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Leaching Effect of Rainfall on Soil under Four-year Saline Water Irrigation

Giovanna CUCCI, Giovanni LACOLLA, Mario A. MASTRO and Gianraffaele CARANFA

Department of Agricultural and Environmental Science, University of Bari Aldo Moro, Bari, Italy

Abstract

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In the context of the overall competition for water resources it is important to understand the complex dynamics of crop water management including evapotranspiration, water quality, and leaching requirement, each of them depending on the site-specific conditions. The research started with grain maize and continued with sunflower, grain maize, and wheat, at the experimental field. On both grain maize and sunflower, 10 irrigation treatments were compared that resulted from the factorial combination of two types of water (fresh and brackish water) with five irrigation regimes; the scheduled treatments were applied by furrow irrigation. The amount of salts brought into the soil with the irrigation water during the three irrigation seasons of our trial increased shifting from the lowest to the highest irrigation regime and with the increase of salinity in the irrigation water. From the study of salt distribution in the soil it follows that at the end of the irrigation season the salt concentration increased by passing from the middle of the furrow, a zone more subject to leaching during irrigation, to the intermediate zone between the furrow and the ridge, and in the middle of the ridge between two contiguous furrows, an area of confluence of the wetting and salt accumulation fronts. The leaching water supplied during the irrigation season was poorly efficient in leaching the salts brought in through irrigation, whereas the rainfall water of the autumn-winter period after the irrigation season ensured a good control of soil salinity.

Keywords: brackish water; irrigation regime; leaching requirement, sodium adsorption ratio (SAR)

Soil degradation is progressing so quickly that many countries will not be able to implement sustainable agriculture in the near future unless suitable strategies are applied (Bahçeci 2009). Impermeabilization, contamination, erosion, salinization, alkalinization, and loss of organic matter are critical issues that need to be addressed (Marandola & Coderoni 2013). Salinization and alkalinization have been identified as a major soil degradation process (Rhoades & Loveday 1990) caused by the dispersion and swelling of clay particles (Shainberg 1990) resulting in the reduction of water infiltration in the soil and of its hydraulic conductivity. In regions where precipitation is low, salinity and sodicity are common problems (FAO 1999). Leaching and drainage can enable recovering saline soils with a high percentage of soluble salts, while sodic soils may be improved by substituting adsorbed sodium with calcium. In regions where precipitation is low, large amounts of irrigation water are usually required to favour leaching. A practical rule is that each water depth unit can remove nearly 80% of salts from the same soil depth unit (Ayers & Westcot 1985; Abrol *et al*. 1988): for example, a 0.30 cm water depth flowing through the soil can remove 70–80% of the existing salts in the top 0.30 cm soil layer. It is important to have a reliable estimate of the amount of water required for leaching (Abrol *et al*. 1988). For this reason many researchers in the world have developed mathematical equations to calculate the leaching requirement (LR) (Reeve 1957; Hoffman 1986). Some equations are empirical and do not take into account soil properties. The empirical approach,

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despite its limitations, seems to be the best because the studies on solute and water flow in the soil have not yet produced sufficient results for practical purposes (van der Molen 1973). Also, Oster *et al.* (1999) report that the different simultaneous processes involved in salt flow in the soil make buildup models and leaching practices difficult to be calculated mathematically. Rainfall usually causes the leaching of salts from the soil top layer (Moreira Barradas *et al.* 2015); in particular, in the geographical areas characterized by an annual average rainfall of 500–600 mm, mostly concentrated in autumn and winter, after the rainy season the salt content in the root-zone drops below the crop tolerance level (De Pascale *et al.* 2005). Hence, in regions where precipitation is low, winter leaching should remove salts so as to reduce the saturation extract electrical conductivity (ECe) in the root-zone below the crop tolerance level. However, the chemical reactions that take place in the soil influence the amounts of leached salts. In sodium-affected fields, crop growth may be negatively affected during the rainy season as well. Epstein (1977) and Russo (1983) reported that a relatively high soil salinity (ECe = 7.5 dS/m) may still remain high after the percolation of 800 mm of water prior to the crop establishment, due to the relatively high amount of soil exchangeable Na. The high activity of Na ions, as compared to Ca and Mg, also influences the soil structure and permeability through the swelling, breaking, and dispersion of clay aggregates (Läuchli & Epstein 1990; Cucci *et al.* 2012). The correction of soil salinity by leaching is even more complicated if the clay fraction is dominated by minerals such as swelling montmorillonite. After water application, due to salt leaching the clay particles swell quickly, reduce the hydraulic conductivity and the macropores that are the main drainage ways (Quadir *et al.* 2008; Cucci *et al.* 2015).

In the context of the overall competition for water resources it is important to understand the complex dynamics of crop water management including evapotranspiration, water quality, and LR, each of them depending on the site-specific conditions (crop type, irrigation method, climate, and soil type) (Isidoro & Grattan 2011). To provide further insight on this issue, a four-year research was undertaken at the DISAAT (Department of Agricultural and Environmental Science) of Bari University with the purpose of assessing the accumulation and distribution of salts as well as the leaching effect of rainfall on a sandy clay soil lying on fissured limestone, irrigated with fresh and saline water using furrow methods.

MATERIAL AND METHODS

Site characterization. The research started with grain maize (*Zea mays* L.) on April 10, 2007 and continued in 2008, 2009, and 2010 with sunflower (*Helianthus annuus* L.), grain maize, and wheat (*Triticum durum* Desf.) respectively, at the experimental field of DISAAT of Bari University in the area of Valenzano (41°46'04N latitude, 16°54'01E longitude), Italy, on a shallow sandy clay loam red soil of good fertility, lying on bedrock characterized by fissured limestone (Ruphtic-Lithic, USDA classification, Soil Survey Staff 1999) and 0.30 m deep, with the physical and chemical characteristics shown in Table 1. The characterization of the soil was achieved using the official methods (Violante 2000).

Table 1. Main properties of the tested soils

Parameters		Values ± SD
Particle-size analysis (g/kg)		
Total sand	2 > ø > 0.02 mm	478 ± 11.2
Silt	0.02 > ø > 0.002 mm	256 ± 10.4
Clay	ø < 0.002 mm	266 ± 14.6
Chemical properties		
Total nitrogen (Kjeldahl method) (g/kg)		1.56 ± 0.2
Available phosphorus (Olsen method)		23.30 ± 0.5
Exchangeable calcium ($BaCl_2$ method)		4150 ± 26.0
Exchangeable magnesium ($BaCl_2$ method)		320 ± 12.0
Exchangeable potassium ($BaCl_2$ method)		480 ± 14.0
Organic matter (Walkley Black method) (g/kg)		21.90 ± 0.4
Total limestone (g/kg)		122.75 ± 5.30
Active limestone (g/kg)		74 ± 2.1
pH		7.18 ± 0.2
ECe (dS/m)		0.42 ± 0.02
ECe 1:5 (dS/m)		0.11 ± 0.03
ESP		0.62 ±0.2
CEC ($BaCl_2$ method) (meq/100 g)		28.10 ± 0.8
Hydrologic properties		
Field capacity (g/kg dw)		310 ± 9.3
Wilting point (–1.5 MPa) (g/kg dw)		160 ± 5.2
Bulk density (t/m^3)		1280 ± 6.0

ECe – saturation extract electrical conductivity; ECe 1:5 – extract electrical conductivity w/w dry soil/water; ESP – exchangeable sodium percentage; CEC – cation exchange capacity; dw – dry weight

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Experimental fields. On both grain maize and sunflower, 10 irrigation treatments were compared that resulted from the factorial combination of two types of water (fresh and brackish water, with an electrical conductivity of 1.2 and 5 dS/m, respectively) under the following irrigation regimes:

(1) seasonal irrigation volume equal to 75% of maximum crop evapotranspiration (ETc);

(2) seasonal irrigation volume equal to 100% ETc;

(3) seasonal irrigation volume equal to 100% ETc plus 50% of leaching requirement (LR) calculated as:

LR = ECw/(5 ECe – ECw)

where:

ECw – electrical conductivity of irrigation water (dS/m)

ECe – electrical conductivity of the saturation extract, corresponding to 10% reduction of the maximum yield, considered to be equal to 2.5 dS/m for both crops

(4) seasonal irrigation volume equal to 100% of ETc plus 100% of LR calculated as above;

(5) seasonal irrigation volume equal to 75% of ETc obtained by skipping one watering at the vegetative stage, supplying watering volumes equal to 100% ETc for three irrigations at the flowering stage and 75% ETc for the rest of the growing season.

The characteristics of the two types of water are reported in Table 2. Water was characterized using the "adjusted sodium adsorption ratio" (adj SAR) (Suarez 1981), as the soil to be irrigated was rich in calcium carbonate. To differentiate the 5 irrigation regimes, the watering volume was changed and the irrigation interval was kept constant. In the treatment irrigated at 100% ETc, irrigation was performed whenever the matric potential of water in the soil layer explored by roots was equal to 0.1 MPa, by supplying the watering volume required to bring the matric potential of the above-mentioned layer to –0.03 MPa.

Based on the irrigation regimes, the irrigation interval was determined following the evapotranspiration criteria, by the relationship:

$$L = V = \sum_{1}^{n} E_d K_p K_c$$

where:

L – irrigation threshold, equal to cumulative maximum evapotranspiration net of effective rainfall (mm)

V – watering volume corresponding to the irrigation regime of l00% ETc (mm) assuming an irrigation efficiency equal to l

E_d – daily evaporation from 'Class A' pan (mm)

K_p – conversion factor of E_d into ETc = 0.8

K_c – crop coefficient, which varied as follows: for maize, 0.4 from sowing to the fourth leaf, 0.9 from the fourth leaf to tasselling, 1.1 from tasselling to milk ripeness, 0.6 from milk ripeness to dough stage. For sunflower it varied as follows: 0.4 from sowing to the 2nd couple of leaves, 0.7 from the 2nd couple of leaves to bud formation, 1.0 from bud formation to the end of flowering, 0.5 later on

Rainfall exceeding 10 mm over 24 h was subtracted from the cumulated ETc values until the rainy day; however, the negative values of such differences were not taken into account.

The split-plot design was adopted with 4 replicates; water types were assigned to the plots and the irrigation regimes to the sub-plots of 5 × 4.9 m. Sowing was performed: on April 10, 2007 and April 16, 2009 for maize; on April 15, 2008 for sunflower and on November 10, 2009 for wheat, in a soil previously fertilized with 150 kg/ha of P_2O_5 and 75 kg/ha of N for maize and sunflower, with 90 kg/ha of P_2O_5 and 36 kg/ha of N for wheat; by adopting a sowing spacing of 0.70 × 0.25 m and the cv. Roberta and Volga (hybrids F_1 class FAO 500), respectively, in 2007 and 2009 for maize; a sowing spacing equal to 0.70 × 0.30 m and the cv. Isa (medium early) for sunflower; rows 0.18 cm apart, using 200 kg/ha of seed of Appulo cv. for wheat.

Immediately after sowing, the following plan was adopted to favour the crop emergence: 3 sprinkler irrigation in the first year, applying a total volume of 600 m^3/ha of fresh water; 3 furrow irrigations to sunflower, in the second year, supplying a total amount

Table 2. Water quality characteristics

	EC (dS/m)	Na^+	Ca^{2+}	Mg^{2+}	$HC0_3^-$	$C0_3^{2-}$	Adj SAR*
		(meq/l)					
Fresh water	1.2	2.3	4.9	1.2	4.7	0.4	1.4
Brackish water	5.0	35.5	9.9	5.0	6.6	1.2	14.5

EC – electrical conductivity; Adj SAR – adjusted sodium adsorption ratio; *calculated according to the indications by Suarez (1981)

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of 1100 m^3/ha to the treatments l, 2, and 5, 1160 and 1450 m^3/ha to treatment 3, 1210 and 1827 m^3/ha to treatment 4, by using, respectively, fresh and brackish water; in the third year, maize was furrow irrigated once by 650 m^3/ha of water, using fresh and brackish water, as scheduled in the experimental layout. In all three years, until the dough stage, in grain maize and sunflower (August 21, 2007; July 27, 2008; and August 19, 2009) the scheduled treatments were applied by furrow irrigation.

No irrigation had been scheduled for wheat; due to the dry conditions, emergence was non-uniform and occurred at the end of December after a heavy rainfall, only in the plots which had been previously irrigated with fresh water. Therefore, on January 8, 2010 the crop was sown again and emergence was observed on January 30. Since climate conditions kept dry, on March 20 a supplementary irrigation was performed with a water volume of 500 m^3/ha.

At the end of the irrigation period of the three years (August 2007, 2008, and 2009), after the rainy season (March 2008 and 2009) and at wheat harvesting in the fourth year (June 2010), soil samples were taken from the surface to 0.10 m, from 0.10 to 0.20 m depth, and – when the soil was furrowed – in the middle of the furrow, mid-way of the ridge between two contiguous furrows and at an intermediate point.

From the above said samples, 1 : 5 extracts were taken and their electrical conductivity was measured; from the samples taken at the end of the rainy season and at wheat harvesting, the saturation extracts were obtained and their electrical conductivity as well as the Na^+, K^+, Ca^{2+}, and Mg^{2+} cation concentrations were determined. From cation concentration values, the exchangeable sodium percentage (ESP) was calculated by the following relation (Sequi 1989):

$$ESP = \frac{100 \times (-0.0126 + 0.01475 \times SAR)}{1 + (-0.0126 + 0.01475 \times SAR)}$$

where:

$$SAR = \frac{|Na^+|}{\sqrt{\frac{|Ca^{2+} + Mg^{2+}|}{2}}}$$

where the concentration of the three cations is expressed in meq/l.

All data collected were subjected to the analysis of variance and the averages compared by the SNK test.

Rainfall pattern. The rainfall pattern during the period of the trial (January–July 2007, July 2010) is illustrated in Figure 1. The total amount of rainfall during the cropping cycle of maize and sunflower (May–August of 2007, 2008, and 2009) was equal to 120–65.4, and 130.2 mm, respectively, whereas during the rainy seasons after irrigation (October–March of 2007–2008, 2008–2009, and 2009–2010) it was respectively equal to 391.2–250.3, and 157.3 mm, with great differences from one year to the other. The monthly values recorded during the last period ranged from 8.0 mm to a maximum of about 9.1 mm. The total rainfall during the rainy season and the depth of each single event favoured, to a variable extent, the leaching of salts brought in by irrigation during the previous irrigation seasons.

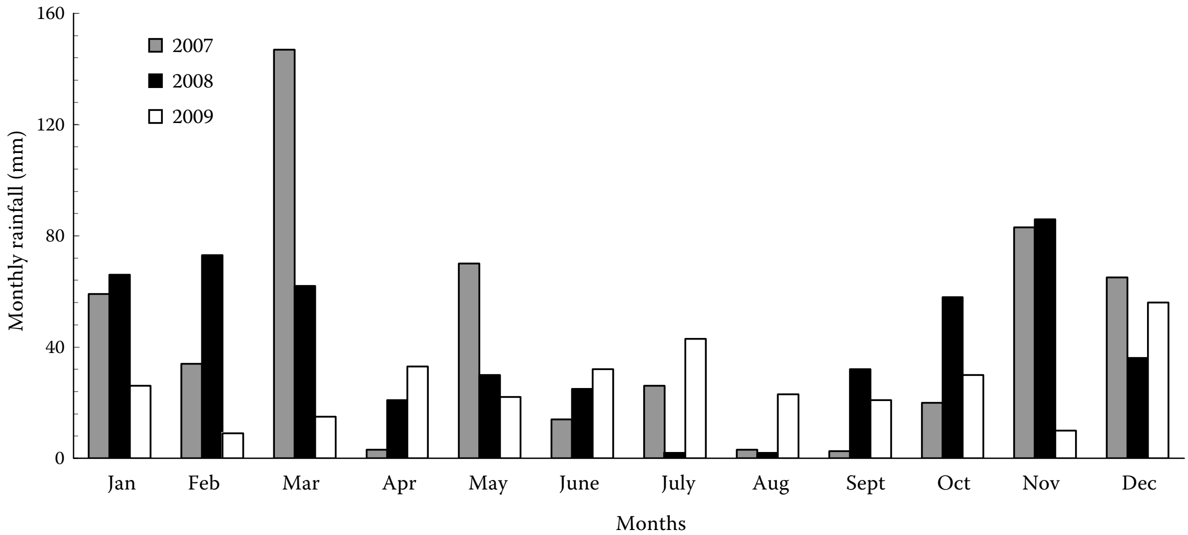

Figure 1. Rainfall pattern during the period of the trial

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Table 3. Seasonal irrigation volumes applied to maize (2007 and 2009) and sunflower (2008) using two types of water with different electrical conductivity

Irrigation volumes (m^3/ha)	Electrical conductivity (dS/m)					
	1.2			5.0		
	2007*	2008	2009	2007	2008	2009
75% ETc	2275	3050	3135	2275	3050	3135
100% ETc	3024	3714	3976	3024	3714	3976
100% ETc + 50% LR	3174	3897	4142	4038	4958	5091
100% ETc + 100% LR	3330	4080	4300	5050	6156	6200
75% ETc°	2275	3050	3135	2275	3050	3135

ETc – crop evapotranspiration; LR – leaching requirements; *to the seasonal irrigation volumes given in the table, you should add 600 m^3 /ha of water supplied immediately after sowing by sprinkling and using fresh water in order to favour seedling emergence; ETc° – in this irrigation regime it was forseen to skip one irrigation during the vegetative stage and the watering volumes were equal to 100% ETc for three irrigation events during the flowering stage

RESULTS AND DISCUSSION

Seasonal irrigation volumes supplied. The seasonal irrigation volumes supplied to the crops grown in the first three-year period of the trial are reported in Table 3: under the lowest irrigation regime (re-establishment of 75% ETc) they were equal to 2875 and 3135 m^3 per ha for maize in 2007 and 2009, and to 3050 m^3/ha for sunflower in 2008, whereas under the highest irrigation regime (re-establishment of 100% ETc plus 100% LR) they were equal to 3930 and 5655 m^3/ha in 2007, 4300 and 6200 m^3/ha in 2009 for grain maize, 4080 and 6156 m^3/ha in 2008 for sunflower, irrigating respectively with fresh and brackish water. Therefore, moving from the lowest (re-establishment of 75% ETc) to the highest (re-establishment of 100% ETc plus 100% LR) irrigation regime, both water volumes and amount of solutes supplied increased.

Following the adopted criteria, the calculated amounts of leaching water (LR) were equal to 9.9 and 67% of the volume of irrigation water needed to satisfy the crop water requirements with fresh and brackish water, respectively.

Salt distribution in the soil and leaching by rainfall. The amount of salts brought into the soil with the irrigation water during the three irrigation seasons of our trial increased shifting from the lowest to the highest irrigation regime and with the increase of salinity in the irrigation water (Table 4); as a whole, they varied from 6.54 and 28.41 t/ha to a maximum value of 8.99 and 59.36 t/ha, by using fresh water and brackish water, respectively.

The salts brought through irrigation caused the electrical conductivity of the soil extracts to increase until reaching the highest values at the end of the irrigation season and the lowest values at the end of

Table 4. Amount of salts (in t/ha) supplied to the soil through two types of irrigation water to maize (2007 and 2009) and sunflower (2008)[1]

Irrigation volumes (m^3/ha)	Eectrical conductivity (dS/m)							
	1.2				5.0			
	2007	2008	2009	total	2007	2008	2009	total
75% ETc	207	220	227	654	792	1010	1040	2842
100% ETc	261	267	295	823	1041	1226	1354	3621
100% ETc + 50% LR	272	281	306	859	1376	1636	1774	4786
100% ETc + 100% LR	283	294	322	899	1710	2032	2194	5936
75% ETc	207	220	227	654	792	1010	1040	2842

ETc – crop evapotranspiration; LR – leaching requirements; [1]amount of salts brought to the soil through irrigation water were calculated by using the relationship reported in Richards (1954); between the electrical conductivity of a solution and the corresponding average salt concentration

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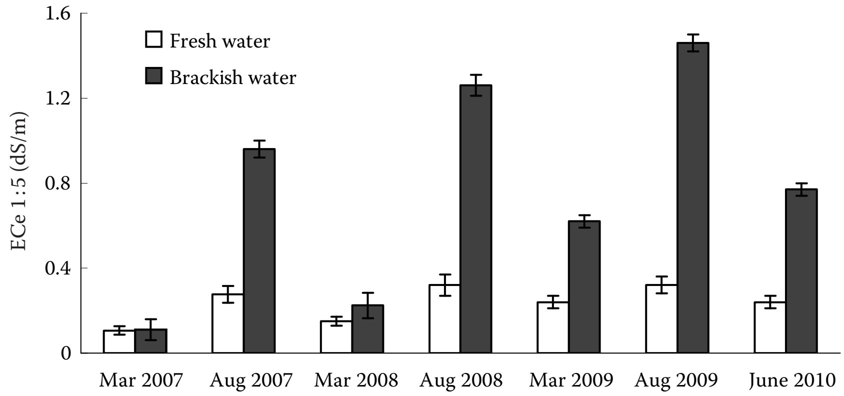

Figure 2. Extract electrical conductivity w/w dry soil/water (ECe 1:5) at the end of the rainfall season (March), at the end of the irrigation season (August), and at the end of the trial (June 2010)

the rainy season (Figures 2 and 3). The application of saline-sodic leaching water to a shallow (0.30 m) sandy clay loam soil, lying on fissured limestone, has probably favoured the formation of temporary salt buildup (Rengasamy 2002), responsible for the soil ECe at the end of the irrigation season, that was subsequently removed by autumn-winter rainfall. Also Moreira Barradas *et al.* (2015), in a hemiboreal climate, have found an effective desalinizing effect of rainfall and snow after winter on soils fertigated with nutrient solutions with an EC up to 2 dS/m. No significant difference was observed in the soil electrical conductivity under different irrigation regimes, probably as a consequence of the low efficiency of the irrigation method used (furrow irrigation) and of the soil characteristics. It is interesting to observe that the autumn-winter rainfall, equal to 394, 250, and 157 mm in 2007–2008, 2008–2009, 2009–2010, respectively, leached such an amount of salts brought in through irrigation that it caused the electrical conductivity of the 1 : 5 extract to drop at the end of the irrigation season by 43.4–22.5 and 25% when irrigating with fresh water, and by 76.5–51.1 and 48.2% when irrigating with brackish water. Because of rainfall scarcity in 2008–2009 and 2009–2010, the electrical conductivity of the 1 : 5 extract, observed at the end of the rainy season, followed an upward pattern from the beginning to the end of the four-year period of the trial. Also, the exchangeable sodium percentage increased during the four years of the trial and varied from the initial value of 0.68% to 1.03 and 2.5% in the plots irrigated with fresh water,

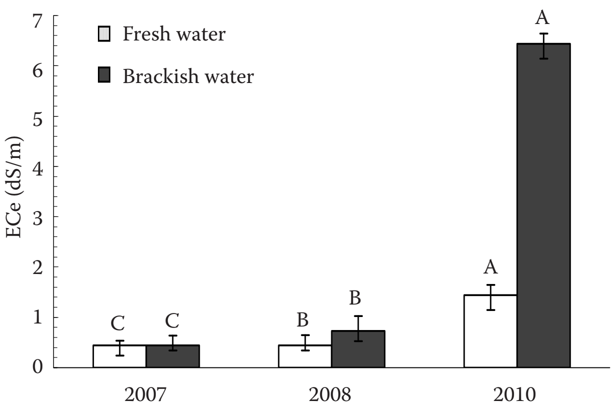

Figure 3. Saturation extract electrical conductivity (ECe) at the end of the rainfall season of the years 2007 and 2008 and at the end of the trial (June 2010); for each effect considered, the values followed by the same letter are not significantly different, according to the SNK (Student-Newman-Keuls) test at $P \leq 0.01$

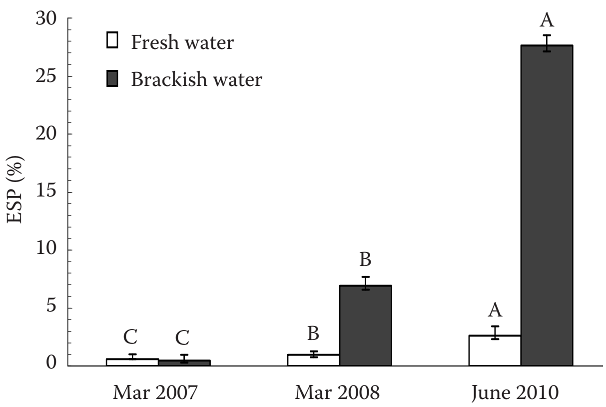

Figure 4. Exchangeable sodium percentage (ESP) at the end of the rainfall season of the years 2007 and 2008 and at the end of the trial (June 2010); for each effect considered, the values followed by the same letter are not significantly different, according to the SNK (Student-Newman-Keuls) test at $P \leq 0.01$

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to 7.06 and 28.0% in the plot irrigated with brackish water, respectively, in March 2008 and at the end of June 2010 (Figure 4). An important condition that should be checked before leaching is applied, concerns the soil sodium hazard due to the interaction between irrigation water quality and soil properties. High SAR and ESP values and significant concentrations of carbonates and bicarbonates in irrigation water should discourage extra water applications for leaching purposes that could damage the soil structure, particularly unstable in fine-textured soils in the presence of high ESP values. Under these conditions, instead of dealing with salinity problems by leaching excess salts, it is important to first face sodium hazard and to apply calcium to substitute it on the exchange complex (Van Hoorn & Van Alphen 1994). For the determination of ESP, which is an indicator of clay dispersion, soil sodicity, and subsequent structural degradation, the correlation equation between ESP and the SAR was applied. No parameters other than the SAR were used, such as the cation ratio of soil structural stability (CROSS) (Rengasamy & Marchuk 2011) and the monovalent cations adsorption ratio (MCAR) (Smiles & Smith 2004), because in the irrigated soil there were not large amounts of exchangeable magnesium (320 mg/kg) and potassium (480 mg/kg) with flocculating and dispersing power. Irrigation waters, both fresh and brackish, were also characterized by not high magnesium concentrations (fresh water 14.4 mg/l and brackish water 60 mg/l). From the study of salt distribution in the soil irrigated by furrow methods, due to the three-dimensional water flow and solute transport processes (Cavazza & Patruno 2005), it follows that at the end of the irrigation season the salt concentration increased by passing from the middle of the furrow, a zone more subject to leaching during irrigation, to the intermediate zone between the furrow and the ridge, and in the middle of the ridge between two contiguous furrows, an area of confluence of the wetting and salt accumulation fronts (Figure 5). Salt accumulation tended to be higher in depth under the furrow and in the intermediate zone between the latter and the ridge, whereas, at the surface, it was higher in the ridge. Water flow in soil during furrow irrigation (percolation and seepage) causes different interactions between EC and SAR with subsequent variations in clay dispersion, macropore and micropore distribution, bulk density, hydraulic conductivity, and salt distribution (Ezlit *et al.* 2013; De Menezes Heitor *et al.* 2014) making ineffective the application of leaching water without soil amendments like gypsum. Many steady and unsteady flow models have been used to study water flow in the soil (Bastiansen *et al.* 2007). Letey and Feng (2007) have concluded that steady flow models tend to overestimate the negative effects of saline water. The problem of water flow in the soil gets more complex considering rainfall and the spatial variability (Bastiansen *et al.* 2007; Isidoro & Grattan 2011).

At the end of the rainy season (March 2009), the salt distribution in the soil was rather uniform, although furrows were still present in winter. On the contrary, the exchangeable sodium percentage was higher in the furrow and lower in the zone between two contiguous furrows (Figure 6). The highest ex-

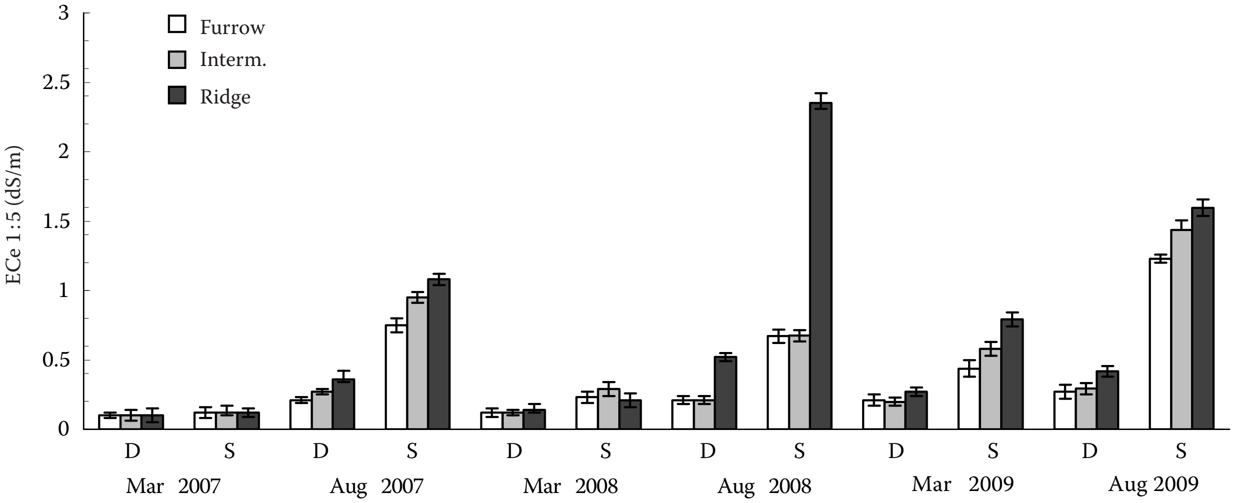

Figure 5. Electrical conductivity of the 1:5 soil extract irrigated with fresh water (D) and brackish water (S); values measured at the end of the rainfall season (March) and at the end of the irrigation season (August)

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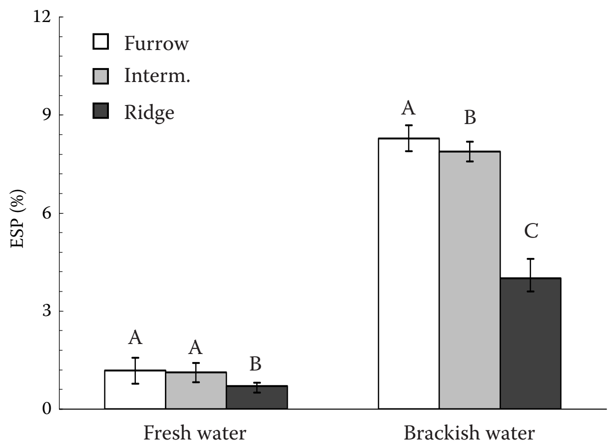

Figure 6. Exchangeable sodium percentage (ESP) in the furrow, on the ridge, and in the intermediate zone, the end of the rainy season (March 2009); for each effect considered, the values followed by the same letter are not significantly different, according to the SNK (Student-Newman-Keuls) test at $P \leq 0.01$

changeable sodium percentage in the furrow is correlated to the deep percolation flow of irrigation water in that area with salt leaching (notably Ca) and subsequent alkalinization and clay dispersion. Between contiguous furrows, instead, water flow and solute transport occur by seepage, so that there are no variations in the ratio of Na concentration to other cations.

CONCLUSION

Based on the results of a research conducted for four years in southern Italy on a shallow sandy clay loam (0.30 m), lying on bedrock characterized by fissured limestone, irrigated by furrow methods with two types of water (brackish and fresh) and five irrigation regimes (including 2 with the application of LR) with the aim to assess salinization, alkalinization, and the leaching effect of rainfall in an environment characterized by an annual average rainfall of 450–500 mm, the following conclusions may be drawn:

- at the end of irrigation seasons soil salinization increased with solute supply and passing from the bottom to the intermediate and ridge areas of the furrow;
- the leaching water supplied (50% LR and 100% LR) during the irrigation season was poorly efficient in leaching the salts brought in through irrigation, whereas the rainfall water of autumn and winter after the irrigation season ensured a good control of soil salinity, at least in the years when rainfall was not much lower than the pluriannual mean;
- to increase the efficiency of both water volumes applied during the irrigation season and the desalinizing effect of rainfall so as to prevent soil alkalinization, especially along the bottom of furrows, it would have been appropriate to supply adequate amounts of amendments such as, for instance, gypsum, before the rainy season.

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Corresponding author:

Prof. Giovanna Cucci, University of Bari Aldo Moro, Department of Agricultural and Environmental Science,
Via Amendola 165/A, 70125 Bari, Italy; e-mail: giovanna.cucci@uniba.it