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Soil salinization as a threat to the sustainability of deficit irrigation under present and expected climate change scenarios

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Abstract

Deficit irrigation (DI) strategies using moderately saline waters save water, but may enhance soil salinization. Based on data gathered during years 2007-2012 in three drip-irrigated grapevine, peach and nectarine crops subject to several irrigation and soil mulching treatments, we assessed trends in root-zone soil salinity (saturation extract electrical conductivity, ECe), related the changes in soil salinity (ΔECe) to field-wide leaching fraction (LF), evaluated management strategies for soil salinity control, and examined the sustainability of DI strategies under present and expected climate change scenarios in the Middle Ebro River Basin (ERB, Spain). ECe increased in 82% of the irrigation seasons and decreased in 75% of the non-irrigation seasons examined. Soil salinization trends were not apparent during the study years due to these annual salt accumulation-salt leaching cycles. ECe increases were higher in the more severe DI treatments and in the geotextile-mulched soil, and lower in the full and less severe irrigation treatments and in the organic-mulched soil. As expected, ΔECe and LF were linearly and negatively correlated ($P < 0.01$), indicating that soil salinization increased with decreasing LF. These linear relationships provided a way to evaluate best management strategies (increased irrigation, rainfall harvesting and soil mulching) for soil salinity control. These strategies decreased soil salinization, but did not guarantee the sustainability of severe deficit irrigations in the study area. The application of these relationships to the climate change precipitation and crop evapotranspiration projections in the ERB shows that the examined DI strategies will be unsustainable due to soil salinization.

Introduction

Deficit irrigation consists in the application of water below full crop water requirements, so that a mild crop water stress is allowed with negligible effects on yield (FAO 2002). The main objective of deficit irrigation is to save irrigation water and increase water productivity (i.e., yield per unit water supply) (Chalmers et al. 1981). For these reasons, several deficit irrigation strategies such as regulated deficit irrigation, partial root-zone drying, and sustained deficit irrigation have expanded in the last decades, particularly in woody crops grown in areas with limited water resources (Fereres and Soriano 2007; Geerts and Raes 2009; Ortega-Farias et al. 2012).

However, it is uncertain whether deficit irrigation is a sustainable strategy in arid and semiarid areas irrigated with low-quality waters. Thus, several publications have indicated the potential soil salinization risks linked to deficit irrigation (Shalhevet 1994; Sarwar and Bastiaanssen 2001; Raine et al. 2007; Geerts and Raes 2009; Chen et al. 2010; Mounzer et al. 2013) but few of them have quantified this thread.

The leaching of salts from the root zone of crops is required under both full and deficit irrigation strategies, since all irrigation waters add salts to the soil and the subsequent crop's evapotranspiration (ETc) causes salt evapo-concentration and increasing salt concentrations in the crop's root zone. Soil salinization under deficit irrigation strategies may be amplified in those periods where irrigation is decreased or interrupted because of the low leaching fractions (LF) attained in these periods. This potential problem may be alleviated using high-frequency drip irrigation because this system has the advantage of providing near the emitters almost continuous and high localized leaching fractions (LF), even though the field-wide LF may be low or even negative (i.e., applied water smaller than crop's ET) (Hanson et al 2008).

Aragüés et al. (2014a,b) examined in a semiarid area of the Ebro River Basin (Spain) the changes in soil salinity (ECe) in two drip-irrigated table grape (*Vitis vinifera* L.) vineyards during three years and in one drip-irrigated peach (*Prunus persica* L. Batsch) orchard during five years. These crops were subject to a full irrigation and two mild and severe deficit irrigation treatments, respectively. Soil salinity tended to increase in the irrigation seasons and tended to decrease in the non-irrigation seasons, and the increases were generally higher in the more severe deficit-irrigated treatments than in the full irrigation treatment. Due to this salt-accumulation and salt-leaching cycles, trends in root zone soil salinization were not evident during the study years. These authors also concluded that the changes in ECe were linearly and negatively correlated ($P < 0.001$) with the field-wide LF values.

This information is complemented in the present work with data on soil salinity changes and its relationships with field-wide LF values gathered during three years in a drip-irrigated nectarine (*Prunus persica* L. Batsch) orchard subject to four soil mulching treatments (Zribi 2013). Based on the information collected in the table grape vineyards and the peach and nectarine orchards, our first three objectives are (1) to quantify in the three irrigation and the four soil mulching treatments the trends in soil salinity during the study years, (2) to relate soil salinity changes (ΔECe) to field-wide LF values and to develop the corresponding ΔECe-LF empirical models for each crop, and (3) based on these models, to assess potential management strategies for soil salinity control (i.e., $\Delta ECe \leq 0$) under the climatic conditions in the Middle Ebro River Basin (Spain).

In the Mediterranean regions, increases in air temperature and decreases in precipitation and water resources represent the main evidences of changing climate (IPPC 2007). The magnitude of the projected climate change (CC) differs considerably depending on locations, models applied and updated information.

Thus, the recent unedited and accepted final draft report of the Working Group I contribution to the IPCC 5th Assessment Report "Climate Change 2013: The Physical Science Basis" indicates that climate change could be less relevant than previous IPPC reports. Climate change in the Ebro River Basin (ERB) will decrease water resources by 5 % between 2013 and 2030 (García-Vera 2013) and by 20 % in the 2041-2070 period (CEDEX 2012). These projections suggest that water for irrigation could be restricted, so that water-saving strategies as controlled deficit irrigation would have to be expanded in the ERB. However, the question remains about the sustainability of these deficit irrigation strategies and its impact on soil salinity tendencies under the projected CC scenarios in the ERB. Since the two climatic variables included in the LF equation (eq. 1) are precipitation (P) and crop evapotranspiration (ETc), their projected changes under different CC scenarios in the ERB will be summarized in the materials and methods section.

Based on these expected P and ETc changes and the ΔECe-LF relationships previously developed for each crop, a fourth objective of this work is (4) to examine the sustainability (i.e., soil salinity control or ΔECe ≤ 0) of full and deficit irrigation strategies under the expected climate change scenarios in the Middle Ebro River Basin by the end of the 21st century.

Materials and methods

The two drip-irrigated table grape vineyards (*Vitis vinifera* L. cv Autumn Royal and Crimson) and the peach (*Prunus persica* L. Batsch cv. Calrico) and nectarine (*Prunus persica* L. Batsch cv. Bigtop) orchards were located in the municipality of Caspe (Middle Ebro River Basin, northeast Spain) (41.16°N, 0.01°W). Table 1 provides information on study years, crops, annual mean irrigation water salinity (ECiw), and irrigation or mulching treatments. Details on these treatments are given in the footnotes to this Table, and additional information may be found in Aragüés et al. (2014a,b) for grapevines and peach, respectively, and in Zribi (2013) for nectarine. Besides the FULL irrigation given to grapevine and peach, both crops received a mild (RDI-L in grapevine and RDI in peach) and a severe (RDI-H in grapevine and SDI in peach) deficit irrigation treatment. In addition to the control treatment or bare soil in nectarine, this crop was subject to three soil mulching treatments (PLA or black plastic film, ORG or organic, and GEO or geotextile mulching materials).

Two meteorological stations recording air temperature, relative humidity, global solar radiation, precipitation (P), and wind speed were installed in the Santa Barbara farm of the ALM Group, the location of the table grape vineyards, and in the AFRUCCAS farm, the location of the peach and nectarine orchards. Table 1 provides information for each crop on the annual mean P (in parenthesis, non-irrigation season mean P) and reference evapotranspiration (ET_0). The 2007-2012 annual mean P and ET_0 were 309 mm and 1449 mm, respectively, and the P/ETo ratio was 0.21, classifying this Mediterranean climate as semi-arid. The daily values of crop evapotranspiration (ETc) were estimated multiplying the ET_0 computed using the FAO Penman-Monteith method (Allen et al. 1998) and the daily averages of the meteorological data, with the crop coefficient (Kc) values obtained from Allen et al. (1998) after being adjusted to take into account the local climate conditions (Zribi 2013; Aragüés et al. 2014a,b).

The soil in the table grape vineyards was classified as Xeric calcigypsid, coarse loamy, mixed (gypsic), thermic, and the soil in the peach and nectarine orchards was classified as calcic haploxerept, fine loamy, mixed, thermic (Soil Survey Staff, 1999). The soil samples, taken by auger as described in the footnotes of Table 2, were analyzed for its gravimetric water content (GWC) and, after air-dried, ground and sieved (< 2 mm), for its saturation extract electrical conductivity (ECe) according to Page et al. (1982).

Additional details on the soil sampling methodology may be found in Aragüés et al. (2014a,b) for grapevines and peach, respectively, and in Zribi (2013) for nectarine.

The irrigation season in the Caspe area is from March-April to September and the maximum irrigation depths are given in July and August. The grapevines, planted at 3.5 m by 2.5 m, were irrigated daily by a single trickle line located in the vine rows with 2.2 l h^{-1} self-compensating emitters spaced 0.5 m. The peach and nectarine trees, planted at 6 m by 2 m, were irrigated daily by two trickle lines located at 0.5 m at both sides of the tree rows with 4.0 l h^{-1} self-compensating emitters spaced 0.5 m. These emitters were used in the FULL irrigation treatments of the four crops, and were substituted in the deficit-irrigated treatments by appropriate emitters with lower discharges to get the desired irrigation depths (Zribi 2013; Aragüés et al. 2014a,b). The irrigation depths were measured in the four orchards with water meters installed in each drip line. The EC of the irrigation water was relatively low to moderate, depending on crops (mean EC values of 1.7 dS m^{-1} in the table grape vineyards and 1.1 dS m^{-1} in the peach and nectarine orchards; Table 1).

Based on the values of irrigation (I), precipitation (P) and crop evapotranspiration (ETc) recorded at given periods, the field-wide leaching fraction (LF) was calculated for each period as:

$$LF = \frac{(I + P - ETc)}{(I + P)} \quad (1)$$

where the inverse of LF express the concentration factor of the irrigation and precipitation waters and their dissolved salts in the soil due to ETc assuming steady-state conditions. In terms of the CC scenarios examined, the LF equation indicates that, for a given I, decreases in P and increases in ETc will imply lower LF values and higher soil water salt concentrations, whereas increases in P and decreases in ETc will imply higher LF values and lower soil water salt concentrations.

Since nectarine was subject to several soil mulching treatments (Table 1), the LF calculations took into account the following P and ETc assumptions: (i) P was taken as zero in the plastic mulch because this impermeable material would not allow its infiltration in the root zone, whereas it was assumed that the bare soil and the organic and geotextile mulching materials would allow all the P to infiltrate in the root zone, (ii) ETc was not affected by water or osmotic stresses because they were considered to be low, (iii) ETc for the bare soil was partitioned into a crop transpiration (Tc) of 0.7 ETc and a soil evaporation (E) of 0.3 ETc, a reasonable partitioning as given by Kool et al. (2014) for orchards and vineyards, (iv) Tc was assumed to be independent of soil mulching, and (v) soil water evaporation was assumed to be 10 % (plastic mulch), 50 % (organic mulch) and 90 % (geotextile mulch) of the bare soil evaporation (Zribi 2013). Some negative and unrealistic field-wide LF values were obtained in some periods where the estimated ETc was higher than the measured I and P. Although actual LF values can not be negative, these negative field-wide LFs reflect the high potential risk for soil salinization during these periods.

Climate change (CC) scenarios in the Ebro River Basin (Spain)

Two General Circulation Models defined by IPCC in 2000 (CGCM2 and ECHAM4) and two greenhouse gas emission scenarios (A2 or medium-high emission and B2 or medium-low emission) were applied to the location of our trials (municipality of Caspe, Middle ERB, northeast Spain) using the precipitation (P) records provided by the Meteorological State Agency (Spanish Ministry for Environment and Rural and Marine Affairs) in combination with a regionalization technique given in Brunet et al. (2008). Based on the average 1961-1990 values, the projected P changes by the end of the 21st century (2071-2100 period) were -20 % for the low CC scenario (CGCM2_B2) and -32 % for the high CC scenario (ECHAM4_A2). Somewhat lower P changes were estimated by CEDEX (2012) in the Middle ERB.

Moratiel et al. (2010) concluded that due to CC, the Ebro River Basin will have by the end of the 21st century the greatest annual increase in reference evapotranspiration (ET_0) of all the basins analyzed in Spain. Depending on CC scenarios, these annual increases would range from 215 to 619 mm, equivalent respectively to increases of 15 % and 42 % over the annual mean ET_0 of 1459 mm obtained for our study period (January 2007 to December 2012) in our trials. However, higher ET_0 do not necessarily imply higher ETc because although soil evaporation (E) will undoubtedly increase, crop's transpiration (Tc) could increase or decrease depending on other interrelated variables such as changes in air temperature and CO_2 concentration, and changes in crop attributes such as phenology and crop coefficients (Kc), physiology, photosynthesis, above and below ground biomass, etc. (Wang et al. 2012).

Kimball et al. (2002) reviewed the responses of agricultural crops to the CC-induced atmospheric CO_2 enrichment and concluded that because elevated CO_2 causes a decrease in stomatal conductance, Tc per unit of leaf area will decrease, but canopy temperature and water vapor pressure inside the leaves will increase, therefore increasing leaf transpiration and negating some of the reductions due to decreases in stomatal conductance. Thus, the final effect of elevated CO_2 on ETc is a combination of individual effects on decreasing stomatal conductance, increasing leaf area, and increasing canopy temperature. Depending on crops and experimental conditions, Kimball et al. (2002) found variations in ETc between 6.2 % and -19.5 %. In most of the CC scenarios and study crops the variations were negative, although modest, due to the indicated counteracting factors affecting Tc. In summary, the net effects of CC on the ETc of woody crops are not conclusive because of the several counteracting phenomena already indicated that could cancel each other with minor final effects on ETc. Specific ETc trends due to CC were not found for the ERB, but FAO (1996) concluded that the trend of water use per unit soil surface area would change only by about ±10 %.

Based on these P and ETc projections, six potential scenarios were foreseen by the end of the 21st century in the ERB:

1- P decrease of 15 % (P = -15 %)
2- P decrease of 30 % (P = -30 %)
3- ETc decrease of 10 % (ETc = -10 %)
4- ETc increase of 10 % (ETc = +10 %)
5- Concurrent P decrease of 15 % and ETc decrease of 10 % (P = -15 %, ETc = -10 %) (lowest potential impact scenario considering both P and ETc projections)
6- Concurrent P decrease of 30 % and ETc increase of 10 % (P = -30 %, ETc = +10 %) (highest potential impact scenario considering both P and ETc projections)

These scenarios were envisaged to assess their effects on soil salinity trends (ΔECe) through the application of the LF-ΔECe empirical models developed in our work. The required irrigation depths for soil salinity control (ΔECe = 0) were then calculated for each CC scenario to determine if deficit irrigation strategies would be sustainable under these CC projections.

Statistical analysis

Statistical analyses were performed using the General Linear Model (GLM) procedure of the SAS 9.1 software (SAS Institute, 2004).

Results and discussion

Soil salinity (ECe) and gravimetric soil water content (GWC) relationships

The mean ECe values of all soil samples taken in the root zone of each crop during the study years were highest in the Crimson vineyard (7.0 dS m^{-1}), intermediate in the peach orchard (4.7 dS m^{-1}) and the Autumn Royal vineyard (4.4 dS m^{-1}), and lowest in the nectarine orchard (3.4 dS m^{-1}), whereas the corresponding mean GWC were lowest in Crimson (15.6 %), intermediate in Autumn Royal (17.2 %) and highest in peach (19.6 %) and nectarine (20.7 %). These inverse GWC-ECe relationships were also shown at different distances from emitters, so that increasing distances generally implied decreases in GWC and concomitant increases in ECe (Table 2). Thus, whereas the soil samples taken in nectarine and peach adjacent to emitters (0 cm) had the highest mean GWC and the lowest mean ECe, the soil samples taken in Crimson at 30 cm from emitters had the lowest mean GWC and the highest mean ECe. These ECe and GWC spatial distributions are typical in drip irrigation systems where LF decreases radially with increasing distances from emitters (Hanson 2012). The only apparent exception to this characteristic distribution would be in nectarine at 50 cm from the emitter, but it is explained because the drip line is located in a small furrow and the system behaves as a line source rather than a point source (Zribi 2013).

GWC and ECe of all the individual soil samples taken in the root zone of the three crops were significantly ($P < 0.001$) and inversely correlated through a power regression equation (Fig. 1). This inverse ECe-GWC relationship indicates that soil salinization was due to a large extent to crop's evapotranspiration (ETc) that decreased soil water content and increased salt concentration. This so-called "evapo-concentration effect" (Aragüés and Tanji 2003) is revealed by the inverse of the LF (eq 1), so that the higher the ETc, the lower the LF and the higher the concentration factor and the root zone salinity. Therefore, ETc was a significant driving mechanism for root zone soil salinization in the study crops. Dehghanisanij et al. (2006) also found in drip irrigation that soil water content decreased and soil salinity increased with distance from emitters, and that a high and inverse power-regression correlation existed between soil salinity and soil water content, indicating that relatively small changes in water content could bring about considerable changes in soil salinity.

Soil salinity (ECe) trends

Figure 2 shows the ECe values measured during the study years at the beginning (March-April) and end (September) of the irrigation seasons in each crop subject to the different irrigation or mulching treatments. Statistical comparisons among these ECe means of the values measured at different sampling positions were not performed because the relatively high standard errors (not given in the figure) were mainly due to the typical high spatial variability of ECe measured at different positions from the emitters (Table 2). Therefore, the information reported in this figure should be evaluated in terms of trends or tendencies.

Soil salinity measured at the end tended to be higher than at the beginning of each irrigation season. These ECe increases in the irrigation seasons correspond to periods of relatively low LF (Fig. 2) and high ETc that evapo-concentrate the salts applied with irrigation. In contrast, soil salinity tended to decrease in the non-irrigation seasons, periods of relatively high LF (Fig. 2) and low ETc where late fall and winter precipitations leached the salts accumulated at the end of the irrigation seasons. Although the non-irrigation season mean precipitation (P) values were similar or lower than the irrigation season mean P in this Mediterranean climate (Table 1), a larger proportion of the P falling in the non-irrigation season was more effective for salt leaching because of the much lower ETc in this season than in the irrigation season. Due to these annual salt accumulation-salt leaching cycles, soil salinization trends were not evident during the study years, although the ECe values in Autumn Royal and, particularly, in Crimson were somewhat higher at the end than at the beginning of the April 2007-September 2009 period (Fig. 2).

Based on the percent ECe changes at the end relative to the ECe values at the beginning of each irrigation season (Fig. 2), ECe tended to increase in 37 out of the 45 irrigation seasons examined. The corresponding ECe changes in the non-irrigation seasons (not shown in Fig. 2 for simplicity purposes) indicate that ECe tended to decrease in 24 of the 32 non-irrigation seasons examined. Six out of the eight exceptions to this annual salt accumulation-salt leaching cycles took place in the peach and nectarine orchards during September 2011-2012 (Fig. 2), when ECe tended to increase rather than decrease in the September 2011-February 2012 non-irrigation season due to the low precipitation recorded in this period (89 mm as compared to corresponding values of about 170 mm in 2010 and 2011; Zribi, 2013) that was not effective for salt leaching. Moreover, ECe tended to decrease rather than increase in the following March-September 2012 irrigation season because the salts accumulated at the end of the non-irrigation season (ECe values close or above 4 dS m^{-1}; Fig. 2) were leached by the irrigation water applied in this irrigation season.

The general trend in salt leaching observed in the non-irrigation seasons shows that even though the average non-irrigation season P was low (about 140 mm; Table 1) compared to other Mediterranean irrigated areas where rainfall is much higher (values above 400 mm; MARM, 2013), it was critical for salt leaching and soil salinity control during the study years. Isidoro and Grattan (2011) also found through modeling that rainfall distribution plays a major role in determining seasonal soil salinity in the root zone, so that winter-concentrated rainfall was more effective in reducing salinity than a similar amount of rainfall distributed uniformly throughout the year.

A comparative analysis of the irrigation treatments given to grapevines and peach shows that in 8 out of the 11 irrigation seasons examined the highest ECe increases at the end of the irrigation season occurred in the more severe deficit irrigation treatments (RDI-H in grapevines and SDI in peach) (Fig. 2). Thus, the average relative ECe increase for all the irrigation seasons and crops was 66 % in the more severe deficit irrigation treatments, as compared to increases of 44 % and 35 % in the FULL and less severe deficit irrigation treatments (RDI-L in grapevines and RDI in peach), respectively. The highest irrigation season ECe average increase (99 %) was measured in Crimson due to the combination of a relatively high irrigation water EC (mean = 1.7 dS m^{-1}, Table 1) and a relatively low LF (mean = 0.08 for the RDI-H treatment, Aragüés et al., 2014a). Autumn Royal showed a lower average ECe increase (48 %) for the same irrigation water EC because of its higher LF (0.15 for the RDI-H treatment, Aragüés et al., 2014a), whereas peach showed an intermediate average ECe increase (57 %) for a lower irrigation water EC (mean = 1.1 dS m^{-1}; Table 1) but a lower LF (mean = -0.33 % for the SDI treatment, Aragüés et al., 2014b).

A comparative analysis of the mulching treatments given to nectarine shows that in the three study irrigation seasons the highest relative ECe increase (average of 27 %) at the end of the irrigation seasons occurred in the geotextile-mulched soil and the lowest (average of 0 %) in the organic-mulched soil. These increases were 17 % in the plastic-mulched soil and 6 % in the bare soil. Zribi (2013) suggested that the higher ECe increase in the geotextile mulch was due to its higher evaporation rate derived from the saturation of their pores with the irrigation and precipitation waters, whereas the lower ECe increase with the organic mulch was due to its ability to reduce the evaporation rate while allowing the infiltration of precipitation in the root zone due to its large pore network configuration. Aragüés et al (2014c) analyzed the effectiveness of plastic and organic mulching materials for soil salinity control in a table grape vineyard drip-irrigated with moderately saline waters and concluded that its efficiency was precipitation-dependent and should be assessed on a case-by-case basis.

Soil salinity (ECe) and field-wide leaching fraction (LF) relationships

The results presented in Fig. 2 suggest that salt accumulation or leaching in a given period was generally related to low or high LF values for the period. Since the analyzed periods had different time spans, the percent relative ECe changes were normalized on a daily basis (i.e., ΔECe in % dS m^{-1} day^{-1}).

Figure 3 shows that ΔECe and field-wide LF were negatively and significantly correlated (at $P < 0.001$ in grapevine and peach and at $P < 0.002$ in nectarine), indicating that soil salinization increased with decreasing LF. Most of the negative ΔECe values (i.e., salt leaching) were observed in the non-irrigation seasons, indicating that late fall and winter precipitations (with EC values well below 0.1 dS m^{-1}) were critical for the leaching of salts accumulated during the irrigation seasons.

The empirical relationships shown in Fig. 3 should be established on a case-by-case basis for each particular environment (crop, soil (texture in particular), climate and irrigation water characteristics). Based on these relationships, salt leaching (ΔECe < 0) would occur at LF values higher than 0.32 in grapevine, 0.11 in peach and 0.06 in nectarine. Given that the measured LF values for the full irrigation treatment were somewhat lower than the LF values for ΔECe = 0 (0.22 in grapevine, 0.03 in peach and -0.04 in nectarine; Table 3), it follows that soil salinization would take place in the three crops during the study years. However, the average percent relative salinization rates would be moderate in grapevine (ΔECe = 0.15 % dS m^{-1} day^{-1}), low in nectarine (ΔECe = 0.08 % dS m^{-1} day^{-1}) and very low in peach (ΔECe = 0.04 % dS m^{-1} day^{-1}) (Table 3). These estimates agree with the low (grapevines) to negligible (peach and nectarine) soil salinization trends shown in Fig. 2. It is noticeable that these relationships indicate that although the measured LF was much higher in grapevine than in peach and nectarine, its soil salinization rate was about two (nectarine) and four (peach) times higher probably due to its higher irrigation water salinity (1.7 dS m^{-1} in grapevine against 1.1 dS m^{-1} in peach and nectarine; Table 1).

The average soil salinity changes (ΔECe) during the study years in grapevine and peach subject to low (RDI-L in grapevine and RDI in peach) and high (RDI-H in grapevine and SDI in peach) deficit irrigation strategies were assessed by calculating the LF values for the respective irrigation depths (I) and estimating the corresponding ΔECe by means of the equations given in Fig. 3. Soil salinization (ΔECe > 0) would occur in all deficit irrigation strategies and particularly in the more severe deficit irrigation treatments, with salinization rates of 0.30 % dS m^{-1} day^{-1} in grapevine and 0.20 % dS m^{-1} day^{-1} in peach (Table 3). For long periods of time, these deficit irrigation treatments given to peach and, particularly, to grapevine would be unsustainable in terms of soil salinity control.

The average soil salinity changes (ΔECe) during the study years in nectarine subject to the different mulching treatments (bare soil and soils mulched with plastic, organic and geotextile materials) were assessed in a similar way as for the deficit irrigation strategies, taking into account for each treatment the changes in P and ETc indicated in the Materials and methods section. Soil salinization (ΔECe > 0) would occur in the bare soil, plastic and geotextile mulched soils, whereas salt leaching (ΔECe < 0) would occur in the organic mulched soil (Table 4). The higher salinization rate estimated with plastic was due to the assumption in that all the rainfall was intercepted by this impermeable material and, therefore, P was set at zero in the LF calculations. In contrast, salt leaching would occur in the organic mulched soil because it was assumed that it decreased the evaporation rate while allowing the infiltration of precipitation in the root zone. These estimates agree with the previously reported lower irrigation season average ECe increase in the organic mulch than in the other treatments, and in the bare soil than in the plastic mulched soil, but not with the geotextile mulched soil that showed the highest relative ECe increase based on the results given in Fig. 2, but not with the model results given in Table 4. Although these ΔECe estimates should be taken with caution because of the many assumptions taken in the analysis, the organic mulch showed to be the most efficient of all the examined materials in terms of soil salinity control. Aragüés et al. (2014c) in grapevine and Chaudhry et al. (2004) in Eucalyptus also found that organic mulching was more efficient than plastic mulching for soil salinity control under the climatic characteristics of their study areas.

Management alternatives for soil salinity control

According to the relationships presented in Fig. 3, salt accumulation (ΔECe > 0) or salt leaching (ΔECe < 0) significantly depended on LF. Therefore, appropriate changes in the three variables of the LF equation (i.e., increasing I and P and decreasing ETc) would be three potential management alternatives for soil salinity control (ΔECe = 0).

The first alternative would be to increase irrigation depths to satisfy the required LF_0 for soil salinity control (ΔECe = 0) shown in Table 5 (0.32 for grapevine, 0.11 for peach and 0.06 for nectarine). If deficit irrigation is to be maintained in the irrigation season for controlling tree biomass, promoting fruit quality and increasing water productivity, the alternative for increasing the required irrigation depths without compromising these potential benefits will be to apply them during the non-irrigation season, when water is readily available. Table 5 shows that if P and ETc maintain their original values, the volume of irrigation (I_r) required for soil salinity control in grapevine would be 21 % higher (978 mm) than the 810 mm applied in the FULL treatment. The corresponding I_r increases for the low (RDI-L) and high (RDI-H) deficit irrigation treatments (not given in the table) would be 30 % and 42 %, respectively. In peach and nectarine the required I_r increases over the FULL irrigation values would be about 14 %, whereas the I_r increases for the low (RDI) and high (SDI) deficit irrigation treatments in peach (not given in the table) would be 23 % and 89 %, respectively. This strategy implies substantial increases in the amount of water used annually, particularly in the more severe deficit irrigation treatments. Therefore, the main objective of deficit irrigation (saving irrigation water and increasing water productivity) would not be accomplished, although other benefits as control of tree biomass and promotion of fruit quality could still be attained.

The second alternative for soil salinity control would be to increase precipitation into the crop's root zone to satisfy the required LF_0 for each crop (Table 5). This increase could be hypothetically achieved through rainfall harvesting and re-direction from the mid-row to the under-crop soil by mulching the soil in the mid-row with an impermeable barrier such as plastic, or through the ridge-furrow rainfall harvesting with film mulching coupled with ridges-furrows planting patterns (Gan et al, 2013). Thus, Stevens et al (2013) showed in a Chardonnay vineyard subject to supplementary saline drip irrigation that this strategy reduced the salinity of under-vine soils by about 48 %. Table 5 shows that if FULL I and ETc retain their actual values, the required precipitation depths (P_r) for soil salinity control would have to increase over the actual P by 58 % (grapevine), 26 % (peach) and 32 % (nectarine). Furthermore, the required P_r depths in the deficit irrigation strategies (not given in the table) would have to increase over the actual P by 78 % (RDI-L) and 100 % (RDI-H) in grapevine, and by 43 % (RDI) and 108 % (SDI) in peach. These high P increases may pose practical problems in terms of the required surface area to be mulched with plastic and the costs associated to this strategy.

The third alternative for soil salinity control would be to reduce crop evapotranspiration (ETc) to satisfy the required LF_0 for each crop (Table 5). Since crop transpiration (Tc) should be maintained to sustain potential yields, the only way to decrease ETc is to reduce soil water evaporation (E). In high frequency irrigation systems, E may be reduced by preventing or minimizing the wetting of the soil surface (for example, by using appropriate subsurface drip irrigation systems), or through appropriate mulching of the soil wetted by the emitters. Since the costs of transformation and maintenance for a subsurface drip system would be too high, the mulching strategy is presented in Table 5, bearing in mind that it should minimize E while allowing the infiltration of precipitation in the crop's root zone. For this reason, organic mulching (less efficient than plastic in decreasing evaporation, but which allows the infiltration of precipitation through it) was selected instead of the plastic mulch impermeable to precipitation (Aragüés et al. 2014c). Table 5 shows that if FULL I and P retain their actual values, the required ETc_r values for soil salinity control would have to decrease over the actual ETc values by -13 % (grapevine), -8 % (peach) and -9 % (nectarine). Assuming that Tc is not affected by mulching, these decreases would imply that the required E_r values for soil salinity control should be 44 % (grapevine), 26 % (peach) and 31 % (nectarine) lower than the actual E (Table 5). These E decreases are feasible with organic mulches, since they may decrease E by about 50 % of the bare soil evaporation (Zribi 2013). Therefore, organic mulching would be efficient for soil salinity control and could be recommended in these orchards subject to FULL I. However, Allen at al. (1998) indicated that Tc could increase under mulched soils in some circumstances, implying that E_r will have to be lower than the estimations given above. The ETc_r values for soil salinity control in the deficit irrigation strategies (not given in Table 5) would have to decrease by -18 % (RDI-L) and -23 % (RDI-H) in grapevine, and by -13 % (RDI) and -33 % (SDI) in peach, with corresponding E_r decreases of -60 % (grapevine-RDI-L), -76 % (grapevine-RDI-H), -44 % (peach-RDI), and a negative and unaffordable value of -26 mm in peach-SDI. Since the required E decreases are greater than the potential E decreases with organic mulches (except for peach-RDI), this strategy would not be feasible in general for soil salinity control in these crops subject to the indicated deficit irrigation treatments.

Deficit Irrigation strategies and soil salinization under expected climate change (CC) scenarios

The six CC scenarios proposed for the Middle Ebro River Basin predict different P and ETc values that, together with the actual full irrigation depths (FULL I) allow to estimate the expected field-wide LF values in each crop by means of eq. 1. The introduction of these LF estimates into the LF-ΔECe relationships developed for each crop (Fig. 3) provide the corresponding soil salinity changes (ΔECe) for each CC scenario subject to FULL I (Fig. 4). The required irrigation depths (Ir) for soil salinity control (ΔECe = 0) were then calculated to assess the sustainability of deficit irrigation strategies (i.e., Ir < FULL I) under the projected CC scenarios.

In the table grape vineyards, the six CC scenarios would lead to soil salinization (ΔECe > 0; Fig. 4). As expected, the higher salinization rates were obtained in scenarios #6 (30 % decrease in P and 10 % increase in ETc), #4 (10 % increase in ETc) and #2 (30 % decrease in P). In contrast, a 10 % decrease in ETc (scenario #3) produced a lower salinization rate (0.04 % dS m^{-1} day^{-1}) than the actual rate of 0.15 % dS m^{-1} day^{-1} for grapevine (Table 3). In the six CC scenarios the required irrigation depths for soil salinity control would be higher than the actual FULL I of 810 mm (increases in water use between 382 mm in scenario #6 and 42 mm in scenario #3; Fig. 4), indicating that deficit irrigation strategies would not feasible in the six scenarios examined.

In the peach and nectarine orchards the results were quite similar, with five out of the six CC scenarios implying soil salinization (particularly in scenarios #6, 4 and 2; Fig. 4), and with required irrigation depths for soil salinity control higher than the FULL I (increases in water use in both orchards between 300 mm in scenario #6 and 30 mm in scenario #5; Fig. 4). In contrast, scenario #3 (10 % decrease in ETc) would lead to salt leaching (ΔECe < 0; Fig. 4) due to concomitant LF increases in both orchards. Deficit irrigation strategies would be only feasible in this scenario #3, although the savings in irrigation water would be negligible (22 mm in peach and 9 mm in nectarine).

The information given in the materials and methods section of this work indicates that the consensus on the projections of CC was rather weak for ETc estimates (positive or negative small changes) and stronger for P estimates (20 to 32 % decreases in P depending on the General Circulation Models and greenhouse gas emission scenarios applied). Therefore, scenarios #1 (15 % decrease in P) and #2 (30 % decrease in P) would be probably the more robust projections, and in both scenarios the deficit irrigation strategies would lead to soil salinization (Fig. 4). However, a constrain to the appraisal of soil salinity changes using these P projections is that they take into account total annual volumes, but not the expected increases in the variability of precipitation (IPCC, 2007) that could play a significant role in salt leaching (Isidoro and Grattan 2011).

CC scenarios also predict that water resources will decrease in the Middle Ebro River Basin (CEDEX 2012; García-Vera 2013). If these decreases imply a reduction of water flows in the Ebro River, a concomitant increase in salinity will take place due to the inverse relationships between flow and EC in this river (Isidoro and Aragüés 2007). The corresponding increases in irrigation water salinity (ECiw) would imply that LF will have to increase further for a proper soil salinity control. This higher ECiw effect was shown in grapevine, where LF for soil salinity control was higher than that in peach and nectarine (Table 5). However, since irrigation water salinity is not provided in the LF equation, this scenario could not be evaluated with the simple and easy to apply equations developed in this work, and more sophisticated, transient state models such as those summarized by Raine et al. (2007) that require increased expertise knowledge and extensive data gathering will have to be applied to asses this potential scenario.

Conclusions

Soil salinity (ECe) in the table grape vineyards and the peach and nectarine orchards drip irrigated with low to moderate saline waters (EC between 1.1 and 1.7 dS m^{-1}) tended to increase in the irrigation seasons due to the high crop's evapotranspiration (ETc) and relatively low leaching fractions (LF) that evapo-concentrated the salts applied with the irrigation waters, and tended to decrease in the non-irrigation seasons due to the low ETc, relatively high LF and late fall and winter precipitations that leached the accumulated salts. Due to these annual salt accumulation-salt leaching cycles, a soil salinization trend was not apparent during the study years. The highest ECe increases at the end of the irrigation seasons generally tended to occur in the more severe deficit irrigation treatments and in the geotextile-mulched soil, whereas the lower ECe increases tended to occur in the full and less severe irrigation treatments and in the organic-mulched soil.

Soil salinity changes (ΔECe) and field-wide LF were linearly and negatively correlated, indicating that soil salinization increased with decreasing LF. These ΔECe–LF relationships developed for each crop and the annual mean LF values for the study years calculated for the full irrigation treatment show that for long periods of time soil salinization (ΔECe > 0) would take place in the three crops, although the salinization rates would be low to moderate, depending on crops. In contrast, the estimated mean soil salinization rates would be high to very high in the more severe deficit irrigation treatments given to grapevine and peach, indicating that for long periods of time this irrigation strategy would be unsustainable in terms of soil salinity control. The ΔECe–LF relationship applied to nectarine shows that soil salinization would take place in the bare soil and in the plastic and geotextile-mulched soils, whereas salt leaching would occur in the organic-mulched soil. Although these results should be taken with caution because of the many assumptions taken in the analysis, the organic mulch would be most efficient in terms of soil salinity control because it decreased soil water evaporation while allowing the infiltration of rainfall in the soil.

Three management alternatives for soil salinity control were analyzed through the application of the ΔECe–LF relationships with the aim to increase LF values to satisfy ΔECe = 0. The first alternative was to increase irrigation volumes in the non-irrigation seasons while maintaining deficit irrigation in the irrigation seasons. This strategy proved to be effective, but the amount of extra water to be applied would be high (between 14 % and 89 % higher, depending on crops and irrigation treatments) so that the main objective of deficit irrigation (increased water productivity) would not be accomplished. The second alternative was to increase precipitation volumes (P) into the crop's root zone through appropriate rainfall harvesting. The required P depths for soil salinity control would have to increase over the actual P by 26 % to 108 %, depending on crops and irrigation treatments. Rainfall harvesting was considered a plausible strategy, but it could pose practical problems in terms of the required surface area to be plastic-mulched for rainfall harvesting, and the associated economic and environmental (plastic residues) costs. The third alternative was to reduce soil evaporation (E) through organic mulching of the soil wetted by the emitters. This strategy would be adequate for soil salinity control under full irrigation, when the required E depths should decrease over the actual E by 26 to 44 % (depending of crops), but not under severe deficit irrigation since the required decreases in soil water evaporation would not be achieved through organic soil mulching. Although the three examined management alternatives would decrease soil salinization, they will not always guaranty the sustainability of deficit irrigation strategies in the study area (Middle Ebro River Basin, Spain).

The assessment of soil salinization for the expected climate change (CC) scenarios in the Middle Ebro River Basin subject to full irrigation proved that in grapevine the six CC scenarios analyzed would lead to soil salinization (ΔECe > 0). Moreover, the required irrigation depths for soil salinity control would be higher than the actual full irrigation depths, implying that deficit irrigation strategies would not be feasible in any of the examined CC scenarios. Similar results were obtained in peach and nectarine (i.e., soil salinization and unsustainable deficit irrigation strategies), except in one CC scenario that assumes a 10 % decrease in ETc, where salt leaching would take place. Therefore, deficit irrigation strategies would be feasible only in this scenario, although the savings in irrigation water would be negligible.

A relevant conclusion from our work is that despite the known limitations implicit in the steady-state leaching fraction approach, the easy to calculate field-wide LF proved to be a simple and sound parameter that could be adequately used on a case-by-case basis for assessment of best management strategies for soil salinity control, and for appraisal of potential soil salinization under expected climate change scenarios.

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Table 1 Summary of trials performed during years 2007-2012: initial and final year, crop, cultivar, annual mean irrigation water electrical conductivity (ECiw), annual mean precipitation (P) (in parenthesis, non-irrigation season (October to March) mean precipitation), annual mean reference evapotranspiration (ET_0), and irrigation and mulching treatments. Details on each trial are given in the footnotes

Year	Crop	Cultivar	ECiw ($dS\ m^{-1}$)	P (mm)	ET_0 (mm)	Treatments
2007-2009	Grapevine	Autumn Royal, Crimson	1.7	291 (110)	1459	Irrigation (FULL, RDI-L, RDI-H)
2008-2012	Peach	Calrico	1.1	318 (154)	1451	Irrigation (FULL, RDI, SDI)
2010-2012	Nectarine	BigTop	1.1	320 (137)	1467	Mulching (BAR, PLA, ORG, GEO)

Irrigation treatments:

FULL: crops irrigated at 100 % of net irrigation requirements (NIR)

RDI-L (regulated deficit irrigation-low): grapevines irrigated at 100 % NIR throughout the irrigation season except from post-veraison till harvest, when irrigation was given at 80 % NIR

RDI-H (regulated deficit irrigation-high): grapevines irrigated at 100 % NIR throughout the irrigation season except from post-veraison till harvest, when irrigation was given at 60 % NIR

RDI (regulated deficit irrigation): peach trees irrigated at 100 % NIR throughout the irrigation season except in the pit hardening Stage II of fruit development, when the trees were irrigated at 50 % NIR

SDI (sustained deficit irrigation): peach trees irrigated at 62.5 % NIR throughout the irrigation season.

Mulching treatments (nectarine trees mulched with 2-m wide materials located over the soil surface in the tree rows):

BAR (bare): soil without mulching

PLA (plastic): black polyethylene sheet

ORG (organic): 10-cm thickness layer of pine bark fragments

GEO (geotextile): needle jute fibers with a density of 650 $g\ m^{-2}$.

Table 2 Mean gravimetric soil water content (GWC) and soil saturation extract electrical conductivity (ECe) of all soil samples taken in Autumn Royal and Crimson table grape vineyards, and peach and nectarine orchards at increasing distances from emitters

Crop	Distance from emitter (cm)	GWC (%)	ECe (dS m^{-1})
Autumn Royal grapevine	10	18.1	3.6
Autumn Royal grapevine	30	16.2	5.3
Crimson grapevine	10	17.6	5.5
Crimson grapevine	30	13.7	7.7
Peach	0	21.1	3.1
Peach	25	18.0	6.2
Nectarine	0	23.6	2.0
Nectarine	50 cm in drip line	21.4	3.0
Nectarine	50 cm in tree line	17.1	5.2

GWC and ECe in table grape vineyards: for each distance from emitters, mean of three years (2007-2009), three irrigation treatments (FULL, RDI-L, RDI-H), and three sampling dates (beginning, middle and end of each irrigation season); soil samples taken for the 0-60 cm depth interval.

GWC and ECe in peach orchard: for each distance from emitters, mean of five years (2008-2012), three irrigation treatments (FULL, RDI, SDI), and two sampling dates (beginning and end of each irrigation season); soil samples taken for the 0-60 cm depth interval.

GWC and ECe in nectarine orchard: for each distance from emitters, mean of three years (2010-2012), four mulching treatments (BAR, PLA, ORG, GEO), and two sampling dates (beginning and end of each irrigation season); soil samples taken for the 0-45 cm depth interval.

Table 3 Soil salinity changes (ΔECe) in grapevine, peach and nectarine estimated for each irrigation treatment (full irrigation, low and high deficit irrigations) using the equations in Fig. 3 and the leaching fractions (LF) calculated with the irrigation values (I) given in each irrigation treatment and the precipitation (P) and crop evapotranspiration (ETc) values (equal in all the irrigation treatments). I, P and ETc are means of the years studied in each crop

Crop	P (mm)	ETc (mm)	Irrigation treatments								
			Full irrigation			Low deficit irrigation			High deficit irrigation		
			FULL I (mm)	LF	ΔECe (% dS m^{-1} day^{-1})	RDI-L I RDI I (mm)	LF	ΔECe (% dS m^{-1} day^{-1})	RDI-H I SDI I (mm)	LF	ΔECe (% dS m^{-1} day^{-1})
Grapevine[a]	291	863	810	0.22	0.15	750	0.17	0.22	688	0.12	0.30
Peach[b]	318	933	648	0.03	0.04	592	-0.02	0.06	386	-0.33	0.20
Nectarine[c]	320	1036	680	-0.04	0.08						

[a]Grapevine: RDI-L = regulated deficit irrigation-low; RDI-H = regulated deficit irrigation-high

[b]Peach: RDI = regulated deficit irrigation; SDI = sustained deficit irrigation

[c]Nectarine: values for bare soil and full irrigation treatment (no deficit irrigation treatments)

Table 4 Soil salinity changes (ΔECe) in nectarine estimated for each mulching treatment using the equation in Fig. 3 and the leaching fractions (LF) calculated with the precipitation (P) and crop evapotranspiration (ETc) values given in each mulching treatment, and the irrigation value (I) (equal in all mulching treatments). P was taken as 0 in the plastic treatment. ETc was partitioned into crop transpiration (Tc) taken as 70 % of the bare soil ETc, and soil evaporation (E) taken as 10 % (plastic mulch treatment), 50 % (organic mulch treatment) and 90 % (geotextile mulch treatment) of the bare soil E. I, P and ETc are means of the years studied

	Mulching treatments			
	Bare soil (BAR)	Plastic (PLA)	Organic (ORG)	Geotextile (GEO)
I (mm)	680	680	680	680
P (mm)	320	0	320	320
ETc (Tc + E) (mm)	1036 (725 + 311)	756 (725 + 31)	880 (725 + 155)	1005 (725 + 280)
LF	-0.04	-0.11	0.12	-0.005
ΔECe (% dS m^{-1} day^{-1})	0.08	0.14	-0.05	0.05

Table 5 Management alternatives for soil salinity control (i.e., ΔECe = 0 with corresponding leaching fractions (LF_0) calculated with equations in Fig. 3) in grapevine, peach and nectarine: (a) increased irrigation (I), (b) rainfall harvesting (increased precipitation P), and (c) organic soil mulching (decreased evaporation E). For each independent alternative, the required irrigation (I_r), precipitation (P_r), crop evapotranspiration (ETc_r) and evaporation (E_r) values to attain soil salinity control are presented. The transpiration values (Tc) for each crop (taken as 70 % of the ETc values given in Table 3) are also shown. The corresponding percent changes relative to the actual FULL I, P, ETc, Tc and E values are given in parenthesis. I, P and ETc are means of the years studied in each crop

Management alternatives for soil salinity control (ΔECe = 0)						
Crop	LF_0 for ΔECe = 0	(a) Increased irrigation I_r (mm)	(b) Rainfall harvesting P_r (mm)	(c) Organic soil mulching		
				ETc_r (mm)	Tc (mm)	E_r (mm)
Grapevine	0.32	978 (21 %)	459 (58 %)	749 (-13 %)	604 (0 %)	145 (-44 %)
Peach	0.11	730 (13 %)	400 (26 %)	860 (-8 %)	653 (0 %)	207 (-26 %)
Nectarine	0.06	782 (15 %)	422 (32 %)	940 (-9 %)	725 (0 %)	215 (-31 %)

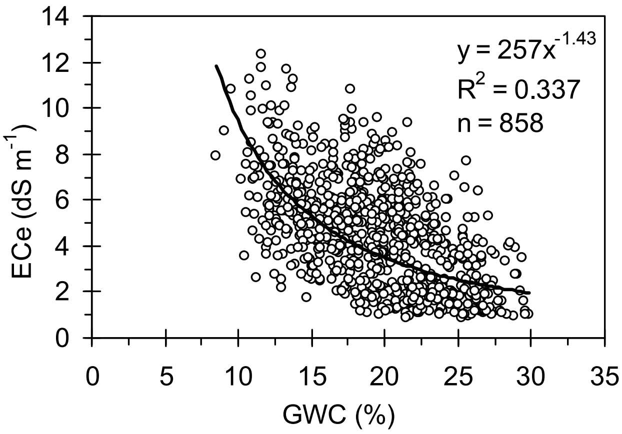

Fig. 1 Relationship and power regression equation between soil saturation extract electrical conductivity (ECe) and gravimetric soil water content (GWC) measured in the soil samples taken in the table grape vineyards and the peach and nectarine orchards in 2007-2012

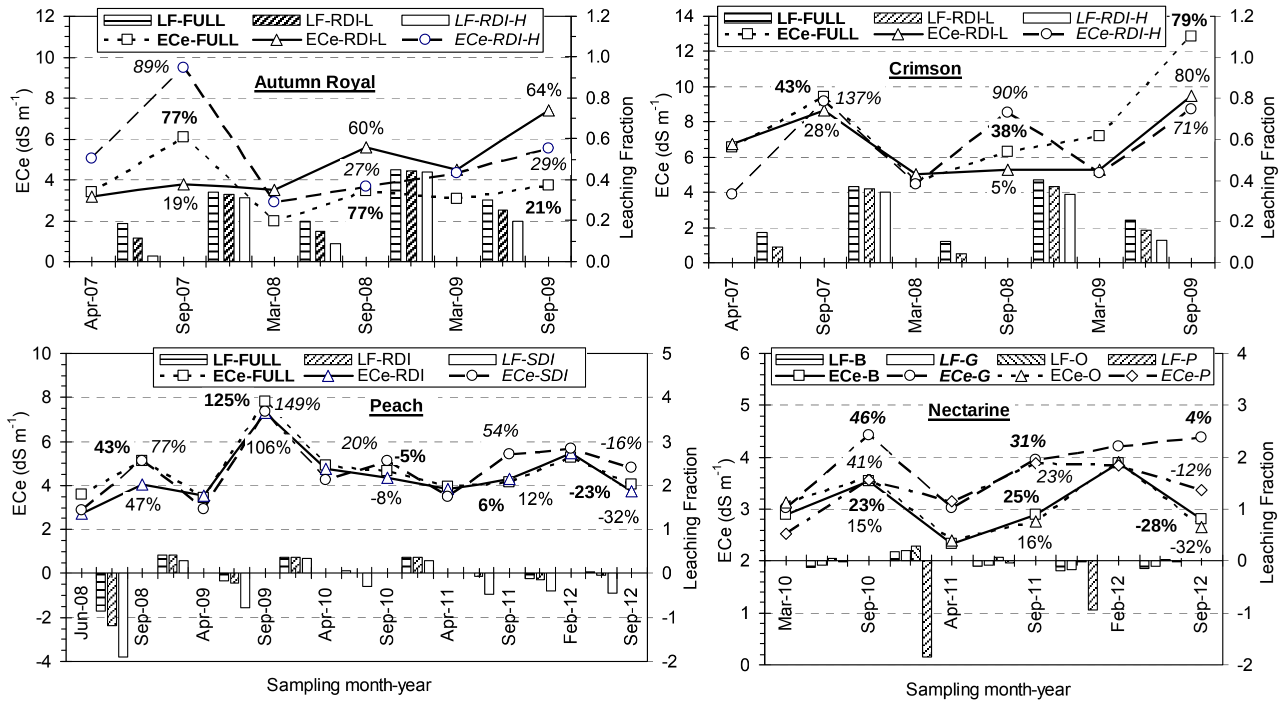

Fig. 2 Mean soil salinity (ECe) measured in each crop (Autumn Royal and Crimson table grape vineyards and peach and nectarine orchards) and irrigation or mulching treatment in the studied years. The percent ECe changes at the end relative to the ECe values at the beginning of each irrigation season and the mean leaching fractions (LF) calculated for the irrigation and non-irrigation seasons are also given

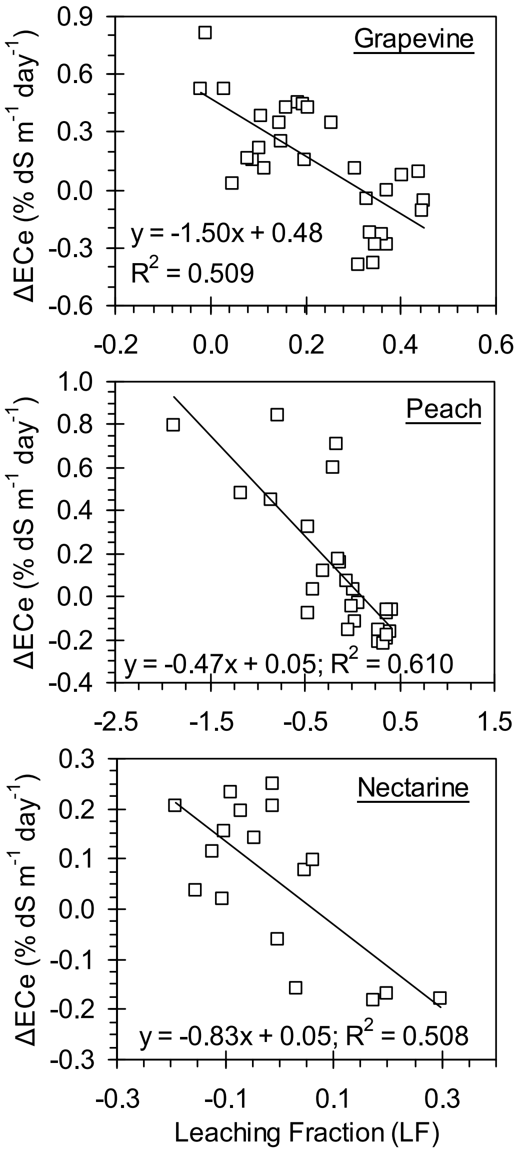

Fig. 3 Relationships and linear regression equations obtained in each crop between the changes in soil salinity (ΔECe) measured between sampling dates and the corresponding leaching fractions (LF) calculated for the periods between sampling dates. Δ is given in terms of percent daily ECe changes at the end relative to the ECe values at the beginning of each period

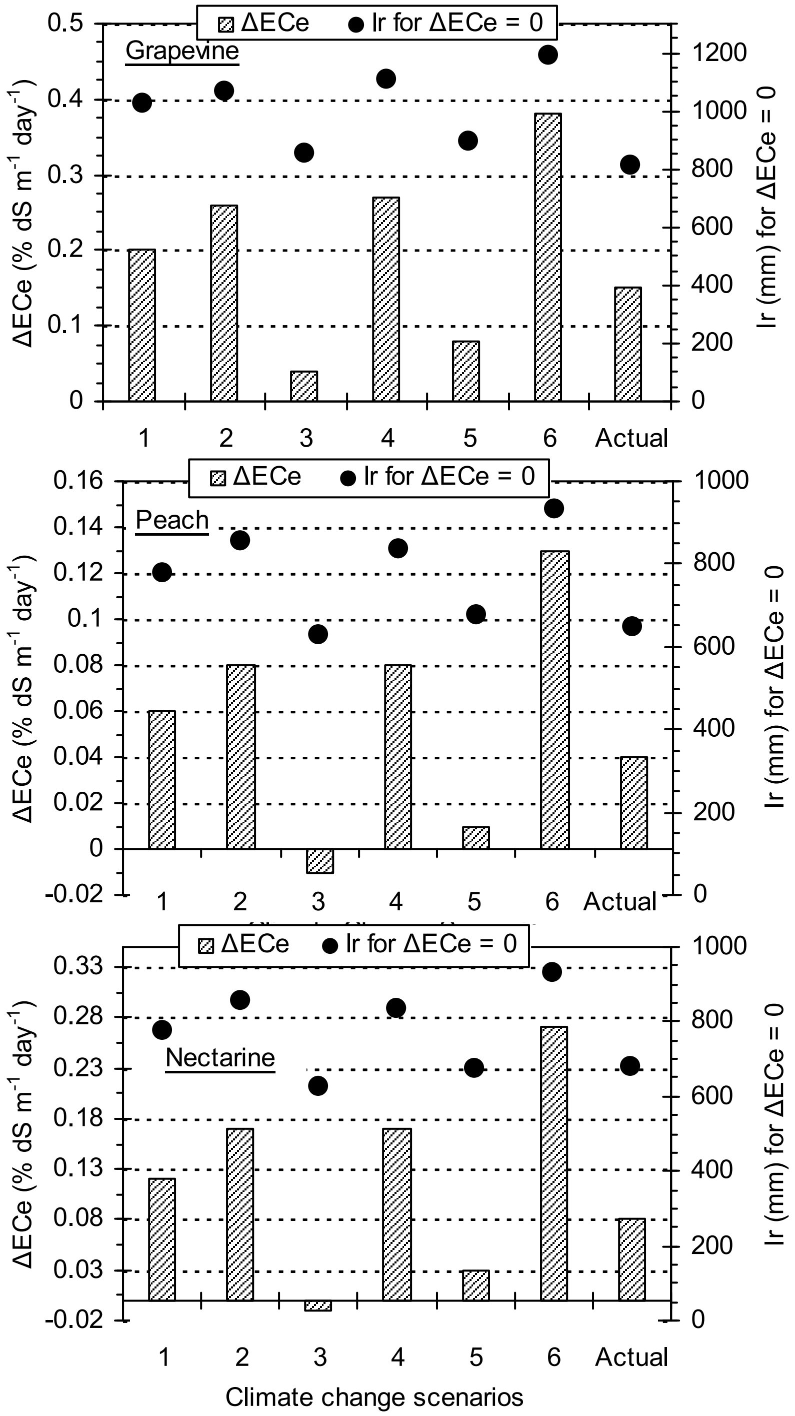

Fig. 4 Predicted soil salinity changes (ΔECe) using the equations in Fig. 3 for table grape vineyards (grapevine) and peach and nectarine orchards subject to six climate change scenarios, and required irrigation depths (I) for soil salinity control (ΔECe = 0). The ΔECe and FULL I values for the actual climate are also given for comparison purposes. The six climate change scenarios are: 1 (P = -15 %), 2 (P = -30 %), 3 (ETc = -10 %), 4 (ETc = +10 %), 5 (P = -15 %, ETc = -10 %) and 6 (P = -30 %, ETc = +10 %)