Yield and plant ion concentrations in maize (*Zea mays* L.) subject to diurnal and nocturnal saline sprinkler irrigations

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Abstract

The increasing competition for good-quality waters is forcing to use saline waters for irrigation in many areas around the world. Maize (*Zea mays* L.) is considered a moderately sensitive crop to soil salinity, but its response to saline sprinkling irrigations and the potential benefits of irrigating at night to minimize leaf Na^+ and Cl^- uptake are not established. Our objective was to appraise plant ion concentrations and yields of maize subject to diurnal and nocturnal saline sprinkling irrigations. The work was performed in the Middle Ebro River Basin (NE Spain) during three years using a triple line source sprinkler system that diverts waters with an electrical conductivity gradient in-between 0.5 and 5 dS m^{-1}. Na^+ and Cl^- concentrations in different plant tissues increased linearly with applied water ECaw. Plant Cl^- was much higher than plant Na^+ at low ECaw, but leaf ion uptake with increasing ECaw was higher for Na^+ than for Cl^-, and yields were more sensitive to plant Na^+ than to plant Cl^- accumulation. Grain yields were slightly affected by saline sprinkling irrigations in the first year, when soil salinity (ECe < 3 dS m^{-1}) and irrigation water Na^+ (12 meq l^{-1}) and Cl^- (26 meq l^{-1}) concentrations were relatively low. Yields decreased drastically in the third year, due to increasing soil salinity (maximum ECe about 4.5 dS m^{-1}) and irrigation water Na^+ and Cl^- concentrations (about 34 meq l^{-1}). Yields in the diurnal and nocturnal sprinkler irrigations were similar, except in the second year where yield decline was somewhat lower in the nocturnal treatment. Plant Cl^- was similar and plant Na^+ was higher in diurnal than in nocturnal saline sprinkler irrigations, but no significant differences ($P > 0.05$) were found in general among the two irrigation treatments. Even though water evaporation rate was about ten times lower at night than at daytime, irrigating at night was not beneficial in maize in terms of reduced leaf Na^+ and Cl^- accumulation and increased yield.

Keywords: Salinity tolerance, Nocturnal irrigation, Diurnal irrigation, Ion toxicity, Sodium, Chloride, Potassium

1. Introduction

Farmers are increasingly forced to irrigate with low-quality waters due to enhanced competition for water resources by other users (Tanji and Kielen, 2002). Sprinkler irrigation is increasing because of its inherently high irrigation efficiency, automation benefits and labour saving. However, the use of low-quality waters in above-canopy sprinkler systems poses the potential problems of foliar absorption, specific ion toxicity (particularly Na^+ and Cl^-) and decreased yields (Bernstein and Francois, 1975).

To alleviate these problems, irrigating at night rather than at day time has been advocated as a beneficial practice because of lower saline water evaporation from the wetted leaves and decreased tissue ion accumulation (Ehlig and Bernstein, 1959). Thus, the work of Eaton and Harding (1958) under pot conditions demonstrated that orange leaves accumulated more Na^+ and Cl^- when the young trees were sprinkler irrigated during the day rather than at night. However, this recommendation has not been extensively documented, and only the work of Busch and Turner Jr. (1967) demonstrated that the yield of cotton under nocturnal was significantly better than under diurnal saline sprinkler irrigation. Other workers also recommend irrigating at night in saline sprinkler irrigation (Ayers and Westcot, 1985; Shalhevet, 1994; Garg and Gupta, 1995; Maas and Grattan, 1999) but without specific data supporting the apparent benefits of this practice. In contrast, Isla and Aragüés (2009 a, b) concluded that alfalfa grown under a semiarid Mediterranean continental climate had not yield benefits when irrigated at night rather than at daytime in saline sprinkler irrigation.

Maize (*Zea mays* L.), one of the most important crops grown in the irrigated areas of the Middle Ebro River Basin (NE Spain), has been classified as moderately sensitive to soil salinity (threshold soil salinity (ECe) = 1.7 dS m^{-1}) (Maas and Hoffman 1977). Sprinkling with saline waters can exacerbate its sensitivity due to leaf ion uptake and specific Na^+ and Cl^- ion toxicity. Maas (1985) indicated that maize leaves were injured when sprinkler irrigated with waters having Na^+ or Cl^- concentrations of 10-20 meq l^{-1}, but corresponding yield losses were not given. In an outdoor pot experiment, Benes et al. (1996) concluded that maize leaf sap Cl^- and Na^+ increased 2.3 and 17 times from the non-saline control when sprinkler-irrigated with waters of EC = 4.2 dS m^{-1}. The corresponding vegetative biomass was 14% lower in the sprinkled than in the control plants. However, the salt tolerance of maize under saline sprinkler irrigation and the beneficial effects of irrigating at night have not been quantified under field conditions.

This study in maize grown under controlled field conditions analyzes the effects of diurnal versus nocturnal saline sprinkling irrigations on (1) accumulation of plant Cl^-, Na^+, Ca^{2+} and K^+, (2) potential relationships between plant ion concentrations and grain yield, and (3) grain yield response and salinity tolerance.

2. Materials and methods

2.1. Experimental design and cultural conditions

The field trials were carried out during the 2004 to 2006 growing seasons at the CITA experimental station located in the Middle Ebro River Basin (Zaragoza, Spain, 0º49'W, 41º44'N). The soil is a deep *Typic Xerofluvent* high in calcite and with a silty clay loam texture. 2004-2006 mean annual air temperature and total annual precipitation were 14.4ºC and 298 mm, respectively.

The experiment was conducted using a triple line source sprinkler system (TLS) (Aragüés et al. 1992; Isla and Aragüés 2009a) consisting in three parallel sprinkler lines spaced 15 m apart, a distance equivalent to the wetted radius of the sprinklers. In our modified TLS, the two laterals divert saline waters of ECiw (Electrical Conductivity of irrigation water) of about 4.5 to 5.6 dS m^{-1} (depending on years), while the central line diverts fresh water (ECiw = 0.4 dS m^{-1}). The central line consist in two parallel lines with half-circle sprinklers that irrigate independently the left and right areas for the diurnal and nocturnal irrigation treatments, respectively. The overlapping of the two laterals and the central sprinkler lines provide an even distribution in the discharge of irrigation water while creating a linear ECiw gradient on both sides of the central lines. This gradient imposes six salinity treatments within each diurnal and nocturnal irrigation treatment designated as T1 (control, less saline) to T6 (more saline) .

In 2004, the saline solution was made up with a mixture of sodium and calcium chloride with a final SAR (Sodium Adsorption Ratio) of around 4. In 2005 and 2006 the sodium chloride was increased to provide a SAR of around 16-17. This increase was intended to better ascertain the potential toxic effects of Na^+ and Cl^- in maize. Table 1 summarizes the general characteristics of the irrigation events. The seasonal-average EC of the applied water (ECaw; Table 1) is used to take into account the dilution effect of rainfall.

In spring 2004 to 2006, maize (*Zea mays* L. hybrid Dracma, FAO 700) was sown with a conventional driller at a planting density of 85000 seeds/ha (Table 1). Twelve four-row maize strips (2.25 m wide by 30 m long) were selected parallel to the sprinkler laterals, six in the diurnal and six in the nocturnal irrigated areas. Each of these six strips corresponded to each of the six T1 to T6 salinity treatments. Before sowing, the field was fertilized with a complex fertilizer made-up of 80-250-250 Kg ha^{-1} of N-P_2O_5-K_2O. An additional sidedress application of 250 Kg N ha^{-1} was given at about V6 maize growing stage to fully satisfy its nitrogen requirements.

2.2. Irrigation scheduling

One to three 1.5-h irrigations were given per week, depending on crop water needs, to maintain soil water contents close to field capacity. The weekly estimations of maize water needs (ETc = ETo · Kc) were calculated from the reference evapotranspiration (ETo) and the maize crop coefficients (Kc) using the methodology proposed by FAO (Allen et al., 1998). The volume of irrigation water applied in each irrigation was measured in 12 pluviometers installed in the center of each strip or salinity treatment. The volume and EC of precipitation was also measured to calculate the volume and the EC of total applied water (ECaw). At each irrigation, an extra 20% water was applied as leaching fraction to avoid excessive build-up of salts in the soil profile.

Diurnal irrigations were given between 7:00 and 15:00, and nocturnal between 1:00 and 5:00 (GMT time) using an irrigation programmer. The meteorological conditions during these time periods were significantly different (Table 2). Diurnal irrigations were given at higher average temperature, wind speed and solar radiation, and lower relative humidity than nocturnal irrigations (Table 2). Based on these values, the water evaporation rate (WER) estimated in the 60-min period following each irrigation was, depending on years, between 4 and 28 times higher at daytime than at night.

2.3. Water and soil analysis

After each irrigation event, the ECiw of the water collected in each of the 12 pluviometers was measured with a portable EC-meter. Diurnal ECiw were somewhat lower than nocturnal ECiw due to the prevailing wind direction and the corresponding wind drift effect.

The apparent soil electrical conductivity was periodically measured (6, 8, and 10 times in 2004, 2005, and 2006, respectively) during the maize growing period in each salinity treatment with an EM-38 electromagnetic sensor (Geonics Ltd., Ontario, Canada) placed on the ground in its horizontal dipole position. A total of six readings separated 3 m apart were taken in the middle of each salinity treatment. The intervals of EMh readings in the 2004-2006 growing seasons are presented in Table 1. During each growing season, a variable number of points covering the entire interval of the EM-38 readings were selected in two dates for calibration purposes. After reading of the EM-38 at each point, soil samples were taken at two depths (0-0.3 and 0.3-0.6 m) and the electrical conductivity of the soil saturation extract (ECe) was measured in the laboratory. The following calibration equations were obtained in each year:

$$2004: ECe = 4.52\ EMh + 0.02,\ R^2 = 0.53,\ n = 19$$

$$2005: ECe = 5.02\ EMh - 0.92,\ R^2 = 0.71,\ n = 60$$

$$2006: ECe = 3.56\ EMh - 0.07,\ R^2 = 0.74,\ n = 37$$

where ECe is the mean of the 0-30 and 30-60 cm soil depths (dS m^{-1} at 25ºC), EMh is the apparent soil electrical conductivity (dS m^{-1} at 25ºC), and n is the number of points.

Using these calibration equations, the seasonal-average EMh values for each T1-T6 salinity treatment in each year were converted into the corresponding ECe estimates. This estimated 0-60 cm soil depth seasonal-average ECe is the soil salinity index used in each treatment and year, and will be simply referred as ECe.

Figure 1 shows the relationships between ECaw and ECe in each experimental year. As expected, the slopes of the regression equations increased from 2004 to 2006 because of the progressive salinization of the soil induced by the continuous application of saline waters with the TLS system.

2.4. Crop measurements and plant analyses

The maize trials were harvested in early autumn (Table 1). Within each salinity treatment, three areas of 5 m^2 were randomly selected to measure grain yield. The ears from these areas were counted and the grain threshed out and weighted. Grain moisture was measured and grain yield was given as kg ha^{-1} at 14% humidity. In each experimental subplot an area of 2 m^2 was selected to measure the total aerial dry matter and a subsample of the vegetative parts (all except seeds) was taken for ion analyses.

Young, mature and ear leaves at different crop stages, and the whole plant (excluding grain and cobs) at harvest were sampled for ion analyses (Table 3). The harvested material was rinsed three times in deionized water to remove surface salts and soil particles. Plant material was oven dry at 65ºC until constant weight and was finely ground using a 0.5-mm sieving mill. A sample of 0.25 g was extracted with 50 mL of an extracting solution made of 900 mL of deionized water, 100 mL of acetic acid, and 6.4 mL of nitric acid. Chloride was analyzed using a chloridometer (Cotlove 1963), and sodium, potassium and calcium by flame photometry using a continuous flow auto analyzer (AA3 - Bran Luebbe). Plant ion concentrations are given in meq kg^{-1} dry weight. Ion concentrations in irrigation water were analyzed with the same equipments.

2.5. Statistical analysis

The statistical analyses were performed using the SAS 9.1 software (SAS Inst., 1996). Comparison of regression lines was made using an F-test, taking the root mean error (RME) of the overall regression as the error for the pairwise comparisons. The Marquardt algorithm (proc NLIN) was used to estimate the non-linear models. The Cate-Nelson (Cate and Nelson, 1971) procedure was also used to estimate the threshold values of plant ion concentrations. The significance of the regression analyses and parameter's comparison were indicated as **, *, and NS for probability levels (P) of < 0.01, < 0.05, and > 0.05, respectively. The standard error of the model parameters is abbreviated as SE. Relative yields in each saline treatment (T2-T6) were obtained by dividing its yields by those in the control treatment (T1).

3. Results and discussion

3.1. Effect of saline sprinkler irrigations on plant Cl^-, Na^+ and Ca^{2+} concentrations

Plant Cl^-, Na^+ and Ca^{2+} concentrations were better correlated with applied water salinity (ECaw) than with soil salinity (ECe). Thus, for the 24 samplings performed during 2004-2006 (Table 3) all the correlation coefficients of Cl^- and Na^+ vs. ECaw were positive and significant ($P < 0.05$), whereas only 12 were significant with ECe. These significant correlations with ECe occurred in samplings 7 to 12 (i.e., in late 2005 and along 2006), when soil salinity increased due to the progressive salinization of the soil along the study period (Fig. 1). These results indicate that plant Na^+ and Cl^- concentrations were preponderantly the result of leaf rather than root absorption. Similar results were found by Benes et al. (1996) showing that leaf uptake accounted for 48 % and 98 % of total leaf Cl^- and Na^+ contents in maize sprinkler irrigated with saline waters (EC = 4.1 dS m^{-1}). The results obtained with plant Ca^{2+} show that 8 and 4 out of the 12 correlations with ECaw and ECe, respectively, were positive and significant ($P < 0.01$). Thus, averaging over the three experimental years, total whole plant Ca^{2+} at harvest in the highest T6 saline treatment (239 meq kg^{-1}) was 1.4 times higher than in the T1 control treatment (174 meq kg^{-1}). These results differ to those of Benes et al (1996), where leaf Ca^{2+} concentrations decreased with increasing saline sprinkling waters.

Figure 2 presents, for each plant tissue analyzed, the scatter plots of plant Na^+ and Cl^- concentrations measured in the 2004-2006 diurnal and nocturnal irrigation treatments *versus* salinity of applied water (ECaw). The pooled 2004-2006 diurnal and nocturnal linear regressions are also presented when slopes and intercepts where not significantly different ($P > 0.05$) between years. No significant differences ($P > 0.05$) were found between the diurnal and nocturnal regressions, indicating that plant Na^+ and Cl^- concentrations were independent of the imposed irrigation treatments.

Plant Cl^- was much higher than plant Na^+ at low ECaw values, but this difference become lower at high ECaw values (Fig. 2), indicating higher relative Na^+ than Cl^- leaf uptake rate. In terms of differences between plant tissues, a comparison based on average concentrations for the two highest saline treatments (T5 and T6) shows that the highest Na^+ concentration was found for the whole plant at harvest (464 meq kg^{-1}), whereas young leaves had the lowest Na^+ concentration (159 meq kg^{-1}) and mature and ear leaves presented intermediate values. For Cl^-, the whole plant also had the highest concentration (883 meq kg^{-1}), whereas the ear leaf showed the lowest (379 meq kg^{-1}) and young and mature leaves presented intermediate values. The differences found between young and mature leaves were probably associated to lower exposure time of young leaves to sprinkling with saline water. These results also suggest that maize plants compartmentalize significant amounts of Cl^- and Na^+ in the stems and/or leaf sheaths, reducing the build-up of toxic ions in the more sensitive leaf blades.

The analysis of the diurnal and nocturnal slopes of the linear regressions of Na^+ *versus* ECaw calculated for each of the 12 samplings shows that one diurnal slope was higher than the nocturnal slope at $P < 0.01$ (sampling nº 8), three diurnal slopes were higher than the nocturnal slopes at $P < 0.05$ (samplings nº 5, 6 and 11), and eight were not significantly different ($P > 0.05$) (Figure 3 a). Diurnal Na^+ slopes were, on the average, 1.4 times higher than nocturnal slopes, suggesting that, although not significant, Na^+ accumulation tended to be higher in diurnal than in nocturnal irrigations. In contrast, diurnal and nocturnal Cl^- slopes were the same in all sampling dates except sampling nº 3, where the diurnal slope was significantly higher ($P < 0.05$) than the nocturnal slope (Figure 3 b). On the average, diurnal Cl^- slopes were only 1.1 times higher than nocturnal slopes, indicating that Cl^- accumulation was similar in diurnal and nocturnal sprinkler irrigations. These results confirm that, even though the water evaporation rate (WER) estimated in the 60-min period following each irrigation was on the average ten times higher at daytime than at night (Table 2), no significant differences were found in general in the absorption of Na^+ and, particularly, Cl^- by the wetted leaves under diurnal and nocturnal sprinkler irrigations.

The work of Busch and Turner Jr. (1967) in cotton sprinkler irrigated with saline waters found a reduction in leaf Na^+ and Cl^- accumulation under nocturnal irrigations. This is a remarkable difference with our results, taking into account that diurnal was on the average ten times higher than nocturnal water evaporation rates in our work, as compared to only three times higher in the Busch and Turner work. These differences may arise from the different pore densities in the cuticle leaves of cotton and maize, which is the main solute's pathway through the leaves (Marschner, 1995). The speed rotation of sprinklers and its overlapping may also have an effect on leaf ion uptake, since Maas et al. (1982) found that it takes place mainly during the drying periods in-between rotations and immediately after the end of each irrigation event.

3.2. Effect of soil salinity on plant K^+ concentration

Since irrigation water K^+ was very low (about 0.3 meq L^{-1}) and similar in the T1 to T6 saline treatments, plant K^+ (young, mature and ear leaves, and whole plant) was related with soil salinity (Table 4). None of the K^+ concentrations in the different plant components were correlated with ECe in 2004, probably due to small differences in ECe between treatments (Fig. 1). Negative and significant ($P < 0.05$) correlations were found in 2005 for ear leaf and whole plant K^+ vs. ECe, whereas all the plant component's K^+ concentrations were negatively and significantly ($P < 0.01$) correlated with ECe in 2006, when differences in soil salinity between treatments were relevant (Fig. 1). Hence, soil salinity build-up caused a decrease in leaf K^+ concentrations in all the analyzed plant components.

Relative whole plant K^+ concentrations of the pooled 2004-2006 years were regressed against soil salinity using a piecewise linear model (Fig. 4). The coefficient of determination (R^2) of this model was significant ($P < 0.01$). The threshold ECe was 4.4 dS m^{-1} (SE = 0.15), and the slope (percent K^+ decline per unit increase in ECe) was 28.1% (SE = 5.9). These results agree with those of Benes et al. (1996) in maize subject to saline sprinkler irrigations in that increases in leaf Na^+ produced significant decreases in plant K^+ and in the plant K^+/Na^+ ratio.

3.3. Relationships between plant ion accumulation and maize yield

Relationships between relative grain yields and plant Na^+ and Cl^- concentrations at harvest were fitted through a piecewise linear model (Figure 5). Since diurnal and nocturnal irrigations behaved similarly, they were pooled together for this analysis. Grain yields and plant concentrations above the threshold values were negatively correlated ($P < 0.05$). The threshold values were 422 meq Na^+ kg^{-1} and 623 meq Cl^- kg^{-1}, and the slope values were -0.16 % /meq Na^+ kg^{-1} and -0.11 %/meq Cl^- kg^{-1}. Hence, Na^+ accumulation was more detrimental (i.e., lower threshold and slope values) than Cl^- accumulation in maize sprinkler irrigated with saline waters. This higher Na^+ sensitivity of maize is not general, since plant species differ in their relative tolerances to Na^+ or Cl^- (Munns and Tester, 2008). Due to the Na^+-K^+ discrimination found in most plant species grown in saline conditions, yields were positively correlated ($P < 0.01$) with plant K^+ (Fig. 5 c) and plant K^+/Na^+ (Fig. 5 d). The threshold values of 416 meq K^+ kg^{-1} and 1.05 for K^+/Na^+ would provide the minimum levels to avoid yield losses under saline sprinkling irrigation.

The above thresholds were also estimated using the Cate-Nelson method (Cate and Nelson, 1971). Both methods of estimation gave similar values, except for plant Cl^- where the Cate-Nelson method provided a significantly higher value (879 meq Cl^- kg^{-1}), reinforcing the conclusion in that the accumulation of Na^+ is more toxic and detrimental than the accumulation of Cl^- in terms of yield decrease in maize.

Relative grain yields and ion concentrations measured at earlier plant stages (young and mature leaves at V8 stage and ear leaf at R1 stage) were also fitted using the piecewise linear response model (Table 5). The R^2 values were lower than those obtained for the whole plant, and two out of the twelve fittings were not significant ($P > 0.05$). Mature leaves gave better correlations than the other plant tissues sampled. In mature and young leaves, Cl^- threshold estimates were 3.6 and 2.9 times higher than Na^+ threshold estimates, respectively, corroborating that maize plants sprinkler irrigated with saline waters are able to cope with leaf

Cl^- concentrations much higher than leaf Na^+ concentrations before grain yields are significantly affected.

3.4. Salinity-yield response functions

Figure 6 presents the response functions of maize grain yield to applied water salinity (ECaw) for the diurnal and nocturnal 2004-2006 sprinkling treatments. The 2004 yields tended to decrease with increasing ECaw values, and the pooled diurnal and nocturnal observations were linearly correlated with ECaw, but only at $P < 0.1$. The individual diurnal and nocturnal linear regressions were not significant ($P > 0.05$), indicating that yields were independent of irrigation water salinity in both irrigation treatments. It should be noted that soil salinity in 2004 was low (Fig. 1) and that the maximum Na^+ (12.4 meq L^{-1}) and Cl^- (25.8 meq L^{-1}) concentrations in irrigation water were lower than in the following years (Table 1).

The 2005 yields were best fitted to ECaw using a piecewise linear model (Maas and Hoffman, 1977) (Fig. 6 b). The R^2 values for this model were significant ($P < 0.05$), although much higher for the diurnal ($R^2 = 0.95$) than the nocturnal ($R^2 = 0.67$) treatment. The threshold ECaw values were similar in the diurnal ($ECaw_{thr.}$ = 2.8 dS m^{-1}, SE = 0.3 dS m^{-1}) and nocturnal ($ECaw_{thr.}$ = 3.1 dS m^{-1}, SE = 1.7 dS m^{-1}) treatments, indicating that the onset of yield decline in maize subject to saline sprinkler irrigation was independent of the irrigation treatment. The slope of the nocturnal treatment was not different from zero ($P > 0.05$), whereas it was significantly different from zero ($P < 0.05$) in the diurnal treatment. Thus, yield decline per unit increase in ECaw above the threshold was lower in the nocturnal than in the diurnal treatment.

In 2006, when soil ECe attained maximum values (Fig. 1), a threshold ECaw was not apparent and grain yields were best fitted to ECaw using a linear regression model (Fig. 6 c). The regression equations of the diurnal and nocturnal treatments were not significantly different ($P > 0.05$), indicating that sprinkling at night with saline waters did not improve yields over those in diurnal irrigation. Irrespective of the irrigation treatment, the 2006 yields close to 11 Mg ha^{-1} in the non-saline control, decreased to values of about 2 Mg ha^{-1} when the maize plants were subject to soil ECe (Fig. 1) and applied water ECaw (Fig. 5 c) of about 4.5 dS m^{-1}.

The 2006 pooled diurnal and nocturnal relative grain yields were significantly correlated ($R^2 = 0.83$, $P < 0.01$) with soil ECe. The slope of the linear regression equation (- 42 %/dS m^{-1}; SE = 5.9), is about 3.5 times lower than the slope of -12% given by Maas and Hoffman (1977) for surface-irrigated conditions. This difference may be attributed to a higher accumulation of toxic ions in the sprinkler irrigated maize plants subject to both root and foliar absorption of salts. Similar results were obtained by Isla et al. (1997) in barley and Isla and Aragüés (2009 b) in alfalfa.

The relationships between maize yield components and salinity of applied water (ECaw) (Table 6) show that in 2004 the ears ha^{-1}, grains ear^{-1} and thousand kernel weight were not affected by ECaw, in agreement with the lack of significant decreases in grain yield (Fig. 6 a). In 2005, the moderate decreases in grain yield with increases in ECaw (Fig. 6 b) were due to the negative and significant ($P < 0.01$) effect of ECaw on grains ear^{-1}, since the rest of components were not affected. In 2006, the significant decreases in grain yield (Fig. 6 c) were due to significant decreases in all the components. Total above ground biomass and harvest index were also negatively affected by ECaw (Table 6).

Under the typical irrigation conditions of the Middle Ebro basin (Spain), with scarce winter precipitations (historical average = 131 mm between November and March), the winter leaching of salts may be insufficient to compensate for the accumulation of salts along the irrigated season. Thus, the response of maize to continuous sprinkling irrigations with saline waters will resemble the results obtained in 2006, when both soil and irrigation water salinity affect yield response drastically. In areas with higher winter precipitations and higher leaching of accumulated salts, the 2004 or 2005 scenarios will be more likely to occur, and maize could be grown under sprinkler irrigation with the given irrigation water salinities without significant decreases in grain yield.

4. Conclusions

Effect of saline sprinkler irrigations on plant Cl^-, Na^+ and K^+ concentrations

Plant Cl^- and, particularly, Na^+ concentrations increased with increases in applied water salinity (ECaw), and were preponderantly the result of leaf rather than root absorption. Plant Cl^- was much higher than plant Na^+ at low salinity values, but the rate of leaf ion uptake for Na^+ was higher than for Cl^-. Maize plants compartmentalize significant amounts of Cl^- and Na^+ in the stems and/or leaf sheaths, reducing the build-up of toxic ions in the more sensitive leaf blades.

Plant Cl^- was similar and plant Na^+ was higher for the diurnal than the nocturnal saline sprinkler irrigations, but no significant differences ($P > 0.05$) were found in general among the two irrigation treatments indicating that, even though water evaporation rate was about ten times higher at daytime than at night, irrigating at night did not significantly reduced plant Na^+ and Cl^- accumulation.

The build-up of soil salinity (ECe) along the study years produced significant decreases in K^+ concentrations in all plant components. Plant K^+ was negatively correlated ($P < 0.01$) with ECe through a piecewise linear model with a threshold ECe of 4.4 dS m^{-1} and a slope (i.e., percent decline in plant K^+ per unit increase in ECe above the threshold) of 28.1%.

Relationships between plant ion accumulation and maize yield

Grain yields and plant Na^+ and Cl^- concentrations measured at harvest were negatively correlated ($P < 0.05$), but plant Na^+ accumulation was more detrimental (i.e., lower threshold and slope values) than plant Cl^- accumulation. In contrast, grain yields, plant K^+ concentrations and K^+/Na^+ ratios were positively correlated ($P < 0.01$).

The slope for the linear regression between relative grain yield and soil salinity in sprinkler irrigation was about 3.5 times lower than the Maas and Hoffman (1977) slope for surface irrigation. The Maas and Hoffman's study compiled data from two experimental works published in 1949 and 1964. Therefore, important genetic differences between the hybrid used in our study and the ones used in the mentioned studies must be expected. In addition the higher sensitivity of sprinkler irrigated maize could be in part attributed to a higher accumulation of toxic ions when plants are subject to both root and foliar absorption of salts (i.e., sprinkler irrigation) than when subject only to root absorption of salts (i.e., surface irrigation).

The fitting of relative grain yields and ion concentrations measured at earlier plant stages corroborate that maize plants sprinkler irrigated with saline waters were able to cope with leaf Cl^- concentrations much higher than leaf Na^+ concentrations before grain yields were significantly affected.

Salinity-yield response functions

Maize grain yields subject to diurnal or nocturnal irrigations were independent of ECaw in 2004, when soil salinity and maximum Na^+ and Cl^- concentrations in applied water were relatively low. In 2005, with higher soil salinity and applied water Na^+ and Cl^- concentrations, yields and ECaw were significantly correlated ($P < 0.05$) through a piecewise linear model. The threshold ECaw values were similar for the diurnal (2.8 dS m^{-1}) and nocturnal (3.1 dS m^{-1}) treatments, whereas yield decline per unit increase in ECaw above the threshold was lower in the nocturnal treatment. Yields in the 2006 diurnal and nocturnal saline sprinkling irrigations were severely and similarly affected, with decreases in yield over the control of about 80% in the highest saline treatment (soil ECe and applied water ECaw of about 4.5 dS m^{-1}).

The observed differences in the yield-EC responses between years is highlighting the different possible scenarios depending of the degree of soil salinization at the beginning of the crop season of maize that is mainly related to the amount of rainfall during the winter intercrop period.

The general conclusion for the three study years is that sprinkling at night with saline waters did not increase maize grain yields over those in diurnal irrigation, and that yield decreases are higher compared to a system where salts are exclusively absorbed by the roots.

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Table 1

General characteristics of the trial and irrigation events for the 2004 to 2006 experimental years.

Experimental year	2004	2005	2006
Sowing date	May 17	April 15	April 27
Harvest date	Oct. 22	Oct. 19	Sept. 28
Number of irrigations	41	31	44
Total water applied[a] (mm)	653	885	951
Crop Evapotranspiration (mm)	632	811	814
First saline irrigation	June 17	May 20	May 20
Last saline irrigation	Oct. 6	Oct. 5	Sept. 12
T1 – T6 EMh interval [b] (dS m^{-1})	0.67 – 0.94	0.91 – 1.31	0.84 – 1.46
Saline treatments T1 to T6			
T1 – T6 ECaw interval [c] (dS m^{-1})	0.3 – 4.1	0.5 – 4.7	0.5 – 4.3
T1 – T6 Na^+ interval (meq L^{-1})	1.5 – 12.4	2.8 – 37.6	2.1 – 32.8
T1 – T6 Cl^- interval (meq L^{-1})	1.5 – 25.8	3.4 – 38.1	3.4 – 34.6
T1 – T6 Ca^{2+} interval (meq L^{-1})	1.0 – 22.9	2.2 – 9.2	2.2 – 8.5
T1 – T6 SAR interval (meq $L^{-1})^{0.5}$	1.9 – 3.4	4.2 – 17.2	4.7 – 17.1

[a] Irrigation + precipitation

[b] EMh: year average of electromagnetic sensor readings in the horizontal-dipole position.

[c] Electrical conductivity of applied water (ECaw) = volume-weighted average of EC irrigation water and EC precipitation.

Table 2

2004-2006 mean temperature (T), relative humidity (RH), wind speed (WS) and solar radiation (SR) measured in the hour after each diurnal and nocturnal sprinkler irrigation. The estimated water evaporation rate (WER) is shown in the last column.

Year	Sprinkler Irrigation	T (ºC)	RH (%)	WS ($m\ s^{-1}$)	SR ($w\ m^{-2}$)	WER[a] ($mm\ h^{-1}$)
2004	Diurnal	27.7	41.9	2.8	662	0.63
	Nocturnal	18.1	76.7	1.6	156	0.03
2005	Diurnal	24.9	60.1	2.2	649	0.55
	Nocturnal	17.1	76.7	1.2	24	0.02
2006	Diurnal	21.2	56.0	2.5	457	0.35
	Nocturnal	16.9	71.3	1.8	103	0.09

[a] WER = Ep (class-A evaporation pan). $Ep=ET_0 \times Kp$; ET_0 estimated using FAO methodology and a Kp coefficient that depends on air humidity and wind speed.

Table 3

2004-2006 sampling number, date of sampling, crop stage and plant material for ion analyses. Total number of samplings = 24 (12 in the diurnal and 12 in the nocturnal irrigation treatments).

Year	Sampling	Date	Crop stage	Plant material[a]
2004	1	June 30	V8	young leaf
	2	July 19	V12	young leaf
	3	Aug. 18	R2	ear leaf
	4	Oct. 22	harvest	whole plant
2005	5	June 23	V8	young leaf
	6	June 23	V8	mature leaf
	7	July 27	R1	ear leaf
	8	Oct. 17	harvest	whole plant
2006	9	June 29	V8	young leaf
	10	June 29	V8	mature leaf
	11	July 27	R1	ear leaf
	12	Oct. 4	harvest	whole plant

[a] Leaf includes only blades; whole plant without grain and cob

Table 4

2004-2006 linear correlations between plant K^+ concentrations (meq kg^{-1}) and soil ECe (dS m^{-1}). Diurnal and nocturnal treatments were pooled at each sampling.

Plant tissue	2004	2005	2006
Young leaf	ns	ns	- 0.60*
Mature leaf	-	ns	- 0.84**
Ear leaf	ns	- 0.80**	- 0.83**
Whole plant	ns	- 0.61*	- 0.88**

Table 5

Slope and threshold parameters (± SE) of the piecewise linear model adjusted to relative grain yields vs. ion concentrations (Na^+, Cl^-, K^+, K^+/Na^+) measured in young, mature and ear leaves at the given samplings. Model fitted to the pooled nocturnal and diurnal irrigation treatments of the 2004 to 2006 experimental years.

Variable	slope (% / meq kg^{-1})	threshold (meq kg^{-1})	R^2
Samplings 1, 5, 9 – Young leaf			
Cl^-	(ns)	434 ± 108	0.10
Na^+	- 0.38 ± 0.10	148 ± 20	0.41
K^+	0.39 ± 0.09	643 ± 18	0.39
K^+/Na^+	13.3 ± 3.4	5.2 ± 0.5	0.43
Sampling 6, 10 – Mature leaf			
Cl^-	- 0.33 ± 0.09	487 ± 34	0.55
Na^+	- 0.26 ± 0.08	136 ± 50	0.50
K^+	0.26 ± 0.04	618 ± 30	0.75
K^+/Na^+	28.3 ± 6.6	3.3 ± 0.4	0.65
Sampling 3, 7, 11 – Ear leaf			
Cl^-	- 0.30 ± 0.06	272 ± 27	0.56
Na^+	- 0.14 ± 0.04	(ns)	0.31
K^+	(ns)	397 ± 81	0.09
K^+/Na^+	8.3 ± 3.6	4.7 ± 1.5	0.24

Table 6

2004-2006 linear correlations between salinity of applied water (ECaw, dS m^{-1}) and maize yield components. Diurnal and nocturnal treatments were pooled.

	2004	2005	2006
Ears ha^{-1}	(ns)	(ns)	- 0.69*
Grains ear^{-1}	-0.55	- 0.82**	- 0.94**
Thousand kernel weight	(ns)	(ns)	- 0.92**
Total aboveground dry matter	- 0.64*	-0.55	- 0.97**
Harvest index	(ns)	(ns)	- 0.87**

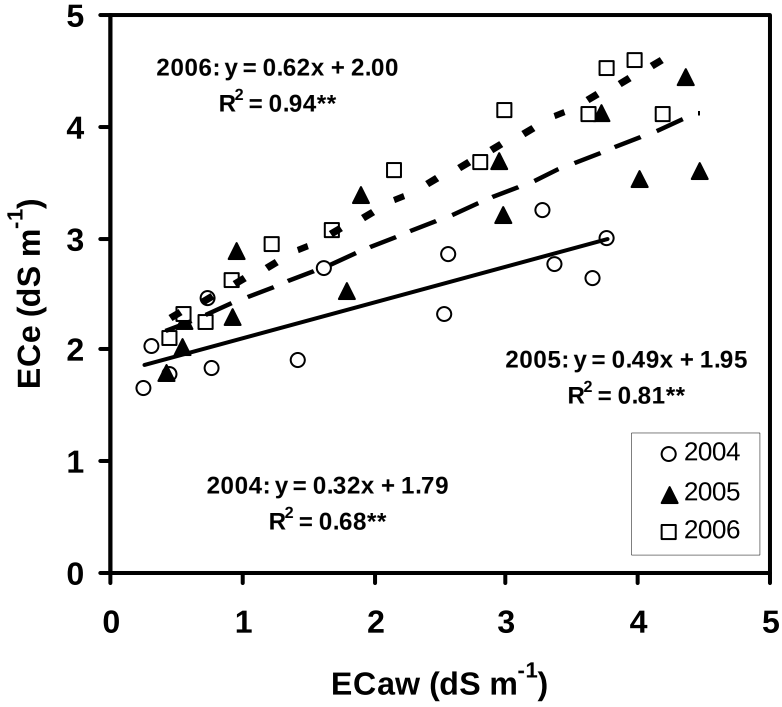

Fig. 1. Relationships and linear regression equations between the seasonal-average salinity of the applied water (ECaw) and the estimated seasonal-average soil salinity (ECe) in each 2004 to 2006 experimental year (pooled diurnal and nocturnal treatments).

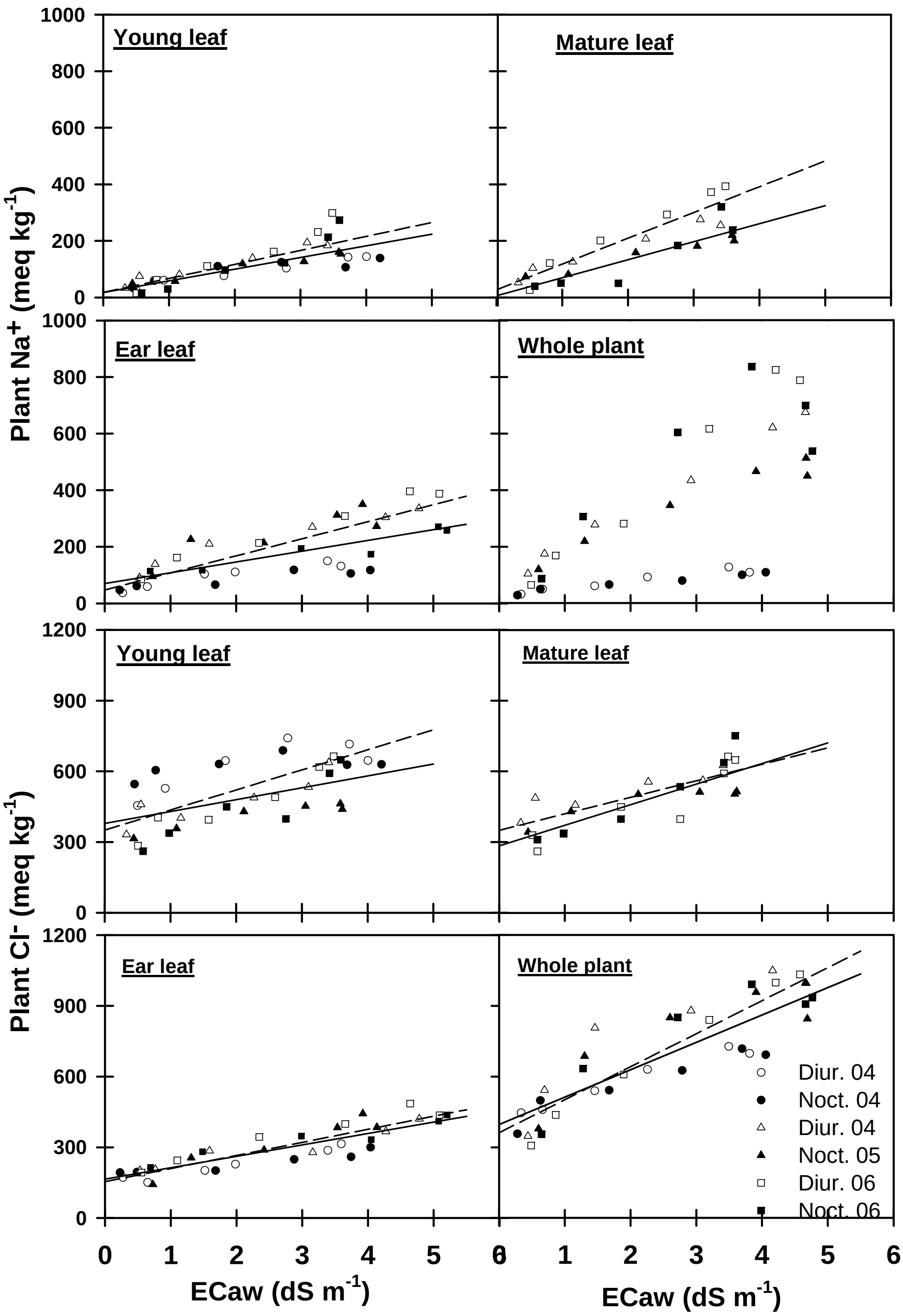

Fig. 2. Scatter plots of plant Na^+ and Cl^- concentrations *versus* the electrical conductivity of applied water (ECaw) in the 2004-2006 diurnal and nocturnal sprinkler irrigations. Data grouped by plant tissue (young, mature and ear leaves, and whole plant). Pooled 2004-2006 linear regressions of diurnal (dashed line) and nocturnal (solid line) irrigations are presented when differences between years were non-significant.

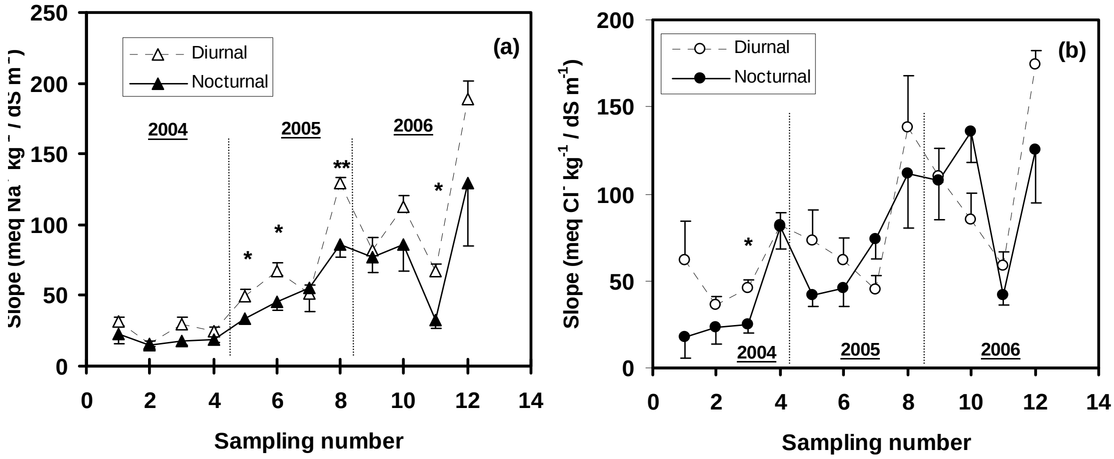

Fig. 3. Slopes of linear regressions of plant Na^+ and Cl^- concentrations *versus* salinity of applied water (ECaw) for each of the twelve samplings of the diurnal and nocturnal sprinkler irrigations. Vertical bars represent one standard error. Symbols *, and ** indicate diurnal and nocturnal slopes statistically different at P < 0.05 and < 0.01, respectively.

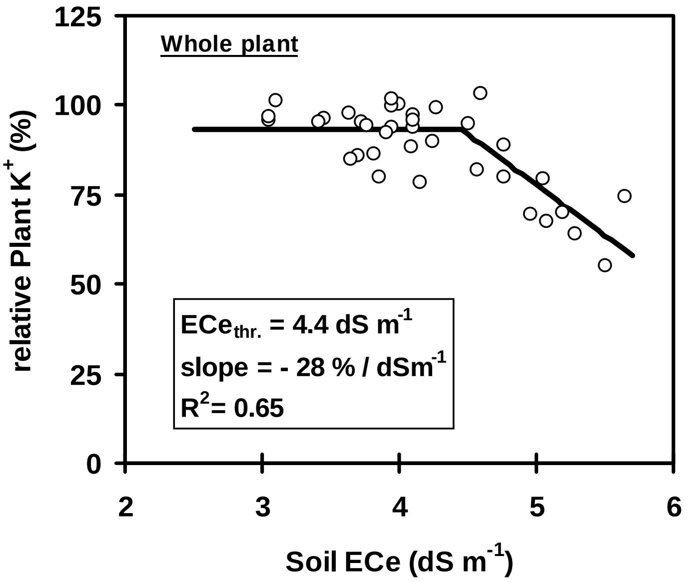

Fig. 4. Piecewise linear model of relative plant K^+ concentration at harvest *versus* soil salinity (ECe) for the 2004-2006 diurnal and nocturnal pooled data.

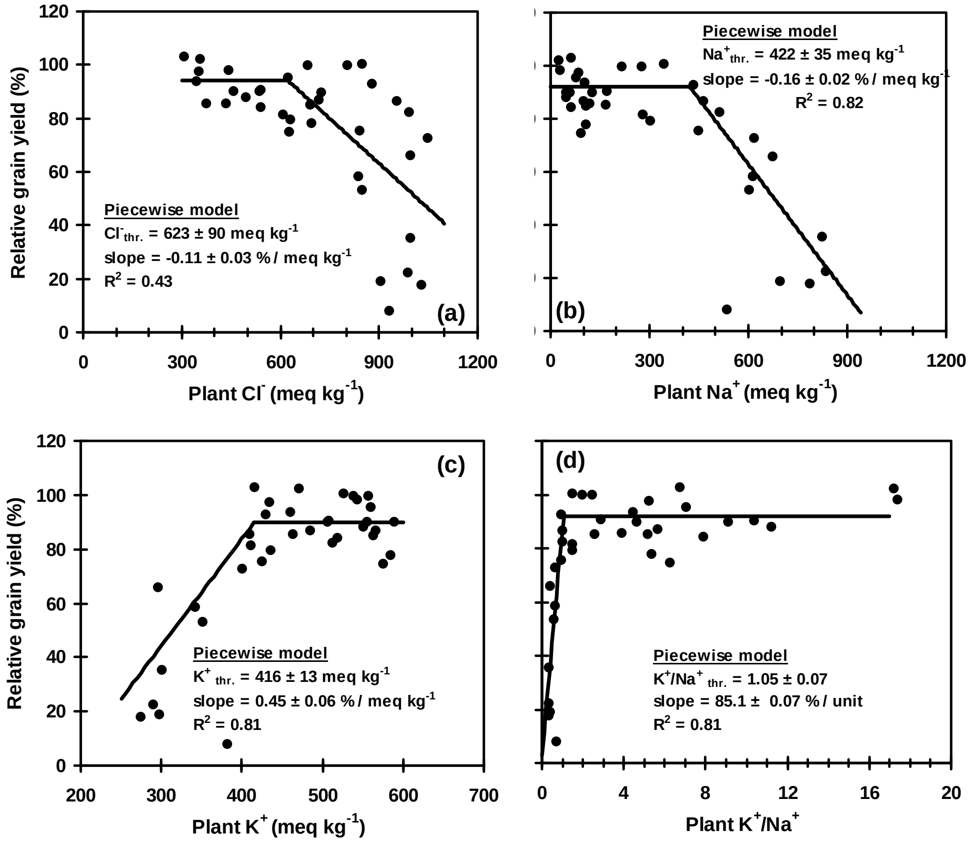

Fig. 5. Relationships and piecewise linear model equations between relative maize grain yield and plant (a) Cl^- , (b) Na^+, (c) K^+ concentrations, and (d) plant K^+/Na^+ ratio for the whole plant (excluding ears) at harvest. Pooled data for the 2004-2006 experimental years and the diurnal and nocturnal sprinkler irrigations. The threshold and slope estimates (± SE) and the R^2 of the models are presented

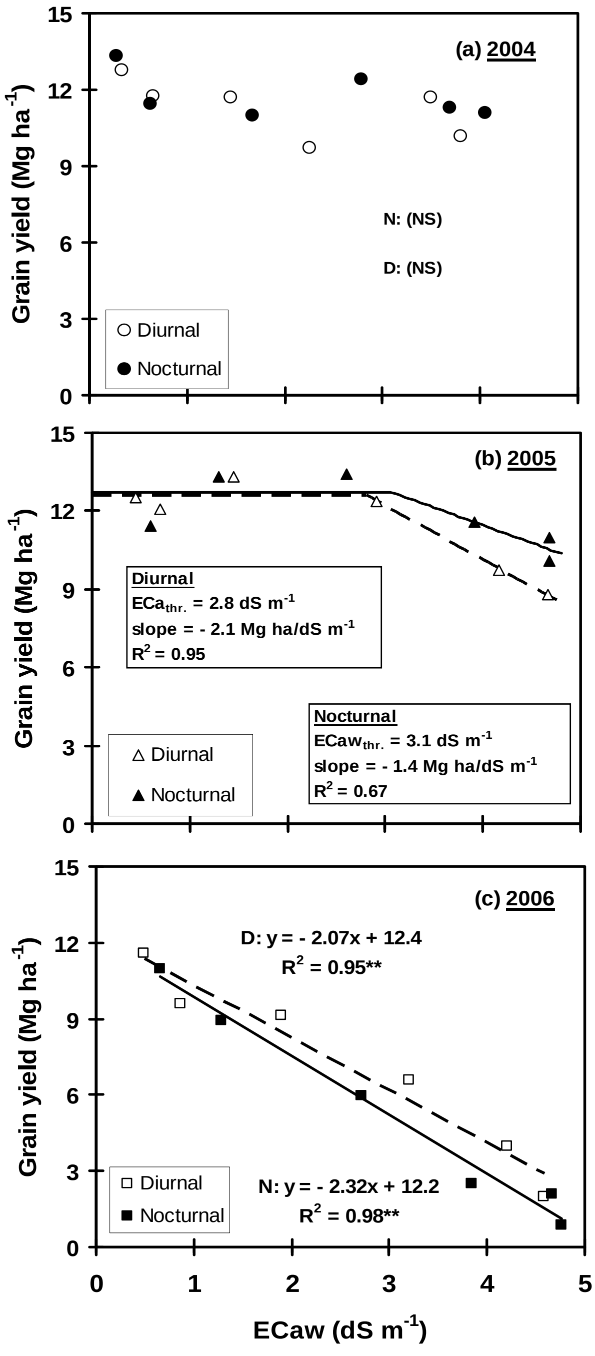

Fig. 6. 2004-2006 relationships between maize grain yield and electrical conductivity of applied water (ECaw) for the diurnal and nocturnal sprinkler irrigations. Linear regression and piecewise linear response models adjusted to the data where appropriate.