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Title: Effects of deficit irrigation strategies on soil salinization and sodification in a semiarid drip-irrigated peach orchard

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Abstract

Deficit irrigation strategies save water, but may enhance soil salinization and sodification when irrigated with low-quality waters. The objectives of this five-year study performed in the middle Ebro Basin (Spain) were to quantify these processes and assess their potential deleterious impact on the response of peach trees subjected to full irrigation (FULL), sustained deficit irrigation (SDI, irrigated at 62.5% of FULL) and regulated deficit irrigation (RDI, irrigated at 50% of FULL in Stage II of fruit development). In relation to FULL, water savings were 40% in SDI and 9% in RDI. Soil salinity (ECe), chloride concentration (Cle) and sodicity (SARe) measured in the saturation extract of 480 soil samples generally increased in the irrigation seasons, particularly in the more severe deficit irrigation strategy (SDI). These increases were counteracted by the leaching of salts induced by high leaching fractions (LF) and low water deficits (WD) attained during the non irrigation seasons. The changes in ECe, Cle and SARe measured between sampling dates were significantly correlated ($p < 0.01$) with WD and LF calculated for the periods between sampling dates. These parameters were therefore suitable to estimate the required irrigation depths for soil salinity and sodicity control. Peach trees were unaffected by the irrigation treatments, but yield productivity tended to decline above a threshold ECe of 4 dS m^{-1}. Under the irrigation salinity (mean EC = 1.1 dS m^{-1}) and the semiarid climatic characteristics of the study area, the three examined irrigation strategies proved to be sustainable in the five studied years.

Keywords: Drip irrigation, salinity, sodicity, leaching fraction, water deficit, leaf ions

1. Introduction

Deficit irrigation consists in the application of water below full crop water requirements, so that a mild crop water stress is allowed with minimal effects on yield. The three most common deficit irrigation strategies are: (1) regulated deficit irrigation (RDI), where water deficit is applied at certain developmental stages, (2) partial root-zone drying (PRD), where alternatively half of the root system is fully wetted while the other half is allowed to dry, and (3) sustained deficit irrigation (SDI), where water deficit is uniformly distributed over the whole crop cycle (FAO 2002).

Deficit irrigation strategies have potential benefits such as substantial savings of water with little impact on the quality and quantity of the harvested yield, increased crop water productivity and farm profitability, and enhanced environmental protection (Ragab 1996; Fereres and Soriano 2007; Geerts and Raes 2009; Ruiz Sanchez et al. 2010). With increasing growing competition for water, there will be a more widespread adoption of deficit irrigation, particularly in areas with limited water resources. However, it is uncertain whether deficit irrigation is a sustainable strategy, particularly in arid and semiarid areas irrigated with low-quality waters. Thus, several publications have indicated that soil salinization is a potential problem linked to deficit irrigation (Sarwar and Bastiaanssen 2001; Kaman et al. 2006; Hsiao et al. 2007; Raine et al. 2007; Geerts and Raes 2009) but few of them have quantified this risk.

Shalhevet (1994) indicated that although deficit irrigation has the potential to improve soil salinity management by a better control of rising water tables and by a reduction in the import of salts by irrigation water, it does not provide the same degree of leaching than full irrigated conditions. Ghrab et al. (2013) evaluated root zone salinity distribution in an olive orchard subjected to PRD that supplied a volume of saline water that was 50% of the volume applied to the full irrigation treatment. PDR added less salts to the soil than the full irrigation treatment, and these salts were leached during the wet season keeping soil salinity to levels not harmful to olive trees. These authors concluded that PRD with their saline waters assured long term olive yields. In contrast, Nasr and Ben Mechlia (2002) studied the application of RDI to reduce soil salinization in an apple orchard and concluded that the potential reductions in soil salinization because of the lower amounts of added salts were only experienced under natural salt leaching arising from high precipitations and that, otherwise, irrigation should be increased to control root zone salt accumulation.

Boland et al. (1993) determined in a lysimeter trial the yield response of thirty-three peach trees to saline irrigations (0.25 to 1.0 dS m^{-1}) when combined with RDI. Significant adverse effects were observed on the productivity of peach trees, even with the low EC water of 0.25 dS m^{-1}. Although these authors indicated that winter leaching under field conditions would be more extensive than in the lysimeters, their results would oppose the use of restricted irrigations given the severe effects of quite low levels of irrigation water salinity, highlighting the need for leaching and modification of current RDI management when using saline waters. Mounzer et al (2013) showed the development of high transient saline-sodic conditions under the combined effects of saline reclaimed water and RDI in Mandarin trees, and concluded that soil water deficits should be avoided whenever saline reclaimed water is used for irrigation.

Soil salinization is a major threat in fruit trees since they are among the most salt-sensitive horticultural crops (FAO 1985). The reduction in growth and yield is related to the osmotic potential of the soil solution and to specific ion toxicities. In the absence of specific ion effects and based on the vegetative response of scions from young trees, Maas and Hoffman (1977) ranked the salinity tolerance of peach trees with a threshold ECe (soil saturation extract electrical conductivity) of 1.7 dS m^{-1} and a slope (yield decrease per unit increase in ECe above the threshold) of 21% per dS m^{-1}. Bernstein (1980) specified that the yield of peach trees decreases by 10% at an ECe of 2.5 dS m^{-1}, whereas Hoffman et al. (1989) reported that peach fruit weight and the number of peach fruits per tree were reduced by about 50% at an ECe, dominated by chloride salts, of about 3 dS m^{-1}.

Besides the osmotic potential effect, fruit trees are also very sensitive to leaf Cl and Na toxic concentrations depending on rootstocks and cultivars. There has been little documentation on the effect of soil salinity on Na and Cl levels on peach trees, although Cl concentrations of about 0.5-1.0% (leaf dry weight) and Na concentrations of about 0.2-0.5% generally cause toxicity problems in most deciduous fruit trees (Bernstein 1980; Boland et al. 1993). In contrast, Myers et al. (1995) quoted “excess” levels as low as 0.02% (Na) and 0.1% (Cl) for pear trees.

Leaching of salts from the root zone is an obligate requirement under both full and deficit irrigation strategies since all irrigation waters add salts to the soil and the subsequent crop ET brings about salt evapo-concentration. The risk of soil salinization under deficit irrigation strategies using moderately saline waters may be relevant in salt-sensitive crops such as peach trees, particularly when grown in arid and semiarid areas with insufficient precipitation for leaching of accumulated salts.

The objectives of this research were (1) to analyze soil salinity [saturation extract electrical conductivity (ECe) and chloride concentration (Cle)] and sodicity [sodium adsorption ratio (SARe)] changes in a peach orchard subjected to a full irrigation and two deficit irrigation strategies, (2) to establish relationships between changes in soil salinity and sodicity with leaching fraction (LF) and water deficit (WD), and (3) to assess the potential impact of deficit irrigation strategies and soil salinity on peach yield, and Na and Cl leaf ion concentrations.

2. Material and methods

2.1. Experimental orchard

The experiment was conducted from 2008 to 2012 in a peach orchard located in the AFRUCCAS (Fruit Growers Association of the Caspe County) experimental farm in the county of Caspe (Middle Ebro River Basin, Spain) (41.16ºN, 0.01ºW). Late-maturin g cv. *Calrico* peach trees (*Prunus persica* L. Batsch) grafted on GF-677 rootstock were pruned to an epsilon system with trees spaced 6 m x 2 m. The 0.1-ha orchard was planted in 2005 on a 1.5-m deep sandy-loam soil (calcic haploxerept, fine loamy, mixed, thermic). The average soil saturation percentage, field capacity (FC) and permanent wilting percentage (PWP) were 36%, 21% and 12%, respectively, and the available water capacity of the 1.5 m soil profile, determined as the difference between the volumetric water contents at FC and PWP, was 224 mm.

The peach trees, managed according to the usual cultural practices in the farm, were daily irrigated by an automated drip system with two laterals per tree row located at 0.5-m from the rows with 1-m spaced self compensating emitters. With this lateral disposition each tree was positioned in the center of 1-m square with the four emitters located in the vertices. Fruits were thinned in early June to a target crop load of about 150 fruits per tree, and the fruits were harvested twice by mid September.

The 2008-2012 average annual values at the site were 318 mm (precipitation, P) and 1451 mm (reference evapotranspiration, ETo) calculated with the FAO Penman-Monteith equation (Allen et al. 1998) using the information gathered through the SIAR (Spanish Irrigation Advisory System) weather station network (MARM 2011). The P/ETo ratio was 0.22, classifying this Mediterranean climate as semi-arid. About 50% of the annual P and 15% of the annual ETo were recorded in the non-irrigation season (October to March).

2.2. Experimental design

Three irrigation treatments were implemented: a) FULL, peach trees irrigated at 100% of Gross Irrigation Requirements (I) estimated by the farmer according to the recommendations of the Irrigation Advisory System of Aragón (http://servicios.aragon.es/oresa/); b) SDI, Sustained Deficit Irrigation irrigated at 62.5% of I throughout the irrigation season; and c) RDI, Regulated Deficit Irrigation irrigated at 100% of I throughout the irrigation season except in the lag phase or pit hardening Stage II of fruit development, when the trees were irrigated at 50% of I. The length of Stage II was about one month and started by early or mid

May, depending on years. Although water savings for late maturing peach trees are small with this RDI, it may have the benefits of controlling vegetative growth and increasing flower density and commercial fruit load (Girona et al. 2003).

In the FULL treatment, four emitters of 4 L h^{-1} per tree were used. In the SDI treatment two emitters of 3 L h^{-1} and two of 2 L h^{-1} were used. In the RDI treatment the 4 L h^{-1} emitters were substituted by 2 L h^{-1} emitters during Stage II. All treatments were irrigated simultaneously with the same duration. Irrigations were scheduled weekly and initiated each season in late March or early April and stopped by late September or early October. Irrigation treatments were arranged in a randomized complete block design with five replicated blocks per treatment. Each treatment plot consisted of three adjacent rows of 7 trees.

The daily values of peach crop evapotranspiration (ETc) were estimated by multiplying the daily ETo by the Kc values obtained by Ayars et al. (2003). These authors developed Kc values for late season peaches in an area of California with climatic conditions relatively similar to those in our study area under regulated deficit irrigation as a function of the intercepted photosynthetic active radiation (iPAR). The following expression was used:

$$Kc = 1.59\ iPAR + 0.082 \qquad (1)$$

The iPAR was measured at weekly intervals with a ceptometer (Sunscan, Delta T) located in 18 positions in the spacing of a tree (6 m x 2 m) in two trees of each treatment. Once full cover was reached, the measurements were made monthly.

The data for soil salinity and its relations with yield and leaf Na and Cl concentrations were examined using individual trees because there was considerable heterogeneity in both soil salinity and yield in each replication. A preliminary assessment was performed in 2008 using 6 trees (two trees per irrigation treatment). Since the gathered data suggested that soil salinity could be a potential problem, a total of 30 trees (2 trees x 3 treatments x 5 blocks) were selected for soil and crop measurements during years 2009 to 2012.

2.3. Measurements

Water applications given at farmer’s demand were measured in each year and irrigation treatment with water meters installed in each drip line. Based on the depths of irrigation (I), precipitation (P) and crop evapotranspiration (ETc) measured in a given period, the corresponding field-wide leaching fraction (LF) and water deficit (WD) parameters were calculated as:

$$LF = \frac{(I + P - E}{(I + P)} \quad (2)$$

$$WD = ETc - I - P \quad (3)$$

where LF express the concentration factor Fc (Fc = LF^{-1}) of the irrigation and precipitation waters and their dissolved salts in the soil due to ETc assuming steady-state conditions, and WD express the peach water needs (ETc) not satisfied by irrigation (I) and precipitation (P).

The LF and WD calculations were based on field-wide or average values for the plot, so that unrealistic and negative LF values were obtained in periods when ETc is higher than I and P. Although actual LF values can not be negative, these field-wide negative LFs reflect the high potential risk for soil salinization during these periods. Similarly, high field-wide WD values would imply a high soil salinization risk due to ETc values higher than water applications (I + P) that prevent salt leaching. Even though field-wide LF could be negative and field-wide WD could be positive, the wetting pattern around the emitters results in higher localized LF and lower localized WD values. Thus, Hanson et al. (2008) demonstrated through HYDRUS-2D computer simulations that the localized LF were positive for applied water amounts equal to or smaller than ETc, when the field-wide LF would be zero or negative for these water applications.

Samples of irrigation water pumped from the Ebro River at farmer's demand were taken on a weekly basis for chemical analysis. The ECw (electrical conductivity of the irrigation water) was low at the beginning of the irrigation seasons (ECw values of about 0.7 dS m^{-1}) and increased up to about 1.6 dS m^{-1} by the end of the irrigation seasons, except in 2012 when ECw remained below 1.2 dS m^{-1} throughout the season. The mean (2008-2012) ECw, SARw , Na, Ca, Mg, Cl, SO_4 and HCO_3 values of irrigation water were 1.1 dS m^{-1}, 2.5 (mmol $l^{-1})^{0.5}$, and 4.6, 4.7, 1.8, 4.6, 4.2 and 2.7 meq l^{-1}. According to FAO guidelines (FAO 1985), waters with these ECw values are suitable for high-frequency irrigated peach trees.

Soil samples were taken by auger at a soil depth of 0-60 cm at the closest emitter to each control tree in two positions from the emitter: next to the emitter (0 cm distance from the emitter) and in front of the emitter in between the drip line and the tree row (25 cm distance from the emitter). For representativeness reasons, this sampling procedure was replicated at both sides of the tree rows and the two sub-samples were mixed together to get one sample at 0 cm and another sample at 25 cm from the emitter. This procedure was performed at the beginning (early April, except in the preliminary 2008 year where the sampling was performed in early June) and the end of each irrigation season (late September) at the emitter's left and right sides, respectively. All the auger holes were refilled with soil after each sampling. The soil samples were analyzed for its gravimetric water content (GWC) and, after air-dried, ground and sieved

(< 2 mm), for its saturation extract electrical conductivity (ECe), chloride concentration (Cle) and sodium adsorption ratio (SARe). The gypsum qualitative analysis performed through the acetone method showed that gypsum was present in 35% of the soil samples. All the soil analyses were carried out according to Page et al. (1982).

The yield of fresh fruits, the fruit weight, the number of fruits per tree and the trunk cross-sectional area were measured annually at harvest in each control tree. The yield productivity (YPR) was calculated as the yield divided by the cross-sectional area (Kg cm^{-2}) of each control tree. The irrigation water productivity (IWP) was calculated as the yield divided by the irrigation depth (g mm^{-1}).

Some 20 young apical leaves located in shoots of the present year were sampled in mid July and mid September between 2009-2011 in ten trees per irrigation treatment. The leaves were washed three times with deionized water for a few seconds to rinse off residual salts on the leaf surface, dried in an oven at 70ºC to a constant weight and finely ground in a blender. The leaf Cl and Na concentrations were determined on dilute nitric-acetic acid extracts of the grounded leaves, expressing the concentrations on a percent dry weight basis.

2.4. Statistical analyses

Data were analyzed by analysis of variance (ANOVA) and General Linear Model (GLM) procedure of the SAS 9.1 software (SAS Institute 2004). The means were separated using the Tukey's multiple comparison test at $p = 0.05$.

3. Results

3.1. Irrigation (I), precipitation (P), crop evapotranspiration (ETc) and field-wide leaching fraction (LF) and water deficit (WD)

Table 1 summarizes the annual depths of I, P and ETc in each year and irrigation treatment. P and ETc were similar among years (coefficients of variation (CV) of the means about 10%), whereas I was more variable (CV close to 30% in the three irrigation treatments). Irrigation depths consistently increased during 2008-2012, although the much lower I value in 2008 was due to technical problems that occurred in the irrigation pumping station.

Overall, the sum of I and P was similar to ETc in the FULL treatment and somewhat lower and much lower in the RDI and SDI treatments, respectively. LF and WD varied according to the irrigation depths given in each irrigation treatment, with maximum LF and minimum WD in FULL, similar values in RDI, and minimum LF and maximum WD values in SDI. In contrast, the non irrigation season 2008-2012 (NIS in Table 1) mean LF values were high (0.27 to 0.18) and the WD values were low (-56 to -32 mm), suggesting that soil salinity and sodicity would be higher in the irrigated than in the non irrigated season. In terms of the yearly values, LF was highest in 2010 and lowest in 2008 and 2009, and vice versa for the yearly WD. Based on previous considerations, these LF and WD values should imply that soil salinity and sodicity would increase more in 2008 and 2009 than in the other years.

3.2. Gravimetric soil water content (GWC), soil salinity (ECe, Cle) and soil sodicity (SARe)

Soil salinity and sodicity were positively correlated (P < 0.001) (SARe = 1.27 ECe + 0.91; $R^2 = 0.72$; n = 479 samples taken during 2009-2012). For the same set of samples, GWC was negatively and linearly correlated (P < 0.001) with ECe, Cle and SARe (R^2 values of 0.34, 0.44 and 0.39, respectively).

Figure 1 shows that GWC was 15% lower, ECe and SARe about 100% higher and Cle about 200% higher at 25 cm than at 0 cm from emitters (all differences significantly different at $p < 0.05$). Due to this large spatial variability, the average values for the 0 and 25 cm distances to emitters will be considered in the next sections in order to have the best possible representativeness of these variables within the crop’s root zone.

Table 2 summarizes the yearly GWC, ECe, Cle and SARe means measured in the soil samples taken in the three irrigation treatments, the two distances to emitters and the two sampling dates. The standard deviations (not shown) were high as a result of the high and typical spatial and temporal variability of these variables in drip irrigation systems and, therefore, they are irrelevant for statistical comparisons. The purpose of this Table is to provide yearly-integrated values of these variables, and to assess general trends during the studied period rather than establishing statistical differences among years.

In agreement with the lower LF and higher WD values in 2009, GWC was generally lower and ECe, Cle and SARe generally higher than in the other years (ECe in 2008 was not compared with the rest of years because of its later initial soil sampling date and its lower number of soil samples) (Table 2). ECe, Cle and SARe decreased during 2009-2011 but increased in 2012, probably because P was lower and ETc was higher than in previous years (Table 1), and these are the main driving variables for salt leaching (P) and salt concentration (ETc). The mean (2009-2012) ECe and SARe values of 4.8 dS m^{-1} and 7.0 (mmol $l^{-1})^{0.5}$, respectively, classify this soil as saline and moderately sodic.

Table 3a summarizes the irrigation treatment's GWC, ECe, Cle and SARe means measured in the 479 soil samples taken in 2009-2012, the two distances to emitters and the two sampling dates. No significant differences were observed among irrigation treatments (except GWC, significantly lower at $p < 0.05$ in SDI) due to the high standard deviations of these means affected by the soil spatial and temporal variability previously indicated. Even so, this table shows that Cle and SARe had a tendency to be higher (13% and 17%, respectively) in SDI than in the other two irrigation treatments. Table 3b summarizes the irrigation treatment's GWC, ECe, Cle and SARe means measured in the 120 soil samples taken in September 2009-2012 at 25 cm distance from emitters. These samples were selected because they should give the lowest water content and the highest soil salinity and sodicity values (i.e., samples taken at the farthest distance to emitters and at the end of the irrigation season). In relation to the FULL and RDI treatments (similar among them), the SDI treatment had GWC values that were 18% lower ($p < 0.05$), and ECe, Cle and SARe values that were 9%, 16% and 9% higher respectively, although in some cases these differences were only significant at $p < 0.1$ (analysis not given).

Figure 2 shows the evolution of ECe, Cle and SARe in the FULL and SDI irrigation treatments during the studied periods. The RDI treatment is not represented because the results were quite similar to those in the FULL treatment. The percent changes at the end of each irrigation season relative to the values at the beginning were higher (except for Cle and SARe in September 2009) in SDI than in FULL; and the percent changes at the end of each non irrigation season relative to the values at the beginning were also generally higher in absolute terms in SDI than in FULL. Thus, soil salinization was higher in the irrigation seasons and salt leaching was higher in the non irrigation season in SDI than in FULL. Fig. 2 also shows that, irrespective of the irrigation treatments, the values of the three variables generally increased in the irrigation seasons and decreased in the non irrigation seasons. Overall, soil salinity and sodicity did not show an increasing trend during the studied period because the accumulation of salts in the irrigation seasons were offset by the leaching of salts in the non irrigation seasons.

The 2009-2012 means at the end of the irrigation season (September) were similar or lower (GWC) and higher (ECe, Cle and SARe) than at the beginning (April) (Fig. 3). All the ECe, Cle and SARe differences were significant at $p < 0.05$, except ECe in RDI. The percent changes of the values measured in September relative to the values measured in April were 6% lower for GWC and 39%, 63% and 30% higher for ECe, Cle and SARe, respectively, in the SDI than in the other two irrigation treatments. As a result of these differential increases, the September ECe, Cle and SARe values were higher in SDI than in the other treatments (Fig. 3). The 2009-2012 September ECe, Cle and SARe values were high, particularly in SDI (5.7 dS m^{-1}, 30.4

meq L^{-1} and 8.7 (mmol $L^{-1})^{0.5}$, respectively). These SDI September values were even higher at 25 cm distance from emitters (7.2 dS m^{-1}, 43.8 meq L^{-1} and 10.6 (mmol $L^{-1})^{0.5}$, respectively; Table 3b).

Based on our findings in this work and those reported in other studies, it was hypothesized that soil salinity (ECe, Cle) and sodicity (SARe) should be correlated with the three main variables affecting salt leaching (irrigation, I and precipitation, P) and salt accumulation (crop evapotranspiration, ETc). These three variables were pooled together to obtain the field-wide LF (eq. 2) and field-wide WD (eq, 3). Fig. 4 shows that, irrespective of the irrigation treatment, the relative percent ECe, Cle and SARe daily changes (Δ) in a given period were significantly (p < 0.01) and linearly correlated with WD (positive relationships) and LF (negative relationships) calculated for the given period. The slopes of the regressions in Fig. 4 indicate that the highest increases with increases in WD and decreases in LF were obtained with Cle, whereas these increases were more similar with ECe and SARe. The higher Cle increases were explained because chloride does not reacts with the soil matrix and does not precipitates in the soil, whereas the cations associated to EC and SAR may react with the soil matrix, and calcium minerals may precipitate as the soil water evapo-concentrates (i.e., as WD increases and LF decreases).

3.3. Effects of soil salinity on peach yield, productivity and leaf Na and Cl concentrations

Peach tree response (yield, fruit weight, number of fruits, trunk cross sectional area and yield productivity) was unaffected by irrigation treatments, except irrigation water productivity (IWP) that was 65% higher in the more severe deficit irrigated treatment (SDI, IWP = 63 g $tree^{-1}$ mm^{-1} water) than in the other two irrigation treatments (about 38 g $tree^{-1}$ mm^{-1} water) (Table 4). The higher irrigation water productivity in the more severe deficit irrigated treatment without any adverse effect on peach tree response has been advocated as a relevant benefit of deficit irrigation strategies (FAO 2002; Fereres and Soriano 2007; Geerts and Raes 2009).

Soil salinity in the root zone of some control trees was relatively high so that, irrespective of the irrigation treatment, they could be negatively affected by this osmotic stress. The data were examined for correlations between yield and soil salinity using data for individual trees because there was considerable heterogeneity in both soil salinity and yield in each replication. There was no correlation between yield and soil salinity because there were some high yielding trees on relatively high ECe soils and, particularly, low yielding trees on relatively low ECe soils that could be affected by a matric or other unidentified stress. Thus, the classical "bent-stick" response model described by Maas and Hoffman (1977) did not fit the experimental data. Even so, based on the upper boundary line approach (Urdanoz and Aragüés 2009) our results suggest that the relative productivity of the individual peach trees examined during 2008-2012 consistently decreased below 100% at a threshold ECe of about 4 dS m^{-1} (Fig. 5), where ECe is the mean of the 0-60 cm soil depth measured in April and September of each year at 0 cm from emitters. This threshold ECe is similar to the FAO threshold ECe of 3.7 dS m^{-1} given for peach trees in soils with gypsum (FAO 1985).

Leaf Cl concentrations almost doubled leaf Na concentrations (0.09% and 0.05%, respectively, means for all the samples taken in 2009-2011). Leaf Cl remained relatively constant, but leaf Na tended to increase during the studied years, so that in 2009 leaf Cl was more than three times leaf Na, whereas in 2011 it was only 50% higher (Fig. 6a). The mean 2009-2011 concentrations in April and September were 0.04% and 0.05% for Na (not significantly different at $p > 0.05$) and 0.07 and 0.11% for Cl (significantly different at $p < 0.05$). Leaf Na and Cl concentrations were low and similar in the three irrigation treatments (Fig. 6b), indicating that these ions did not accumulate in the leaves when the peach trees were subject to these irrigation strategies.

4. Discussion

In relation to the FULL irrigation treatment, the 2008-2012 mean depths of saved water were 262 mm (40% saving) in SDI and 56 mm (9% saving) in RDI. Thus, irrigation savings were very high with SDI and low with RDI. Water savings of similar magnitude using these deficit irrigation strategies were previously reported in the literature (Girona et al. 2003; Fereres and Soriano 2007; Ruiz Sanchez et al. 2010).

The lower soil water content and higher soil salinity and sodicity values at 25 than at 0 cm from emitters (Fig. 1) are consistent with the localized LFs in drip irrigation systems that decrease radially with distance to emitters (Hanson 2012). Cle increased more (196%) than ECe and SARe (about 98%) at 25 cm from emitters because chloride does not precipitates in the soil with increases in soil salinity, whereas both ECe and SARe are affected by the selective precipitation of calcium minerals with increases in soil salinity. This chemical process results from the evapo-concentration of salts in the soil and explains the positive correlation between ECe and SARe indicating that soil salinization induced soil sodification. Similarly, the negative correlations between GWC and ECe, Cle and SARe indicate that the increases in soil salinity and sodicity were largely driven by ETc and the corresponding decreases in soil water content. Dehghanisanij et al. (2006) found a high and negative power-regression correlation between soil water content and soil salinity, showing that relatively small changes in water content could bring about considerable changes in salinity.

Both on a yearly and on a year-average basis, the more severe deficit irrigation treatment (SDI) provoked a higher soil salinization and sodification in the irrigation seasons then the FULL and RDI irrigation treatments. The high SDI September values, particularly at 25 cm from emitters (Table 3b) could be potentially deleterious to peach trees in terms of yield (threshold ECe of 3.7 dS m^{-1} in soils with gypsum) and chloride toxicity (maximum permissible Cl without leaf injury of 10 to 25 meq L^{-1} in stone fruits), and to soils in terms of soil's structural stability (slight to moderate reductions in rate of infiltration for a combination of 8.7 or 10.6 SARe and 1.1 EC irrigation water) (FAO 1985). However, the highest September values decreased in the non-irrigation seasons (Fig. 2), so that peach trees and soils were subject to lower soil salinity and sodicity values in other periods of the year.

Overall, the seasonal variation of soil salinity and sodicity showed that they increased in the irrigation season and decreased in the non-irrigation season. The higher soil salinity and sodicity increases were observed in 2009, when P, I and LF were lower (Table 1) and Fc was higher than in 2010-2012. These results are in agreement with findings of Melgar et al. (2009) showing that salts were leached by rainfall occurring at the end of the irrigation period in southern Spain, with a Mediterranean climate where the average mean annual precipitation was 702 mm. Results reported by Intrigliolo and Castel (2011) showed similar levels of soil salinity (ECe of about 0.7 dS m^{-1} measured in winter at the end of the 7-years experiment) in the control treatment (watered at 100% ETc) and in the more severe deficit-irrigated treatment (33% water saving with respect to the control treatment), indicating that in conditions of relatively low salt concentrations (EC irrigation water = 1.1 dS m^{-1}), well drained soils and high rainfall in autumn (about 200 mm), deficit irrigation applied during seven consecutive years did not increase soil salinity in the root zone of a drip irrigated Japanese plum tree orchard. Metochis (1999) reported that soil salinity under saline drip irrigation remained stable after nine years with rainfall about 400 mm $year^{-1}$, whereas there was a high risk of soil salinization for rainfall values lower than 250 mm. Raine et al. (2007) indicated that there is sufficient evidence to suggest that in situations of point water applications and associated salt distribution, rainfall could be advantageously used in displacing salts and moving them below the root zone. Domínguez et al (2011) indicated that according to results with the MOPECO-Salt model, deficit irrigation strategies without LF are remediable if the off-season rainfall is sufficient to leach out the salts supplied with irrigation water. Kaman et al (2006) evaluated soil salinization under full irrigation and partial root zone drying (irrigation water reduced by 50% of full irrigation) in tomato and cotton irrigated with a good-quality water (EC = 0.4 dS m^{-1}) and concluded that although soil salinity at harvest under partial root zone drying was 35% higher compared to full irrigation, there will be no risk of salt accumulation and decreased yields if soils initially have no salinity problems and available irrigation water is of good quality.

The significant correlations between soil salinity and sodicity changes and field-wide WD (positive correlation) and LF (negative correlation) indicate that they are suitable parameters to estimate the required irrigation depths for soil salinity and sodicity control. Based on the equations presented in Fig. 4, field-wide WD values of -35 to -100 mm and field-wide LF values of 0.10 to 0.16 would be needed to avoid soil salinization and sodification risks (i.e., $\Delta \leq 0$) in this peach orchard which is drip irrigated with moderately saline irrigation waters. The values obtained in the non irrigation season (NIS in Table 1) were similar or lower (WD) and higher (LF) than the estimated WD and LF values obtained with the equations presented in Fig. 4, justifying the lack of significant salinization and sodification trends during the studied period (Fig. 2). These equations depend on soil, climate and irrigation characteristics, and should be developed on a case by case basis. It is interesting to notice that even though LF and WD vary with distance to emitters in drip irrigation systems (Hanson 2012), and although salt concentrations in irrigation and precipitation may be different by one order of magnitude or higher (i.e., salt leaching per volume of water would be more efficient for precipitation than for irrigation waters), these easily obtainable field-wide LF and WD parameters may be satisfactorily applied to assess trends on the accumulation or leaching of salts in the crop's root zone.

In relation to the response of peach trees to soil salinity, the results were not conclusive due to large data scattering. Nevertheless, Fig. 5 suggests that the relative productivity tended to decrease with soil salinity, so that all the observations (with two exceptions) were below the relative productivity of 100% for ECe values above 4 dS m^{-1}. Hoffman et al. (1989) reported that peach fruit weight and the number of peach fruits per tree were reduced by about 50% at an ECe, dominated by chloride salts, of about 3 dS m^{-1}. The results obtained in our work (data not given) show that fruit weight was independent of soil salinity, whereas the number of peach fruits per tree was significantly reduced ($p < 0.05$) by soil salinity, so that the maximum decreases obtained at 5 dS m^{-1} in this gypsum-rich soil (equivalent to about 3 dS m^{-1} in chloride-dominated soils) were of the same order of magnitude as those reported by these authors. Overall, our tentative results suggest that the relative productivity of peach trees tended to decrease above a threshold ECe value of about 4 dS m^{-1} (i.e., similar to the threshold ECe of 3.7 dS m^{-1} reported by FAO (1985) in soils with gypsum, Fig. 5) and that these decreases could be ascribed to decreases in the number of fruits per tree rather than to decreases in fruit weight.

Leaf Na and Cl concentrations were similar in the three irrigation treatments and were well below levels reported as toxic in fruit trees (0.2 to 0.5% Na and 0.5 to 1% Cl as reported by Bernstein 1965, Hoffman et al. 1989 and Boland et al. 1993). The higher Cl than Na levels in the leaves indicate that peach trees were able to take less Na than Cl from the soil during the three studied irrigation seasons, and/or that Na was preferentially excluded from the leaves. Boland et al. (1997) also reported that leaf Na was consistently lower than leaf Cl, but the former increased more rapidly after several years of exposure to salts. Overall, these results indicate that the *Calrico* peach trees grafted on GF-677 rootstock did not show leaf Na and Cl toxicity symptoms when subject to drip irrigation during the studied years using moderately saline waters.

5. Conclusions

A drip-irrigated peach orchard located in a semi-arid area of Northeastern Spain was subject during five years to three irrigation treatments (FULL irrigation, SDI or Sustained Deficit Irrigation, and RDI or Regulated Deficit Irrigation). In relation to FULL, irrigation water use was reduced by 40% in SDI and 9% in RDI, and irrigation water productivity was increased by 65% in SDI without adverse effects in peach tree response (i.e., yield, productivity and Na and Cl toxicity symptoms).

Soil salinity (ECe, Cle) and sodicity (SARe) increased in the April to September irrigation seasons (low field-wide leaching fraction LF, high field-wide water deficit WD), particularly in the more severe deficit irrigation strategy (SDI). ECe, Cle and SARe at the end of the irrigation season were high and potentially deleterious to peach trees and soil's structural stability. However, these values decreased by salt leaching in the October to March non-irrigation seasons (high LF and low WD).

Despite the typical high spatial variability of LF and WD in drip irrigation systems, the changes in soil salinity and sodicity and the field-wide LF and WD at given periods were significantly correlated. Hence, these variables could be advantageously used on a case by case basis to estimate the required irrigation depths for root zone soil salinity and sodicity control.

Overall, soil salinity and sodicity did not increase during the 2008-2012 study period because of salt leaching by precipitation in the low-ETc non irrigation seasons. Thus, climatic characteristics are critical when assessing the sustainability of deficit irrigation strategies in arid and semi-arid areas subject to irrigation waters of low to moderate salinity (EC of about 1 dS m^{-1}).

The ultimate conclusion is that without significant changes in the actual irrigation, soil and climate characteristics in the area, both SDI and RDI strategies could be advantageously used to save high to moderate irrigation volumes without compromising soil quality and peach orchard performance.

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Table 1. Annual depths of irrigation (I), precipitation (P) and crop evapotranspiration (ETc), and field-wide leaching fraction (LF) and water deficit (WD) in each year (2008 to 2012) and irrigation treatment (FULL-full irrigation, SDI-sustained deficit irrigation, and RDI-regulated deficit irrigation). The mean 2008-2012 values and the mean 2008-2012 values for the October-March non-irrigation season (NIS) are also given.

Year	P (mm)	ETc (mm)	FULL			SDI			RDI		
			I (mm)	LF	WD (mm)	I (mm)	LF	WD (mm)	I (mm)	LF	WD (mm)
2008	355	823	390	-0.11	79	209	-0.46	260	328	-0.21	141
2009	277	903	543	-0.10	83	305	-0.55	321	516	-0.14	110
2010	315	877	734	0.16	-172	489	-0.09	73	682	0.12	-121
2011	347	1007	740	0.07	-80	429	-0.30	232	675	0.01	-15
2012	298	1055	831	0.07	-74	499	-0.32	258	759	0.00	-1
2008-2012											
Mean	318	933	648	0.03	-33	386	-0.33	229	592	-0.02	23
NIS	148	148	56	0.27	-56	31	0.18	-32	55	0.27	-55

Table 2. Gravimetric soil water content (GWC) and soil saturation extract electrical conductivity (ECe), chloride concentration (Cle) and sodium adsorption ratio (SARe) measured in years 2008-2012: mean values of the 120 soil samples taken in each year (except in 2008, where 48 samples were taken) at 0-60 cm soil depth in the three irrigation treatments (FULL, SDI and RDI), the two distances to emitters (0 and 25 cm) and the two sampling dates (April and September).

	2008	2009	2010	2011	2012
GWC (%)	---	17.1	21.9	22.9	17.0
ECe (dS m^{-1})	3.9	5.4	4.7	4.2	4.8
Cle (meq l^{-1})	---	27.6	18.0	17.4	27.3
SARe [(mmol $l^{-1})^{0.5}$]	---	7.4	6.9	5.7	8.0

Table 3. Gravimetric soil water content (GWC) and soil saturation extract electrical conductivity (ECe), chloride concentration (Cle) and sodium adsorption ratio (SARe) measured in the irrigation treatments FULL (full irrigation), SDI (sustained deficit irrigation) and RDI (regulated deficit irrigation): (a) mean values of the 479 soil samples taken in years 2009-2012 at 0-60 cm soil depth, the two distances to emitters (0 and 25 cm) and the two sampling dates (April and September); (b) mean values of the 120 soil samples taken in years 2009-2012 at 0-60 cm soil depth, 25 cm distance to emitters and September sampling date. For each variable, values with different letters are significantly different at $p < 0.05$.

	(a) all soil samples (479)			(b) soil samples taken in September at 25 cm from emitters (120)		
	FULL	SDI	RDI	FULL	SDI	RDI
GWC (%)	20.7 a	17.9 b	20.6 a	18.9 a	15.5 b	19.2 a
ECe (dS m^{-1})	4.8 a	4.9 a	4.7 a	6.6 a	7.2 a	6.2 a
Cle (meq l^{-1})	22.0 a	24.5 a	21.3 a	37.9 ab	43.8 a	33.4 b
SARe [(mmol $l^{-1})^{0.5}$]	6.7 a	7.7 b	6.5 a	9.7 ab	10.6 a	9.0 b

Table 4. Yield, fruit weight (FW), number of fruits (NF), trunk cross sectional area (TCSA), yield productivity (YPR) and irrigation water productivity (IWP) measured at harvest in the irrigation treatments FULL (full irrigation), SDI (sustained deficit irrigation) and RDI (regulated deficit irrigation): mean values of the two control trees measured in 2008 and the ten control trees measured in 2009-2012 in each irrigation treatment. For each variable, values with different letters are significantly different at $p < 0.05$.

	FULL	SDI	RDI
Yield (kg tree^{-1})	24.5 a	24.6 a	24.1 a
FW (g fruit^{-1})	197 a	179 a	191 a
NF (No. tree^{-1})	125 a	140 a	129 a
TCSA (cm^{2})	79.1 a	77.7 a	73.7 a
YPR (kg tree^{-1} cm^{-2} TCSA)	0.34 a	0.37 a	0.36 a
IWP (g tree^{-1} mm^{-1} water)	37 a	63 b	39 a

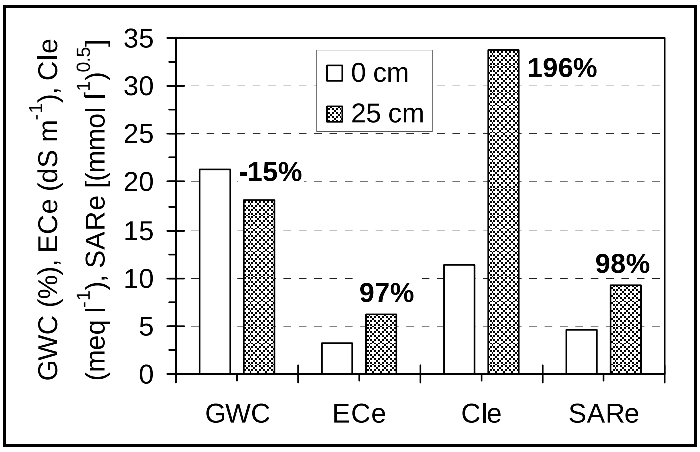

Fig. 1. Mean (2009-2012 years, irrigation treatments FULL, SDI and RDI, and April and September sampling dates) gravimetric soil water content (GWC), soil salinity (ECe), chloride concentration (Cle) and sodicity (SARe) measured at 0 and 25 cm distances from emitters. The percent changes of the values measured at 25 cm relative to the values measured at 0 cm are also given.

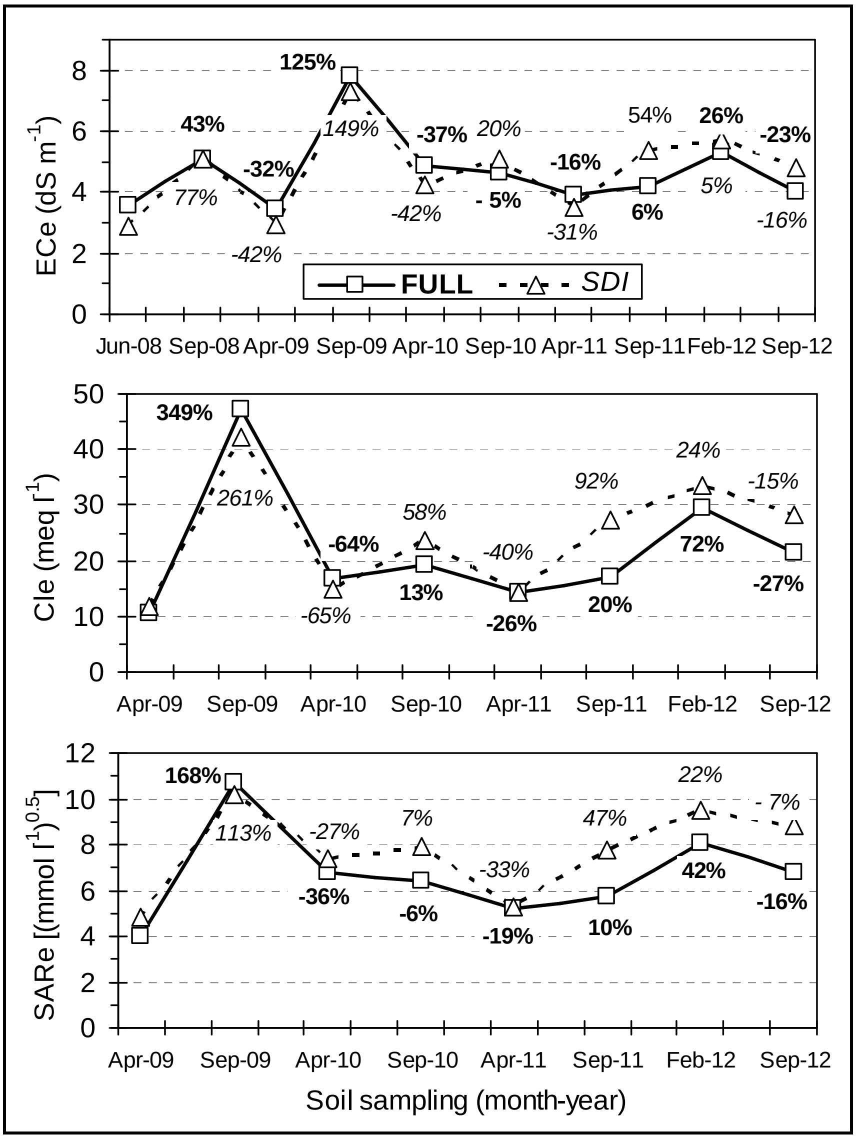

Fig. 2. Mean soil salinity (ECe), chloride concentration (Cle) and sodicity (SARe) measured in the irrigation treatments **FULL** (full irrigation) and *SDI* (sustained deficit irrigation) during the studied years. The percent ECe, Cle and SARe changes at the beginning (end) relative to the values at the end (beginning) of each irrigation season are also given.

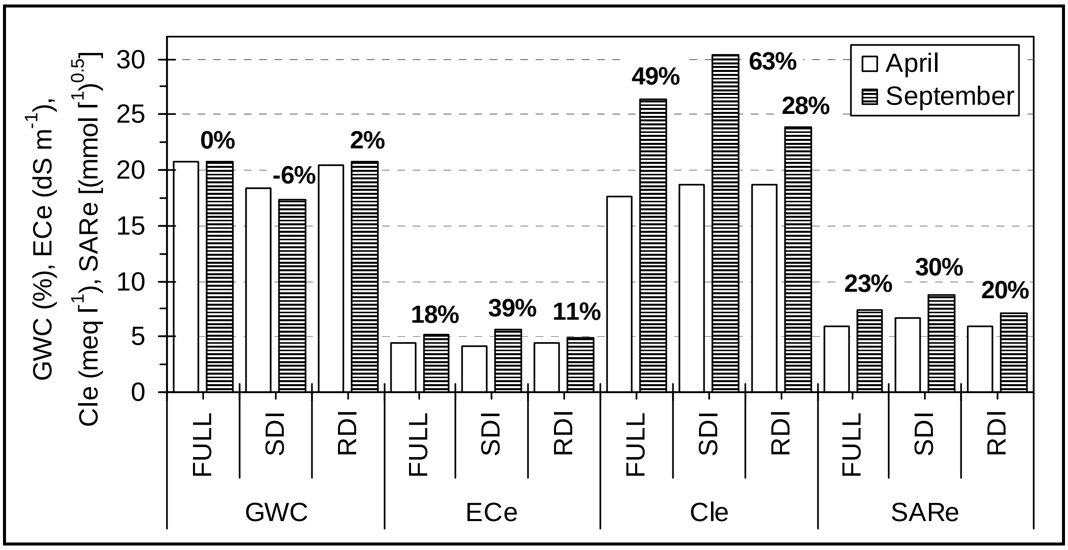

Fig. 3. Mean (2009-2012 years, 0 and 25 cm from emitters) gravimetric soil water content (GWC), soil salinity (ECe), chloride concentration (Cle) and sodicity (SARe) measured in the irrigation treatments FULL (full irrigation), SDI (sustained deficit irrigation) and RDI (regulated deficit irrigation) at the beginning (April) and end (September) of the irrigation season. The percent changes of the values measured in September relative to the values measured in April are also given.

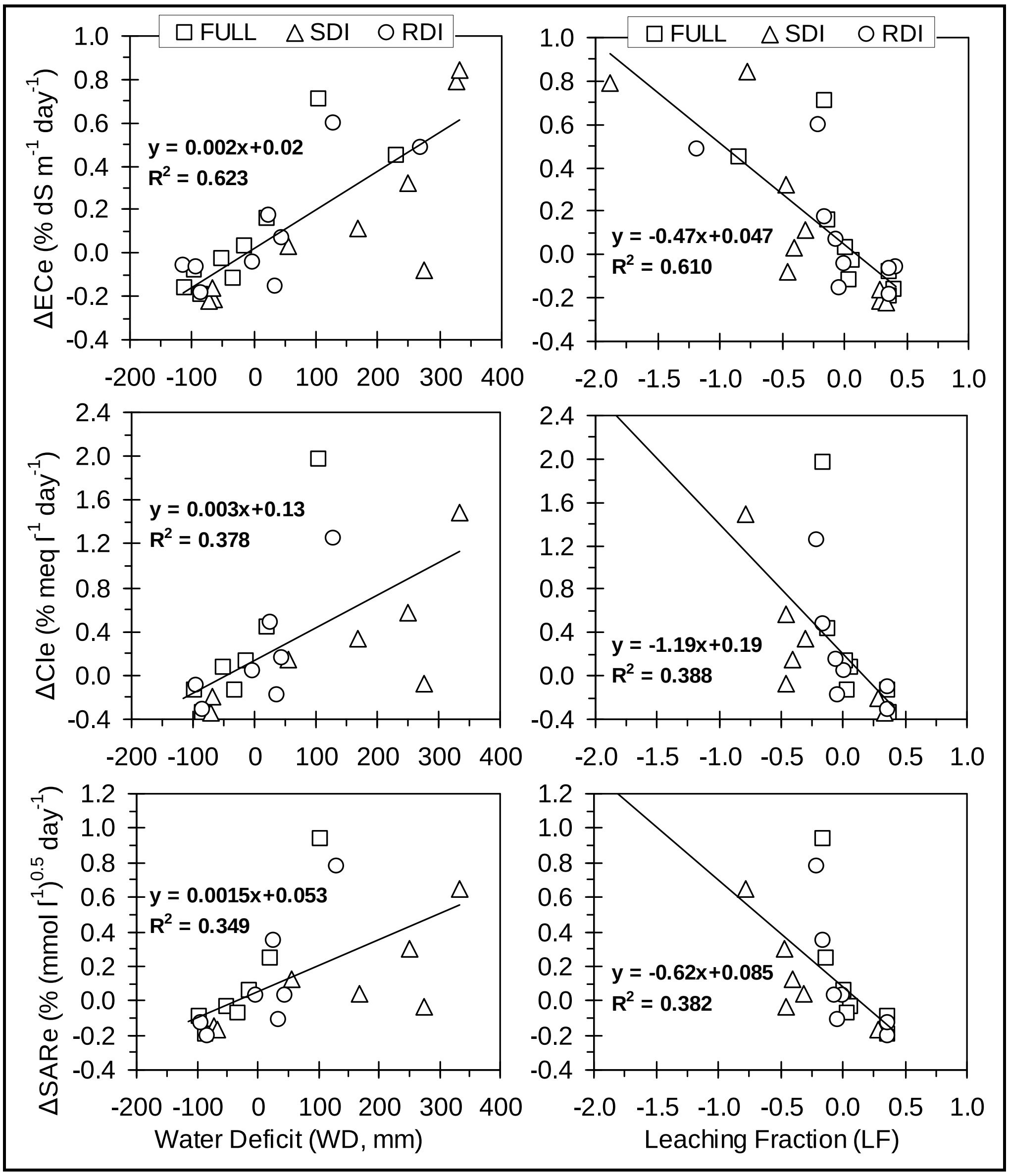

Fig. 4. Relationships and linear regression equations between changes in soil salinity (ΔECe), chloride concentration (ΔCle) and sodicity (ΔSARe) measured between sampling dates, and field-wide Water Deficits (WD) and leaching fractions (LF) calculated for the periods between sampling dates. Δ is given in terms of percent change per day at the end of each period between sampling dates relative to the values at the beginning.

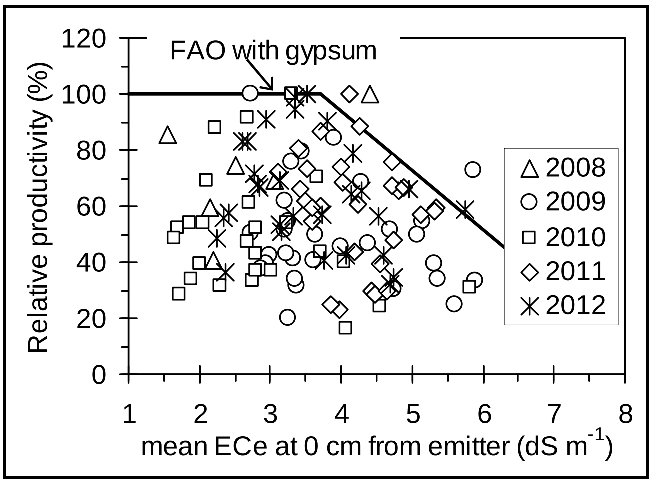

Fig. 5. Relationships between relative productivity of peach trees and soil salinity (mean ECe of soil samples taken at 0-60 cm depth and at 0 cm distance to emitters in each year). The FAO piecewise linear response model of peach to soil salinity in gypsum-rich soils is also represented for comparison purposes.

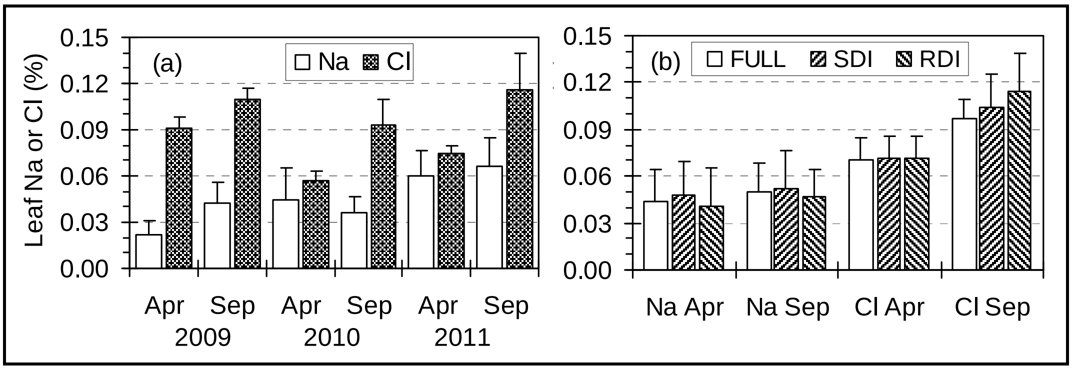

Fig. 6. Leaf Na and Cl concentrations measured at the beginning (April) and end (September) of (a) each 2009-2011 irrigation season, and (b) each irrigation treatment FUL (full irrigation), SDI (sustained deficit irrigation) and RDI (regulated deficit irrigation). Vertical bars represent one standard deviation.