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Effect of sodium and nitrogen on yield function of irrigated maize in southern Portugal

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ABSTRACT

Salinization and nitrate leaching are two of the leading threats to the environment of the European Mediterranean regions. Inefficient use of water and fertilizers has led to a nitrate increase in the aquifers and reduction in crop yields caused by salts. In this study, a triple emitter source irrigation system delivers water, salt (Na^+), and fertilizer (N) applications to maize (*Zea mays* L.). The objective of the study was to evaluate the combined effect of saline water and nitrogen application on crop yields in two different textured soils of Alentejo (Portugal) and to assess if increasing salinity levels of the irrigation water can be compensated by application of nitrogen while still obtaining acceptable crop yield. Maximum yield was obtained from both soils with an application of 13 g m^{-2} of nitrogen. Yield response to Na^+ application was different in the two studied soils and depended on the total amount of Na^+ or irrigation water applied. No significant interaction was found between nitrogen and sodium, but a positive effect on maize yield was observed in the medium textured soil for amounts of Na^+ less than 905 g m^{-2} when applied in the irrigation water.

1. Introduction

In the Portuguese southern region of Alentejo, irrigated agriculture is the most important farm enterprise. Water is the key factor limiting crop production. Mediterranean conditions prevail with hot summers and scarce rainfall, and with mild and rainy winters. Because of arid conditions, hundreds of thousands of hectares have been converted to irrigation in the last years. Improving crop productivity by using water and nutrients more efficiently has been the leading research approach for the region. Field experiments were conducted to measure the effects and interaction of water and fertilizer input on grain yields of major crops such as maize (*Zea mays* L.), sugar beet (*Beta vulgaris* L.), tomato (*Lycopersicum esculentum* Miller), potato (*Solanum tuberosum* L.), and lettuce (*Lactuca sativa* L.) (Ramos et al., 1996; Beltrão et al., 2002a).

Inefficient usage of water and fertilizers has led to an increase in nitrate (NO_3^-) levels in the aquifers of the region. Since the 1970s, a steady increase in nitrate levels has been recorded at shallow depths. Currently, the European legislation 91/676/CEE limits the level of nitrate permissible in waters used for human consumption. Waters from aquifers of some irrigated areas have reached threshold values. As a result, such water can no longer be used for human consumption. Furthermore, a considerable degree of caution must be exercised when using such waters for irrigation (Duque and Almeida, 1998). As a result, only limited fertilizer application is

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permissible in some of the most important agricultural areas of Alentejo.

Compounding the problem, electrical conductivity (EC) values of 0.4–2.6 dS m^{-1} have been recorded in collective irrigation water reservoirs of the region in the past years. In addition, values between 0.7 and 3.0 dS m^{-1} have commonly been found in the small private water reservoirs located in the farmers' fields throughout the region (Oliveira and Varela, 2005). Waters that are generally classified according to the U.S. Salinity Laboratory (Richards, 1954) as medium (C_2) to high (C_3) salinity and of low sodification (S_1) risk present a soil salinization hazard and may cause significant reduction in yield for a large number of crops, especially vegetables and fruits (Ayers and Westcot, 1985; Mass, 1990; Steppuhn et al., 2005). Salinization by irrigation water is a process whereby soluble salts from the irrigation water accumulate in the soil due to inadequate leaching, high water tables and/or high evaporation rates. Soil salinity affects plants directly through osmotic effects, which limit the ability of the plants to absorb water from the soil solution. Specific ion effects and changes in soil physical and chemical properties can have long-term detrimental effects on crop production (Keren, 2000). If the salts are primarily sodic salts, as is frequently the case, their accumulation increases the concentration of sodium ions in the soil exchange complex, affecting soil properties and behaviour. Thus, salinity can also have an indirect effect on plant growth through deleterious modification of soil properties such as swelling, and porosity, water retention and permeability changes (Hillel, 1998).

Currently, protecting the natural resources is of more concern than optimising crop production. Soil and water resource conservation are the key priorities of agricultural research for European regions like Alentejo. Soil salinization/sodification and nitrate leaching to aquifers are two of the leading threats to the environment of the region. Study of the combined effects of saline water and nitrogen application on the yield function could give answers about how to overcome the soil salinization/sodification process and how to reduce nitrate leaching in areas where irrigation water is of poor quality. Crop yield–water consumption relationships at certain fertility levels have been widely examined in a variety of water management studies (Ramos et al., 1996; Kipkorir et al., 2002; Brumbelow and Georgakakos, 2007; Liu and Zhang, 2007; Igbadun et al., 2007). However, many production function studies have been limited to non-saline water. Very few studies exist for crop response under saline conditions. In cases of poor water quality, the level of sodium content in water should be considered as a third factor because sodium content strongly affects crop production (Dinar et al., 1991; Datta et al., 1998; Beltrão et al., 2002a).

Despite a large number of studies demonstrate that salinity reduces nutrient uptake and affects nutrient partitioning within the plant, little evidence exists that adding nutrients at levels above the optimal levels in non-saline environments improves crop yield (Grattan and Grieve, 1999). In fact, several studies show that at high-salinity levels, increasing N is ineffective in counteracting adverse effects of increased salt concentrations on growth and yield (Papadopoulos and Rending, 1983; Makus, 2003; Villa-Castorena et al., 2003). However, other studies also show that N applications can be beneficial in reducing the detrimental effects of salinity by partial substitution of NO_3^- with NH_4^+. Furthermore N applications can be beneficial due to the lower energy cost of N assimilation with NH_4^+ as compared to NO_3^- administration (Sandoval-Villa et al., 1999; Flores et al., 2001; Kant et al., 2007).

The objective of this study was to evaluate the combined effects of saline water and nitrogen application on maize (*Zea mays* L.) yield function in two different soils of Alentejo (Portugal) and to assess if increased salinity levels of the irrigation water can be compensated by application of nitrogen while still obtaining acceptable yields.

2. Materials and methods

2.1. Site description

Field plot experiments were conducted at the Alvalade Experimental Station (37°56′48″N and 8°23′40″W), and at the Herdade da Mitra of the University of Évora (38°31′55″N and 8°00′59″W), both located in southern Portugal, in the Alentejo region. The soil chemical, physical and hydraulic properties of both soils were measured in the beginning of the experiments.

In Alvalade, the experiments were performed on a field with Eutric Fluvisol soil (WRB, 2006). In the top 30 cm, particle sizes between 2000 and 200 μm (coarse sand), 200 and 20 μm (fine sand), 20 and 2 μm (silt), and less than 2 μm (clay) were, according to the Atterberg scale, 8.3, 52.4, 26.3, and 13.0 wt.%, respectively, corresponding to a loam soil. Dry bulk density (ρ) was 1.49 g cm^{-3}, total porosity was 39.2 vol.%, the field capacity and wilting point were 31.0 and 9.8 vol.%, respectively, and the saturated hydraulic conductivity was 14.2 cm d^{-1}. The pH (H_2O) was 7.0, the average organic matter was 26.5 g kg^{-1}, and total nitrogen, available phosphorus, and potassium were, respectively, 1.15 g kg^{-1}, and 131 and 100 mg kg^{-1}. Cation exchange capacity (CEC) was 13.59 $cmol_c$ kg^{-1}, Electrical conductivity of the saturation extract was 0.42 dS m^{-1}, and the exchangeable sodium percentage (ESP) was 2.06%.

In Mitra, the field experiments were carried out on a Hortic Antrosol (WRB, 2006). Also in the top 30 cm, particle sizes between 2000 and 200 μm, 200 and 20 μm, 20 and 2 μm, and less than 2 μm were 46.1, 35.9, 10.1, and 7.9 wt.%, respectively, thus classifying the soil as a sandy loam textural class. Dry bulk density (ρ) was 1.51 g cm^{-3}, total porosity was 36.0 vol.%, the field capacity and wilting point were 22.3 and 9.9 vol.%, respectively, and the saturated hydraulic conductivity was 42.3 cm d^{-1}. The pH (H_2O) was 6.6, the average organic matter was 33.3 g kg^{-1}, and total nitrogen, available phosphorus and potassium were, respectively, 1.28 g kg^{-1}, and 458 and 118 mg kg^{-1}, respectively. CEC was 13.72 $cmol_c$ kg^{-1}, EC of the saturation extract was 0.48 dS m^{-1}, and ESP was 0.63%.

2.2. Climate and water application

The experiments were conducted from 2004 to 2006. Fig. 1 shows the monthly precipitation collected at Alvalade and Mitra meteorological stations, and the reference evapotranspiration rate (ET_0) determined from the collected meteorological data by the Penman–Monteith method (Allen et al.,

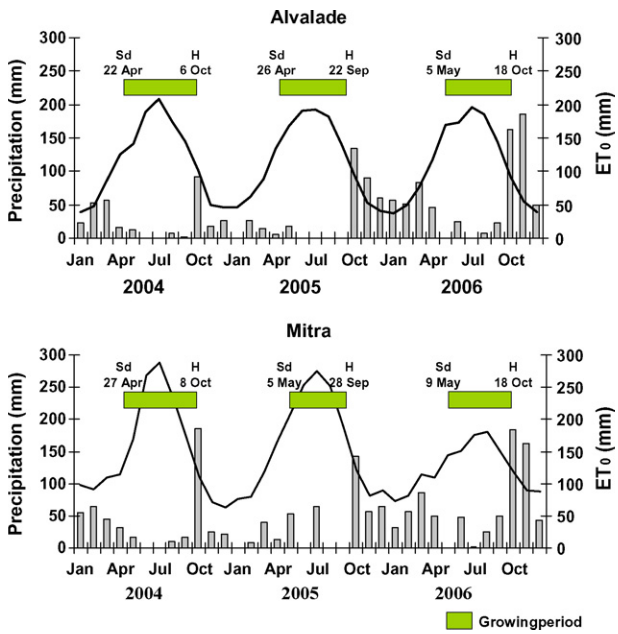

Fig. 1 – Monthly precipitation (mm), and monthly reference evapotranspiration rate (mm), for the period of 2004–2006. Sd and H correspond to the sowing and harvest dates, respectively.

1998) during the 3 years of the experiment. The climate in both experimental areas is mostly dry sub-humid, with hot dry summers, and mild winters with irregular rainfall. ET_0 in Alvalade presented values between 859 and 873 mm during the growing seasons (May–September) of the 3 years period, while in Mitra the ET_0 varied between 801 and 1181 mm.

In the 3 years of the experiment, precipitation was very low during the crop cycle, which corresponded with the time of the year when the evaporative demands of the atmosphere were higher and crop water needs had to be fulfilled by irrigation, as it is common in the summer season under Mediterranean conditions. Years 2004 and 2005 were extremely dry with higher reference evapotranspiration values than average, especially in the most water sensitive stages of crop development, in late July and August. The total amount of water applied during the 3 years of the experiment is presented in Table 1. Experimental fields were irrigated three times per week between June and September. In Alvalade, application amounts averaged 23 mm per irrigation event while in Mitra the mean application amount was 18 mm per irrigation event. In July, nitrogen fertilization was applied in both experimental fields in five irrigation events during the vegetative stage.

Table 1 – Total amount of water applied in Alvalade, and Mitra during the three irrigation seasons of the experiment.

Experimental field	Water applied (mm)		
	2004	2005	2006
Alvalade	997	1012	1028
Mitra	1067	725	729

2.3. *Experimental design and treatments*

Multifactorial experiments require complex designs and large experimental areas. Such experiments are very time consuming and expensive. To significantly reduce the cost and size of the experimental area, sprinkler single-line (Hanks et al., 1976; Lauer, 1983; Magnusson et al., 1989; Levy et al., 1999), double-line (de Malach et al., 1996), crossed triple-line (Magnusson and Ben Asher, 1990), and triple-line source methods (Beltrão et al., 2002b) have been used instead. The layouts of these systems were tested in salinity and fertilization experiments on several crops and in small areas to produce mixing between the maximal and minimal concentrations of the required production factors. When the mixing gradations were arranged in a sequential order, the results showed that gradual changes of salinity were well distributed throughout the experimental layout.

A triple emitter source irrigation system was used in this experiment to deliver water, salt (Na^+), and fertilizer (N) applications to the crop. This system, adapted from Beltrão et al. (2002b), consists of three trickle laterals connected together in order to form a triple joint lateral. The first of the laterals was connected to the salt stock solution while the second one was connected to the nitrogen reservoir. The third lateral delivered fresh water and was used to obtain a constant water application rate for each dripping point along the triple joint lateral. Gradients of applied salt (Na^+) and nitrogen (N) concentration were produced by placing different emitters along the laterals and varying their discharge rate to obtain various mixtures between the three lines. A constant application rate was maintained at each dripping point.

Each experimental field (Fig. 2) was divided into four groups (I–IV) with three triple joint laterals each, establishing a N gradient decreasing from groups I–IV. Each group was then divided into three treatment areas, A–C, each with surface area of 6.75 m^2 (2.25 m wide × 3 m long), and with the Na^+ gradient decreasing from A–C. The dripping points were spaced 1 m apart, with a total of nine emitters in each of the 12 treatment areas. Two laterals of fresh water bordered the different groups. Each treatment area was bordered with earthen ridges, which prevented surface runoff from crossing over during rainfall and irrigation.

The overall discharge of a dripping point Q_i, at different locations of the jth triple joint lateral (where $i = m$ and $j = n$) was maintained constant, at 18 L/h in all 12 treatments, but with variations in the discharge of the emitters located at each single triple point line of salt $qS_{i,j}$ (Na^+), nitrogen $qN_{i,j}$ (N) and fresh water $qW_{i,j}$, delivering system as:

$$Q_{i,j} = qS_{i,j} + qN_{i,j} + qW_{i,j} \tag{1}$$

The mass of each solute $MS_{i,j}$ (Na^+) and $MN_{i,j}$ (N) applied at each ith dripping point located at the jth triple joint lateral is obtained as:

$$MS_{i,j} = qS_{i,j}\,CS_{i,j} \tag{2}$$

$$MN_{i,j} = qN_{i,j}\,CN_{i,j} \tag{3}$$

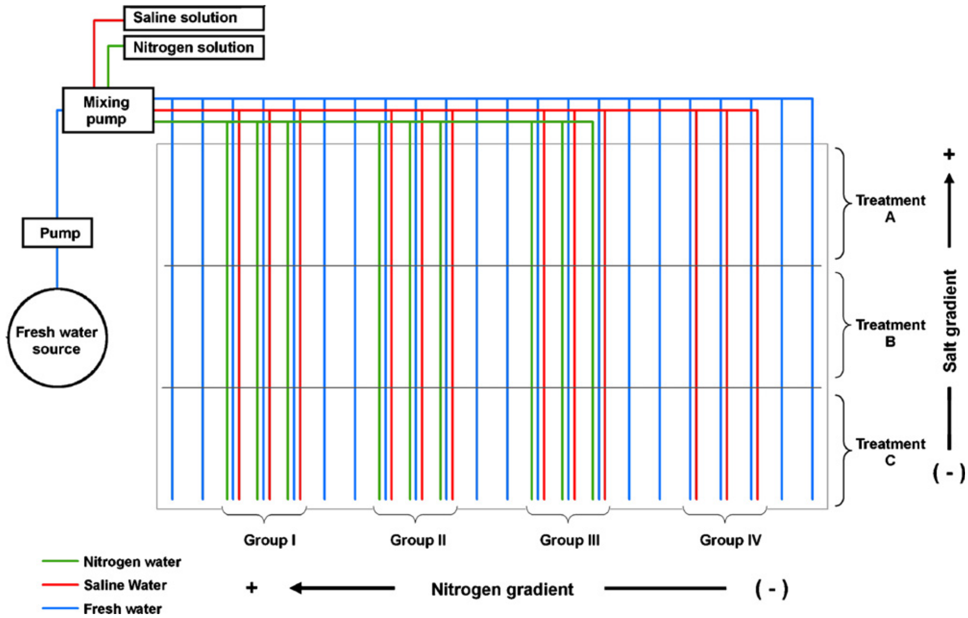

Fig. 2 – Layout of the triple emitter source design. The salt gradient decreases from Treatments A–C and the fertilizer gradient decreases from groups I–IV.

where $CS_{i,j}$ and $CN_{i,j}$, the Na^+ and N concentrations at each ith dripping point and jth triple joint lateral, respectively, were calculated as:

$$CS_{i,j} = \frac{MS_{i,j}}{Q_{i,j}} \tag{4}$$

$$CN_{i,j} = \frac{MN_{i,j}}{Q_{i,j}} \tag{5}$$

The discharges of the emitters along the triple joint laterals are presented in Table 2.

The concentration of saline and the applied fertilizer waters in all salt and nitrogen laterals was constant in each year. However, different emitter discharges from the laterals resulted in different applied amounts of N and Na^+ in all plots of the four groups. The amount of applied N and Na^+ in all groups and treatments is described in Table 3.

2.4. *Relationship between applied factors and yield function analysis*

At the end of each crop cycle, grain yield and interrelationship with applied factors (nitrogen and sodium) were evaluated. By multiple stepwise regression analysis, it was determined that at Alvalade and Mitra grain yield was related to the total amount of salt (Na^+), nitrogen (N) and water (W) applied during the irrigation cycles. In the process, two dummy variables were introduced as orthogonal polynomial coefficients to take into account the two types of soil (Soil) and each year of the experiment (Year). The results from the two experimental fields were analysed in cluster as well as separately by field plot.

3. Results

Mean grain yield of the individual treatments and the standard deviations of the three repetitions for each experimental field are presented in Table 4.

Table 2 – Discharge rates of the laterals applying salt (Na^+), nitrogen (N) and fresh water (W) in experimental plots. The emitters on the three coupled lines have different discharges, resulting in different salt and nitrogen concentrations. A constant cumulative discharge rate of 18 L/h was used at each dripping point.

Treatment	Application rates (L/h)											
	Group I			Group II			Group III			Group IV		
	Na^+	N	W	Na^+	N	W	Na^+	N	W	Na^+	N	W
A	12	6	0	12	4	2	12	2	4	12	0	6
B	6	6	6	6	4	8	6	2	10	6	0	12
C	0	6	12	0	4	14	0	2	16	0	0	18

Table 3 – Total amount of salt (Na^+), and nitrogen (N) applied in Alvalade (Alv.) and Mitra (Mit.), in each group and treatment (Tr.), during the three irrigation seasons of the experiment.

Group	Tr.	Salt ($g\,m^{-2}$)						Nitrogen ($g\,m^{-2}$)					
		2004		2005		2006		2004		2005		2006	
		Alv.	Mit.	Alv.	Mit.	Alv.	Mit.	Alv.	Mit.	Alv.	Mit.	Alv.	Mit.
I	A	1365	1352	2055	962	2792	1229	19	9	20	15	22	21
	B	683	676	1027	481	1396	614	19	9	20	15	22	21
	C	0	0	0	0	0	0	19	9	20	15	22	21
II	A	1365	1352	2055	962	2792	1229	13	6	13	10	15	14
	B	683	676	1027	481	1396	614	13	6	13	10	15	14
	C	0	0	0	0	0	0	13	6	13	10	15	14
III	A	1365	1352	2055	962	2792	1229	6	3	7	5	7	6
	B	683	676	1027	481	1396	614	6	3	7	5	7	6
	C	0	0	0	0	0	0	6	3	7	5	7	6
IV	A	1365	1352	2055	962	2792	1229	0	0	0	0	0	0
	B	683	676	1027	481	1396	614	0	0	0	0	0	0
	C	0	0	0	0	0	0	0	0	0	0	0	0

3.1. *Yield response curves at Alvalade*

From the result of the multiple stepwise regression analysis between grain yield (Y) and the input factors nitrogen (N), salt (Na^+), water (W), and their interactions at Alvalade for the period of 2004–2006 (Year), the following relationship was established:

$$Y_{Alvalade} = 804.98 + 43.46\,\text{Year} + 43.35\,N - 1.6075\,N^2 + 0.1575\,Na^+ - 0.000087(Na^+)^2 \quad (6)$$

The analysis of variance for Eq. (6) indicates a sum of squares due to regression (SSR) of 8.187×10^5, a sum of squares due to error (SSE) of 4.950×10^5, a determination coefficient (R^2) of 0.623, a F-value of 9.92, and $P < 0.0001$ for $n = 36$ observations. Fig. 3 shows the response curves of yield to different levels of N and Na^+ at Alvalade.

3.2. *Yield response curves at Mitra*

From the result of the multiple stepwise regression analysis between grain yield (Y) and the input factors nitrogen (N), salt (Na^+), water (W), and their interactions at Mitra for the period of 2004–2006 (Year), the following relationship was established

$$Y_{Mitra} = 572.73 + 89.45\,\text{Year} + 51.55\,N - 1.9562\,N^2 - 0.5898\,Na^+ + 0.000649\,W\,Na^+ \quad (7)$$

The analysis of variance for Eq. (7) shows a SSR of 1.430×10^6, a SSE of 0.562×10^6, a R^2 of 0.718, a F-value of 15.25, and $P < 0.0001$ for $n = 36$ observations. Fig. 4 shows the response curves of yield to different levels of N and Na^+ at Mitra.

Table 4 – Average maize grain production ($g\,m^{-2}$) at Alvalade and Mitra experimental fields. The values in brackets are the standard deviation of the three repetitions.

Groups	Treatments	Average grain production ($g\,m^{-2}$)					
		2004[a]		2005		2006	
		Alvalade	Mitra	Alvalade	Mitra	Alvalade	Mitra
I	A	1008.9	1184.4	778.4 (0.0)	471.8 (72.4)	818.8 (45.9)	892.1 (80.4)
	B	927.3	902.0	1069.9 (239.1)	566.1 (55.5)	1212.1 (76.2)	866.8 (172.2)
	C	1223.2	866.7	1093.8 (2.2)	681.8 (103.2)	911.2 (150.4)	758.2 (136.0)
II	A	1388.5	970.6	866.3 (130.2)	467.1 (91.3)	830.2 (54.3)	886.1 (37.2)
	B	1270.6	1180.7	1103.4 (126.0)	583.6 (97.9)	1103.2 (101.8)	1051.9 (65.4)
	C	1244.8	1128.9	1023.3 (120.6)	634.2 (87.7)	1212.5 (244.2)	1028.9 (91.6)
III	A	1353.9	1116.1	772.7 (222.8)	563.8 (65.2)	822.9 (64.1)	759.3 (128.8)
	B	1140.1	976.7	1014.6 (308.6)	630.2 (63.1)	1022.1 (139.0)	654.3 (101.6)
	C	821.1	683.7	947.2 (91.6)	663.0 (62.3)	1116.9 (139.2)	988.5 (93.1)
IV	A	1063.4	538.6	773.2 (115.6)	375.2 (40.3)	722.5 (82.8)	394.7 (55.6)
	B	734.8	705.1	728.5 (187.5)	471.5 (66.4)	897.5 (44.4)	428.7 (16.5)
	C	715.5	758.7	780.2 (96.6)	516.3 (39.6)	823.4 (41.4)	484.9 (0.0)

[a] The standard deviation values of the 2004 maize production are not presented because in the first year, the three lines were harvested together. In the following years they were harvested separately.

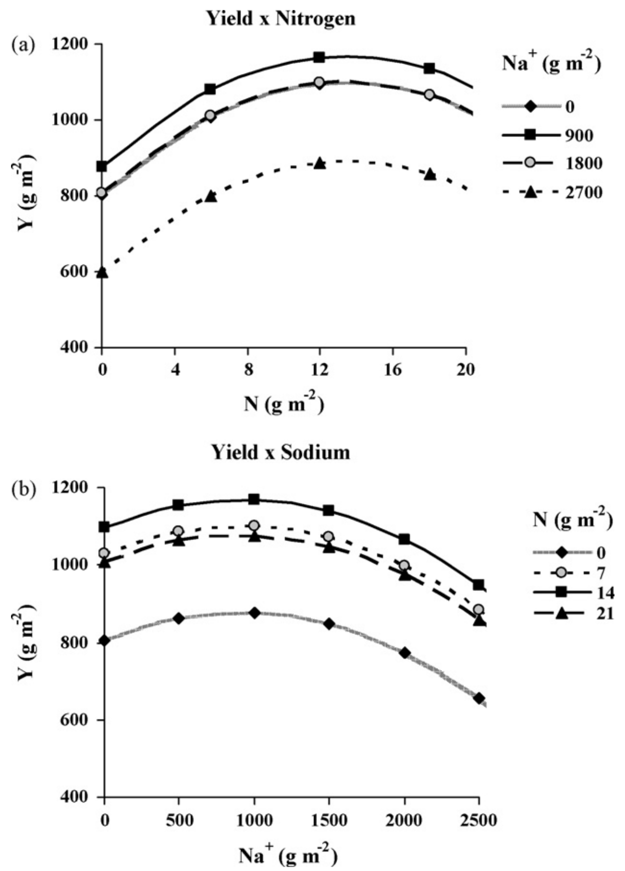

Fig. 3 – Grain production curves with decreasing returns to nitrogen (a), and to sodium (b), at Alvalade. Response measured while maintaining all other input factors constant.

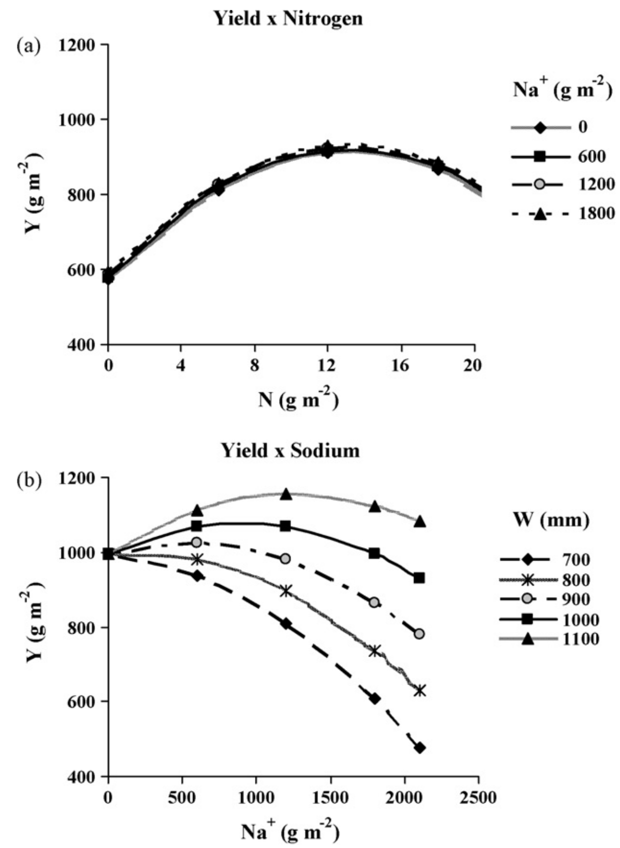

Fig. 4 – Grain production curves with decreasing returns to nitrogen (a), and to sodium (b), at Mitra. Response measured while maintaining all other input factors constant.

3.3. *Yield response curves on both locations*

The result of the multiple stepwise regression analysis between grain yield (Y) and the input factors nitrogen (N), salt (Na^+), water (W), and their interactions for all experimental data set (Alvalade and Mitra) for the period of 2004–2006 was established as:

$$Y = 681.87 + 66.91\,\text{Year} + 46.63\,\text{N} - 1.7382\,\text{N}^2 - 0.5353\,\text{Na}^+ - 0.000102(\text{Na}^+)^2 + 0.000719\,\text{W}\,\text{Na}^+ - 100.62\,\text{Soil} \qquad (8)$$

The analysis of variance for Eq. (8) presents a SSR of 3.145×10^6, a SSE of 1.165×10^6, a R^2 of 0.730, a F-value of 24.67, and $P < 0.0001$ for $n = 72$ observations. Fig. 5 shows the response curves of yield to different levels of N and Na^+ considering all data from both experimental fields.

4. Discussion

4.1. *Analysis of yield response curves at Alvalade*

For the field experiment carried out in the textured medium Eutric Fluvisol of Alvalade, the adjustments to Eq. (6) were statistically significant. The model explains 62% of the observed variations, with a total of 36 observations analysed. The effect of different years was only significant in the variability of mean annual yield. No significant interaction was found between nitrogen and sodium indicating that yield response to one of the input factors is not dependent on the other factor. Beltrão et al. (1993) studying the combined effects of N and salinity on sweet corn growth also found no interaction between these two input factors, when applying combined gradients of salinity (1–6.2 dS m^{-1}) and N fertilization (0–6.4 g m^{-2}). Pang and Letey (1998) using a combined plant–N–salinity–water response model (ENVIRO-GRO) and similar irrigation rates as in this study (1050 mm), also found no interactions between N and salinity due to high levels of deep percolation resulting in higher salt and nitrogen leaching. With more moderate irrigation rates (630 mm), they found a significant interaction between salinity and nitrogen, with high-salinity waters affecting N uptake and crop yield. Shenker et al. (2003) reported that N and salinity were inversely related (when salinity increases N uptake decreases).

Regression analysis shows that the yield response curves to N and Na^+ are quadratic, with diminishing response for each incremental change of the analysed variable factor. Each additional unit of input adds less to the total output than the previous unit does. Taking the partial derivate of the multiple regression equation (6) with respect to nitrogen (N) yields:

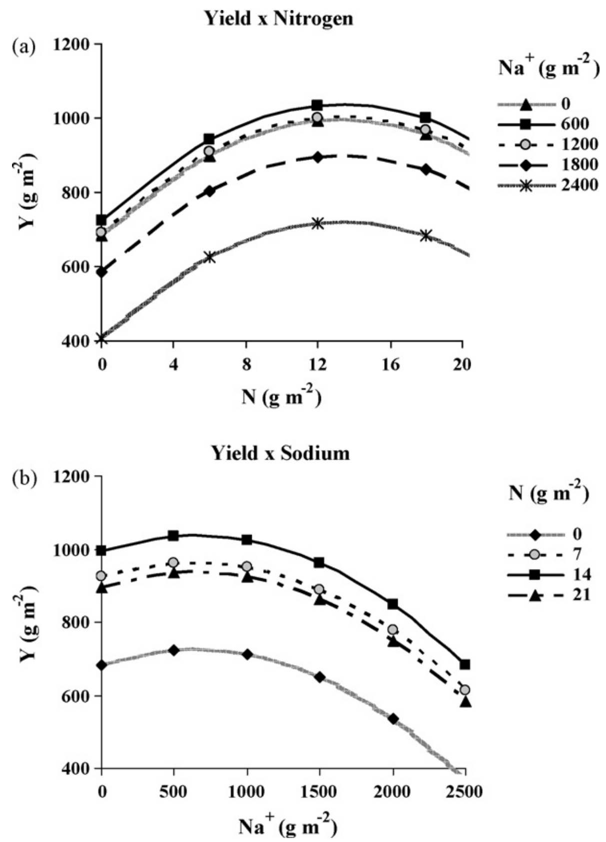

Fig. 5 – Grain production curves with decreasing returns to nitrogen (a), and to sodium (b), in production fields at Alvalade and Mitra. Response measured while maintaining all other input factors constant.

$$\frac{\partial Y}{\partial N} = 43.35 - 3.215\,N \quad (9)$$

Eq. (9) shows the decrease in yield per unit increase in nitrogen levels. The data shows that increasing nitrogen application indefinitely will not result in a direct increase in production. By equating nitrogen application to zero and solving for N, the maximum yield (Y) was determined to be obtained for 13.48 g m^{-2} of N. This value is considerably lower than the 29.59 g m^{-2} of N obtained by Ramos et al. (1996) for the same soil and the same amount of water. When using only good quality waters and a N range of 26.0–30.0 g m^{-2}, as recommended by the Portuguese Ministry of Agriculture (Dias, 2000), an acceptable crop yield was achieved in the same soil unit. Similarly Shenker et al. (2003) analysed different models describing the relationships between N fertilization and water salinity on yield response of sweet corn plants. The resultant response curves suggest lower demand for N at increasing salinity levels.

Likewise, taking the partial derivate of the multiple regression equation (6) with respect to sodium (Na^+) yields

$$\frac{\partial Y}{\partial Na^+} = 0.1575 - 0.000174\,Na^+ \quad (10)$$

Eq. (10) shows that total yield increases at a decreasing rate per unit increase in the Na^+ level. The maximum yield is obtained when the total applied Na^+ equals 905.17 g m^{-2}. Adding more sodium to the irrigation water will lead to yield reductions. Possible exchange reactions between N–NH_4^+ and Na^+ in the exchange complex cation of the soil may help explaining why the maximum yield was obtained when the total applied Na^+ was of 905.17 g m^{-2} instead of 0 g m^{-2}. This phenomenon seems to be associated with the gradual exchange of adsorbed ion NH_4^+ in the soil for a monovalent cation provided with the irrigation water. This observation is in agreement with the reports of Nommik and Vahtras (1982), Drury and Beauchamp (1991), and Green et al. (1994). These authors studied fixation and release of NH_4^+ in different soils when adding K^+ to the soil solution. Singh et al. (1969) suggested that depending on the existing salt concentration the effects of adding Na^+ was similar to K^+. According to those studies and the obtained results in this study, N-NH_4 fixation in clay minerals provides protection against its lixiviation and provides a gradual release to plants throughout the vegetation cycle, at a rate dependent on the exchange of Na^+ with NH_4^+:

$$\text{Clay Na} + NH_4^+ \leftrightarrow \text{Clay } NH_4 + Na^+ \quad (11)$$

The exchange relation, expressed in Eq. (11), explaining the importance of low sodium content in irrigation waters on yields, is only briefly mentioned in the literature (Evangelou, 1998; Evangelou and Lumbanraja, 2002) and needs further study. However, previous studies suggest that fixation and release of NH_4^+ within a growing season is important in many agricultural soils (Green et al., 1994). The rate of fixation and release of NH_4^+ in the Eutric Fluvisol of Alvalade should be studied in the future. Another possible explanation is a reduction of nitrification of N-NH_4 to N-NO_3 due to the increase of salinity as described by McClung and Frankenberger (1987) and Irshad et al. (2005, 2008) with consequent N losses through leaching.

4.2. *Analysis of yield response curves at Mitra*

In the field experiment conducted in the coarse textured Hortic Anthrosol of Mitra, the adjustments to Eq. (7) were statistically significant with the model explaining 72% of the observed variation with a total of 36 observations analysed. Interactions between years and treatments also were not statistically significant in the experimental field data. The effect of the different years was again only significant in the variability of the mean annual yield. At Mitra the interaction between N and Na^+ was also not statistically significant, indicating that nitrogen was ineffective in counteracting the adverse effects on yield from high concentrations of sodium in the irrigation water.

Regression analysis results show that yield response curves are quadratic for N indicating diminishing yield returns for this factor. Taking the partial derivate of the multiple regression equation (7) with respect to nitrogen (N) yields:

$$\frac{\partial Y}{\partial N} = 51.55 - 3.9124\,N \quad (12)$$

Eq. (12) shows the decrease in yield per unit increase in nitrogen levels. The results are similar to Alvalade. Yield decreases with each unit increase in the level of nitrogen. Maximum yield is obtained for a level of N of 13.18 g m^{-2}. This value is slightly lower than the 17.14 g m^{-2} of N found by Ramos et al. (1996) for a similar soil and the same amount of water, but using fresh water. The maximum yield is also lower than the range of 17.0–22.0 g m^{-2} N recommended by the Portuguese Ministry of Agriculture as an amount for an acceptable crop yield in this type of soil also when using waters of good quality (Dias, 2000). The model obtained at Mitra suggests a lower demand for N at increasing salinity levels, in accordance with Shenker et al. (2003). Similarly, no interaction (positive or negative) was found between those two input factors.The results from Mitra were different from Alvalade, in that yield was not affected by changes in the level of Na^+. Yield was only responsive to water as the partial derivate of the multiple regression equation (7) expressed with respect to sodium (Na^+), demonstrate:

$$\frac{\partial Y}{\partial Na^+} = -0.5898 + 0.000649\,W \tag{13}$$

Eq. (13) suggests that the sandy loam textural class of the Hortic Antrosol at Mitra, with its lower water retention capacity and higher saturated hydraulic conductivity, was favourable to sodium leaching with each irrigation event. This resulted in a low sodium concentration in the soil profile throughout the irrigation seasons and did not negatively affect yield. Nevertheless, the results also show that a substantial increase in the concentration of sodium in the irrigation water would require an ever-increasing depth of water to maintain the same yields. Letey et al. (1985), Bresler (1987), Beltrão and Ben Asher (1997), and Pang and Letey (1998) have also shown that salt stress can be ameliorated by additional irrigation water. Richards (1954) recommended increasing the amount of water when using waters of worse quality in order to prevent soil salinization/sodification and achieve higher crop yields. However, Shani and Dudley (2001) report that the critical irrigation level decreased with increasing salinity, thus demonstrating that additional water did not compensate for salt stress. In their work, a decrease in maximum yield was associated with decreased transpiration. The result was that less irrigation was required to produce the highest yield at a given salinity level.

4.3. *Analysis of mean yield response curves on both locations*

By combining the data set of Alvalade and Mitra, the adjustments proved to be statistically significant, with the model explaining 73% of the total observed variations. Furthermore, the model included all the trends verified in the analysis of each individual experimental field. The regression result shows that yield response curves to N and Na^+ are quadratic indicating, as in Alvalade, diminishing returns to the two variable factors. Taking the partial derivate of the multiple regression equation (8) with respect to nitrogen (N) yields:

$$\frac{\partial Y}{\partial N} = 46.63 - 3.4762\,N \tag{14}$$

showing that the rate of yield decreases per unit change in nitrogen level, with the maximum yield being achieved at a level of 13.41 g m^{-2} of N. This result is identical to the N application required at Alvalade and Mitra. The partial derivate of the multiple regression equation (8) with respect to sodium (Na^+):

$$\frac{\partial Y}{\partial Na^+} = -0.5353 - 0.000204\,Na^+ + 0.000719\,W \tag{15}$$

reflects the difference in behaviour between Alvalade and Mitra when taking into account the effect of sodium on yield. Indeed, the rate of yield decreased per unit change in Na^+ level, reaching its maximum at 629.10 g m^{-2} of Na^+ in the irrigation water when considering the mean amount of irrigation water applied on both sites during the 3 years of the experiment (923 mm). Combining all data and observing that Na^+ and W in Eq. (15) have opposite signs, the results show that, similar to Mitra, when the sodium concentration of the irrigation water is increased higher water depths will be required to maintain the yield at similar levels.

5. Conclusions

The models obtained from the multiple stepwise regression analysis of grain yield (Y) and the input factors nitrogen (N), sodium (Na^+), water (W) and their interactions explained 62 and 72% of the total observed variation at Alvalade and Mitra, respectively.

For both experimental sites, yield increases at a decreasing rate per unit change in the N level. The yield response to N application diminishes as N level increases. Maximum yield is obtained by applying 13 g m^{-2} N. Increasing N application above this level will not result in an increase in yield.

At the medium textured soil of Alvalade, yield response to Na^+ application also diminishes with increased Na^+. A maximum yield was achieved at 905.17 g m^{-2} of Na^+ application. This useful effect of irrigation water salinity could be due to the displacement and subsequent availability for the crop of NH_4^+ adsorbed in the soil exchange complex but displaced by increased concentrations of Na^+. In the coarse textured soil of Mitra, yields are not affected by changes in Na^+ level. They respond solely to changes in the level of the input water. In addition, the use of irrigation waters with higher sodium content at Mitra will require the use of more water to maintain yield at the same level as when irrigating with low sodium waters.

The combined results from both sites embody the same trends observed in each individual site, including the positive effect of sodium on maize yield when small amounts up to 630 g m^{-2} are in the irrigation water.

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