casamento and Cavalhada), there was also an increase in Ca + Mg concentrations in soil solution at a depth of 40 cm (Figure 5a,b). This may be due to leaching from the upper layers, or to desorption of Ca + Mg ions, caused by Fe^{2+} and Mn^{2+} replacement at the exchange sites, as a result of redox reactions caused by flooding (DeDatta, 1983). Increasing the Ca and Mg concentration in flooded soil solutions may have been the cause of the negative values observed for the difference between the amount of Ca + Mg in the soil solution and plant uptake in Cavalhada and especially in Casamento, where the uptake was much higher than at the other sites (Table 4).

In a study performed in flooded Albaqualfs without rice plants, Sousa et al. (2002) found an increase in Ca and Mg in the soil solution until 35 DIS followed by a decrease until stability. Similar results were obtained by Silva et al. (2003), with and without rice plants. However, both studies were performed in pots, which prevented a downward hydraulic flow that could leach these elements deeper, as shown by Santos et al. (2002), in a field trial, at a depth of 60 cm. Thus, in the present study, it can be inferred that Ca and Mg depletion (Figure 5) was mainly due to leaching, since the highest losses were observed in the two areas of highest salinity (Figure 5c,d). The positive and similar values of the difference between the amount of Ca + Mg in solution and plant uptake, observed in Banhado and Sinval, indicate a significant leaching loss of Ca + Mg. This is mostly due to the high levels of these elements in the soil solution in the first days

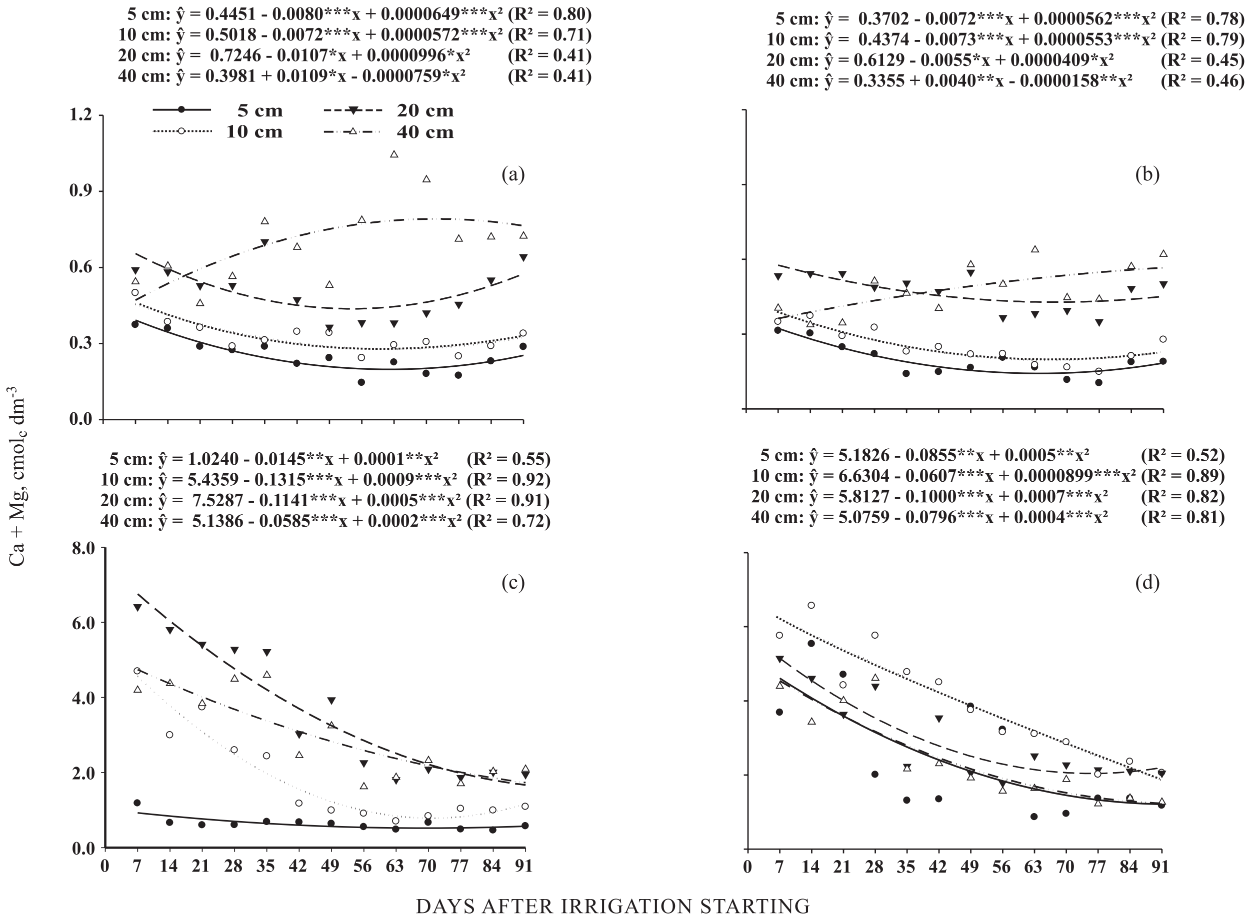

Figure 5. Calcium + magnesium concentration in the soil solution at different depths and salinity levels: Casamento (a) Cavalhada (b) Banhado (c) Sinval (d). *, **, *: significant at 10, 5 and 1 %, by the F-test, respectively.**

of flooding (Figure 5c,d). For being less required by rice, the depletion of Ca and Mg in the soil solution was less marked than of K, which virtually disappeared from the soil solution in some cases (Figure 3a,c).

The electrical conductivity (EC) of the soil solution, determined by the ion concentration, especially of Na, followed a similar trend to that of basic ions. It increased with the level of soil salinity (Table 1) and decreased throughout the rice cycle at all sites, in the 0–20 cm soil layer (Figure 7). At 40 cm depth, EC decreased in the soil solution in Cavalhada and Sinval (Figure 7b,d) and was constant in Casamento and Banhado (Figure 7a,c). Similar to the basic cations, the EC of the water layer (Figure 8a) was related to the EC of the soil solution, decreasing during the crop cycle, proportionally to the soil salinity level, but not to the EC of the irrigation water (Figure 8b). The small decrease in EC at two locations (Banhado and Sinval) was probably due to a dilution effect caused by regular rainfall (Table 2), as mentioned above.

The variable EC is used to monitor soil salinity, due to the practicality of measurement and high correlation with the amount of soluble salts, since it represents the phenomenon of transfer of electric current exerted by charged particles, ionic solutes (cations and anions) and colloids on a force applied to an electric field. In general, the EC of soils increases after flooding, reaching a maximum and decreasing to stable values (Ponnamperuma, 1972). This was however not observed in this study, which reflects the cation dynamics (Figures 1, 3 and 5) with generally lower contents in the topsoil. The reduction in EC was most significant in the soil with highest salinity (Sinval - Figure 7d), similar Na (Figure 1d). In Sinval, however, the EC levels remained above 3.0 dS m^{-1}, a level considered harmful to rice (Ayers & Westcot, 1985), at all depths.

Ion mobilization during the first weeks of flooding causes an increase in EC, which varies according to the soil type. In soils with higher CEC, this process tends to be stimulated. Boivin et al. (2002), for example, noted an increase in EC from 0.3 to 1.2 dS m^{-1}, during a rice cycle in a Vertisol, richer in cations than the Albaqualf used in this study. However, these authors studied an African region characterized by a negative annual water balance (2,000 mm), with average rainfall of 280 mm in the rainy season (July-October) during the rice cycle. Rice cultivation in the low-rainfall period may not allow the dilution of salts contained in the irrigation and soil solution water. This climate pattern is antagonistic to that observed at the site in Mostardas, where rainfall was distributed regularly throughout the experiment (Table 2), favoring the reduction of EC in both the water layer (Figure 8a) and irrigation water (Figure 8b). However, in both cases, the values were similar at the end of the rice cycle.

In pot experiments, rice transpiration induces a hydraulic gradient toward the roots, which mainly governs the dynamics of soil EC, since plant development causes a greater accumulation of ions in the topsoil, due to the effect of evapoconcentration in the rhizosphere. This phenomenon usually occurs near the period of panicle differentiation of rice, when nutrient uptake is highest (Lopes et al., 1993). In a study on different soil types, including an Albaqualf, Schoenfeld et al. (2007) observed a sharp EC increase at depths of 5 and 10 cm 42 DIS, precisely because of the increased transpiratory demand in this period. Similar dynamics were observed by Sousa et al. (2002), for K, Ca and Mg, 35 DIS. In rice cultivated in pots but with outflow of leachates, Chhabra & Abrol (1977) found a drastic reduction in the salinity of a highly salty soil, as in the present field study. This showed

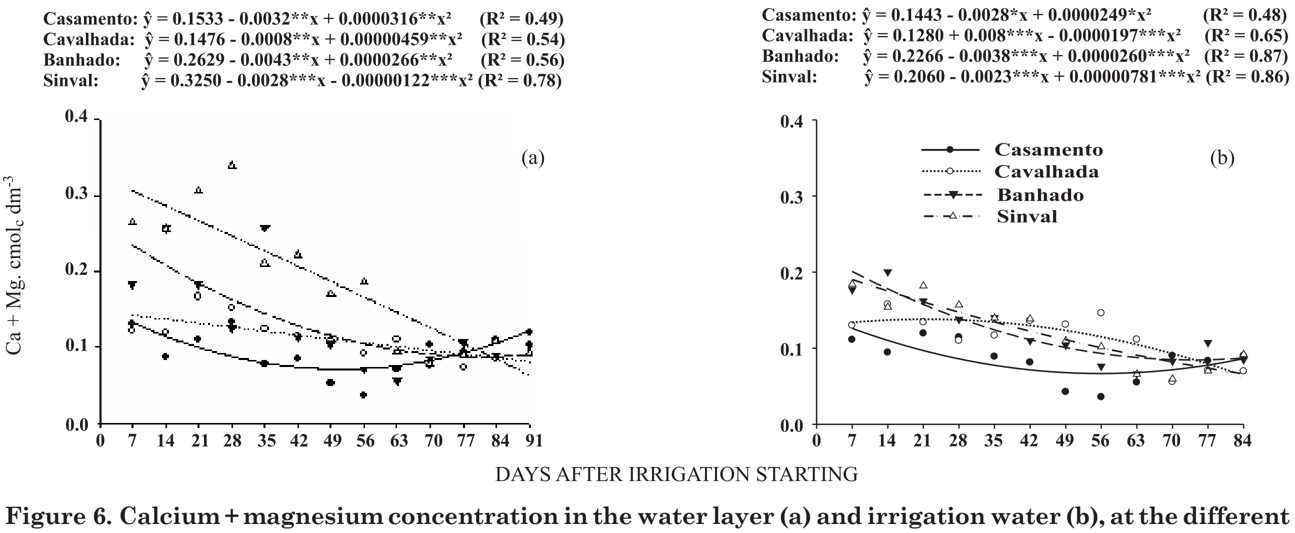

Figure 6. Calcium + magnesium concentration in the water layer (a) and irrigation water (b), at the different sites. *, **, *: significant at 10, 5 and 1 %, by the F-test, respectively.**

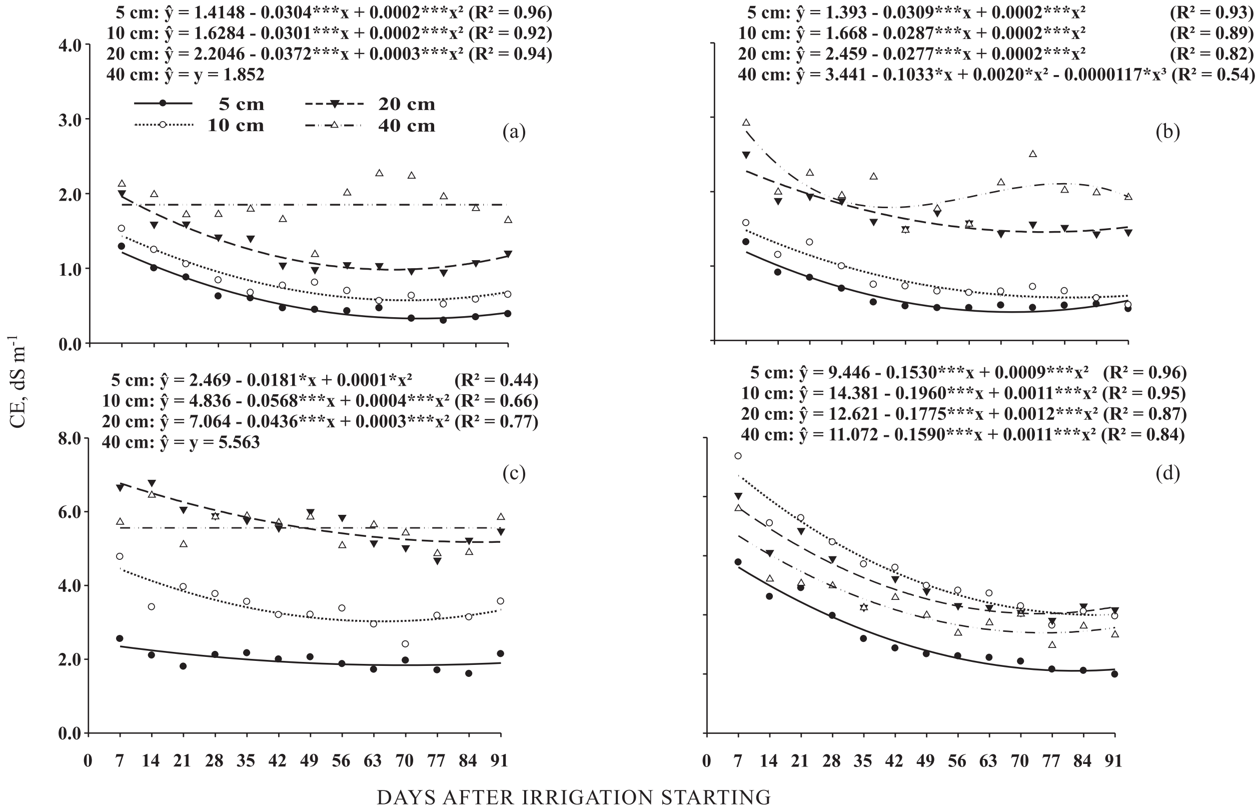

Figure 7. Electrical conductivity in the soil solution at different depths and salinity levels: Casamento (a) Cavalhada (b) Banhado (c) Sinval (d). *, **, *: significant at 10, 5 and 1%, by the F-test, respectively.**

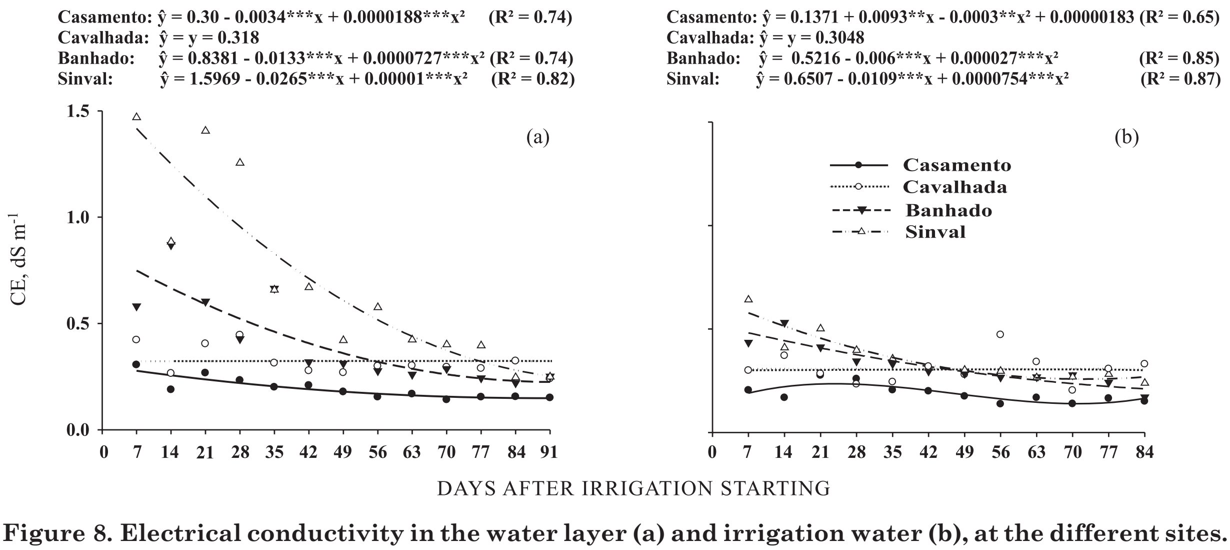

Figure 8. Electrical conductivity in the water layer (a) and irrigation water (b), at the different sites. *, **, *: significant at 10, 5 and 1 %, by the F-test, respectively.**

that water percolation and salt leaching, as well as ion depletion by root uptake are more relevant than a possible effect of nutrient concentration in the soil surface layers, caused by plant transpiration.

CONCLUSIONS

1. Rice contributed to the depletion of Na, K, Ca and Mg contents and, consequently, stimulated a

decrease of the electrical conductivity of the soil solution in the rhizosphere, regardless of the original soil salinity.

2. Root uptake and basic cation leaching influenced the dynamics of basic cations in the soil solution in the rhizosphere, more than the effects of nutrient evapoconcentration.

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