Regulated deficit irrigation, soil salinization and soil sodification in a table grape vineyard drip-irrigated with moderately saline waters

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Abstract

Irrigation with moderately saline waters may provoke soil salinization and sodification. The objectives of this three-year study were (1) to quantify these processes in two seedless table grapevines (*Vitis vinifera* cvs. Autumn Royal and Crimson) subject to a full irrigation and two regulated deficit irrigations (RDI, irrigated at 80% and 60% of net irrigation requirements from post-veraison till harvest) with 1.7 dS m^{-1} electrical conductivity irrigation waters, and (2) to assess the impact of soil salinization on grapevine's response. Soil samples were taken three times along each irrigation season and soil solution samples were extracted weekly by suction cups. Soil saturation extract electrical conductivity (ECe) and sodium adsorption ratio (SARe) were high in Autumn Royal (4.4 dS m^{-1} and 6.1 (mmol $l^{-1})^{0.5}$) and very high in Crimson (7.0 dS m^{-1} and 8.6 (mmol $l^{-1})^{0.5}$) due to relatively low leaching fractions (LF) (0.20 in Autumn Royal and 0.13 in Crimson). Soil solution salinity and sodicity were generally higher in the more severe RDI than in the full irrigation treatment. Soil salinity and sodicity generally increased along the irrigation seasons and decreased along the non-irrigation seasons. Salt accumulation or leaching and LF were significantly correlated, so that LF estimates could anticipate the required irrigation depths for soil salinity control. Grapevine yield declined with increases in soil salinity. Leaf Na concentrations were very low (< 0.1%), but leaf Cl concentrations were higher and the maximum value of 0.61% measured in the more severe Crimson RDI treatment was within the interval reported as toxic in grapevine. Despite the water saving benefits of drip irrigation in combination with deficit irrigation strategies, its implementation in low-precipitation semiarid areas must be cautiously assessed and monitored because soil salinization and sodification may threaten the sustainability and profitability of these grapevine orchards irrigated with moderately saline waters.

Keywords: deficit irrigation, salinity, sodicity, Vitis vinifera, leaf chloride, leaching fraction

1. Introduction

Regulated deficit irrigation (RDI), first proposed by Chalmers et al. (1981) as an irrigation strategy to save water without reducing crop yields, consists in the reduction of irrigation water to predetermined levels at certain developmental stages when the effects on crops are neutral or positive. RDI has expanded in the last decades in wine grapevines to improve water productivity (i.e., yield per unit water supply), berry composition, and wine quality (McCarthy et al., 2002; Ortega-Farias et al., 2012). However, RDI studies on table grapes are limited (Blanco et al., 2010), and the quality requirements are different than those of wine grapes since berry appearance and quality is mostly desired in table grapes.

Drip irrigation is generally used in RDI because of its capability to distribute water uniformly and to control the amount of water applied timely and precisely. Hoffman and Shannon (2007) and Hanson (2012) discussed the fundamentals and strategies to cope with saline waters when using drip irrigation. This system has the advantage of providing near the emitters high leaching and salt levels only slightly higher than those of the irrigation water. Since plant roots tend to proliferate near emitters, this allows water of relatively high salt content to be used successfully in many cases. Thus, Hanson et al. (2008) demonstrated that the wetting pattern around emitters results in higher leaching fractions (LF) and lower salinity levels than in other irrigation systems for a given amount of applied water. These authors defined the localized leaching fraction (LLF) as the actual LF representative of the local root domain near the drip line. Through HYDRUS-2D computer simulations, they concluded that LLF were positive for applied water amounts equal to or smaller than crop’s ET, when the field-wide LF calculated through a water balance method would be zero or negative for these water applications.

Despite the benefits of drip irrigation for soil salinity control, the LLF in RDI could be insufficient to displace the salts from the active root zone of crops in the periods with interrupted irrigation. Therefore, a potential risk of RDI is reduced salt leaching by the applied irrigation water, increased evapo-concentration of salts present in the irrigation water, root-zone soil salinization and concomitant yield decreases. However, quantification on the effects of deficit irrigation strategies on soil salinization and sodification is lacking, particularly in table grape vineyards subject to low-quality waters. In other crops such as cotton, Chen et al. (2010) concluded in a three-year study performed in an arid region of northwest China that deficit irrigation using saline waters was not sustainable due to the accumulation of salts in the soil to levels that exceeded the cotton salt tolerance. This soil salinization may also have a deleterious impact on the structural stability and hydraulic conductivity of sensitive soils due to sodification (i.e. increased sodium adsorption ratio and soil exchangeable sodium percentage) derived from the selective precipitation of calcium minerals as the soil water evapo-concentrates.

The total salt content in the soil as well as the concentration of specific ions such as Cl and Na, may have detrimental effects on vines such as reduced growth and yield, early leaf senescence and necrotic spots on leaves (Shani and Ben Gal, 2005). Grapevines have been classified on the basis of its shoot growth as moderately sensitive to soil salinity, with a threshold ECe (electrical conductivity of the soil saturation extract) of 1.5 dS m^{-1}, and a 9.6% growth decline per unit increase in ECe beyond this threshold (FAO, 1985). However, Zhang et al. (2002) concluded that these values were too conservative and that, depending on cultivars and rootstocks, they could range between 1.8-4.0 dS m^{-1} (threshold ECe) and 2.3-15.0% (slope). Leaf Cl and Na toxic concentrations were also variable depending on rootstocks and cultivars (Downton, 1977), although Cl concentrations of 0.3-1.0% (dry-weight basis) and Na concentrations of 0.25-0.5% generally caused toxicity problems (Bernstein et al, 1969; Stevens et al., 2011; Walker et al., 2004). These problems may be mitigated by the use of rootstocks that reduce the accumulation of these ions as compared to own-rooted vines (Downtown, 1977).

The objectives of this research were (1) to quantify soil salinization and sodification in two table grapevines subject to different irrigation strategies, including regulated deficit irrigation, and (2) to assess the impact of soil salinization on the yield, productivity and Na and Cl leaf ion concentrations in these table grapevines.

2. Material and methods

2.1. Field conditions, plant material and irrigation management

A three-year study (2007-2009) was conducted in a 12-ha, four year-old table grape vineyard located in the Santa Barbara commercial orchard of the ALM Group, in the county of Caspe in Northeastern Spain (Ebro River Basin, 41.16ºN, 0.01ºW). Two seedless table grape cultivars (*Vitis vinifera* cvs. Autumn Royal and Crimson) grafted onto Richter 110 rootstock (moderately tolerant to salinity according to South Australian Research and Development Institute-SARDI) were planted at a density of 1142 plants ha^{-1} in two sectors of the vineyard at a distance of 2.5 m between vines and 3.5 m between rows. The vineyard, managed according to the usual cultural practices in the farm, was cultivated using a Spanish horizontal trellis system with a protective plastic mesh 2.5 m above ground. The vines were irrigated at night by a single trickle line located close to the vines with 2.2 l h^{-1} self compensating emitters spaced 0.5 m. The weekly irrigation depths (I), measured with volumetric water meters installed in each lateral, were calculated as: I = NIR / Ea, where NIR is Net Irrigation Requirements calculated as ETc – Pef (where ETc is crop evapotranspiration and Pef is effective precipitation (P) taken as 75% of total P, according to Blanco et al., 2010) and Ea is the irrigation application efficiency taken as 0.95. These weekly I values were split in daily applications. Irrigations were applied daily from April to September, the typical irrigation season for the area. Eventual irrigation applications were also applied in February, March and October depending on the actual meteorology.

Samples of irrigation water were taken on a weekly basis. The irrigation water was moderately saline, with 2007-2009 mean values of 1.7 dS m^{-1} (ECw), 2.4 $(\text{mmol l}^{-1})^{0.5}$ (SARw), 5.5 (Na), 6.5 (Ca), 3.2 (Mg), 6.1 (Cl), 6.2 (SO_4) and 3.4 (HCO_3) (ions in meq l^{-1}). Table 1 gives the irrigation-season mean ECw and SARw and the coefficients of variation for each studied year.

The mean annual values in the area for the period 2007-2009 were 291 mm for precipitation (P) and 1430 mm for reference evapotranspiration (ETo) calculated with the FAO Penman-Monteith (Allen et al., 1998) according to the SIAR weather station network (MARM 2011). The P/ETo ratio was 0.20, classifying the Mediterranean climate as arid (P/ETo ≤ 0.2). A meteorological station was installed in the vineyard recording air temperature, relative humidity, global solar radiation, precipitation, and wind speed. The sensors were placed just below the protective mesh, except the rain gage that was placed above. The daily values of vineyard crop evapotranspiration (ETc) were estimated multiplying the ETo computed using the FAO Penman-Monteith method (Allen et al., 1998) and the daily averages of the meteorological data by the crop coefficients (Kc) adjusted for this particular vineyard. The seasonal curves of daily Kc were developed using the procedure described by Allen et al. (1998). The tabulated vineyard Kc values (Allen and Pereira, 2009) were adjusted to take into account (a) the P and average ETo during the initial stage, and the averages of wind speed and minimum relative humidity during the mid and end-season stages, and (b) the effect of the plastic mesh in reducing ETc by using a net coefficient of 0.65 (Moratiel and Martínez-Cob, 2012). The duration and dates of the different periods for calculation of Kc were determined from the soil ground cover data measured by digital photography (Blanco et al., 2010; Suvočarev et al., 2013).

Three irrigation treatments were given based upon a percentage of NIR: control (T1 or full), irrigated at 100% NIR throughout the irrigation season, and two RDI treatments irrigated at 100% NIR throughout the irrigation season except from post-veraison till harvest, when they were irrigated at 80% (T2 or RDI-80%)

and 60% (T3 or RDI-60%) NIR. In the studied years, veraison in these grapevines started from mid July to early August, and harvest from mid to late September in Autumn Royal and early to mid October in Crimson. The 80% (T2) and 60% (T3) irrigation depths were obtained by substituting the 2.2 L h^{-1} emitters by 1.6 L h^{-1} emitters spaced 0.45 and 0.60 m, respectively.

2.2. Soil sampling and analysis

The soil in this vineyard is deep, well drained, medium to coarse textured, and high in calcite and gypsum (Blanco et al., 2010). Field capacity (mean = 23.7%) and permanent wilting point (mean = 7.8%) were determined with the Richards pressure plate apparatus. The soil is classified as Xeric calcigypsid, coarse loamy, mixed (gypsic), thermic (Soil Survey Staff, 1999).

The soil samples were taken by auger in consecutive years at the right and left sides of the selected vines (one vine per cultivar and irrigation treatment). Each sample was a composite of two sub-samples taken at both sides in the front of the closest emitter to the vines at two distances (10 and 30 cm) from each emitter and at three soil depths (0-20, 20-40 and 40-60 cm). This procedure was performed at three times: (1) beginning of each irrigation season (mid February), (2) beginning of the RDI treatments (mid July to early August), and (3) end of each irrigation season (early November). The total number of soil samples taken in the three studied years was 324 (1 vine x 2 cultivars x 3 irrigation treatments x 3 sampling dates x 3 soil depths x 2 distances from emitters x 3 years).

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 (Cle) and sodium adsorption ratio (SARe). The Cle data are not reported because they were conceptually similar to those of ECe. These analyses were performed according to Chapter 10 in Page et al. (1982).

2.3. Soil solution sampling and analysis

Ceramic suction cups (Soilmoisture Eq. Corp.) were installed in each irrigation treatment for the weekly extraction of the soil solution and analysis of salinity (ECss), chloride (Clss) and sodicity (SARss). The extractions were performed one day after vacuum application. The suction cups were installed at a soil depth of 30 cm and at 10 and 30 cm from the closest emitter to the selected vines (one vine per cultivar and irrigation treatment in 2007 and two vines per cultivar and irrigation treatment in 2008 and 2009). The number of cups installed was 12 in 2007 and 24 in 2008 and 2009.

The total number of soil solution samples taken along the three studied years was 547 in Autumn Royal and 464 in Crimson. Some extractions, particularly in Crimson, were not effective because of low soil water contents and/or vacuum losses through the rubber caps.

2.4. Grapevine sampling and analysis

Two vines per cultivar and irrigation treatment were selected in 2007-2009 for appraisal of the effect of soil salinity on grapevine yield (Kg of harvested grapes vine^{-1}) measured at harvest (September in Autumn Royal grapevine and October in Crimson grapevine). The total number of observations were 2 vines x 2 cultivars x 3 irrigation treatments x 3 years = 36. For each vine and year the yield was related to the average soil salinity (ECe or ECss).

In 2008 and 2009 the grapevine productivity (Kg/cm^2), calculated from the weight of the harvested grapes (Kg) and the trunk section (cm^2) measured in each selected vine, was also related to the average soil salinity (ECe or ECss). The year 2007 was not included in this analysis because the trunk section was not measured.

Some 40 young apical leaves located in shoots of the present year were sampled in mid July and late September of each studied year in two vines per cultivar and 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 dryness and finely ground in a blender. The Cl (Cotlove (1963) coulometric–amperometric titration) and Na (flame photometry) concentrations were determined on dilute nitric–acetic acid extracts of the grounded leaves, expressing the concentrations on a dry weight basis.

2.5. Statistical analyses

Statistical analyses were performed using Analysis of Variance (ANOVA) and General Linear Model (GLM) procedure of the SAS 9.1 software (SAS Institute, 2004). Multiple comparisons were performed using Tukey test at $p = 0.05$.

3. Results and discussion

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

Table 1 summarizes the annual depths of the recorded I and P and the estimated ETc in each year, grapevine cultivar and irrigation treatment. The ETc and P depths were similar among years, with more than 80% of the annual P recorded in spring (March to June). The actual evapotranspiration was not measured as the requirements of micrometeorological methods (such as eddy covariance) for fetch and measurement height above crop canopy did not fit the experimental unit. Also, a soil water balance approach would require the soil water content to be measured in many points around the plant. Nevertheless, a limited comparison of our estimated ETc vs. the actual transpiration measured by Suvočarev et al. (2013) using the heat pulse method indicates that they were similar. This result was confirmed by the vegetative growth and grape production measured in the three irrigation treatments that were not significantly different ($P > 0.05$) (data not given).

The farmer applied an I (average of the three years and irrigation treatments) 10% higher in Autumn Royal (784 mm) than in Crimson (714 mm). The slight differences in irrigation depths applied to Autumn Royal and Crimson were due to its different phenology. In consequence, the 2007-2009 average LF [LF = (I+P-ETc)/(I+P)] was 54% higher in Autumn Royal (LF = 0.20) than in Crimson (LF = 0.13). Since the records of the farm indicate that the irrigation depths given in previous years were also higher in Autumn Royal than in Crimson, the systematic lower LF in Crimson than in Autumn Royal should imply that soil salinity would be higher in Crimson than in Autumn Royal, because the inverse of LF determines the ET-concentration factor in the soil of the salts present in the irrigation water (assuming steady-state conditions and that the only source of salts is the irrigation water).

In terms of irrigation treatments (T), both grapevines received 2007-2009 average irrigation depths that were 15% lower in T3 and 7% lower in T2 than in the control (T1). Hence, these T2 and T3 RDI treatments imply significant savings in irrigation water. The corresponding 2007-2009 average LF values were highest in T1 (0.25 in Autumn Royal and 0.18 in Crimson), intermediate in T2 (0.21 in Autumn Royal and 0.14 in Crimson) and lowest in T3 (0.15 in Autumn Royal and 0.08 in Crimson). Hence, it should be expected that soil salinity will be lowest in T1, intermediate in T2 and highest in T3.

The irrigation season average ECw values were similar in 2007 and 2009 (1.8 dS m^{-1}) and 20% higher than in 2008 (ECw = 1.5 dS m^{-1}). A similar trend was observed for SARw (Table 1). According to the FAO (1985) guidelines, grapevine yield potential will decrease by about 10-15% for these ECw values, whereas the combination of ECw and SARw will not have a negative impact on the infiltration rate of water into the soil. Watsuit (Wu et al, 2012) classifies this water as suitable in high-frequency irrigation of grapevine at any LF (data not given) due to calcite and gypsum precipitation in the soil that diminishes the effective salinity.

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

Table 2 summarizes the GWC, ECe and SARe measured in Autumn Royal and Crimson grapevines in 2007-2009 years. These values are averages of 18 soil samples taken in each year and irrigation treatment (T1, T2 and T3) at three soil depths (0-20, 20-40 and 40-60 cm), two distances from emitters (10 and 30 cm) and three sampling dates (April-March, July and September). A statistical comparison of these means is not valid because they are a combination of irrigation treatments, soil depths, distance from emitters and sampling dates. The high coefficients of variation (CV) of these means (about 20% for GWC and 40% for ECe and SARe) reflect the high spatial variability of these variables in drip-irrigation.

The mean GWC values were lower than field capacity (21%) and higher in Autumn Royal (2007-2009 mean = 17.2%) than in Crimson (15.6%), in correspondence with the higher irrigation depths given to Autumn Royal (Table 1). As expected, GWC values were higher at 10 cm (18.2% in Autumn Royal and 17.6% in Crimson) than at 30 cm (16.3% in Autumn Royal and 13.7% in Crimson) from emitters. GWC were highest at 0-20 cm soil depth (2007-2009 mean = 16.2%), slightly lower at 20-40 cm soil depth (15.7%) and lowest at 40-60 cm soil depth (14.6%). GWC were quite similar among years and irrigation treatments (data not given). These results reflect the daily irrigations given to both grapevines (i.e., relatively high GWC values close to emitters and lower GWC values away from emitters).

The yearly ECe averages were consistently higher in Crimson than in Autumn Royal (Table 2), in agreement with the lower Crimson LF previously reported. Thus, the average 2007-2009 ECe was 59% higher in Crimson (7.0 dS m^{-1}, average LF = 0.13) than in Autumn Royal (ECe = 4.4 dS m^{-1}, average LF = 0.20). ECe in the two grapevines was highest in 2009, intermediate in 2007 and lowest in 2008 (Table 2). The lower soil salinity in 2008 was explained by (1) the lower ECw and higher irrigation-season P (Table 1), (2) the P recorded between the initial and final sampling dates that was 42% higher in 2008 (188 mm) than in 2007 (132 mm), and (3) the different rainfall distributions and progressively higher monthly P values along the season in 2008 relative to the same month in 2007 and 2009, as shown by the ratios of cumulative monthly P in 2007 to that in 2008 (decreases from 3.3 in April to 0.8 in October), and in 2009 to that in 2008 (decreases from 2.3 in April to 0.6 in October). Thus, the amount and distribution of precipitation along the 2008 irrigation season played an important role in the leaching of salts.

ECe was similar at 0-20 and 20-40 cm soil depths (average ECe of all soil samples taken along the trial = 6.0 and 5.7 dS m^{-1}, respectively), and somewhat lower at 40-60 cm soil depth (5.2 dS m^{-1}). This inverted salinity profile would reflect a higher root density (and, therefore, a higher ET-concentration factor) at shallower soil depths, as well as water evaporation from the wetted surface typical in high-frequency drip irrigation systems (Hoffman and Shannon, 2007, Shalhevet, 1994).

ECe was consistently higher at 30 than at 10 cm distances to the emitter in the two grapevines and the three irrigation treatments (Table 3), due to the continuous and higher leaching of salts close to emitters. In relation to the ECe values measured at 10 cm, the ECe values at 30 cm were about 50% higher in both grapevines. In Autumn Royal, these increases were highest in T3 (71%), intermediate in T2 (44%) and lowest in T1 (27%), following the same order than the increases in deficit irrigation (T3 > T2 > T1). In Crimson, these increases were similar in the three irrigation treatments (Table 3).

For simplicity purposes and in order to integrate soil salinity both laterally and vertically, the rest of results will be given in terms of average ECe for the three soil depths and the two distances to emitters.

Figure 1 shows the evolution of the average ECe values between April 2007 and September 2009 in the three irrigation treatments (T1, T2 and T3) of Autumn Royal and Crimson grapevines. The percent ECe changes at the end of each irrigation season (September) relative to the ECe at its beginning (April or March) are also shown in this figure. In general, ECe increased along the irrigation seasons (periods of highest ETc and lowest LF) and decreased along the non-irrigation seasons (periods of lowest ETc and highest LF). Thus, late fall and winter precipitations played a major role in the leaching of salts along the non irrigation seasons.

The 2007-2009 average ECe increases along the irrigation season (April, July and September soil samplings) are shown in Fig. 2. The maximum ECe increases occurred between July and September (increases of 1.3 dS m^{-1} in Autumn Royal and 1.8 dS m^{-1} in Crimson), the period when RDI was imposed in irrigation treatments T2 and T3, and the minimum between April and July (0.4 dS m^{-1} in Autumn Royal and 1.5 dS m^{-1} in Autumn Royal), the period when the three treatments where fully irrigated.

A general increasing ECe trend was observed along the three studied years, particularly in Crimson (Fig. 1). The relative ECe changes at the end of each irrigation season were always positive, and the overall relative ECe changes between April 2007 and September 2009 for the average ECe of the three irrigation treatments were 43% in Autumn Royal and 82% in Crimson. These results indicate that soil salinization took place along the studied period in this grapevine orchard drip-irrigated with moderately saline waters (ECw = 1.5-1.8 dS m^{-1}). In relation to the irrigation treatments, no clear trends were obtained, since in some cases ECe in T3 (treatment with the highest water deficit) increased more than in the other treatments (particularly in Crimson), whereas in others the increases were similar (as in September 2009 for Crimson) or lower (as in September 2008 for Autumn Royal).

Irrespective of grapevine cultivars and irrigation treatments, the relative ECe changes between sampling dates (ΔECe) were significantly correlated ($p < 0.001$) with the field-wide LF calculated between sampling dates (Fig. 3). Based on the regression equation shown in this figure, field-wide LF above 0.3 will imply salt leaching (ΔECe < 0), and below 0.3 salt accumulation (ΔECe > 0). Most of the negative ΔECe values were obtained in the non irrigation seasons, indicating that late fall and winter precipitations (with EC values below 0.1 dS m^{-1}) were crucial for the leaching of salts accumulated during the irrigation seasons.

Even though LF in drip irrigation is highly variable and decreases with increasing distances from emitters (Hanson, 2012), the field-wide LF could be an interesting management variable for appraisal of potential soil salinization. The developed equation is case-sensitive and should be established in each particular environment (crop, soil, climate and irrigation water characteristics) to assess the required irrigations depths for a proper soil salinity control.

The SARe results were conceptually similar to those obtained with ECe because both variables were significantly correlated (SARe = 1.24 ECe; $R^2 = 0.791$, $p < 0.001$; n = 313), indicating that soil sodification was the result of soil salinization and the concomitant selective precipitation of calcium minerals in the soil. Thus, according to Watsuit, the soil solution was saturated in calcite and close to saturation or saturated in gypsum at medium to low LF values (data not given).

The yearly SARe values were higher in Crimson than in Autumn Royal (2007-2009 average 41% higher in Crimson than in Autumn Royal, Table 2). SARe slightly decreased with soil depth (average SARe of all soil samples taken along the trial = 7.7 at 0-20 cm, 7.4 at 20-40 cm and 6.9 (mmol $l^{-1})^{0.5}$ at 40-60 cm soil depths).

The SARe values were consistently higher at 30 than at 10 cm distances to emitters in the two grapevines and the three irrigation treatments (Table 3). In relation to the SARe values measured at 10 cm to emitters, the mean SARe values at 30 cm were 37% higher in Autumn Royal and 57% higher in Crimson, and a general increasing SARe trend was observed along the three studied years (data not given). These results indicate that soil sodification took place in this grapevine orchard drip-irrigated with low sodicity waters [SARw about 2.4 (mmol $l^{-1})^{0.5}$].

In terms of the infiltration of water in the soil, soil sodicity in the upper soil is most important. The SARe values of all the soil samples taken at 0-20 cm soil depth along the three years were 7.0 (mmol $l^{-1})^{0.5}$ (CV = 40%) in Autumn Royal and 8.7 (mmol $l^{-1})^{0.5}$ (CV = 43%) in Crimson. These values, in combination with the salinity of the irrigation water (ECw = 1.5-1.8 dS m^{-1}) and, particularly, with the low salinity of precipitation (EC < 0.1 dS m^{-1}), could have a deleterious effect on the infiltration rate of water in these soils due to clay dispersion and clogging of pores in the surface soil layer (Amezketa et al., 2004).

3.3. Soil solution salinity (ECss), chloride (Clss) and sodicity (SARss)

Table 4 summarizes the 2007-2009 ECss, Clss and SARss values measured in the soil solution samples extracted by the suctions cups installed at 30 cm soil depth in the T1, T2 and T3 irrigation treatments of Autumn Royal and Crimson grapevines. The results with the soil solution samples were in general agreement with those obtained with soil samples. The comparison among years is worthless because the number of samples extracted were different (Table 4). However, for the 2007-2009 average, where the number of samples was very high (above 400 in all cases, Table 4), the results indicate that ECss, Clss and SARss were, respectively, 62%, 64% and 35% higher in Crimson than in Autumn Royal.

In relation to the irrigation treatments, the 2007-2009 values show that ECss, Clss and SARss were consistently higher in T3 (high deficit irrigated treatment) than in T1 (full irrigated treatment) in both grapevines. These values were also slightly higher in T2 (moderately deficit irrigated treatment) than in T1 in

Crimson but not in Autumn Royal. However, these comparisons should be taken with caution because of the different number of successful extractions in each irrigation treatment. In both grapevines, the values measured at 30 cm from emitters were higher than the values measured at 10 cm (about 40% higher for ECss and SARss, and about 60% higher for Clss; data not given). These ECss ans SARss increases were of the same order of magnitude than those obtained with ECe and SARe (Table 3).

The advantages of the results obtained using suction cups are that (1) the analysis are performed on the actual soil solution rather than on the soil saturation extract where the soil solution is diluted with distilled water, (2) the soil solution samples are taken in the same position and at the desired frequency, whereas consecutive soil samplings must be performed in different positions, and (3) trends based on a large number of data taken in the same positions are more reliable than those obtained with only three soil samplings performed along the irrigation seasons.

The comparisons of ECss, Clss and SARss measured in the two extreme irrigation treatments T1 (control, irrigated at 100% NIR throughout the irrigation season) and T3 (RDI, irrigated at 60% NIR from post-veraison till harvest) show that they were between 38 and 56% (Autumn Royal) and between 5 and 14% (Crimson) higher in T3 than in T1 (Table 5). Hence, the high RDI imposed in irrigation treatment T3 increased the soil solution salinity and sodicity in relation to the control treatment (T1), in agreement with the lower LF in T3 than in T1 (Table 1). The results obtained with the T2 irrigation treatment were not as consistent (i.e., the T2 values were also higher than the T1 values in Crimson, but not in Autumn Royal) probably because of the lower water deficit and higher LF as those in the T3 irrigation treatment.

The daily ECss, Clss and SARss temporal trends obtained in Autumn Royal and Crimson grapevines along the 2007, 2008 and 2009 irrigation seasons show that they increased significantly ($p < 0.001$) in 2007 and 2009 (except SARss in Autumn Royal 2007), but not in 2008 (although the final values in 2008 were always higher than the initial values) (Fig. 4). This lack of significance in year 2008 could be explained by the same reasons given previously in section 3.2. The slopes of the significant linear regressions were in all cases higher in Crimson than in Autumn Royal, indicating that soil solution salinization and sodification was higher in Crimson. The slopes were higher in 2007 than in 2009 (except SARss in Crimson), indicating that soil solution salinization (ECss and Clss) was higher in 2007.

The ECss at 30 cm soil depth and the ECe at the equivalent 20-40 cm soil depth interval measured in the same days in the two grapevine cultivars, the three irrigation treatments and the three years were significantly correlated ($p < 0.001$) (Fig. 5), even though the depths of measurement and the positions of the suction cups and of soil samplings were not exactly the same. The slope of the linear regression was 0.97 (Fig. 5), an unexpected result since based on an average GWC of about 16% (Table 2), a measured average saturation percentage (SP) of 34%, and assuming mass conservation (i.e., ECss · GWC = ECe · SP), , the slope should be 2.1 (ECss = ECe · 34/16). This apparent anomaly is explained because the mass of dissolved salts is not conserved as calcite and gypsum are dissolved in the soil saturation extract. Thus, only two ECe values were below the 2.2 dS m^{-1} EC-saturated gypsum solution at 25º C (Fig. 5), indicating that the samples were saturated in calcite and gypsum. The saturation extract concentrations of Ca (27.3 meq l^{-1} in Autumn Royal and 41.3 meq l^{-1} in Crimson), SO_4 (24.2 meq l^{-1} in Autumn Royal and 41.3 meq l^{-1} in Crimson) and HCO_3 (7.3 meq l^{-1} in Autumn Royal and 6.8 meq l^{-1} in Crimson) measured in a set of soil samples in 2007 also indicate that they were saturated or over-saturated in these minerals. Thus, in practical terms ECe and ECss could be considered similar.

3.4. Effects of soil salinity on grapevine yield, productivity and leaf Na and Cl concentrations

Since ECe and ECss were similar (Fig. 5), the six vines of the two cultivars with ECe measurements and the six vines of the two cultivars with ECss measurements were pooled together for the three studied years to get a total of 36 yield-EC observations (Fig. 6). The FAO (1985) threshold-slope salinity model for the vegetative response of grapevine is also plotted in this figure, where the threshold ECe of 3.5 dS m^{-1} corresponds to soils with gypsum. For each year and cultivar, differences in yield between irrigation treatments were nos significantly different ($P > 0.05$) (data not given).

Although data scattering is very high, Fig. 6 shows that the FAO threshold ECe fits reasonably well the maximum grapevine yield (85.1 Kg $vine^{-1}$), and that the FAO slope (9.6%) is somewhat lower (in absolute terms) than the upper boundary line (Webb, 1972) that will represent the maximum yield observed at a given value of soil salinity. This boundary line analysis, applied by Urdanoz and Aragüés (2009) to the salinity response of drip-irrigated Tempranillo grapevine, represents the limiting response to soil salinity, and values falling below the boundary represent sites where other stress factors limit growth. Although these results are not conclusive because of the low number of observations close to the boundary line, they show that grapevine yield tended to decline with increases in soil salinity so that above an EC of about 7 dS m^{-1}, all yields except two decreased by 50% or more in relation to the maximum yield. However, low yields were also obtained at low EC values, particularly in Autumn Royal (Fig. 6), suggesting that they were negatively affected by other unidentified stresses besides salinity.

Grapevine productivity was also calculated for years 2008 and 2009 (no data for year 2007). Grapevine productivity decreased with increasing soil salinity and the eye-fitted upper boundary line, represented in this figure for comparison purposes, had a somewhat higher slope (in absolute terms) than the FAO response function. Urdanoz and Aragüés (2009) also found a higher slope (17.1%) for the

Tempranillo cultivar, indicating that depending on cultivars, rootstocks and soil salinity characteristics, salinity tolerance above the threshold ECe could be different to that given by FAO.

Figure 7 gives the 2007-2009 July + September mean leaf Na and Cl concentrations measured in the T1, T2 and T3 irrigation treatments of Autumn Royal and Crimson grapevines. No significant differences ($p > 0.01$) were obtained between sampling dates, years or irrigation treatments. Leaf Na concentrations were very low (< 0.1%) in both grapevines, similar in the three irrigation treatments, and well below the toxic threshold interval of 0.25-0.50% reported by Stevens et al (2011) and Walker et al (1997) depending on rootstocks and varieties. These values agree with those of Ehlig (1960) indicating that toxic levels of Na are uncommon in grapevine leaves because it is not translocated in appreciable amounts from the roots to the leaves. In contrast, leaf Cl concentrations were much higher (all values close or higher than 0.4%) in both grapevines and tended to increase with increases in deficit irrigation (T3 > T2 > T1), although differences among irrigation treatments were not significant ($p > 0.05$). Since soil Cle was lower than soil Nae (mean concentrations of all soil samples taken along the 2007-2009 years = 23.0 meq Cle l^{-1} and 28.2 meq Nae l^{-1}), the higher leaf Cl than leaf Na indicates that the combination of the two cultivars and Richter 110 rootstock excluded more efficiently Na than Cl from the young apical leaves.

The mean leaf Cl concentration for all years and irrigation treatments was 22% higher in Crimson (0.50%) than in Autumn Royal (0.41%), in agreement with the higher soil salinity values measured in Crimson. The maximum leaf Cl concentration was obtained in Crimson T3 (0.61%) (Fig. 7). This concentration is in the medium range of the toxic interval given for grapevine (0.3-1.0% depending on rootstocks and cultivars; Berstein et al, 1969; Walker et al, 2004). Although toxicity symptoms (leaf burning and necrosis) were not generally observed in these grapevines, the Cl concentrations above 0.5% measured in the two Crimson RDI treatments indicate that Cl toxicity could be a significant problem in this grapevine orchard deficit irrigated with moderately saline waters since several authors (Hoffman et al, 1989; Boland et al, 1997; Aragüés et al, 2005) have shown that woody perennial crops become more sensitive with time due to the gradual build-up of salts within the plant.

4. Conclusions

Soil salinity and sodicity values measured along three years in a drip irrigated table grape vineyard located in an arid area of the Ebro River Basin (Spain) were high in Autumn Royal and very high in Crimson grapevines due to the coupled effects of the application of moderately saline irrigation waters and the imposition of relatively low (Autumn Royal) or very low (Crimson) field-wide leaching fractions (LF), particularly at periods of regulated deficit irrigation.

Soil solution salinity, chloride and sodicity in both grapevines were higher in the more severe regulated deficit irrigation treatment than in the full irrigated treatment. Irrespective of grapevine cultivars and irrigation treatments, soil salinity and sodicity tended to increase along the irrigation seasons (periods of highest ETc and lowest LF) and to decrease along the non-irrigation seasons (periods of lowest ETc and highest LF).

Even though precipitation in this arid area is low, its amount and distribution was important for the partial leaching of salts in the irrigation season and, particularly, in the non irrigation season. Thus, late fall and winter precipitations were crucial for soil salinity control in this vineyard drip-irrigated with moderately saline waters.

The changes in soil salinity and the field-wide LF obtained at given periods were significantly correlated. Based on the equation developed in this study, a threshold field-wide LF of 0.3 determined positive or negative changes in soil salinity. Therefore, this variable could be applied on a case by case basis to assess salt accumulation or salt leaching and to anticipate the required irrigation depths for a proper soil salinity control.

Although scattering of data was very high and the results were therefore not conclusive, the yield and productivity in both grapevines tended to decline with increases in soil salinity. Leaf Na concentrations were always below levels reported as toxic in grapevine, but leaf Cl concentrations tended to increase with increases in deficit irrigation, and the maximum leaf Cl concentrations were within the toxic interval for grapevine. However, further work is needed to assess Cl toxicity if soil salinization and its concomitant build-up in plants persist in this grapevine orchard.

Overall, drip irrigation in combination with deficit irrigation strategies may save significant amounts of water, but the observed root zone soil salinization and sodification may have potential negative impacts on vines (increased osmotic stress and chloride toxicity) and soils (decreased water infiltration rates) that could threaten the sustainability and profitability of this grapevine orchard irrigated with moderately saline waters. Therefore, in low-precipitation arid and semiarid areas, a cautious assessment and the extension of the detailed monitoring presented in this work on the temporal and spatial soil salinity and sodicity trends is mandatory to implement best management strategies aimed at its control.

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Table 1. Annual depths of irrigation (I), precipitation (P) and crop evapotranspiration (ETc), and field-wide leaching fractions (LF) in each year, grapevine cultivar and irrigation treatment [T1 (full), T2 (RDI-80%) and T3 (RDI-60%)]. The irrigation-season P and ETc depths are given in parenthesis. The irrigation-season mean electrical conductivity (ECw) and sodium adsorption ratio (SARw) of the irrigation water and their coefficients of variation (CV) are also given.

Year	Grapevine cultivar	Irrigation Treatment	I (mm)	P (mm)	ETc (mm)	LF	ECw (dS m^{-1})	SARw [(mmol l^{-1})$^{0.5}$]
2007	Autumn Royal	T1	877	274 (235)	890 (835)	0.23	1.77 (CV = 12%)	2.5 (CV = 19%)
		T2	807			0.18		
		T3	733			0.12		
	Crimson	T1	855		894 (844)	0.21		
		T2	787			0.16		
		T3	716			0.10		
2008	Autumn Royal	T1	808	310 (256)	870 (787)	0.22	1.46 (CV = 46%)	2.2 (CV = 41%)
		T2	757			0.19		
		T3	703			0.14		
	Crimson	T1	704		869 (795)	0.14		
		T2	647			0.09		
		T3	587			0.03		
2009	Autumn Royal	T1	851	288 (231)	813 (749)	0.29	1.76 (CV = 22%)	2.4 (CV = 30%)
		T2	792			0.25		
		T3	730			0.20		
	Crimson	T1	763		842 (784)	0.20		
		T2	712			0.16		
		T3	658			0.11		

Table 2. Gravimetric soil water content (GWC) and soil saturation extract electrical conductivity (ECe) and sodium adsorption ratio (SARe) measured in Autumn Royal and Crimson grapevines: yearly 2007-2009 mean values of the 54 soil samples taken in the three irrigation treatments [T1 (full), T2 (RDI-80%) and T3 (RDI-60%)] at three soil depths (0-20, 20-40 and 40-60 cm), two distances to the emitter (10 and 30 cm) and three sampling dates (April-March, July and September).

	Autumn Royal				Crimson			
	2007	2008	2009	2007-2009	2007	2008	2009	2007-2009
GWC (%)	18.2	16.4	17.5	17.2	15.2	14.9	16.8	15.6
ECe (dS m^{-1})	4.7	3.7	5.0	4.4	7.0	5.6	8.4	7.0
SARe [(mmol l^{-1})$^{0.5}$]	6.5	5.3	6.4	6.1	7.8	7.4	10.6	8.6

Table 3. 2007-2009 mean ECe and SARe (0-60 cm soil depth at 10 and 30 cm distances to the emitter) in irrigation treatments T1 (full), T2 (RDI-80%) and T3 (RDI-60%) of Autumn Royal and Crimson grapevines. The percent ECe and SARe increases at 30 cm relative to the ECe and SARe at 10 cm (Δ) are also given.

	ECe (dS m^{-1})						SARe [(mmol l^{-1})$^{0.5}$]					
	Autumn Royal			Crimson			Autumn Royal			Crimson		
	------------------------------------ Distance to emitter (cm) ------------------------------------											
	10	30	Δ (%)	10	30	Δ (%)	10	30	Δ (%)	10	30	Δ (%)
T1	3.0	3.8	27	6.2	9.5	53	4.6	5.8	26	7.1	11.8	66
T2	3.9	5.6	44	5.5	7.9	44	5.0	7.2	44	5.5	10.2	85
T3	3.8	6.5	71	5.2	7.8	50	5.8	8.1	40	7.6	9.5	25
Mean	3.6	5.3	47	5.6	8.4	50	5.1	7.0	37	6.7	10.5	57

Table 4. Soil solution electrical conductivity (ECss), chloride (Clss) and sodium adsorption ratio (SARss) measured at 30 cm soil depth in irrigation treatments T1 (full), T2 (RDI-80%) and T3 (RDI-60%) and years 2007, 2008 and 2009 of Autumn Royal and Crimson grapevines: mean values of the data gathered at 10 and 30 cm distances to the emitter. The number of samples is also listed in parenthesis.

		Autumn Royal			
		2007	2008	2009	2007-2009
ECss (dS m^{-1})	T1	4.3 (21)	2.2 (16)	3.7 (126)	3.6 (163)
	T2	5.9 (28)	2.0 (37)	2.7 (90)	3.1 (155)
	T3	5.9 (21)	1.8 (20)	5.2 (188)	5.0 (229)
	T1+T2+T3	5.4 (70)	2.0 (73)	4.2 (404)	4.0 (547)
Clss (meq l^{-1})	T1	12.0 (5)	7.0 (16)	16.9 (126)	15.6 (147)
	T2	20.5 (7)	6.5 (37)	10.9 (90)	10.2 (134)
	T3	21.9 (6)	7.0 (20)	26.4 (188)	24.4 (214)
	T1+T2+T3	18.6 (18)	6.7 (73)	19.9 (404)	17.9 (495)
SARss [(mmol l^{-1})$^{0.5}$]	T1	2.8 (5)	3.4 (15)	5.4 (126)	5.1 (146)
	T2	3.4 (7)	3.3 (37)	4.0 (90)	3.8 (134)
	T3	3.6 (6)	4.5 (20)	7.8 (186)	7.4 (212)
	T1+T2+T3	3.3 (18)	3.7 (72)	6.2 (402)	5.7 (492)
		Crimson			
		2007	2008	2009	2007-2009
ECss (dS m^{-1})	T1	9.6 (19)	4.2 (30)	6.0 (93)	6.1 (142)
	T2	9.2 (23)	4.4 (15)	6.7 (95)	6.9 (133)
	T3	6.8 (11)	3.9 (17)	6.6 (166)	6.4 (194)
	T1+T2+T3	8.9 (53)	4.2 (62)	6.5 (354)	6.4 (469)
Clss (meq l^{-1})	T1	42.3 (7)	17.3 (32)	29.7 (92)	27.3 (131)
	T2	28.6 (6)	16.5 (15)	33.5 (95)	31.1 (116)
	T3	24.6 (5)	16.0 (17)	32.7 (165)	30.9 (187)
	T1+T2+T3	32.8 (18)	16.7 (64)	32.1 (352)	29.9 (434)
SARss [(mmol l^{-1})$^{0.5}$]	T1	4.8 (7)	5.3 (30)	7.9 (93)	7.2 (130)
	T2	3.3 (6)	5.3 (15)	8.0 (95)	7.4 (116)
	T3	3.1 (5)	4.7 (16)	8.6 (166)	8.1 (187)
	T1+T2+T3	3.8 (18)	5.1 (61)	8.3 (354)	7.7 (433)

Table 5. Soil solution electrical conductivity (ECss), chloride (Clss) and sodium adsorption ratio (SARss) measured at 30 cm soil depth in the irrigation treatments T1 (full), T2 (RDI-80%) and T3 (RDI-60%) of Autumn Royal and Crimson grapevines: mean values of the three studied years (2007-2009) at 10 and 30 cm distances to the emitter. The number of samples is also listed. Δ refers to the percent change in T2 or T3 relative to T1.

	Autumn Royal					Crimson				
	T1	T2	T3	Δ_{T1-T2} (%)	Δ_{T1-T3} (%)	T1	T2	T3	Δ_{T1-T2} (%)	Δ_{T1-T3} (%)
ECss (dS m^{-1})	3.6	3.1	5.0	-14	38	6.1	6.9	6.4	13	5
Nº samples	163	155	229			142	133	194		
Clss (meq l^{-1})	15.6	10.2	24.4	-35	56	27.3	31.1	30.9	14	13
Nº samples	147	134	214			214	116	187		
SARss [(mmol $l^{-1})^{0.5}$]	5.1	3.8	7.4	-26	45	7.2	7.4	8.1	4	14
Nº samples	146	134	212			130	116	157		

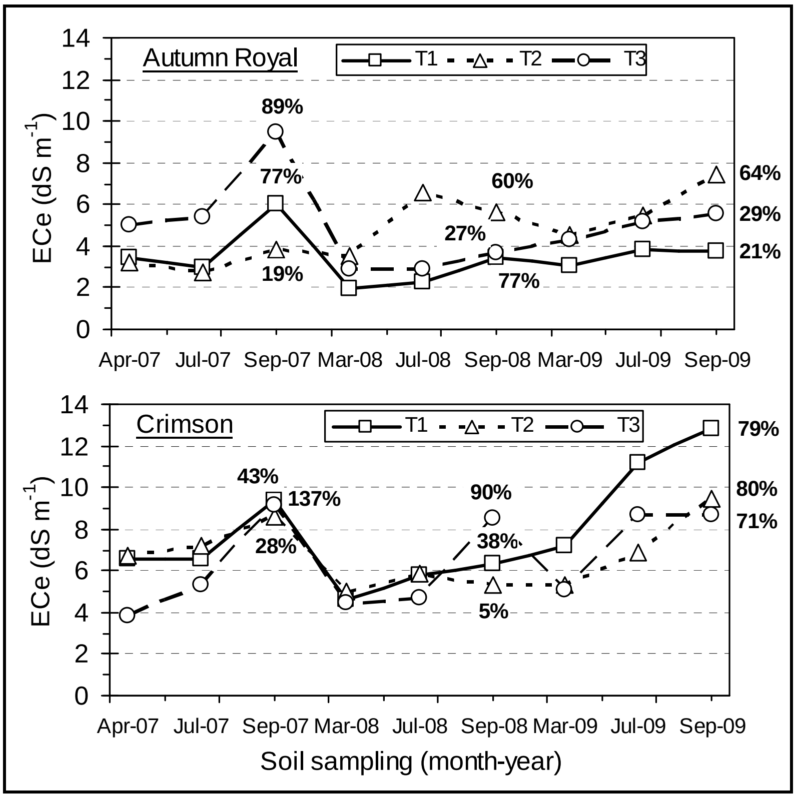

Figure 1. Mean soil saturation extract electrical conductivity (ECe, values measured at 0-20, 20-40, 40-60 cm soil depths and at 10 and 30 cm distances to the emitter) in the T1 (full), T2 (RDI-80%) and T3 (RDI-60%) irrigation treatments of Autumn Royal and Crimson grapevines along April 2007-September 2009. The percent ECe changes at the end of each irrigation season (September) relative to the ECe at the beginning (March or April) are also given.

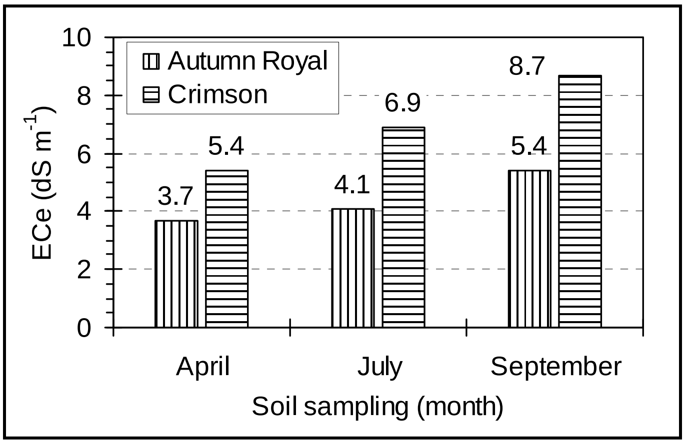

Figure 2. Mean soil saturation extract electrical conductivity (ECe, values measured at 0-20, 20-40, 40-60 cm soil depths and at 10 and 30 cm distances to the emitter in years 2007-2009 and irrigation treatments T1 (full), T2 (RDI-80%) and T3 (RDI-60%)] in Autumn Royal and Crimson grapevines in April, July and September soil sampling months.

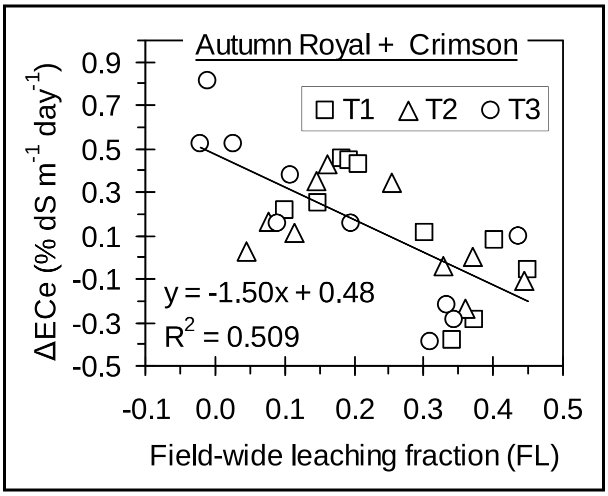

Figure 3. Relationships and linear regression equation between changes in soil salinity in-between sampling dates (ΔECe, where the soil saturation extract ECe is the mean of the 0-20, 20-40, 40-60 cm soil depths at 10 and 30 cm distances to the emitter) and field-wide leaching fractions (LF) calculated for the periods between sampling dates. ΔECe is given in terms of relative percent change ECe per day (ΔECe = 100 (ECe final – ECe initial)/ECe final · number of days between sampling dates) for each period between sampling dates (total of 30 periods) along the 2007-2009 studied years.

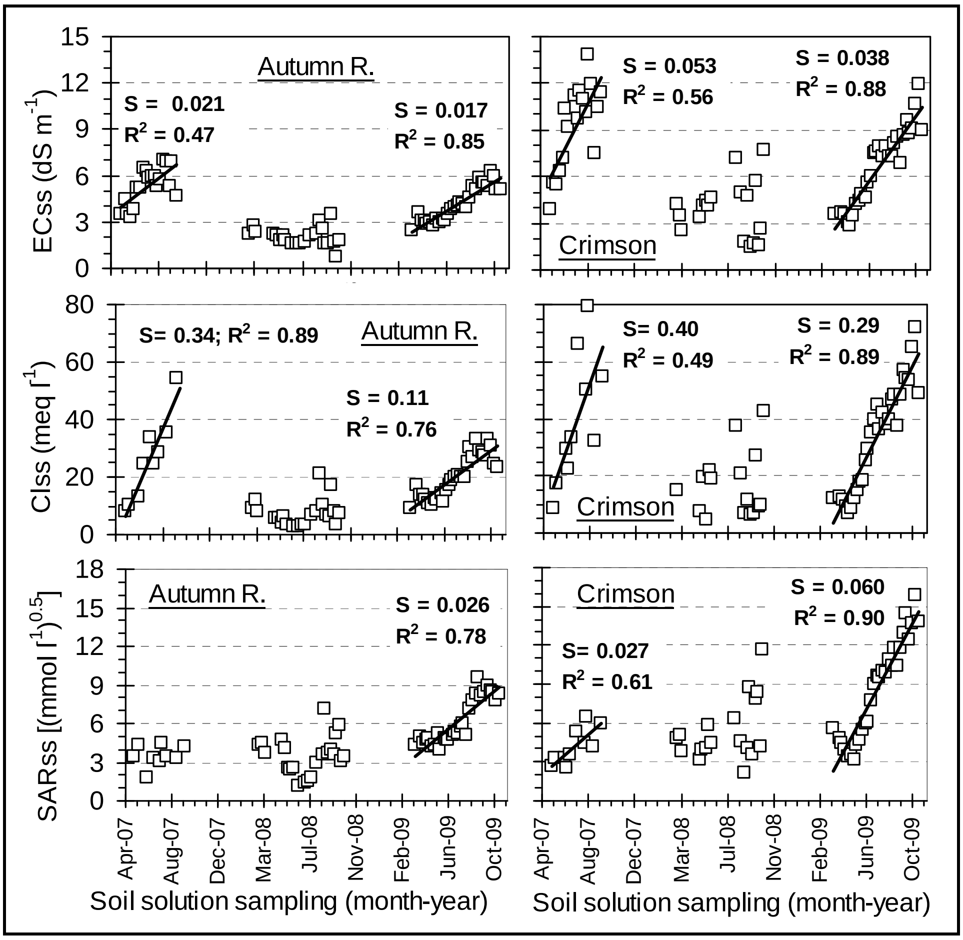

Figure 4. Daily mean soil solution electrical conductivity (ECss), soil solution chloride concentration (Clss) and soil solution sodium adsorption ratio (SARss) [values measured at 30 cm soil depth and at 10 and 30 cm distances to the emitter in irrigation treatments T1 (full), T2 (RDI-80%) and T3 (RDI-60%)] of the soil solution extracted by suction cups in the 2007, 2008 and 2009 irrigation seasons of Autumn Royal and Crimson grapevines. The slopes (S) and coefficients of determination (R^2) of the significant ($p < 0.001$) linear regressions are also given.

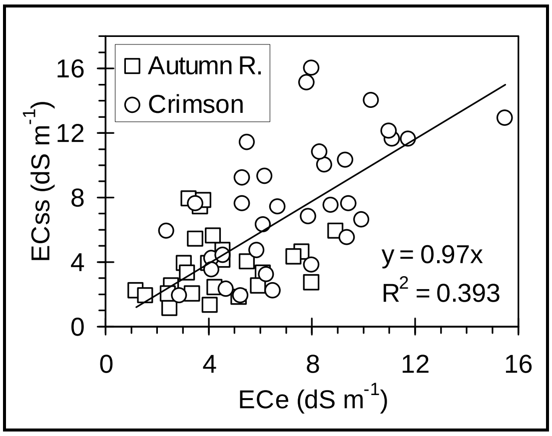

Figure 5. Relationships and linear regression equation between soil solution electrical conductivity (ECss at 30 cm soil depth) and soil saturation extract electrical conductivity (ECe at 20-40 cm soil depth) measured in the same dates in Autumn Royal and Crimson grapevines at 10 and 30 cm distances to the emitter in years 2007-2009.

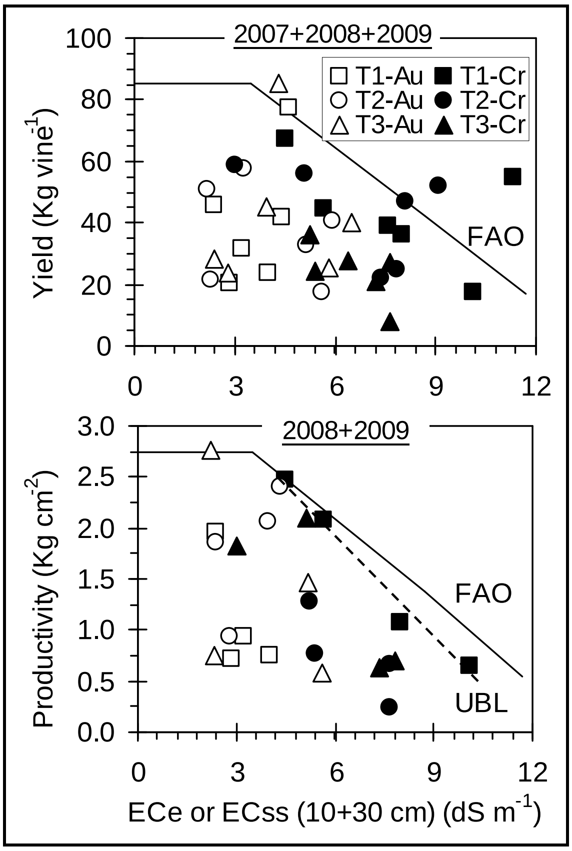

Figure 6. Relationships between grapevine yield in years 2007, 2008 and 2009 and grapevine productivity in years 2008 and 2009 versus soil saturation extract electrical conductivity (average ECe of soil samples taken at 20-40 cm depth and at 10 and 30 cm distances to the emitter along each year) and versus soil solution electrical conductivity (average ECss of soil solution samples taken at 30 cm depth and at 10 and 30 cm distances to the emitter along each year). The FAO piecewise linear response model of grapevine to soil salinity with gypsum in the soil is represented (solid line). For productivity, the eye-fitted upper boundary line (UBL, dashed line) is also given for comparison purposes.

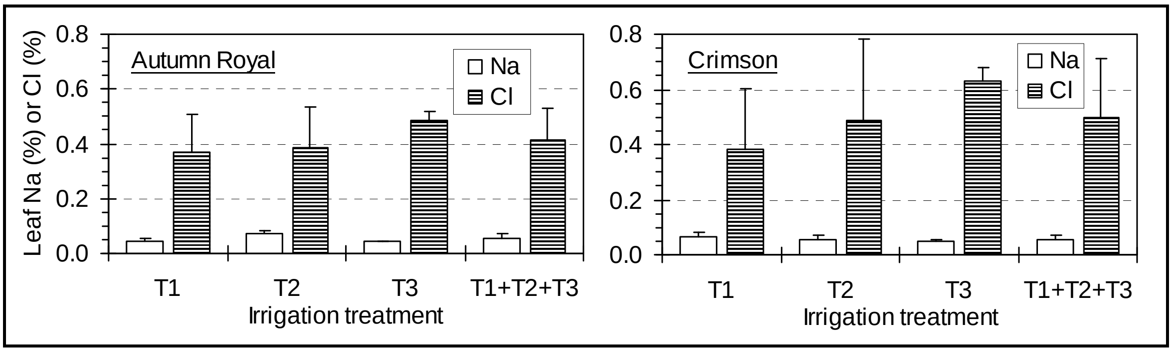

Figure 7. Mean 2007-2009 leaf Na and Cl concentrations in the T1 (full), T2 (RDI-80%) and T3 (RDI-60%) irrigation treatments of Autumn Royal and Crimson grapevines. Vertical bars indicate one standard error of the mean (n = 6 for each irrigation treatment).