Irrigation management in Mediterranean salt affected agriculture: how leaching operates

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Abstract

In the frame of a crop rotation currently applied in a farm of the Apulian Tavoliere (Southern Italy), this paper reports the effect of brackish water irrigation on soil, outlines the corresponding salinity balance, formulates quantitative relations to model salt outflow below the soil root-layer and defines operational criteria to optimize irrigation management at farm level in order to control soil salinity through leaching. The general aim is to contribute to a sustainable use of the available water resources and a proper soil fertility conservation. A three-year trial (2007-2010) was carried out on a farm located close to the coast of the Manfredonia gulf (Mediterranean - Adriatic sea), where irrigation with brackish water is frequently practiced due to seawater intrusion into the groundwater. An especially designed experimental field-unit was set-up: the bottom of three hydraulically insulated plots was covered with a plastic sheet to intercept the percolating water and collect it into tanks by means of drain tubes. Each year a double crop cycle was applied to the soil; a spring-summer crop (tomato, zucchini and pepper, respectively) was followed by a fall-winter crop (spinach, broccoli and wheat). Short *fallow* periods (completely bare soil) were inserted between two crop cycles. Irrigation or rain completely restored crop water consumptions (with the exception of wheat, considered a rainfed crop) and leaching was performed both unintentionally (by rainfalls) or intentionally (supplying higher irrigation volumes whenever the soil electrical conductivity exceeded a fixed threshold). The soil electrical conductivity was periodically measured together with volume and electrical conductivity of irrigation and drainage water. All these measures allowed to draw-up the salt-balance of the soil, respectively at the beginning and the end of each crop cycle. Absolute and relative variations in soil salt content were interpreted with respect to absolute and relative drainage volumes according to a three steps procedure of covariance analysis. A simple, general and comprehensive leaching model is thus presented. Results showed that salt build up into the soil can be very rapid, generally occurring within a single irrigated summer crop cycle. Rainfalls of the autumn-winter period had a crucial role in the removal of salts brought into the soil by summer irrigation. This paper strongly emphasises that additional fresh water supply is of great importance to establish acceptable soil conditions. Two suitable periods for intentional leaching were identified.

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Introduction

Irrigated agricultural areas in arid and semi-arid regions of the world frequently suffer from soil salinization because of poor quality water (Tanij, 1990; Maas and Grattan, 1999; Schoups *et al.*, 2005). In these areas, good quality water resources are becoming increasingly scarce and are primarily allocated to civil uses (Bertlan, 1999). Consequently, non-conventional water resources, such as brackish water, often represent an important contribution to narrow the gap between freshwater availability and crop demand.

The Mediterranean coastal areas are a typical example of regions where water resources for agriculture are rather limited and irrigated agriculture is possible using also brackish water. Indeed, several intensively cropped Italian coastal plains are progressively becoming salt affected. Intensive groundwater exploitation together with low precipitations are causing the progressive lowering of the water table and the consequent gradual intrusion of the marine *water cone*, bringing about a significant increase in water and soil salinity. This is particularly true along the coastal areas of the Apulian region (South Italy), where brackish irrigation water is ordinarily used, determining the risk of secondary soil salinization (Monteleone *et al.*, 2006). An appropriate irrigation management should preserve the root-zone from salinity; on this respect, on-farm irrigation management requires a certain amount of leaching in order to displace excessive soluble salts from the soil profile and ensure soil sustainability (Barnard *et al.*, 2010; Corwin *et al.*, 2007). The *leaching requirement* has been defined as the minimum amount of the total water supplied that must pass through the soil root zone to prevent excessive salt accumulation (USSLS, 1954). Leaching must not necessarily remove the total salt amount brought into the root-zone by irrigation water; more realistically, the aim should be to keep root-zone salinity within limits that are consistent with an acceptable crop yield, thus minimizing salts affecting plant growth. Such limits vary considerably according to cropping systems, soil and climate characteristics as well as crop or variety tolerance traits (Rhoades and Loveday, 1990). The combination of all such issues allows to modulate the leaching water application technique.

Leaching efficiency increases at higher soil salinity content (Barnard *et al.* 2010; Monteleone *et al.*, 2004b): it is therefore recommended that periodic leaching (*i.e.* not at every watering) should be applied when soil salinity reaches the threshold level capable of interfere with crop yield (Monteleone *et al.*, 2004b; Monteleone, 2006; Hamdy, 2002). Consequently, it is generally accepted that leaching requirement could be satisfied not necessarily during the irrigated cropping cycle but whenever it is believed useful in the course of the year (Chen *et al.*, 2010). Periodic seasonal leaching applications reduce total water consumption compared to continuous leaching because over-irrigation is applied during periods of the year marked by a lower evaporative demand or only whenever soil salinity reaches a level dangerous for the present or following crop. Furthermore, a reduction in the amount of irrigation water supplied to the soil leads to a decrease in the quantity of salt brought into the soil (*salinity load*) as well as a reduction in the volume and salinity of the leached water that needs to be disposed (Hillel, 2000).

The same advantage results from exploiting the leaching effect of rainfalls. This is particularly true with reference to the Mediterranean climate, characterized by dry summers and rainy autumn-winters (Monteleone *et al.*, 2004a). Exploiting the effect of autumn-winter rainfalls allows to decrease intentional applications of excess saline water and consequently reduce the overall yearly salt load in the soil. When waters of different salinity levels are available, their *conjunctive use* can follow two different schemes (Hamdy, 1994; Rhoades *et al.*, 1989): blending or alternate cyclic use. It is almost certain that the latter offers several advantages over the former (Letey, 1993): yields are generally higher or not lower (Minhas and Tyagi, 1998); further studies (Naresh *et al.*, 1992; Minhas *et al.*, 1998) have confirmed the beneficial effects of cyclic use, especially when fresh waters are applied during the initial stages of crop establishment. Water of good quality could be applied in the early, more sensitive stages (such as germination and emergence) as well as to promote salt leaching; conversely brackish water could be used during later stages.

A *flexible* seasonal leaching and a *dynamic* leaching strategy, promoting salts removal only when soil salinity reaches a threshold level, was experimentally applied, matching water quality, soil characteristics and crop sensitivity with expected productivity and farm economic return. In the frame of a crop rotation commonly applied in the Apulian Tavoliere (Southern Italy), where irrigating with brackish water is a usual practice, this paper reports the effect of brackish water irrigation on soil, outlines the corresponding salinity balance, formulates quantitative relations to model salt outflow below the soil root-layer and, finally, defines operational criteria to optimize irrigation management at farm level in order to control soil salinity through leaching. The general aim was to contribute to a sustainable use of the available water resources and to soil fertility conservation.

Materials and methods

Experimental set-up

The trial was carried out in the north-eastern part of the Apulia region (Southern Italy), a Mediterranean area in the Foggia district, during the period 2007-2010. The experimental field (41°34' N, 15°43' E) is located 15 km from the coast of Manfredonia gulf (Adriatic sea) within a cereal-vegetables farming system.

The experimental set-up was arranged in autumn 2006; it included (Figure 1) three adjacent and identical plots of 100 m^2 (6.4 m wide and 15.6 m long). At the center of each plot, an artificial draining basin was arranged; it was obtained by digging the soil out of a trench of 50 m^2 (3.2 m wide and 15.6 m long), at the depth of 0.70 m, covering the bottom of each trench with a plastic sheet in order to prevent water percolation and installing a set of draining pipes (two groups per trench, three drains per group) over the plastic cover, in order to collect the percolating water. Each set of drains was connected to a tank placed at one edge of the plot (two tanks per plot) in order to drain away the percolating water. The trenches were filled with the same soil obtained by the excavating procedure, trying to correctly reproduce the original soil stratification.

As a result of this experimental set-up, the natural soil hydraulic gradient is disrupted and a water-saturated zone must form at the bottom of each basin before water can drain. This condition mimics the presence of a shallow water table 0.7 m deep. The use of an experimental set-up arranged in this way permits to elaborate a soil hydro-salinity balance, over several cropping seasons, in order to check and fine-tune a correct irrigation management.

The experiment was carried out on a loam soil (sand 45.8%; silt 34.3%; clay 19.9%), with an organic matter content equal to 1.6%; a total N content of 1.08 ‰ (Kjeldahl method) and a P_2O_5 content of 62.4 ppm (Olsen method). The water content (w/w) at field capacity (-0.03 MPa) was equal to 29.9 % and at wilting point (-1.5 MPa) to 17.4 %. The initial values of soil pH and EC_e (EC of the soil saturation water extract) were, respectively, 7.6 and to 2.5 dS m^{-1}.

Experimental crop rotation

Each cropping year can be split into two growing periods, a spring-summer (*S1*) and an autumn-winter (*S2*) season, respectively. The limits of these periods are defined according to the main characteristics of the Mediterranean climate, particularly to the rainfall distribution over the *median* year (Figure 2). *S1* approximately begins at the spring equinox (the 21st of March, *81 DOY* - day of the year), at the time when the median monthly rain becomes lower than the annual mean, as showed in Figure 2; the first annual sowings are generally prepared at that time and completed few weeks later. *S2*, by contrast, conventionally begins at the autumn equinox (the 21th of September,

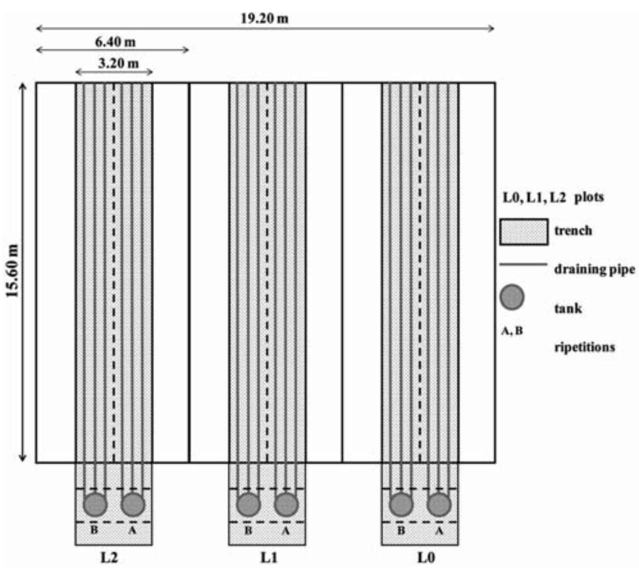

Figure 1. Experimental set-up: three adjacent plots (*L0, L1* and *L2*) having an area of 100 m^2 each; a trench of 50 m^2 at the centre of each plot; two groups of draining pipes per trench (A and B); three drains per group connected to tanks.

263 DOY), when the median monthly rains rise above their mean annual value (Figure 2).

Each *seasonal* period *S*, in turn, consists of two sub-phases, *C* and *F*; in the first sub-phase a vegetable crop (*C*) is grown, while in the second, after crop harvesting, a sort of *fallow* period (*F*) occurs, with the soil left completely bare, frequently removing occasional weeds. Figure 3 displays this kind of temporal arrangement. Two cropping cycles are thus identified in the course of a year: *C1* and *C2*; the dry and hot *C1* can only be carried out with a regular irrigation supply, while *C2* generally involves only supplementary irrigation, when needed. In the third year of trial, being wheat the *C2* crop, *F2* was completely suppressed (Figure 3). Salinity hazard is strictly related to the summer period (*C1* crop), when the use of a large amount of brackish irrigation water leads to salt build-up into the soil; differently, the autumn and winter period could be very useful to promote salt leaching from the soil, thus re-establishing the salt balance.

In the course of the trial, from spring 2007 to spring 2010, the following *C1* and *C2* crop were respectively cultivated: tomato (*Lycopersicon esculentum* Mill) and spinach (*Spinacia oleracea* L.), on 2007-2008, followed by zucchini (*Cucurbita pepo* L.) and broccoli (*Brassica oleracea* L. var. *italica* Plenk), on 2008-2009, and finally pepper (*Capsicum annuum* L.) and wheat (*Triticum durum* L.), on 2009-2010, (Figure 3). All the cropping operations were carried out according to the ordinary local farming techniques. Thus, fertilization as well as weed and pest control were accomplished according to currently management practice; crop rotation and the related choice of crop varieties were also determined according to the criteria usually adopted by local farmers.

Experimental treatments

Three *Leaching* treatments (*L0*, *L1* and *L2*) were planned according to the following criteria: *L0* was the control and brackish groundwater was always supplied without any leaching fraction application; in *L1* brackish groundwater was always supplied but intentional leaching was applied each time soil conductivity exceeded a fixed threshold; finally, in *L2*, in addition to brackish groundwater, an amount of freshwater not exceeding 200 mm per year was eventually available for crop irrigation or intentional leaching.

A critical EC_e *threshold value* (EC_t) was set for each crop; it approximately corresponded to a 20% reduction in the estimated crop yield, according to the model proposed by Mass and Hoffman (1977). For zucchini the EC_t was set at 6.8 dS m^{-1}; for tomato and broccoli it was equal to 5.0 dS m^{-1}; for spinach it was fixed at 4.6 dS m^{-1}; pepper is more sensitive to soil salinity and the threshold was set at 3.0 dS m^{-1}; finally, referring to wheat, a more resistant crop to salinity, a threshold value equal to 11.0 dS m^{-1} was assumed.

Irrigation scheduling (times and volumes of water supplied to the crops) was performed according to the soil water balance approach. Therefore, the gravimetric soil moisture was periodically measured; the reference evapotranspiration ET_0 (mm) was daily calculated according to the FAO version of the Penman-Monteith equation (Allen *et al.*, 1998); the maximum crop evapotranspiration ET_c (mm) was daily estimated according to the classical *two-step* procedure, multiplying the reference crop evapotranspiration by the crop coefficient K_c. The applied crop coefficients were those proposed by the FAO Irrigation and Drainage Paper N. 56 (Allen *et al.*, 1998). The amount of applied irrigation water and the volumes of collected drainage water were regularly recorded. Full ET_c restorations were performed each time the soil water depletion reached a threshold value equal to 50% of the crop available water; the amount of water supplied with irrigation re-established the soil water content to field capacity. Wheat was the only crop totally rainfed.

Whenever soil salinity EC_e exceeded the crop threshold value EC_t, leaching was performed and an extra amount of water (as compared to the estimated ET_c) was applied. Therefore, the irrigation volume was

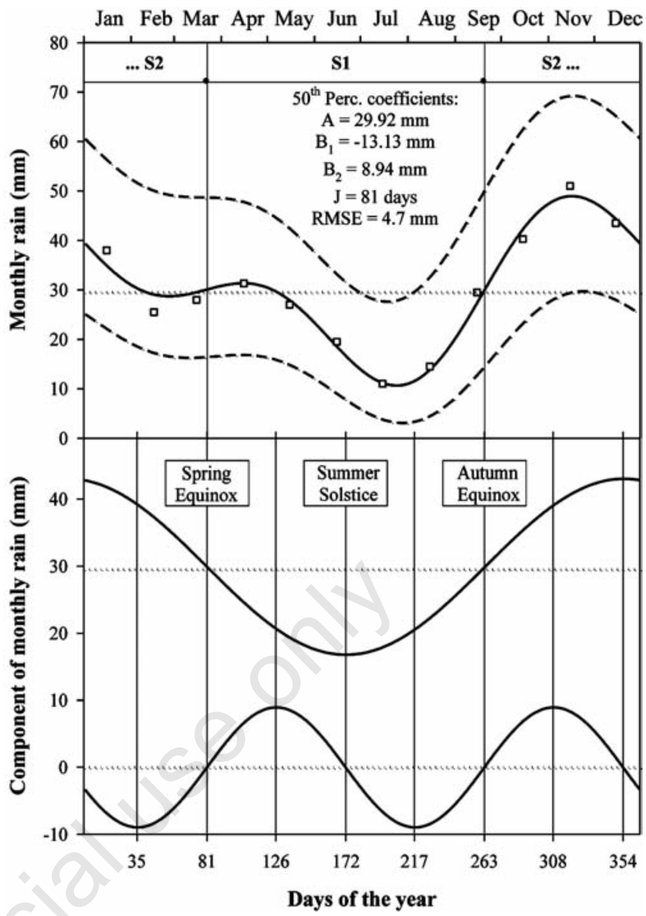

Figure 2. Time-course of rainfalls expressed as monthly precipitations (mm) related to the long-term period 1921-2003. Open symbols are monthly median values (50th percentile) fitted by the solid curve; the two dashed lines indicate the 25th (lower) and 75*th* (upper) percentile, respectively. The horizontal dotted line shows the monthly average value (A coeff.). *S1* and *S2* correspond to the spring-summer and fall-winter period, respectively. The graph below shows the two additive periodic curves that account for the time course of rainfalls; they were obtained through Fourier decomposition analysis whose coefficients are also reported.

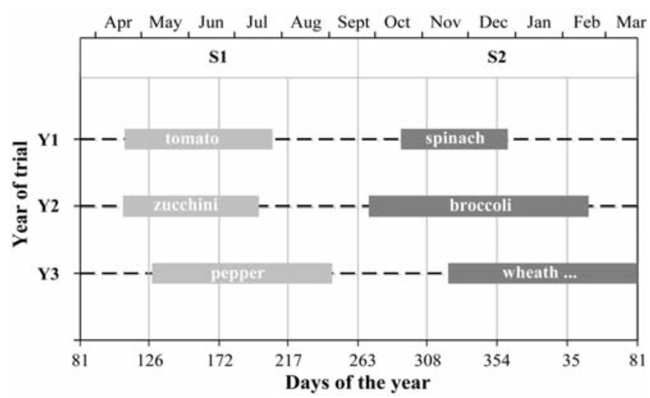

Figure 3. Time arrangement and length of each cropping cycle with respect to the two growing season (*S*) and the three years of trial (*Y*). N.B. the wheat cropping cycle goes beyond *Y3* also involving *Y4*.

increased by a leaching fraction (*LF*) calculated considering the electrical conductivity of the irrigation water (EC_{iw}), according to the following equation (van Hoorn and van Alphen, 1994; Monteleone, 2006):

$$LF\ (\%) = 100 * EC_{iw} / (2 * EC_t)$$

Groundwater used for irrigation was characterized by an electrical conductivity EC_{iw} that ranged from 4.7 to 5.8 dS m^{-1}; it progressively increased in the course of the summer period. A dripping irrigation system was employed, with twelve dripping lines per plot placed at a distance of 0.5 m; emitters were installed every 0.4 m along the lines, with a flow rate of 3 l h^{-1}. A water meter was inserted at the head of the irrigation system to record the amount of water supplied.

Soil and water sampling

During the cropping cycles and the fallow periods a set of determinations were carried out on soil as well as on irrigation and drainage water. Gravimetric moisture (w/w), pH and EC_e were monitored in the soil. As to water (both irrigation and drainage), pH and electrical conductivity were determined (EC_{iw} and EC_{dw} respectively). Soil samplings were extracted from each plot, each time in two randomly selected sites and at three different depths (0.20–0.40–0.60 m); samplings were performed every 10 days along the cropping season (*C*) and every 20 days during the fallow periods (*F*). On each soil sample, wet and dry weight was determined, the latter till a constant weight was reached inside an air-forced oven at the temperature of 105°C. Due to the large number of soil samples to be analysed, soil electrical conductivity was determined on the filtrate of a 1:2 soil-water suspension ($EC_{1:2}$), this procedure being less time-consuming compared to the water extraction procedure of a saturated soil sample. Then, in order to convert $EC_{1:2}$ in EC_e, an empirical, multiple linear regression considering the percentage of clay and silt in the soil was used (Monteleone *et al.*, 2003). Soil pH was determined on the filtrate of a 1:2.5 soil-water suspension.

ESP on soil and SAR on irrigation and drainage water were periodically calculated; these data are not presented in this paper; on the base of their values, however, it is possible to assert that the effect of sodium on soil (*sodicity*) was never significant. Groundwater was sampled in three random repetitions every time it was applied to crops; drainage water was collected in the tanks and sampled in three random repetitions from each tank whenever drainage occurred. Electrical conductivities were measured with an EC-Meter GLP 31+, CRISON; pH was measured with a pH-& Ion Meter GLP 22+, CRISON.

In order to estimate ET_0 and to periodically update the water balance, meteorological data were daily recorded by means of a weather station placed close to the experimental field. The recorded variables (maximum and minimum values) were: air temperature (°C), air humidity (%), wind speed (m s^{-1}), rain (mm); they were acquired every 10 min, averaged and recorded every 30 min by a data logger.

Data analysis and statistical procedures

In this paper only a few of the collected data will be presented; according to criteria already presented in Libutti *et al.* (2008), different kinds of data sources and variables have been considered here: i) EC_e values along the soil profile and during the three-year experimental trial (respectively at the beginning and at the end of each *Season S*); ii) water volumes into and out the soil as well as their corresponding EC_{iw} and EC_{dw} values, in order to compute the amount of salts ($t\ ha^{-1}$) respectively added (S_{IN}) and subtracted (S_{OUT}); as a consequence, the temporal variations in soil salt content ΔS ($t\ ha^{-1}$) were determined. The soil *salt load* S_{LOAD} ($t\ ha^{-1}$) was computed as the sum of the initial salt content of the soil S_0 and the salts supplied to the soil by irrigation S_{IN}. The soil *relative salt variation* ΔS_0 is equal to the ratio $\Delta S/S_0$ while the *salinity ratio SR* is expressed as the ratio of S_{OUT} over S_{LOAD}; the *relative leaching* (*RL*), in conclusion, is defined as the volumetric fraction of drainage water (*D*) over the total water supply (*W*), namely the sum of rain (*R*) and irrigation (*I*) water. The latter three variables (ΔS_0, *SR* and *RL*) can conveniently be expressed as percentages.

Absolute and relative variations in soil salt content were interpreted with respect to absolute and relative drainage volumes according to a three steps procedure of covariance analysis (ANCOVA).

First step: with reference to both growing seasons (*S1* and *S2*), the variations in soil salt content ΔS were linearly related to the corresponding drainage volumes *D* collected from the tanks. Considering that an initial amount of drainage water can remove more salts than the following amounts, leaching turns out to be increasingly difficult as more water volumes pass through the soil profile; for this reason, a decimal logarithm transformation of drainage volumes was performed, according to the following formula: $D_{trf}=log\ (D+1)$. The addition of the unit value to *D* is necessary in order to prevent an impossible solution in case of $D=0$ as well as to assign a physical meaning to the intercept value.

Second step: still with reference to both growing seasons, the relative variations in soil salt content ΔS_0 were linearly related to the corresponding relative leaching volumes *RL*.

Third step: the same as before, but ΔS_0 values were replaced by *SR* values as a function of the relative leaching volumes *RL*.

A full factorial statistical ANCOVA model was applied, taking into account *Year* (*Y*), *Season* (*S*) and *Leaching* treatments (*L*) as experimental factors. The first model (expressed in absolute terms) is useful to assess the leaching process as actually influenced by the three experimental factors and their combinations. The other two models (expressed in relative terms) are intended to define a generalized, unique and comprehensive leaching pattern not influenced by any variable but *RL* (taken as statistical regressor).

Results

Rain, irrigation and drainage

Considering the great relevance of rainfalls in promoting soil leaching, a climatic analysis was performed in order to represent the precipitation pattern over a long stretch of time (1921-2003). The ordinary time-course of precipitation is reported in Figure 2, expressed in terms of moving average of rainfalls over a time window of 31 days. The Fourier decomposition analysis allowed to interpret the precipitation regime as the superposition of two (and simply two) different periodic curves. The first one, with a semi-amplitude oscillation (B_1) of approximately 13 mm, is perfectly tuned to the alternation of a dry (spring-summer) and a wet (autumn-winter) season, according to the *phase coefficient* (*J*) equal to 81 DOY, corresponding to the spring equinox (the 21st of March); the second curve, with a semi-amplitude oscillation (B_2) of approximately 9 mm, can be considered as an intra-seasonal modulation, allowing a rain increase during spring with respect to summer and during autumn with respect to winter. From Figure 2 is possible to derive that 63% of the total annual precipitation is usually distributed in *S2* (221 mm) while the remaining 37% in *S1* (131 mm), with respect to a yearly amount equal to 352 mm.

With regard to the rain amounts occurred during the three-year trial in each seasonal period (*S1* and *S2* respectively), significantly higher precipitations as compared with the median long-term amount were detected (Figure 4A), both in *S1* (+26, +126 mm, in *Y2* and *Y3* respectively) and in *S2* (+52, +228, +113 mm, in the three consecutive years). Due to extraordinary rainy fall-winter periods (*S2*), particularly with respect to the second and third year of trial, salt leaching was considerably favoured. This can be considered an exceptional and very unlikely event in the Mediterranean climate.

Water amounts applied as irrigation and extra-irrigation (*i.e.* intentional leaching) in the course of the trial are given in Figure 4B. Spring-summer crops were regularly irrigated: tomato, zucchini and pepper profited of a seasonal water supply equal to 544, 356 and 499 mm, respectively. In the course of tomato and zucchini cropping cycles (*Y1* and *Y2* respectively), no leaching was applied because the fixed critical EC_t value was reached only at the end of cropping season, when the crops were not particularly vulnerable to soil salinity. On the contrary, during the pepper cropping cycle (*Y3*), the critical EC_t was reached 40 days after transplanting and the application of an extra-irrigation volume was therefore needed.

In the first year, autumn rainfalls completely satisfied spinach water requirements and no irrigation was needed along the cropping cycle; the situation was different for broccoli, on the second year of trial: during the first 40 days after transplanting irrigation was supplied to the crop. At the same time, the critical EC_t was reached, mostly as a result of the brackish irrigation water applied to the previous crop (*C1*-zucchini). As a consequence, a leaching application was performed. Wheat (*Y3*) was considered a rainfed crop. At the end of the first *fallow* period (*F1*, first year of trial: from tomato harvesting to spinach sowing) a pre-sowing watering was applied to the three plots (*L0*, *L1* and *L2*). This watering supplied a brackish water amount of 63 mm. The aim of this pre-sowing irrigation was to bring soil moisture to field capacity to facilitate the subsequent leaching due to seasonal rains. Again, in the following experimental year, at the end of the first *fallow* period (*F1*, second year of trial: from zucchini harvesting to broccoli transplanting) an amount of 150 mm brackish water and 110 mm fresh water was applied, on *L1* and *L2* respectively, with the aim of obtaining a preliminary leaching before the incoming autumn rainfalls. Total drainage amounts collected during each *S* period are reported in Figure 4C. Considering the spring-summer cropping seasons (*S1*), drainage water amount was much higher during the third year (*Y3*) than in the first (*Y1*) and the second (*Y2*): 165 *vs* 61 and 45 mm respectively. As to the *S1* period of the third year, the large drainage volumes collected were mostly the result of the leaching application along the pepper cropping cycle.

The fall-winter period (*S2*) accounted for a very large drainage volume in the second year of trial. In these period, as a consequence of the abundant rainfalls, an impressive quantity of drainage water, amounting to 228 mm, was collected. The same seasonal period accounted for more limited drainage volumes both in the first (86 mm) and in the third (52 mm) year of trial.

Salinity along the soil profile

Variations in EC_e along the soil profile during the three-year trial are showed in Figure 5. The periodical dynamic of soil salinity is clearly showed; it is the consequence of the balance between water supplies (irrigation and rain) and drainage. Two separate phases can be recognized in the course of each cropping year: a salt accumulation phase (*recharge*) and a salt removal phase (*discharge*).

EC_e considerably increased along the soil profile at every *S1* period (*recharge*), as a result of the salt load due to irrigation with brackish water. A reverse behaviour was observed in *S2*; EC_e appreciably decreased along the soil profile (*discharge*) due to autumn and winter rains. Not every year the salts recharged into the soil were counterbalanced by the salts discharged from the soil to reach an *equilibrium* condition (Figure 5). In the first year of trial (*Y1*), the autumn-winter rains were not sufficient to ensure a complete salt leaching along the soil profile; indeed, a salt displacement from the top to the bottom of the soil was observed. The exceptional amount of precipitation occurred in the second year of trial (*Y2*) greatly favoured leaching; a consequent and significant reduction in the soil EC_e at all depths occurred, thus soil salinity profile levelled off completely. In the third year of trial (*Y3*), salt discharge due to drainage occurred at all considered depth and a condition of soil salinity equilibrium was attained.

Leaching modelling

The output of the ANCOVA is made of a set of linear regressions (GLM - *general linear model*) whose coefficients (intercepts and slopes) are statistically discriminated. Table 1 summarises the statistical results of the three ANCOVA models in terms of *F-ratio* and their corresponding probability, for each experimental treatment (*Year, Season, Leaching*) and their factorial combinations.

The first applied model (ΔS as a function of D_{trsf}) resulted highly significant (R^2=0.98; P<0.0001) and of quite good precision (RMSE=1.71 $t\ ha^{-1}$; CV=35,4%). A highly significant influence on the model coefficients was displayed by the *Season* and by the *Year*, both on the inter-

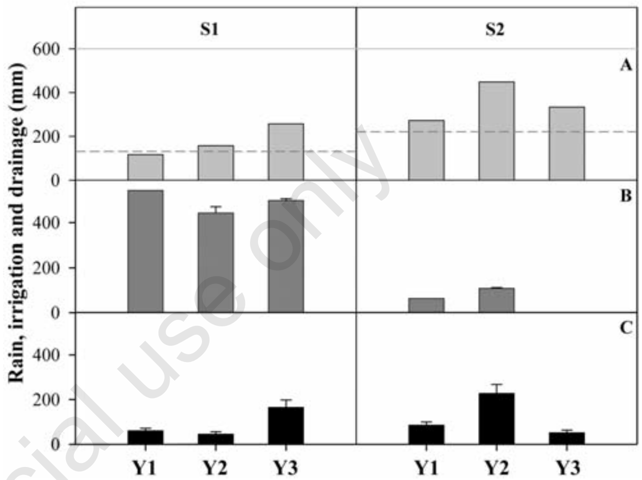

Figure 4. Amount of rain (A), irrigation (B) and drainage (C) with respect to the two growing season (*S*) and the three years of trial (*Y*). Horizontal dashed lines (in A) refer to the median long-term seasonal values of precipitations.

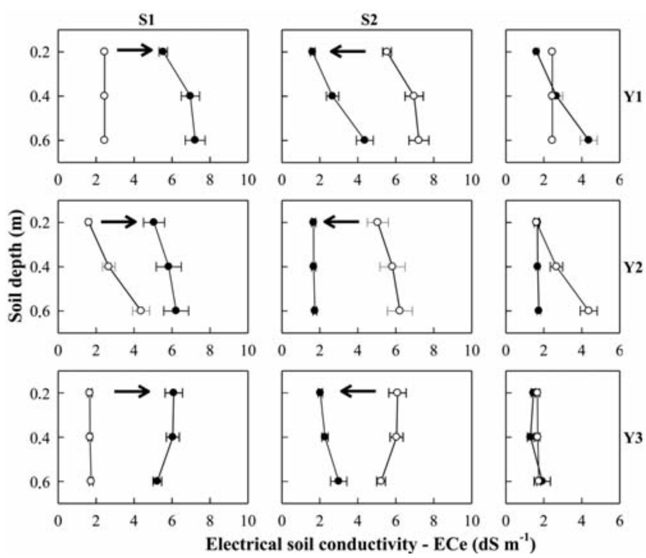

Figure 5. Salinity along the soil profile (0.20, 0.40 and 0.60 m of depth) expressed in terms of electrical conductivity of the soil saturated water extract EC_e (dS m^{-1}) with respect to spring-summer (*S1*) and autumn-winter (*S2*) seasons as well as the whole year (*Y*). Empty and full dots refers to the initial and final conditions of every period, respectively. Horizontal bars indicate the standard error of the mean.

cept and slope values. Also their interactions showed highly significant values. The intercept value of the model can be interpreted as the total amount of salt built up in the soil as a consequence of brackish irrigation along the season; the slope value, on the other hand, explains the leaching effectiveness, that is the amount of salts that are discharged from the active soil profile by a (log transformed) unit volume of drained water. According to those definitions, *S1* greatly increased the average value of the intercept (to 13.28 $t\ ha^{-1}$ on average), while *S2* resulted in a much lower value (1.92 $t\ ha^{-1}$ on average). This kind of results related to the intercept value can be explained considering that, in *S1*, crop irrigation is absolutely required and systematically performed using brackish water (thus the intercept is always significantly positive, irrespective of the year of trial) while in *S2* irrigation has only a supplementary function, so that no or limited amount of salts are added to the soil (thus the intercept is usually zero or slightly positive). Considering the slope coefficient, *S2* showed a remarkable lower (more negative) slope compared to *S1* (-2.60 *vs* -1.07 on average); this result can be interpreted with the fact that leaching in *S2* is normally worked out by rain water, while in *S1* by the irrigation brackish water. As a consequence, autumn and winter leaching are more effective than leaching performed in the spring-summer period. The effect of *Leaching* is significant on the intercept values but not significant on the slope coefficient; the *L1* intercept is always significantly higher than in *L0* and *L2*, because in *L1* leaching is performed adding extra-volumes of brackish water. Although statistically not significant, a general trend in promoting salt removal in *L1* and *L2* is observed by their slope values, lower (more negative) than the corresponding *L0* value. The model (with respect to the *Season* effect only) is showed in Figure 6A.

The second model (ΔS_0 as a function of *RL*) also resulted highly significant (R^2=0.88; P<0.0001) but quite rough in precision (RMSE=34.64; CV=68.2%). ΔS_0 is the ratio of the variation of soil salt content (ΔS) and the initial soil salt content (S_0). *Season* is the only factor that greatly influenced the intercept value, almost doubled in *S1* (122.9%) compared to the average value while in *S2* it was not significantly different from zero (9.6%, Prob.=0.22). The model (with respect to the *Season* effect only) is showed in Figure 6B. Differently from the first model, the slope was not considerably influenced either by *Season*, *Year*, or *Leaching*; the two lines being statistically parallel one to the others. This is directly the consequence of the standardization of ΔS into ΔS_0, and can be considered as a step forward on the way to a unifying leaching model. Leaching, therefore, is greatly influenced by the initial amount of salt in the soil (S_0), but it also could be greatly affected by the quantity of salts actually supplied to the soil during the cropping cycle, when irrigation with brackish water is performed; this means that the *salinity ratio* (*SR*) could be the unifying variable we are looking for; the *SR* values, indeed, depend on the *salinity load* (S_{LOAD}) that, as we already know, is the sum of S_0 and S_{IN}.

The third model (*SR* as a function of *RL*), explained a significant fraction of the total deviance (R^2=0.99; P<0.0001) and showed a very good degree of precision (RMSE=3.00; CV=24.8%). This time, as was expected, no significant influence was displayed by *Season, Year* and *Leaching*, both on the intercept and slope coefficients; as a consequence, S_0 and S_{IN} greatly affected leaching and a unique and comprehensive regression line (passing through the origin) can be set to quantitatively describe salt accumulation into and removal from the soil. The slope value is 1.28 (no unit) as reported in Figure 6C.

Considering our experimental conditions, an average annual salinity value (S_0) of approximately 18 $t\ ha^{-1}$ can be assumed (corresponding to an EC_e value of 5.0 dS m^{-1}). A seasonal irrigation of approximately 500 mm of brackish water (EC_{iw}=5.0 dS m^{-1}) brings about an annual salt addition (S_{IN}) equal to 16 $t\ ha^{-1}$; it means that the same amount of salt should be removed by leaching in the course of the year (S_{OUT}). The proper balance *salinity ratio* ($SR^*=100\times S_{OUT} / (S_0+S_{IN})$) thus corresponds to 47 %. Applying our general leaching model (*SR*=1.28**RL*), the annual leaching requirement to be targeted (*RL**) is equal to 37%. According to this conditions, an annual steady-state soil salinity needs that D, the amount of drainage water, should be the 37% of W, the total water supplied, sum of irrigation (500 mm) and rain (average value equal to 352 mm per year). An effective leaching supply of, at least, 310 mm of fresh water are therefore needed in order to assure salt balance. If 200 mm of brackish water are also available as extra-irrigation supply (S_{IN} =22.4 $t\ ha^{-1}$, *SR**=55% and *RL**=43%), the net effective fresh water needed in order to accomplish salt balance is reduced to approximately 170 mm.

Table 1. Statistical results of the three full factorial ANCOVA models (ΔS *vs D*, ΔS_0 *vs RL*, *SR vs RL*). For each factor (*Year, Season* and *Leaching*) and factors interaction, F-Ratio and the corresponding Probability are reported. Summary of fit is showed in the lower part of the table.

Source	DF	ΔS vs D F Ratio	ΔS vs D Prob >F	ΔS₀ vs RL F Ratio	ΔS₀ vs RL Prob >F	SR vs RL F Ratio	SR vs RL Prob >F
Intercept							
Year	2	5.02	0.01	0.18	0.84	0.33	0.72
Season	1	398.11	<0.001	106.54	<0.001	0.54	0.47
Year; season	2	9.84	0.00	0.47	0.63	0.08	0.92
Leaching	2	3.91	0.03	1.45	0.25	0.77	0.47
Year; leach	4	1.77	0.16	0.61	0.66	0.16	0.96
Season; year	2	2.93	0.07	1.25	0.30	0.13	0.87
Year; season; leach	4	1.54	0.21	0.50	0.74	0.01	1.00
Slope	1	169.58	<0.001	7.53	0.01	585.40	<0.001
Year	2	6.96	0.00	0.27	0.77	3.20	0.05
Season	1	29.42	<0.001	0.07	0.79	1.22	0.28
Year; season	2	5.64	0.01	0.28	0.76	2.17	0.13
Leaching	2	1.09	0.35	0.22	0.80	0.98	0.39
Year; leach	4	0.23	0.92	0.11	0.98	0.70	0.60
Season; year	2	0.45	0.64	0.47	0.63	1.37	0.27
Year; season; leach	4	0.34	0.85	0.12	0.97	1.49	0.22
R square		0.98		0.88		0.99	
Root mean square error		1.71		34.64		3.00	
Mean of response		4.84		50.77		12.09	
Variation coefficient		35.38		68.22		24.82	

Discussion and conclusions

Considering the whole outcome of the experimental trial, the following remarks can be outlined.

The intensive agricultural use of the soil, when exposed to frequent rotations of crops constantly irrigated with low quality water during the spring-summer months, is a matter of great concern; under these conditions, the occurrence of an unsustainable soil salinity level is quite certain, unless a sufficient amount of precipitations does not re-establish the salt equilibrium.

This scenario is clearly demonstrated by our results with reference to the salt built-up during the *S1* periods. A single spring-summer cropping cycle could be sufficient to bring about severe salinity conditions, particularly when: the irrigation water is characterized by high electrical conductivity (5-6 dS m^{-1}), the required ET_c is high and the total amount of water delivered is in the range of 400-500 mm, the average soil salinity is already high at the beginning of the cropping season.

Nevertheless, both in tomato and zucchini, unacceptable EC_e levels were attained only at the end of cropping season. This consideration suggests to delay leaching to the following *S2* season, thus avoiding an extra-water application during a period of the year characterized by large evaporation requirements and huge crop water consumptions (thus greatly increasing the leaching water volumes). This strategy can be easily applied to crops that are not too sensitive to soil salinity (like tomato and zucchini). Another reason to postpone leaching, as demonstrated by our work, is related to its effectiveness: the higher the soil salinity, the higher is the amount of salts displaced from the active soil profile per unit volume of drained water. The salt already present in the soil (S_0) and those added by irrigation (S_{IN}) play an important role in improving salt removal effectiveness. A *dynamic* leaching strategy is thus suggested: to operate soil salt leaching not at every crop watering but only when the soil salinity is close to a dangerous level, jeopardizing crop yield.

The most effective salt reduction in the soil profile occurred during the autumn-winter period, thanks to rainfalls. When a year of very abundant precipitations occurs, soil leaching and drainage allow a significant salt discharge from the soil and the restoration of salinity conditions that are not limiting to crop productivity. This particular conditions were experimentally observed in the second and third year of the experiment; as a consequence, conditions of salt equilibrium were almost reached. However, rain is usually not sufficient to ensure soil leaching; without intentional leaching there are generally no chances to remove the accumulated salts.

The leaching treatments performed during the three-year trial had no statistically significant effect; this can be explained through two reasons: the exceptionally high rain amounts reduced the frequency of intentional leachings and the unintentional leaching carried out by precipitations almost totally offset the results of the few intentional leachings.

Avoiding leaching in the course of the spring-summer season postpones the problem of salt removal from the soil to the following autumn-winter season. In such circumstances, two different options are possible (Figure 2), depending on the crop rotation: i) if the soil, in the course of the autumn-winter period, is going through a *fallow*, waiting for the following spring cropping cycle, a leaching application is not particularly urgent and time is still available to rely on the expected rains; ii) otherwise, if an autumn cropping cycle is just starting (the same circumstances faced in the experiment with spinach and broccoli) it could be useful to mitigate soil salinity with leaching, in order to avoid crop failure, particularly in the first and more vulnerable stages of germination and emergence. Differently for spinach and broccoli, wheat is very tolerant to salinity and its cropping cycle can be considered the same of a *fallow* period.

Intentional leaching application could be preferentially performed in the course of the *fallow* periods: at the end of *F1* a sort of *precautionary* leaching should be carried out, just before the autumn-winter rains start falling, using fresh or brackish water (according to the available water quality); a second possible and final (or *consumptive*) leaching could be eventually performed at the end of *F2*, soon after the autumn-winter rains, in case their amount was not sufficient to achieve salt removal from the soil; only water of good quality is to be employed in this latter case, because sowing or seedling transplanting are very close in time.

The simple and comprehensive leaching model (Figure 6C) is to be used to *plan, do and check* salt leaching from the soil. Under the experimental conditions, an annual steady-state salinity control at EC_e around 5-6 dS m^{-1} requires, at least, 310 mm of fresh drainage water; if 200 mm of brackish water are also available as extra-irrigation supply, the amount of fresh drainage water is reduced to approximately 170 mm. If rains were not efficient to play this crucial role, additional leaching irrigation should be performed.

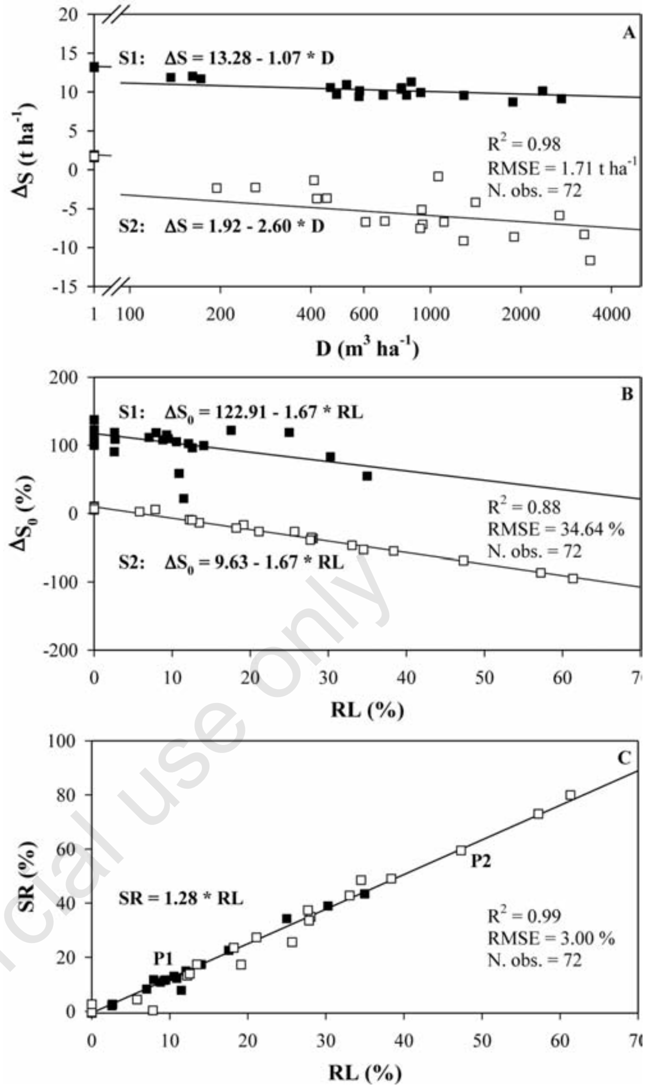

Figure 6. Set of linear regressions as a result of the ANCOVA on soil salinity balance: A) variations in soil salt content (*ΔS*) related to the corresponding (log scale) drainage volumes (D); B) relative variations in soil salt content (*ΔS₀*) with respect to the corresponding relative leaching volumes (*LR*); C) salinity ratios (*SR*) as function of relative leaching volumes (*LR*). Symbols relate to data averaged by year and leaching treatments

It can be concluded that, in order to prevent soil salinity build-up to levels limiting crop productivity and maintain salt equilibrium, a recommended strategy is to supply an extra amount of fresh irrigation water before or, alternatively, after the autumn-winter rains (*precautionary* and *consumptive* leaching, respectively). The larger is the seasonal rainfall and the available brackish water, the less amount of fresh water will be needed to promote leaching. These operational criteria allow to preserve the equilibrium conditions between irrigation and drainage as well as the sustainability of irrigated agriculture.

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