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Irrigation Recommendation for Water Saving and Salinity Control in Horticulture in the Semi-arid Lower Cheliff Plain (Algeria)

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Abstract: Salinity and water deficit are two major issues for agricultural development in Algeria. The Lower Cheliff plain, northwestern Algeria, is, furthermore, characterised by semi-arid Mediterranean climate, and soils with high clay content. Our study area was a 4 ha farm located in Oued Rhiou and another 1 ha farm located in Ouarizane, both upstream in the Lower Cheliff plain, and irrigated with waters of different salinities: 1.8 and 5.5 dS m^{-1}, respectively. The plots were equipped with drip irrigation and subsurface drainage systems. Farmer's irrigation management of artichoke and melon were observed during the respective cropping seasons from September 2010 till June 2011, and from April till July 2011. The total irrigation amounts were, respectively, 364 mm and 240 mm, while the precipitations were 367 mm and 67 mm. The soil properties were determined in the entire rooting depths down to 80 cm for artichoke and 60 cm for melon. In addition to these, irrigation water composition, and crop development parameters were used to simulate soil salinity using the SALTIRSOIL_M model. Simulations and observations of soil pH, main ion concentrations and ECe showed reasonable agreements for June 2011. Next, the irrigation schedules that would have met the water needs of both crops, while simultaneously keeping soil salinity below harmful levels were estimated using the model. For the artichoke plot, a lower irrigation rate (290 mm yr^{-1}) could have kept water deficit and soil salinity below their respective harmful thresholds. For the melon plot, on the contrary, a higher irrigation rate (480 mm yr^{-1}) is able to neutralise the water deficit, though not completely the salinity stress would have been adequate. Farmers' irrigation practices in the context of the climate, water quality and soil properties of the Lower Cheliff plain can be analysed and improved with the aid of soil salinity modelling.

Key words: Drip irrigation, soil salinity, modelling, SALTIRSOIL, sustainable agriculture.

Introduction

Secondary soil salinisation results from poor irrigation and drainage management in agricultural irrigated lands mainly under arid, semi-arid and dry sub-humid climates (Zhou et al., 2013). Secondary soil salinisation along with freshwater depletion and pollution, soil waterlogging and nutrient leaching are the main threats

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to the sustainability of irrigated agriculture in the World (Burkhalter and Gates, 2005; Houk et al., 2006; Jia et al., 2011; Kiggundu et al., 2012). Globally, 76 Mha of agricultural land are already salt-affected (Ghassemi et al., 1995), and this figure is going to increase in the upcoming years because of the expected climate aridification in several important irrigation areas in the World: Mediterranean Basin, southwestern United States, northern Mexico, southern Australia, southern Africa, and parts of South America (Seidel et al., 2008).

Secondary salinisation is a soil degradation process that decreases the soil fertility resulting in reduced agricultural productivity, and loss of crop diversity. Soils in the Mediterranean basin are especially prone to degradation and vulnerable to salinisation (Lahmar and Ruellan, 2007; citations therein). In Italy, soil salinisation is an important land degradation process, particularly in Tuscany, Sardinia and the coastal plains (Corribia Val di Val di Cecina, Pianura Versiliese) (Ministero dell'Ambiente, 1997). In Spain, salt-affected soils cover an area between 0.6 and 2.4 Mha (Crescimanno, 2003). In Egypt, about 1.26 Mha of areas are salt-affected, including 50% of the irrigated soils (Hachicha and Abdelgawed, 2003). In Morocco, the area of saline soils is currently estimated to reach 0.35 Mha, most of which is located in the Tafilalet, Ouarzazate, Bahira, Tessaout Downstream Moulouya Tadla, Doukkala and Gharb (Badraoui et al., 1998). In Tunisia, salt-affected soils are are spread around 1.5 Mha, that is 10% of the total area (Hachicha and Abdelgawed, 2003). In Algeria, the total agricultural area is around 8.5 Mha, in which the salt-affected area has been estimated to be 20% of the total area of the country (Douaoui et al., 2006). This salinity is mainly due to irrigation by salt water. Of the irrigated land in Algeria, about 25% is salt-affected, specifically in the north-west region (Hachicha and Abdelgawed, 2003). The Lower Cheliff plain is located in this part of the country. It covers an area of about 60,000 ha where agriculture is the main economic activity. The climate in the Cheliff plain is characterised by scarce rainfall (R < 400 mm yr^{-1}) and high evaporation rates (ET_0 > 1400 mm yr^{-1}), which boosts soil salinisation and is very intense in various places within the plain affecting 80% of the total area (Douaoui et al., 2006).

Agriculture in the lower Cheliff plain consists of permanent crops including citrus, olive and various fruit trees (apple, apricot, and pomegranate). Horticulture is also important, and it focusses especially on artichoke and melon. The globe artichoke, hereafter just artichoke, is a plant native to the Mediterranean, which has a significant commercial interest in the area of the plain of lower Cheliff. This plant is well adapted to the soils of the area because it is moderately tolerant to soil salinity with 4.9 dS m^{-1} of threshold electrical conductivity in the saturation extract (ECe) (Shannon and Grieve, 1999), and because it thrives well in the very fine textures of the soils in the region. In addition to this, there is cantaloupe melon, hereafter just melon, from the area which is recognised worldwide. It is an annual plant, native to southern Asia. An important variety cultivated in the area is the yellow and green melon "Valencia". The water requirement of this crop is estimated to be 472 mm in the Lower Cheliff region with a threshold ECe of 2.2 dS m^{-1} (Turini, 2011).

Since the beginning of the 20th-century, near-surface temperature has significantly increased between 1 and 2°C in North Africa, whereas rainfall has seen a decreasing trend, though non-significant, it does exists (Niang et al., 2014). Both rising temperatures and decreasing precipitations impact agriculture through the increase of crop water requirements (Döll, 2002). By using 2722 km^3 yr^{-1} of freshwater on a global scale, agriculture attains 71% of total water withdrawals (FAO, 2015). In Algeria, agricultural water withdrawal reaches 3502 hm^3 yr^{-1} which is 61% of the total in this country (FAO, 2015). A global increased agricultural water demand will reach 3000 km^3 yr^{-1} by 2050 (FAO, 2011) and have serious consequences on both environment and agriculture in this century. To minimise environmental damages and maximise agricultural yields, several adaptation strategies must be devised and implemented to increase water use efficiency (WUE) in agricultural systems. WUE at the plot scale can be increased by limiting runoff and also by limiting unnecessary water percolation into the deep soil away from the plants' roots, i.e. by increasing the water application efficiency (Hsiao et al., 2007). However, in salt-threatened lands, part of the irrigation water must percolate into the deep soil away from the plants' roots in order to ensure some salt disposal away from the soil-water-plant system. The question of how much irrigation is necessary to allow salt leaching without wasting water can be answered with the use of soil salinity models capable of simulating both water and salt balance in the soil-water-plant system. There are several salinity models useful to appropriately schedule irrigation so as to avoid soil salinisation while preserving water resources. The one-dimensional monthly transient-state SALTIRSOIL_M model is one such model (Visconti et al., 2013). This model has been developed to maximise the applicability-to-data requirements ratio, and hence its target audience is formed by engineers, extension specialists, irrigation managers and land planners. Whatever the case, models must be tested before being used to elaborate on irrigation recommendations.

The objectives of this study were to develop an original analysis with the SALTIRSOIL_M model in order to elaborate on the most adequate irrigation practices for managing salinity while saving water in the horticulture of the Lower Cheliff plain in northwestern Algeria. Previously the ability of the SALTIRSOIL_M model to simulate the soil salinity of two plots irrigated by drip and planted with artichoke and melon was tested by comparing simulated against observed soil salinity values.

Materials and Methods

Model Description

The one-dimensional monthly transient-state SALTIRSOIL_M model is based on a tipping bucket algorithm for simulating the soil water downward flow where the soil is split in a number *n* of stacked layers or nodes. In the SALTIRSOIL_M model, a water balance is carried out each month for one year, and as a consequence, a concentration factor of the irrigation water in the soil solution is assessed monthly, hence 12 concentration factors are obtained. Next, every month the main ion concentrations in the irrigation water (Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-} and alkalinity) are multiplied by the corresponding concentration factor to obtain a soil solution away from equilibrium. These soil solutions away from equilibrium are fed into a chemical module called SALSOLCHEM to calculate the ion concentrations at equilibrium with calcite, and gypsum in the quantities present in the soil, and the CO_2 partial pressure of the soil solution of interest. The calculations implemented in the model to assess the soil water downward flow through the stacked layers, and how the crop development, and the irrigation management, influence them through the plant water uptake (evapotranspiration), were presented in previous works (Visconti et al., 2011; Visconti and de Paz, 2012; Visconti et al., 2014).

The main advantage of SALTIRSOIL_M model is that it has been devised to maximise the quotient of reliability to data requirements (Shaffer and Delgado, 2001), i.e., it is aimed at giving acceptable predictions of soil salinity using just information available through regular land surveys and soil analyses. From the beginning of its development the SALTIRSOIL_M model has been subjected to sensitivity and validation analyses crediting a high enough reliability. Another advantage of the SALTIRSOIL_M model is its graphical user interface, which allows intuitive and rapid learning of the model use (Visconti et al., 2013).

Study Area

The Lower Cheliff plain is located to the northwest region of Algeria 250 km from Algiers, between 0° 40' and 1° 6' 8" east longitude, and between 34° 3' 12" and 36 ° 5' 57" north latitude. The plain of Lower Cheliff is one of three plains in the Valley of Cheliff River (high, medium and lower Cheliff). It is part of the watershed Cheliff and occupies the western part. Oued Rhiou, Djédiouia, Hmadna, and Ouarizanze are the main cities covering its perimeter from east to west (Figure 1). The main water resources consist of (i) the dam of Gargar, on the Oued Rhiou with a capacity of 450 hm^3 (Figure 1), is one of the largest dams in Algeria and (ii) the dams of Merdjet Sidi Abed are an off-stream reservoir with a capacity of 50 hm^3 (Figure 1).

The Lower Chéliff plain covers 60,000 ha and includes several large irrigated districts. Its irrigated area was created during the colonial period since 1937. Currently, the irrigable area is estimated to be 16,000 ha of which less than 7,000 ha is used for irrigation. The main irrigation districts of the plain are Ouarizane, H'madna, Oued Rhiou, Djédiouia and Garouaou (Figure 1).

Soil and Water Sampling

Two experimental plots were selected in the area and sampled in June 2011. Plot 1 (P1) was planted with globe artichoke and located in the perimeter of Oued Rhiou (Figure 1). Only one sample representing the entire depth interval of 0-80 cm was taken. Plot 2 (P2) was planted with melon and located in the perimeter of Ouarizane (Figure 1). Again only one sample representing the entire depth interval of 0-60 cm was taken. The samples were collected using a 1m long auger.

Water samples were collected also in June 2011 from the wells used for irrigation of these plots which drill the alluvial aquifer of Lower Cheliff at a depth ranging from 60 to 100 m. The choice of this time corresponds to the senescence of the artichoke and the ripening of the melon.

Soil and Water Analyses

In the laboratory, the soil samples were air dried, and disaggregated, and the coarse fragments were removed

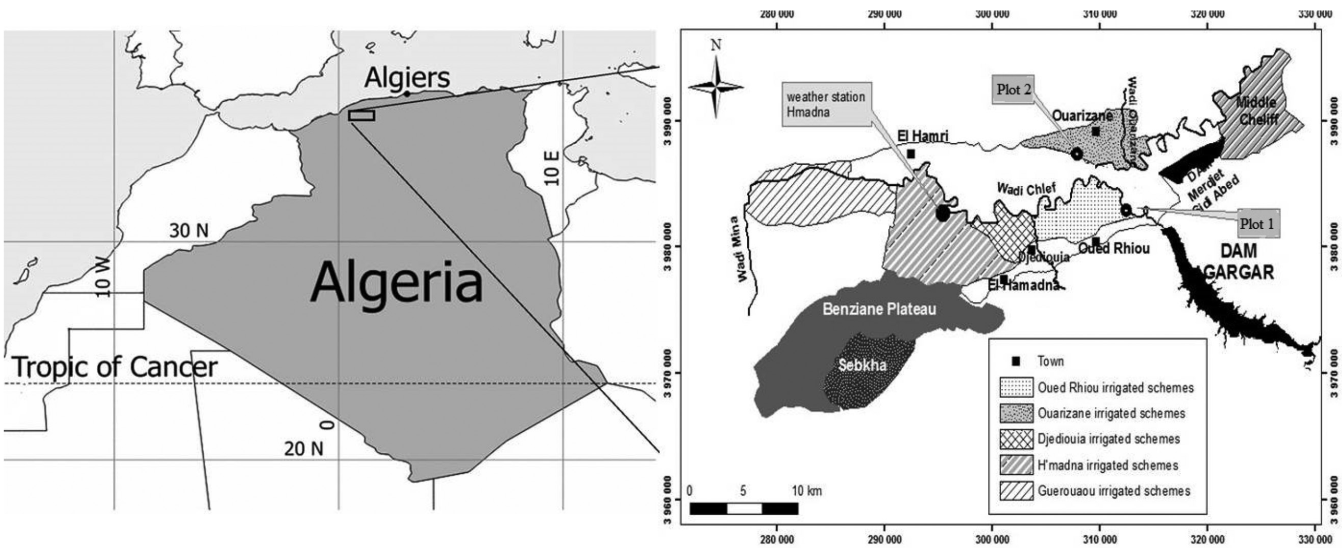

Figure 1: The geographical location of the study area in Algeria.

to pass a 2 mm mesh sieve (Mathieu and Pieltain, 2003). The soil organic carbon content (OC) was determined according to the international standard method NF ISO 14235 (Nelson and Sommers, 1982), and then the soil organic matter content (OM) was calculated by multiplying by a conversion factor of 1.72 (OM = 1.72 OC). Soil texture was determined according to the standard method of the Soil Survey Staff (1951 and 1993).

For the preparation of the saturated pastes, 120 g of fine earth were placed in a 500 mL beaker, and distilled water was added while stirring with a spatula until the criteria for saturation were fulfilled (USDA, 1954). The saturation percentage (PS) was determined as the water content of the saturated paste on an oven-dry (105ºC) soil basis. The extraction of the soil saturation extract was obtained by centrifugation to 200 g in a Spinchron KR 15 R (Beckman Coulter, California, USA). Clear solutions were collected in bottles after filtration.

The saturation extracts and water samples were analysed for electrical conductivity (EC_{25}), and sodium, potassium, calcium, magnesium, sulphate, chloride, alkalinity and pH. Assessments of EC_{25}, pH and alkalinity were performed within 2 h of extract collection. Alkalinity was determined by the method given by Gran (1952). The chloride (Cl^-) and sulphate (SO_4^{2-}) anions were determined through the titration method using ultra-breached spectrometry acacia (Mathieu and Pieltain, 2003). EC_{25} and pH were measured with a Multiparametre 340i (WTW GmbH, Weilheim, Germany) measurement instrument. Sodium (Na^+) and potassium (K^+) were analysed using flame emission photometry at 589 nm and 766.5 nm, respectively (Helmke and Sparks, 1996; Robbins and Wiegand, 1990). Determination of the Ca^{2+} and Mg^{2+} cations was carried out by titration with Na_2 EDTA (Rodier et al., 2009). The calcium carbonate equivalent and gypsum content in the soil samples were determined by means of Nelson (1982). The determination of the bulk density was made by using the clod method (Grossman and Reinsch, 2002) on disturbed soil samples.

Estimation of the Water Contents at Field Capacity and Wilting Point

The pedotransfer functions were developed by Rawls et al. (1982) to estimate the soil water contents at the specific matric potentials of -33 and -1500 kPa, which were used to estimate the water contents at, respectively, field capacity (FC) using Equation 1, and wilting point (WP) with Eq. 2, both in cm^3/cm^3, where Sn (%) is the percent of sand, Cy (%) is the percent of clay, and OM (%) is the percent of organic matter.

$$FC = 0.2391 - 0.0019\ Sn\ (\%) + 0.0036\ Cy\ (\%) + 0.0299\ OM\ (\%) \quad (1)$$

$$WP = 0.0260 + 0.005\ Cy\ (\%) + 0.0158\ OM\ (\%) \quad (2)$$

Weather, Crop and Irrigation Data

The only costs for the application of SALTIRSOIL_M at plot scale are those derived from its data requirements, which are listed in Table 1. The weather data used in the simulations were taken from the Hmadna bourokba station which is situated in the Algerian National Institute of Agronomic Research, based in El Hmadna (20 km from Relizane, 16.1 from P1, and 23.9 from

P2) (Figure 1). In 2011 the rainfall amount was 289 mm yr^{-1}, which was collected in 79 days. The reference evapotranspiration (ET_0) was 1434 mm yr^{-1} according to the Penman-Monteith methodology (Allen et al., 1998). Drip irrigation method was used in both experimental plots, and they were equipped with drainage systems, at 1.5 m depth and 90 cm spacing.

The crop in P1 was globe artichoke (*Cynara scolymus* L. cv. "Violet de Provence"), with basal crop coefficients (Kcb) taken from the study by Allen et al. (1998), and the growing season selected was from 1st September 2010 until 8th June 2011, i.e. a total crop length of 280 days, maximum canopy ground cover of 75% (Fc = 0.75), and maximum rooting depth (SD) of 80 cm. The rainfall amount during the cropping season was 367 mm, which was collected in 73 days, and ET_0 was 929 mm.

The crop in P2 was melon (*Cucumis melo* var. *cantalupo* Ser.), with Kcb also from Allen et al. (1998), and growing season from 1st April until 29th July 2011, i.e. a total crop length of 120 days, maximum canopy ground cover of 35% (Fc = 0.35), and SD of 60 cm. The rainfall amount, number of irrigation days and ET_0 correspond to the year 2011, and during the cropping season they were, respectively, 67 mm, 20 days and 724 mm.

Simulations

SALTIRSOIL_M was applied to the calculation of the water balance, and the main chemical properties of the rooting depth average soil solution at water saturation, and the drainage water, i.e. main ion composition, pH and electrical conductivity. Two simulations were carried out: simulation 1 was the growing of artichoke in P1 irrigated with water from the Fodile well, and simulation 2 was the growing of melon in P2 irrigated with water from the Belaid well. A CO_2 apparent partial pressure at equilibrium with the saturation extract of $10^{-2.5}$ atm was used for both simulations. Since soil salinity appraisal is based on the saturated paste standard (USSL Staff, 1954), the simulations of the soil solutions at water saturation obtained for June 2011 were compared to the experimental determinations carried out in the saturation extracts from the soil samples taken the same month. The comparisons were made by means of scatter plots of observations against predictions, and assessing the coefficient of determination (R^2) of the line of predictions (P) against observations (O), the root mean square error (RMSE) in percentage, and the index of agreement (IA) (Wilmott, 1982):

$$\mathrm{RMSE} = \frac{100}{\bar{O}}\sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \quad (3)$$

$$\mathrm{IA} = 1 - \frac{\sum_{i=1}^{n}(P_i - \bar{O})^2}{\sum_{i=1}^{n}\left(\left|P_i - \bar{O}\right| - \left|O_i - \bar{O}\right|\right)^2} \quad (4)$$

The range of variation of R^2 is from 0 to 1, 1 being the optimum; for RMSE, it is from 0 to ∞, 0 being the optimum, and for IA, it is from 0 to 1, again 1 being the optimum (Loague and Green, 1991; Willmott, 1982).

Estimation of the Optimal Irrigation Amounts

The effects of different irrigation schedules on ECe were simulated in order to estimate the optimum monthly irrigation amounts during the cropping season in both experimental plots. The optimum irrigation scheduling is the one that fulfils the crop water requirements while simultaneously keeping soil salinity below plant damaging values. Therefore, the fulfilment of the crop water requirements was first checked by calculating the monthly evapotranspiration deficit, i.e., the difference between crop and actual evapotranspiration each month (ETc − ETa). As a consequence of the months with evapotranspiration deficit, the irrigation dose was increased in an amount equal to the aforementioned deficit. In case the irrigations had increased, the simulations were repeated to assess the soil salinity that would have resulted from this new irrigation schedule. Next, depending on the resulting soil salinity in the previous simulation, the monthly irrigations were decreased or increased in 10% steps. The criteria to stop increasing or decreasing the irrigations were based on the avoidance of both water and salinity stress on the crops. To characterise the tolerance of both crops to soil salinity the threshold-slope model was used with parameters of 4.9 dS m^{-1} and 10.7 dS m^{-1} for artichoke (Shannon and Grieve, 1999), and 2.2 and 7.4 dS m^{-1} for melon (Turini, 2011). A 10% yield loss was selected as the maximum permissible salinity stress. A water deficit of 5 mm for just one month was selected as the maximum permissible water stress.

Results and Discussion

Soil Properties

The soil in both plots is non-stony, clay-textured, strongly compacted, low-to-very-low in organic matter,

Table 1: Weather, Irrigation Management and Crop Development Data used in the Simulations*

Plot 1 / Artichoke													
Month Year	Sep 2010	Oct 2010	Nov 2010	Dec 2010	Jan 2011	Feb 2011	Mar 2011	Apr 2011	May 2011	Jun 2011	Jul 2011	Aug 2011	TOTALS 2010-2011
Weather													
R (mm)	4.4	63.9	66.7	17	68.6	17.5	62.4	58.6	7.4	1	0	0.2	367.7
Rf (day)	2	4.3	6	6.5	12.5	6.1	11.7	11.2	4.8	4	0	3.9	73
ET_0 (mm)	148.7	124.6	84.6	61.4	34.8	53.2	81.8	103.2	178.6	207.1	234.8	198.5	1511.3
Irrigation management													
I (mm)	56	57.9	65.5	54	29	26.2	29	28.1	15.3	3	0	0	364
If (day)	2	2	2	2	2	2	2	2	1	0	0	0	17
Crop development													
Fc,m	0.13	0.13	0.41	0.77	0.75	0.75	0.75	0.75	0.46	0.02	0.00	0.00	–
Kcb,m	0.15	0.15	0.50	0.92	0.90	0.90	0.90	0.90	0.55	0.12	0.00	0.00	–
Plot 2 / Melon													
Month Year	Jan 2011	Feb 2011	Mar 2011	Apr 2011	May 2011	Jun 2011	Jul 2011	Aug 2011	Sep 2011	Oct 2011	Nov 2011	Dec 2011	TOTALS 2011
Weather													
R (mm)	68.6	17.5	62.4	58.6	7.4	1	0	0.2	0.9	3.2	52.5	17	289.3
Rf (day)	12.5	6.1	11.7	11.2	4.8	4	0	3.9	4	4.3	10.5	6	79
ET_0 (mm)	34.8	53.2	81.8	103.2	178.6	207.1	234.8	198.5	130.6	101.8	63.1	46.2	1433.7
Irrigation management													
I (mm)	0	0	4	101	52	44	39	0	0	0	0	0	240
If (day)	0	0	0	3	2	2	2	0	0	0	0	0	9
Crop development													
Fc,m	0.00	0.00	0.00	0.08	0.21	0.35	0.25	0.00	0.00	0.00	0.00	0.00	–
Kcb,m	0.00	0.00	0.00	0.22	0.60	1.00	0.80	0.00	0.00	0.00	0.00	0.00	–

*R, millimeters of rainfall; Rf, number of rainy days; I, millimeters of irrigation; If, number of irrigation days; Fc,m, canopy ground cover; Kcb,m, basal crop coefficient

Table 2: Soil Properties in both Experimental Plots*

Prop. / Plot	Top limit / cm	Bottm limit /cm	Sn (%)	St (%)	Cy (%)	SP / $g\ g^{-1}$	FC / $cm^3\ cm^{-3}$	WP / $cm^3\ cm^{-3}$	BD / $g\ cm^3$	CF (%)	CCE (%)	OM (%)	Gy (%)	EC_e / $dS\ m^{-1}$	SAR
1	0	80	12.0	36.0	52.0	0.584	0.457	0.314	1.75	0.0	12.6	1.8	12.2	2.48	2.0
2	0	60	12.0	40.0	48.0	0.563	0.434	0.289	1.88	0.0	16.6	1.5	10.1	8.05	4.0

* Sn, sand content; St, silt content; Cy, clay content; SP, saturation percentage; FC, volumetric water content at field capacity; WP, volumetric water content at wilting point; BD, bulk density; CF, coarse fragments content; CCE, calcium carbonate equivalent; OM, organic matter content; Gy, gypsum content; EC_e, electrical conductivity at 25C in the saturation extract; SAR, sodium adsorption ratio in the saturation extract.

moderately calcareous, and slightly gypsiferous (Table 2). The soil in plot 1 is slightly saline (EC_e = 2.48 dS m^{-1}) and non-sodic (SAR = 2), while in plot 2 is from moderately to strongly saline (EC_e = 8.05 dS m^{-1}) and slightly sodic (SAR = 4). On the basis of the threshold-slope model and data from, Shannon and Grieve (1999), and Turini (2011), the soil salinity that causes a 10% drop in yield is 5.83 dS m^{-1} for artichoke, and 3.55 dS m^{-1} for melon. Therefore, in plot 1 artichoke is not subjected to any salinity stress, while in plot 2 melon is subjected to remarkable salinity stress able to decrease yield down to 57% of the potential one if sustained during the whole cropping season.

Water Quality

The well water from Fodile used in plot 1 to irrigate the artichoke is slightly saline, non-sodic (SAR = 2.1), non-alkaline (RSC = –10 meq/L) and medium in chloride, while the well water from Belaide used in plot 2 to irrigate the melon is moderately-to-strongly saline, non-sodic (SAR = 3.9), non-alkaline (RSC = –47 meq/L) and high in chloride (Table 3). The water in plot 1 is representative of the most common groundwater salinity in the Lower Cheliff plain, while the water in plot 2 represents the upper extreme of groundwater salinity in the area (Bradaï et al., 2012). Contrary to this, both waters are non-representative of the groundwater sodicity (SAR) in the area which is usually higher, i.e. ranging from 5 to 31 (Bradaï et al., 2012).

The charge balance errors of the water analyses were 4.7 and 1.5% featured by the underestimation of anion contents. This underestimation is likely due to the non-determination of nitrate contents, which would be roughly 2 mmol/L in both samples. Therefore, uncertainties due to the analytical methodology are assumed to be acceptable with regard to the standards. According to the chemical speciation carried out with the SALSOLCHEMIS software (Visconti, 2009), both waters are at equilibrium with CO_2 partial pressures of 0.022 and 0.014 atm, i.e. 50 times higher than the atmosphere, which is typical of groundwater. Besides, according to the ionic activity products of calcium carbonate and gypsum ($IAP_{CaCO3} = a_{Ca}^{2+} a_{CO3}^{2-}$, $IAP_{CaSO4\cdot 2H2O} = a_{Ca}^{2+} a_{SO4}^{2-}$), both waters are saturated in calcite ($IAP_{CaCO3} = 10^{-8.41}$ and $10^{-8.31}$, respectively), and from undersaturated to slightly undersaturated in gypsum ($pIAP_{CaSO4\cdot 2H2O} = 10^{-5.46}$ and $10^{-4.82}$, respectively).

Simulated Soil Water Balances in the Plots

The annual soil water balances in both experimental plots as simulated by SALTIRSOIL_M are shown in Figure 2. Crop evapotranspiration (ETc) during the cropping seasons was 687 mm and 392 mm for, respectively, artichoke (P1) and melon (P2).

In plot 1, which was the one cultivated with artichoke, during the growing season the actual evapotranspiration (ETa) amounted to 601 mm while the crop evapotranspiration (ETc) amounted to 687 mm according to the model simulations. The 86 mm of water deficit occurred mainly in September (37 mm) and June (47 mm), i.e. the first and last month of cultivation. In September most of the soil was still uncovered by the artichokes' canopies due to the early stage of plant development and therefore, most of the crop evapotranspiration was actually evaporation from the bare soil between plants. On June 8th, the crop was removed and again most of the crop evapotranspiration was evaporated from the bare soil since June 8th onwards. During the rest of the season, the water deficit jointly amounted to just 2 mm, and therefore we can assume that the crop was never subjected to any water stress. The sum of irrigation and rainfall during the growing season, which was 361 + 367 = 728 mm, i.e. 127 mm over the ETa, not only made the actual evapotranspiration to match the crop evapotranspiration during plant growth, but it also provided 109 mm of water to flow below the maximum rooting depth at 80 cm. Therefore, a leaching fraction of 15% was produced. Under Mediterranean climates, annual rainfall usually presents two peaks, a primary one in autumn and a secondary one in spring. During the 2010-2011 seasons these occurred in October-November with 131 mm, and in March-April with other 121 mm. Besides, another

Table 3: Water quality in both experimental plots*

Plot \ Ion	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	NO_3^-	SO_4^{2-}	Alk.	pH	EC_{25}
1	5.8	0.1	5.4	2.2	6.9	nd	3.6	5.1	7.10	1.80
2	20.1	0.06	10.8	15.7	21.4	nd	21.9	5.8	7.30	5.52

*All ions in mmol L^{-1}, alkalinity (Alk.) in mmol L^{-1} and electrical conductivity at 25 C (EC_{25}) in dS m^{-1}; nd, no data

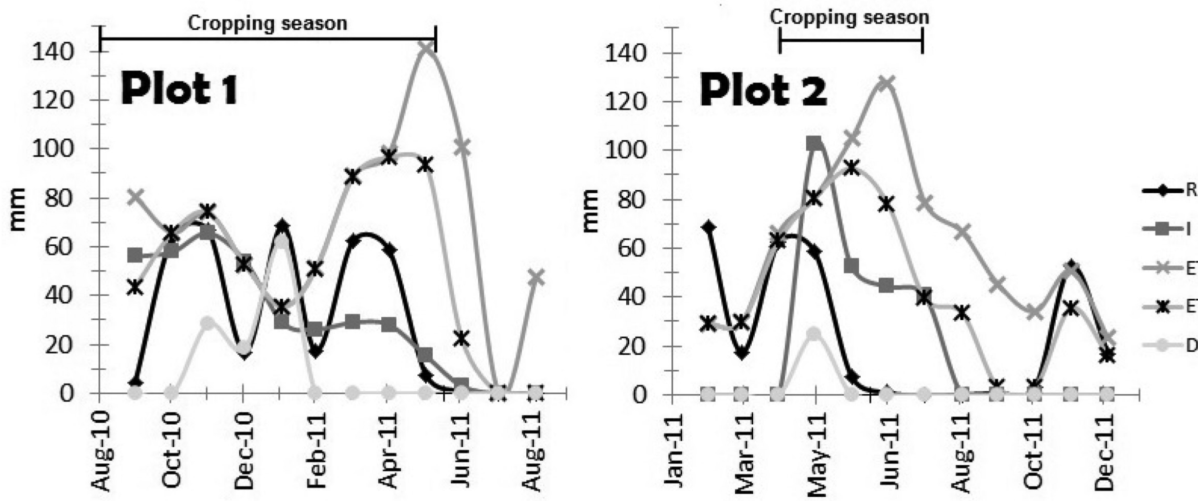

Figure 2: Monthly terms of the soil water balance throughout the 2010-2011 cropping seasons as simulated by SALTIRSOIL_M in the artichoke plot (left) and the melon plot (right) (R: rain, I: irrigation, ETc: crop evapotranspiration, Eta: actual evapotranspiration, D: drainage).

little peak occurred in winter with 69 mm in January. The autumn and winter rainfalls helped produce the important leaching of 109 mm. In spring, no leaching was produced due to the high ETc caused by (i) the advanced stage of crop development and subsequent high Kcb and (ii) the remarkably higher ET_0 in spring regarding autumn and winter.

In plot 2, which was the one cultivated with melon, during the growing season ETa amounted to 291 mm, while ETc amounted to 392 mm. The 101 mm of water deficit occurred in May (13 mm), June (49 mm) and July (39 mm), which are high enough to produce remarkable water stress on the plants in these important stages of crop development and fruit ripening. The amount of irrigation and rainfall during the growing period, which was 240 + 67 = 307 mm, not only did not provide the melons with their water requirements but also barely produced 25 mm of leaching. Thus the corresponding leaching fraction for the whole season was just 8%, which seems very low taking into account the high salinity of the irrigation water in this plot (5.52 dS m^{-1}; Table 3).

Simulated and Observed Salinity in the Plots

In Figure 3, the simulated and observed main ion contents and ECe in addition to the pH of the saturated pastes are shown. In the case of the artichoke plot (P1), the regression line between observations and predictions presents a coefficient of determination (R^2) of 0.95, a root mean square error (RMSE) of 23% and an index of agreement (IA) of 0.98. In the case of the melon plot (P2), the R^2 is 0.90, whereas the RMSE is 84% and the IA is 0.97.

In the artichoke plot (P1), the observed and predicted ECe differs in the second significant figure, i.e. 2.48 and 2.94 dS m^{-1}, respectively. In the melon plot (P2), the observed and predicted ECe also differs in the second significant figure, i.e 8.05 and 8.66 dS m^{-1}. Therefore, in both plots, the soil salinity was a little overestimated by SALTIRSOIL_M. In the artichoke plot (P1), the most abundant ions are calcium and sulphate, which reflect the presence of remarkable gypsum in the soil (Table 2), and the balance between calcium and sulphate in the irrigation water (Table 3). Calcium and sulphate are followed by sodium and chloride as the, respectively, most abundant cation and anion. In the melon plot (P2), the most abundant ions are sulphate, chloride, sodium and magnesium, which reflect the fact that these four are also the most abundant ions in the irrigation water (Table 3). Interestingly, despite the presence of gypsum in the soil in P2, the unbalanced concentrations of sulphate and calcium with an excess of the former in the irrigation water leads to a diminished concentration of calcium in the saturation extract because of a common ion effect on gypsum dissolution due to sulphate. Both in P1 and P2, the different ion abundances in the saturation extract were satisfactorily simulated by the model, which means that (i) the main source of salts to the soil is the irrigation water in addition to the soil gypsum and (ii) that the soil water regime is downward. As the SALTIRSOIL_M model is based on these two hypotheses, this gave us the confidence to subsequently

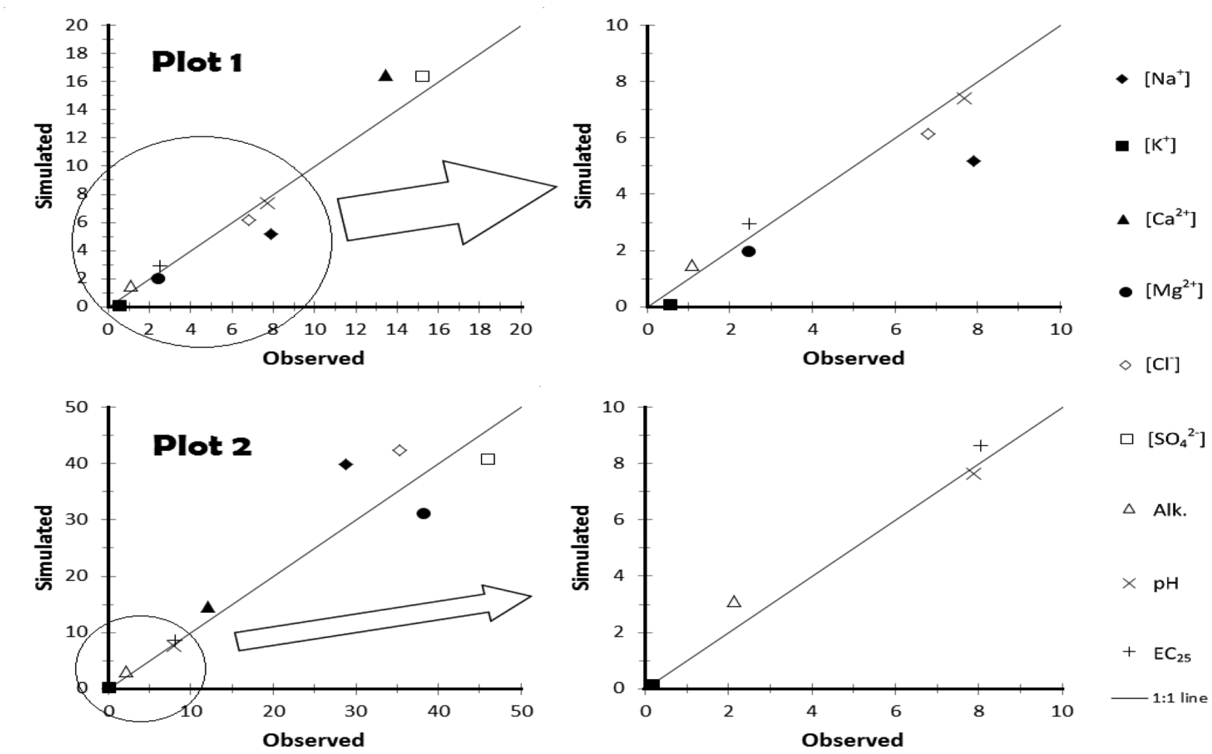

Figure 3: Scatter plots of simulated versus observed concentrations of main ion, pH and ECe in the artichoke (top) and melon (bottom) plots in June 2011. All parameters are for the saturation extract except pH, which is for the saturated paste, all ions in mmol L^{-1}, alkalinity (Alk) in $mmol_C$ L^{-1} and EC_{25} in dS/m.

use the model with the aim of irrigation scheduling for water saving and salinity control in both plots. The agreement between simulations and observations further confirms that a simple tipping-bucket model with just equilibrium chemistry such as the SALTIRSOIL_M, though based on a simple representation of the soil-water-plant system, provides reasonable results with low data and calibration requirements. This is why it constitutes the core of an on-line decision support system for a semi-arid Mediterranean region in Spain similar to the Lower Cheliff plain, the DSS-SALTIRSOIL (http://agrosal.ivia.es/).

Estimation of Optimal Irrigation Amounts

In plot 1, artichoke was not subjected to any water or salinity stress according to the water balances (Figure 2) and soil salinity (Table 2). Conversely, in plot 2, melon was subjected to both water (Figure 2) and salinity (Table 2) stress. Therefore, in plot 1, the average ECe values between 0 and 80 cm depth that would have resulted from irrigating with less water, i.e. 90, 80, 70, and 60% of the actual irrigation rate (Table 4) were simulated. Conversely, in plot 2 where there is a water deficit, the irrigation doses were increased in amounts equal to this deficit. Next, the average EC_e values between 0 and 60 cm that would have resulted from irrigating with even more water, i.e. 100, 120,140, and 160% (Table 4) were simulated.

In plot 1 if 70% of the farmer's irrigation rate, i.e. 233 mm yr^{-1}, had been applied to the crop, it would have suffered water shortage during the cropping season, specifically in December and April with, respectively, 6 and 10 mm of water deficit, i.e. over the threshold of 5 mm for just one month we chose as water stress criterion. On the contrary, if 80% of the farmer's irrigation rate, i.e. 291 mm yr^{-1}, had been applied, deficits over 5 mm would have not been observed any month. Besides, using 80% of the farmer's irrigation rate the maximum monthly ECe would have resulted to be 3.24 dS m^{-1}, i.e. well below the threshold ECe for artichoke (4.9 dS m^{-1}). Then the irrigation schedule optimisation in this plot can be carried out on basis of just the water requirements, and 290 mm yr^{-1} would have been an adequate irrigation rate for this plot in the 2010-2011 season. This means a leaching fraction of just 8% compared to the leaching fraction of 15% actually produced, i.e. the drainage water production would have dropped from 109 to just 50 mm yr^{-1}. Along

Table 4: Simulation of different irrigation schedules and their effects on soil salinity

Plot 1 / Artichokes													
Month	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*TOTALS*
Year	*2010*	*2010*	*2010*	*2010*	*2011*	*2011*	*2011*	*2011*	*2011*	*2011*	*2011*	*2011*	*2010-2011*
100% (mm)	56.0	57.9	65.5	54.0	29.0	26.2	29.0	28.1	15.3	3.0	0.0	0.0	364
90% (mm)	50.4	52.1	59.0	48.6	26.1	23.6	26.1	25.3	13.8	2.7	0.0	0.0	328
80% (mm)	44.8	46.3	52.4	43.2	23.2	21.0	23.2	22.5	12.2	2.4	0.0	0.0	291
70% (mm)	39.2	36.5	41.3	34.0	18.3	16.5	18.3	17.7	9.6	1.9	0.0	0.0	233
60% (mm)	33.6	27.8	31.5	25.9	13.9	12.6	13.9	13.5	7.3	1.4	0.0	0.0	181
Plot 2 / Melons													
Month	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*TOTALS*
Year	*2011*	*2011*	*2011*	*2011*	*2011*	*2011*	*2011*	*2011*	*2011*	*2011*	*2011*	*2011*	*2011*
160% (mm)	0.0	0.0	0.0	206.8	105.3	89.2	81.7	0.0	0.0	0.0	0.0	0.0	483
140% (mm)	0.0	0.0	0.0	180.7	92.0	77.9	71.4	0.0	0.0	0.0	0.0	0.0	422
120% (mm)	0.0	0.0	0.0	155.0	78.9	66.8	61.3	0.0	0.0	0.0	0.0	0.0	362
100% (mm)	0.0	0.0	0.0	129.3	65.8	55.8	51.1	0.0	0.0	0.0	0.0	0.0	302

with the decrease in the drainage water, the soluble salts leached from the plot would have also decreased from 4.4 Mg ha^{-1} yr^{-1} to 2.6 Mg ha^{-1} yr^{-1}.

Usual irrigation doses for artichoke in lower Cheliff are between 300 and 700 mm yr^{-1} using drip irrigation (according to the farmer). In fact, in this case of study crop evapotranspiration (ETc) amounted to 687 mm during the artichoke cropping season of 2010-2011. However, as the rainfall during the same time span amounted to 387 mm, it adequately contributed to roughly half of the crop water requirements with the subsequent irrigation water savings. The adequate amount and monthly distribution of irrigation water can be calculated by trying to compensate for water deficit while keeping salinity within a safe range. Therefore, since annual rainfall in the lower Cheliff was between 201 and 368 mm during the reference period 1985-2010, i.e. usually lower than the 2010-2011 cropping season, a general irrigation rate between 310 and 480 mm yr^{-1}, distributed in 30% in September and October, 35% in November and December, 15% in January and February, 15% in March and April and, finally, 5% in May and June can be recommended, and used for planning of water resources.

In plot 2, only after rescheduling the irrigations and increasing in 60% the irrigation rate up to 483 mm yr^{-1}, the water deficit would have been under 5 mm all months, i.e. the water stress would have been avoided. Notwithstanding this, the average soil salinity during the cropping season would have still been high, specifically 6.31 dS m^{-1}, which means having salinity stress able to decrease the potential melon yield down to 70%. To achieve 80 or 90% yields, the average soil salinity during the cropping season should have been, respectively, 4.90 and 3.55 dS m^{-1}. The irrigation rates required to achieve these target yields could be estimated taking advantage of the linear relationship between the average ECe and the reciprocal of the irrigation rate which was obtained in the simulations of the melon crop (Figure 4), i.e., $ECe = -2.5 + 4200\ I^{-1}$. Accordingly, irrigation rates of 570 and 696 mm would have been required in the 2011 cropping season to attain 80 and 90% yields, respectively. The subsequent simulation of these irrigation rates gives rise to leaching fractions of 30 and 40% respectively, very high compared to the LF of 8% actually produced.

Usual irrigation doses for melon in lower Cheliff are between 300 and 500 mm yr^{-1} using drip irrigation (according to the farmer). Thus the use of 570 and overall 696 mm yr^{-1} of irrigation water are not sustainable in the area. Besides, the required irrigation rates for 80-90% melon yields would lead to 190−300 mm yr^{-1} of drainage waters loaded with 20-26 Mg ha^{-1} yr^{-1} of soluble salts. These high amounts of salts leached from the plot would constitute an important off-site effect with deleterious implications for downstream water users. The important input of salts to the hydrologic system caused by irrigating in

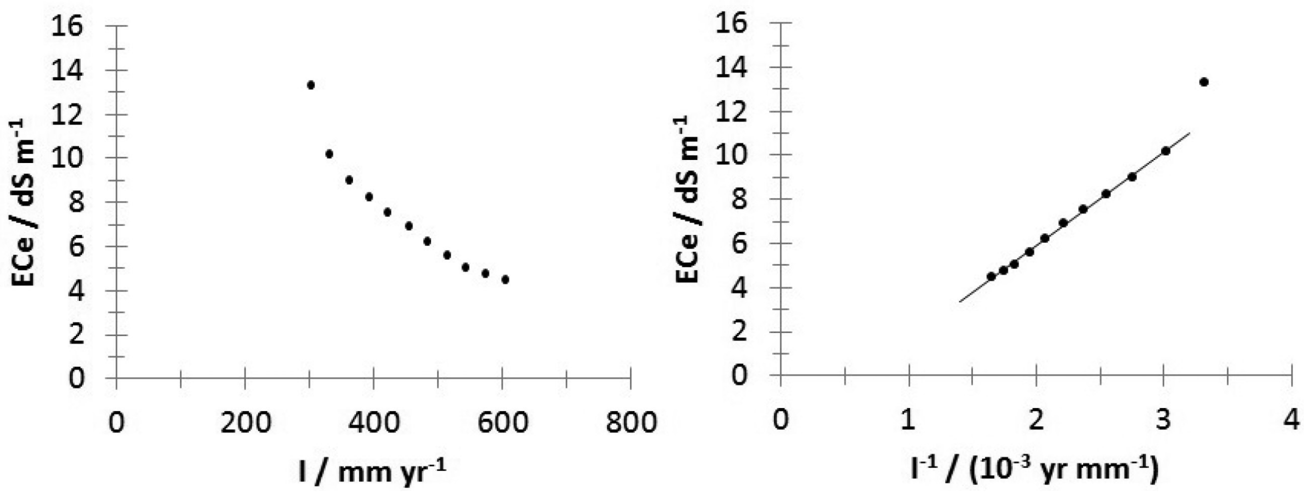

Figure 4: Mean ECe of the soil in the melon plot in the cropping season versus the irrigation rate simulated by SALTIRSOIL_M (left), and versus the inverse irrigation rate.

excess of crop water requirements has been previously stressed (van Schilfgaarde and Rhoades, 1984). It is an effect that leads to further unsustainability of irrigation in salt-threatened lands, and hence must be controlled.

Therefore, as provided water quality cannot be changed, two alternative irrigation and crop management recommendations can be given for the sustainable cropping of this plot. In the first one a general irrigation rate of roughly 480 mm yr^{-1} would be recommended to avoid the water stress and to have at least 70% melon yields, i.e. 13% over those estimated for 2011. Yields of just 70% could be acceptable for melons since the total soluble sugar content of melons increases, and the percent of soft unmarketable fruit decreases, as a consequence of moderate soil salinity stress (Bustan et al., 2005). Thus the melon marketability increases compensating for lower yields in salt-affected soils. In this case, the irrigation water should be monthly distributed approximately in the following way: 35% April, 20% in May, 30% in June and 15% in July. This schedule would still give rise to an LF of 19% with 103 mm yr^{-1} of drainage waters loaded with 15 Mg ha^{-1} yr^{-1} of soluble salts. A second alternative for the sustainable management of this plot would imply the cultivation of another more tolerant crop, e.g., artichoke.

Importantly for both the artichoke and the melon specific irrigation dates and amounts within each month should be scheduled based on other criteria in addition to modeling with SALTIRSOIL_M such as farmer's expert knowledge, sensors, etc. This way, modelling complements traditional and/or modern methods in order to optimise drip irrigation.

Conclusions

The simulation of the soil salinity of one artichoke and one melon field in the Lower Cheliff plain (NW Algeria) was carried out using the SALTIRSOIL_M model. Simulations and observations of major inorganic ions and hence electrical conductivity at 25ºC in the saturation extracts (ECe) were similar with IA over 0.95 for June 2011. Such agreement indicated that the agricultural management in both plots fulfilled the conditions for applying the model and hence, that it could be reliably used for irrigation recommendation in both fields. In the artichoke plot, neither water nor salinity stress was revealed by both observations and simulations. Therefore, the optimum irrigation schedule in plot 1 was sought to simulate the ECe that would have resulted from irrigating with less water. The use of 280 mm yr^{-1} could have saved irrigation water, and reduced water losses and salt leaching through drainage, while having soil salinity well below harmful levels. In the melon plot, on the contrary, the crop was subjected to remarkable water and salinity stress. Therefore the optimum irrigation schedule in plot 2 was sought first of all rescheduling the irrigations to avoid water stress, and second, simulating the effects on water deficit and soil salinity of using higher irrigation rates. The use of 480 mm yr^{-1} could have removed the water deficit, but not completely the salinity stress. However, in this case, having moderate stress could be compensated by an increase in fruit quality. Provided the agricultural systems fulfill the conditions for applying soil salinity models, and specifically SALTIRSOIL_M, these can be of remarkable use to improve irrigation for water saving and salinity control in semi-arid Mediterranean horticulture like in the Lower Cheliff plain.

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