Irrigation with saline-sodic water: effects on two clay soils

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Abstract

The results of a 4-year experiment aimed at evaluating the effect of irrigation with saline-sodic water on the soil are reported. The research was carried out at the Campus of the Agricultural Faculty of Bari University (Italy) on 2 clay soils (Bologna – T_1 and Locorotondo – T_2). The soils were cropped to borlotto bean (*Phaseolus vulgaris* L.), capsicum (*Capsicum annuum* L.), sunflower (*Helianthus annuus* L.), wheat (*Triticum durum* Desf) grown in succession; the crops were irrigated with 9 saline-sodic types of water and subjected to two different leaching fractions (10% and 20% of the watering volume). The 9 solutions were obtained dissolving in de-ionised water weighted amounts of sodium chloride (NaCl) and calcium chloride ($CaCl_2$), deriving from the combination of 3 saline concentrations and 3 sodicity levels. The crops were irrigated whenever the water lost by evapotranspiration from the soil contained in the pots was equal to 30% of the soil maximum available water. The results showed that, though the soils were leached during the watering period, they showed a high salt accumulation. Consequently, the saturated soil extract electrical conductivity increased from initial values of 0.65 and 0.68 dS m^{-1} to 11.24 and 13.61 dS m^{-1} at the end of the experiment, for the soils T_1 and T_2, respectively. The saline concentration increase in irrigation water caused in both soils a progressive increase in exchangeable sodium, and a decrease in exchangeable calcium and non-significant variations in exchangeable potassium (K) and magnesium (Mg).

Introduction

The problems related to the use of highly saline water mostly occur in desert areas of South America, in some states of the USA such as California, Arizona (Ayers and Westcot, 1985), in many Asian regions including Pakistan, India, Bangladesh, China, Japan (Levy *et al.*, 1988), in the Middle East in the areas between Tigris and Euphrates (Iraq), Bahrain (Ayers and Westcot, 1985), Negev Desert (Israel) (Pasternak and De Malach, 1987), in the Mediterranean (Levy *et al*., 1988) in Italy, notably in central-southern areas, and along the coast (Postiglione *et al.,* 1994). An attempt to collect information on the spread of salt-affected soils at European and world levels has been made by Szabolcs (1974, 1979) and Massoud (1977), respectively. Statistics may differ according to the authors. However, it is estimated that there are on the whole planet one billion hectares of saline soils (Gupta and Abrol, 1990) with a persisting increase of approximately 2 million hectares per year in arid and semiarid areas (Postel, 1996).

The reasons for concern are not especially related to the crop response to irrigation with brackish water (mostly short-term) but to long-term changes that can seriously modify soil productivity. These changes concern the processes of soil salinisation and sodification, the former is more subtle for its poorly specific effects on crops, the latter is more dangerous because it appears after a long time and has characteristics that make it difficult for these modifications to be corrected. A major role is played by sodium content and its relationship with divalent cations (notably calcium and magnesium) whose action is mostly addressed towards clay materials. Under such a high relative concentration of sodium, soil colloids are to some extent deflocculated, and their structure and properties degraded (Levy and Torrento, 1995). The deflocculating effect of sodium ion on clay increases with the concentration of adsorbed sodium; the threshold of the exchangeable sodium percentage (ESP) is usually established at 15% of cation exchange capacity, although in some cases sodification characteristics appear at much lower values (Murray and Quirk, 1990). The detrimental effects of sodium in clay soils change depending on the clay mineral composition (Saskatchewan Water Corporation, 1987); sodium excess reduces permeability in soils with predominant montmorillonitic clays much more than in soils with illite-vermiculite and kaolinite. Montmorillonitic clays have a higher number of exchange sites per mass unit where soil may bind and cause dispersion. Instead, illite and kaolinite are characterised by potassium and hydrogen bonds, respectively, so they tend to keep the structural sheets of clay crystals more tightly (Violante, 2002).

The dispersion of clay particles can result in clogging of soil pores causing a significant reduction in porosity, permeability, hydraulic conductivity (Frenkel *et al.,* 1978; Amézketa, 1999) and of the stability of aggregates to water (Varallyay, 1977). Many mathematical models have been used to study water flow and solute uptake through the soil (Bastiaanssen *et al.,* 2007). Letey and Feng (2007) concluded that steady-state models tend to overestimate the adverse effects of irrigation with saline water, thus pointing to water quality standards for salinity higher than necessary (Corwin *et al.,* 2007). There are also issues with spatial variability that limit the application of these models on a large-scale basis (Bastiaanssen *et al.,* 2007). In order to provide further insight into the subject, a long-term research was undertaken at the Department of Agricultural and Environmental Science (DiSAAT) of Bari University with the aim of assessing the effects of different salt concentration and sodicity sodium adsorption ratio (SAR) levels of water on 2 soils subjected to two leaching fractions. The results of a 4-year trial are reported.

Materials and methods

The research was carried out over a 4-year period at the Campus of Bari University, Italy, on 2 soil types contained in cylindrical pots 0.40 m in size and 0.60 m in height, equipped with a bottom valve for drainage water, placed under a shed roof to prevent the rain leaching effect. The 2 soil types, both rich in clay materials, have been classified as follows (Cavazza *et al.,* 2002; Patruno *et al.,* 2002): i) Bologna soil (T$_1$) – with clay mineral rich in vermiculite and illite, poor in iron and aluminium sesquioxides, resulting from horizon AP, of a *Udertic Ustochrept* (fine, mixed, mesic), Montefalcone series, of Emilia Romagna soil map; ii) Locorotondo soil (T$_2$) – with clay mineral rich in illite and kaolinite, rich in iron and aluminium sesquioxides, resulting from horizon AP *Pachic Haploxeroll* (fine, mixed, thermic), Cutino series, of Apulia soil map; this soil type is common in the south-eastern area of Bari.

The 2 soil types have been grown with four crops in succession (borlotto bean in the first year, capsicum, sunflower, wheat in subsequent years), irrigated with 9 different types of saline-sodic water and subjected to 2 different leaching fractions (LR=10% and 20% of watering volume).

The trial was run on a total of 72 pots, arranged by a split plot design and 2 replicates, with the soil types in large plots (18 containers), leaching fractions in sub-large plots (9 containers) and water types in plots (single containers). The main chemical, physical and hydrological properties of the 2 soils before the 4-year irrigation period with saline-sodic water are shown in Table 1.

The 9 types of brackish water were obtained by dissolving the appropriate amounts of sodium chloride (NaCl) and calcium chloride (CaCl$_2$) in de-ionised water, by the factorial combination of 3 salt concentrations (0.001, 0.01 and 0.1 M L^{-1} in first year and 0.01, 0.032 and 0.064 M L^{-1} in subsequent years) and 3 SAR levels (SAR=5, 15 and 45). The quality properties of resulting irrigation waters are shown in Table 2.

The text and graphs refer to the salt concentrations (0.01, 0.032 and 0.064 M L^{-1}) of the irrigation water applied to capsicum, sunflower, wheat in the 3-year period. Throughout the cropping cycle the cultivated species were irrigated whenever 30% of the maximum available water was lost by evapotranspiration from the whole pot by an applied volume equal to the amount required to bring to field capacity the whole soil mass contained in each pot plus the expected leaching fraction. All current cropping practices were also applied.

Evapotranspiration was measured on a daily basis by weighing lysimeters equipped with a spring balance. Under the applied water regime, neither soil cracks nor preferential flow paths of the leachate were observed along the sides of pots despite their small size.

Throughout the cropping cycles the water drained from each container was collected and measured, and soluble bases [sodium (Na), potassium (K), magnesium (Mg), calcium (Ca)] were analysed by atomic absorption. To characterise the soils submitted for four years to irrigation with saline-sodic water, in the late season of wheat, once the soil was brought to field capacity whenever it lost by evapotranspiration 30% of maximum available water, the 0.60 m soil profile of each container was characterised, by 0.20 m increments, for the following parameters: saturation extract, electrical conductivity and pH of the saturation extract, soluble bases (Na, K, Mg, Ca), exchange bases (Na, K, Mg, Ca), cation exchange capacity, and ESP. The characterisation of the soils to be reclaimed was achieved using the official methodologies (Violante, 2000). At the end of the 4-year period of irrigation with saline-sodic water, mean samples were taken along the soil profile and tested for the structure stability after separating wet-sieved aggregates of 1 and 2 mm by the vertical oscillation method with or without pretreatment in alcohol (Hénin *et al.,* 1969; Kemper and Rosenau, 1986).

All measured and calculated parameters were submitted to the variance analysis using the SAS software (S.A.S. Institute Inc., Cary, NC, USA) and the differences between means were assessed applying Student-Newman-Keuls (SNK) test.

Table 1. Main chemico-physical and hydrologic properties of the two soil types before irrigation for four years with saline-sodic water.

		Soil type	
		Bologna (T$_1$)	Locorotondo (T$_2$)
Particle-size analysis			
Total sand	2>ø>0.02 mm (g 100 g^{-1})	30.27	20.94
Silt	0.02>ø>0.002 mm (g 100 g^{-1})	33.10	44.00
Clay	ø<0.002 mm (g 100 g^{-1})	36.63	35.06
Chemical properties			
Total N (Kjeldahl method)	(g 1000 g^{-1})	0.79	1.65
Available P (Olsen method)	(mg kg^{-1})	31.50	52.50
Exchangeable K (BaCl$_2$ method)	(mg kg^{-1})	160.00	352.00
Organic matter (Walkley Black method)	(g 100 g^{-1})	1.21	3.13
Total limestone (met. calc. Dietrich-Fruhling)	(g 100 g^{-1})	0.47	2.58
Active limestone	(g 100 g^{-1})	0.05	1.40
ECe	(dS m^{-1})	0.65	0.68
ESP	(%)	0.70	0.80
pH (pH in H$_2$O)	-	7.09	7.18
CEC (BaCl$_2$ method)	(meq 100 g^{-1})	34.00	38.00
Hydrological properties			
Field capacity (field determination)	(g 100 g^{-1} d.m.)	34.50	35.80
Wilting point (−1.5 MPa)	(g 100 g^{-1} d.m.)	14.70	18.40
Bulk density (t m^{-3})	(t m^{-3})	1.20	1.20

N, nitrogen; P, phosphorus; K, potassium; BaCl$_2$, barium chloride; met. calc., method calcimeter; ECe, saturation extract electrical conductivity; ESP, exchangeable sodium percentage; CEC, cation exchange capacity.

Results and discussion

Under the applied water regime the irrigation variables were not statistically different for the 2 soil types, but they changed as a function of irrigation water quality. The number of water applications and the seasonal irrigation volumes applied to each container based on evapotranspiration, decreased as the irrigation water salinity increased, due to the lower development of plants.

Table 3 shows the seasonal irrigation volumes for each crop and for each type of water based on evapotranspiration and the corresponding volumes of drainage water for each container.

The seasonal irrigation volume increased when the LR was doubled from 10% to 20% of the watering volume while it decreased as the salinity of the irrigation water increased. This is due to the fact that salts induced less crop growth and reduced evapotranspiration.

The soil applied solutes increased proportionately to the applied water

volume and its salinity. The drainage water volumes differed in relation to the applied leaching requirements. In the first year, because of the soil pore-size reduction, due to soil compaction, and water salinity, drainage water volumes were low, when low and medium salinity waters were used, while they were higher when higher salinity water was used. In the following years, when the salt concentrations of low and medium salinity waters were higher than those of the first year, the drainage water volumes were higher as compared to the applied leaching requirement. The electrical conductivity of drainage water varied with the salt concentration of irrigation water during the four years (Table 4). The amounts of leached solutes varied with the amount and salt concentration of drainage water. However, with the same amounts of leaching requirements, the leached solute percentage, as compared to those supplied with irrigation water, decreased considerably as the irrigation water salinity increased, with a subsequent reduction in the leaching efficiency of applied water. Therefore, the amounts of solute accumulated in the soil increased as the salt concentration of irrigation water increased

Table 2. Salt concentration, sodium adsorption ratio and electrical conductivity of the irrigation water.

Water types	Salt concentration $(M L^{-1})$	Bean SAR	ECe $(dS m^{-1})$	Salt concentration $(M L^{-1})$	Capsicum, sunflower, wheat SAR	ECe $(dS m^{-1})$
1	0.001	5	0.13	0.01	5	1.47
2	0.001	15	0.12	0.01	15	1.24
3	0.001	45	0.12	0.01	45	1.19
4	0.01	5	1.47	0.032	5	4.65
5	0.01	15	1.24	0.032	15	3.86
6	0.01	45	1.19	0.032	45	3.59
7	0.1	5	13.55	0.064	5	11.55
8	0.1	15	11.18	0.064	15	11.18
9	0.1	45	10.2	0.064	45	10.2

SAR, sodium adsorption ratio; ECe, electrical conductivity.

Table 3. Seasonal irrigation volumes and drainage water volumes for each container during the growing season of the 4 crops in succession irrigated with 9 types of water and subjected to 2 leaching fractions (LR=10% and 20% of the watering volume).

Water types	LR	Bean Vi $(L pot^{-1})$	Vd	Capsicum Vi $(L pot^{-1})$	Vd	Sunflower Vi $(L pot^{-1})$	Vd	Wheat Vi $(L pot^{-1})$	Vd
1		34.8	2.7	67.3	6.8	83.1	8.8	52.2	4.7
2		32.2	2.6	67.1	6.7	81.0	8.6	52.7	4.6
3		31.8	2.5	67.3	6.7	81.5	7.4	52.7	4.4
4		31.0	2.6	67.1	6.6	79.9	8.8	49.5	4.8
5	LR=10%	28.6	2.4	65.9	6.6	81.4	8.7	50.7	4.7
6		26.6	2.2	66.3	6.5	75.7	8.1	50.7	4.4
7		15.8	2.2	55.2	6.2	50.9	4.9	26.2	2.5
8		14.6	2.1	55.7	6.1	51.4	4.6	27.8	2.4
9		13.1	1.9	59.8	6.1	51.7	4.4	27.5	2.1
1		40.0	6.2	75.0	14.5	93.7	16.8	58.1	10.6
2		37.1	6.1	75.8	14.4	93.4	16.4	57.8	10.4
3		34.3	5.2	75.4	14.4	91.8	15.6	58.5	10.2
4		33.9	5.1	73.5	14.3	91.7	16.5	54.9	10.1
5	LR=20%	32.6	5.1	74.8	14.2	93.5	16.4	56.5	9.8
6		31.9	4.9	71.2	14.0	91.7	16.1	56.3	9.5
7		17.6	3.3	54.2	11.3	56.6	9.7	28.5	5.3
8		16.4	3.1	63.9	12.8	57.5	9.2	29.7	5.1
9		15.8	3.0	67.4	11.4	56.7	9.1	33.3	4.8

LR, leaching fractions; Vi, seasonal irrigation volumes; Vd, drainage water volumes.

while there was a slight variation with the higher leaching requirement and between the 2 compared soils.

Therefore, shifting from the lowest to the highest salt concentration of water, the total salt build-up in the soil in the 4-year period changed on average from 314 to 2840 mg 100 g^{-1} of dry mass (d.m.) and from 351 to 2914 mg 100 g^{-1} of d.m., applying leaching fractions of 10% and 20% of the watering volume, respectively, without significant variations with the change in the leaching fraction (Figure 1).

As a result of the salt build-up in the 4-year trial period, the saturation extract electrical conductivity (ECe) increased on average from 0.65 and 0.68 dS m^{-1} prior to salinisation, to 11.24 and 13.61 dS m^{-1} after salinisation (Figure 2), respectively, for the Bologna (T$_1$) and Locorotondo (T$_2$) soils. Along the soil profile the ECe decreased progressively from the top to the deep layer, with values of 13.84-10.94 and 8.97 dS m^{-1} for soil T$_1$ and 19.39-11.79 and 9.67 dS m^{-1} for soil T$_2$, respectively, for the layers 0-0.20, 0.20-0.40 and 0.40-0.60 m (Figure 2).

In a study conducted by Lavini (2000) to test the effects of irrigation

with water of different salt concentrations on silty-clay soils in the Volturno plain, Italy, after four years of irrigation with saline water, he found that the salt build-up during the irrigation season was more pronounced in the top layer (0-0.37 m) in relation to the amounts of salt applied by irrigation and independently of the applied irrigation technique. Moreover, he observed that winter rainfall leached only a part of the salts accumulated in the topsoil layer during the irrigation season displacing them towards the deeper layers, thus causing a progressive increase in salinity in the top layer, especially when using more saline water. This may be attributed to a higher sodicity of top layers compared to deep layers and to a greater dispersion of clay with the subsequent reduction of hydraulic conductivity (Frenkel *et al.,* 1978; Postiglione *et al.,* 1994).

In contrast, Hamdy (2004) reported that in the semi-arid Mediterranean areas, supplied with a good drainage system, winter precipitation provides effective leaching of the root zone salinity resulting from past irrigation practices.

Table 4. Variation of the mean electrical conductivity of the water drained from each container during the growing season of the 4 crops in succession irrigated with 9 types of water and subjected to 2 leaching fractions (LR=10% and 20% of the watering volume).

Water types	LR	Bean	Capsicum	Sunflower	Wheat
			EC (dS m^{-1})		
1		2.40	5.33	5.40	5.72
2		2.40	5.12	5.19	5.04
3		2.00	4.88	4.95	4.59
4		15.10	12.23	12.41	16.22
5	LR=10%	10.00	10.39	10.54	13.12
6		5.50	8.35	8.47	11.43
7		28.70	20.90	21.21	21.09
8		24.90	19.69	19.57	20.91
9		22.10	19.30	19.99	20.11
1		2.10	5.13	5.20	5.91
2		1.80	4.44	4.51	4.82
3		1.70	4.12	4.17	4.76
4		10.40	12.82	13.01	15.15
5	LR=20%	9.70	11.38	11.55	11.60
6		7.00	9.14	9.27	11.68
7		32.00	22.01	22.32	21.87
8		28.60	20.88	21.18	19.91
9		25.10	21.00	21.02	19.77

LR, leaching fractions; EC, electrical conductivity.
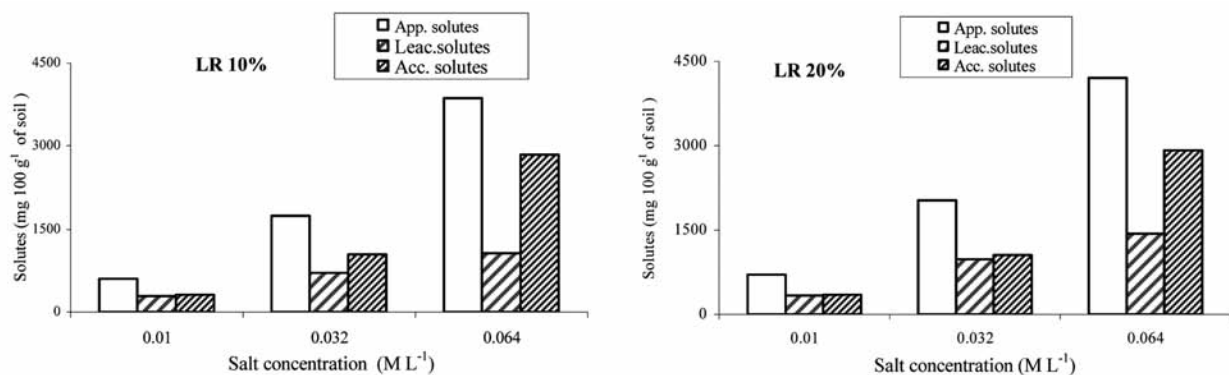
Figure 1. Applied (App.), leached (Leac.) and accumulated (Acc.) salts in the soil irrigated with water of different salt concentrations and subjected to 2 leaching fractions (LR) in the 4-year period.

Moreover, the ECe was closely correlated to the salt concentration of the applied irrigation water, increasing, on average, from 5.46 to 10.04 and 18.23 dS m^{-1} for soil T_1 and from 6.22 to 12.32 and 22.30 dS m^{-1} for soil T_2, respectively, when irrigated with water of salt concentration levels of 0.01, 0.032 and 0.064 M (Figure 2). Obviously, using irrigation water with SAR values of 5, 15 and 45, the ECe decreased on average from 13.01 to 10.94 and 9.78 dSm^{-1} for soil T_1 and from 15.67 to 13.32 and 11.85 dS m^{-1} for soil T_2 (Figure 2), because at the same salt concentration the irrigation water electrical conductivity decreased as the SAR increased. In Turkey, Yazar *et al.* (2004) studied wheat response to irrigation with water of varying salinity levels (0.5, 3, 6, 9, 12 dS m^{-1} and 12 dS m^{-1} +10% of LR). After two water applications (at emergence and late flowering) they found a nearly linear increase in soil salinity in relation to the irrigation water salt content, and a reduction in the ECe and in the SAR with the increase in soil depth. In particular, in the plots irrigated with water characterised by higher salinity levels in the top layer 0-0.10 m, they found ECe values of 4.3 dS m^{-1} which decreased to 0.80 dS m^{-1} in the deeper layer being considered (1-1.20 m).

Irrigating with saline-sodic water, the pH of the saturation extract of both soils has slightly changed from the initial values of 7.09 and 7.18 to 7.80 and 7.78 after a 4-year irrigation period, respectively, for soils T_1 and T_2. The pH is on average significantly higher in the top rather than in the deep layer and it has changed little with the variation of irrigation water salt concentration, although for the soil T_2 lower values have been observed when using irrigation water of 0.01 M salt concentration. In both soils, on average, the highest pH values have been recorded when using water with SAR of 45 (Figure 3). The persistent use of saline-sodic irrigation water favours the increase in the pH and ESP in the top layers of the soil with subsequent dispersion of clay and clogging of soil pores, and reduction of water infiltration rate (Ayers and

Westscot, 1985; Josan *et al.* 1998). The findings of salt distribution along the soil profile in this trial are in agreement with the results achieved by Choudhary *et al.* (2004) in a research carried out in India for ten years (1989-1999) to test the long-term effect of irrigation with sodic and saline-sodic water, in the absence or presence of conditioners (manure, gypsum applied with irrigation, or both treatments) on the soil properties and on sugar cane crop. The same Authors found out that long-term irrigation with sodic and saline-sodic water influences salt distribution, the ESP and the pH through the soil profile with significant increases in the top layer explored by roots (0-0.60 m layer) due to the reduced infiltration rate of water caused by clay dispersion and the subsequent clay accumulation in soil pores.

The increase in irrigation water salt concentration resulted in both soils in a gradual increase of exchangeable sodium and a subsequent reduction of exchangeable calcium; the variations in exchangeable potassium and magnesium were not significant. In particular, the exchangeable sodium content increased from 1.09 to 2.18 and 4.09 cmol kg^{-1}, for soil T_1 and from 0.96 to 2.36 and 4.11 cmol kg^{-1}, for soil T_2; exchangeable calcium decreased, on average, from 32.37 to 31.18 and 30.14 cmol kg^{-1} for soil T_1 and from 35.78 to 34.38 and 32.58 cmol kg^{-1} for soil T_2, using water with salt concentrations of 0.01, 0.032 and 0.064 M, respectively (Figure 4). The different SAR levels of irrigation water have mostly affected the exchangeable sodium content of both soils. For the Bologna soil, the exchangeable sodium increased from 1.89 to 2.68 and 2.80 cmol kg^{-1}. For the Locorotondo soil, it rose from 1.97 to 2.44 and 3.02 cmol kg^{-1}, respectively, when irrigated with water of SAR 5, 15 and 45. The increase in exchangeable sodium occurred mostly to the detriment of calcium and, to a lesser extent, of magnesium. In this case too, exchangeable potassium has not experienced any significant difference (Figure 4).
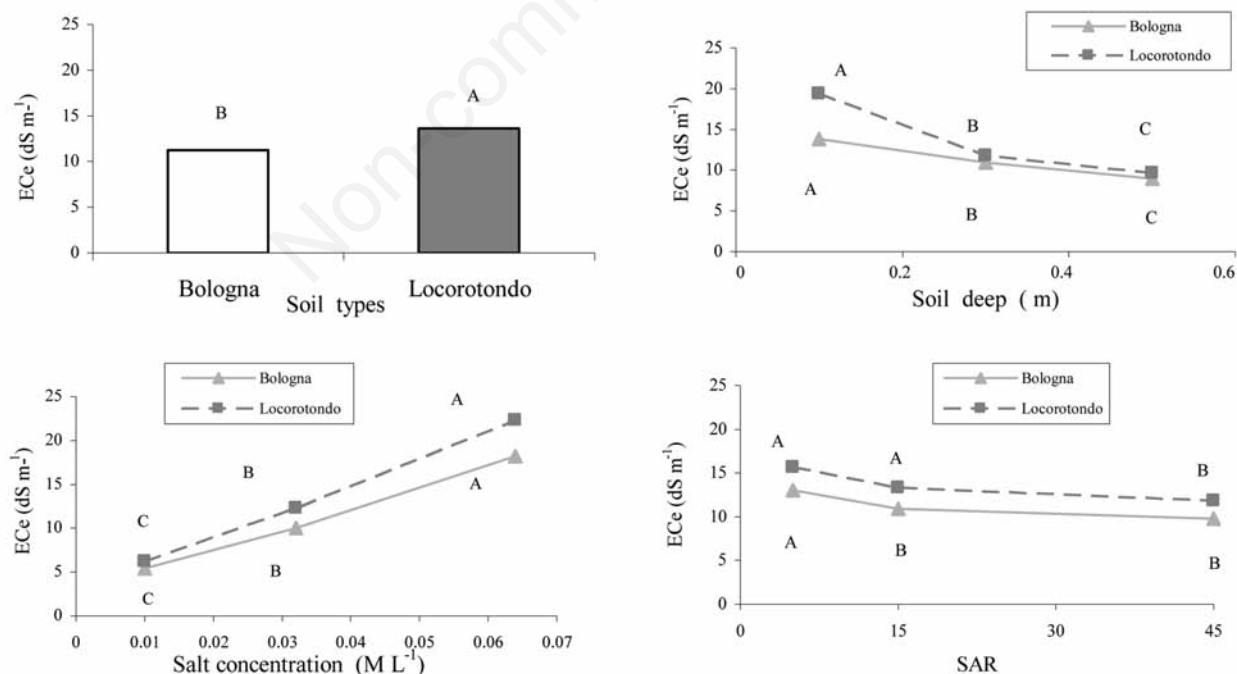

Figure 2. Electrical conductivity of the saturation extract (ECe) of the 2 soils after a 4-year irrigation period with saline-sodic water, as related to the soil type, soil profile, salt concentration and sodium adsorption ratio (SAR) of applied irrigation water. For each effect considered, the values followed by the same letter are not significantly different, according to the Student-Newman-Keuls test at P≤0.01.
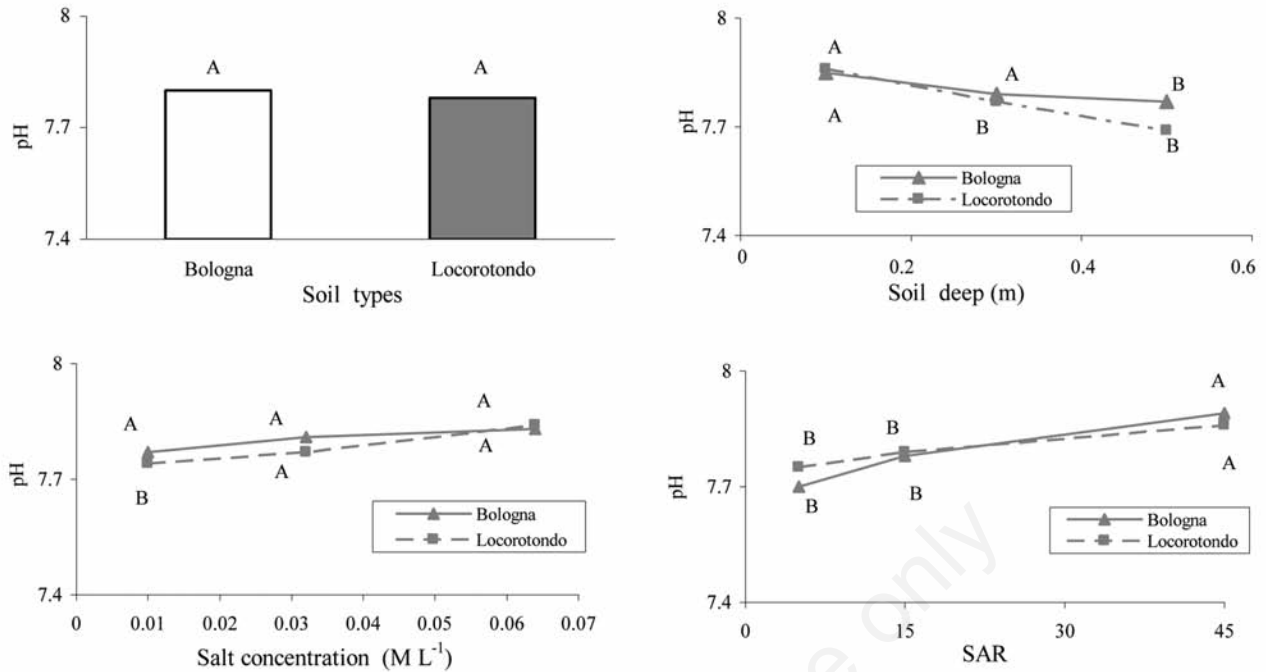
Figure 3. pH of the saturation extract of the 2 soils after a 4-year irrigation period with saline-sodic water, as related to the soil type, soil profile, salt concentration and sodium adsorption ratio (SAR) of applied irrigation water. For each effect considered, the values followed by the same letter are not significantly different, according to the Student-Newman-Keuls test at P≤0.01.
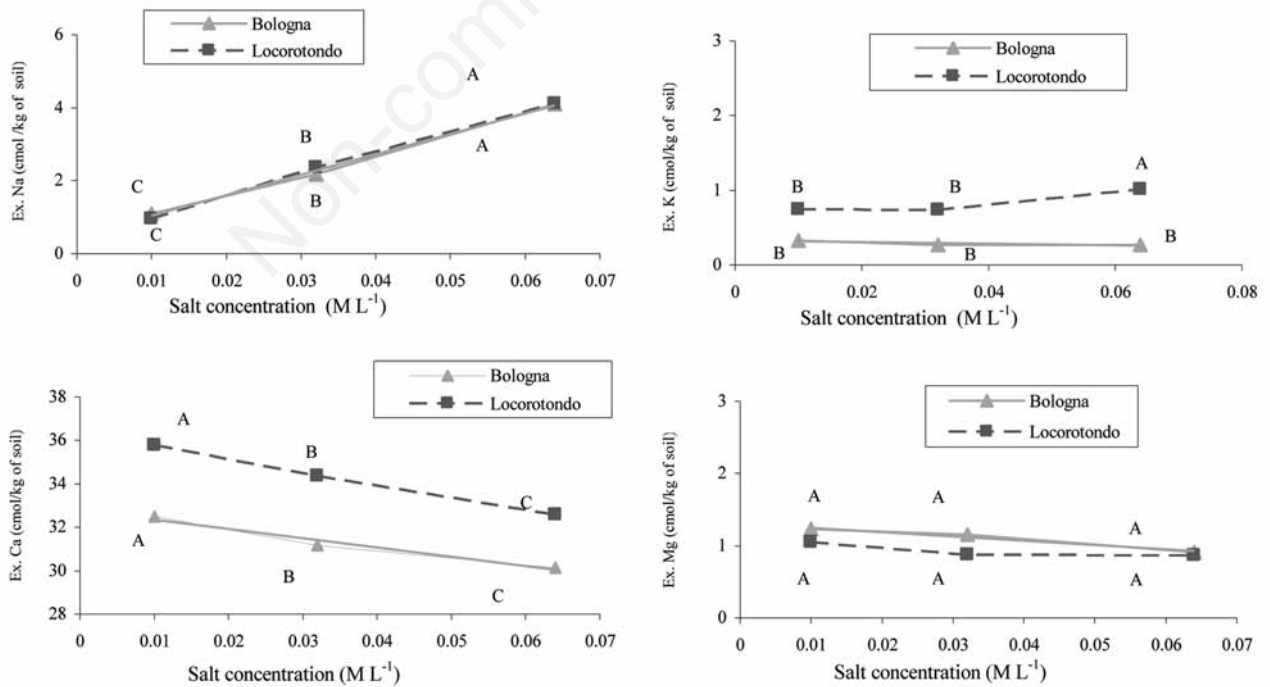

Figure 4. Exchange (Ex.) bases [sodium (Na), potassium (K), magnesium (Mg) and calcium (Ca)] of the 2 soils after a 4-year irrigation period with saline-sodic water, as related to the salt concentration of the applied irrigation water. For each effect considered, the values followed by the same letter are not significantly different, according to the Student-Newman-Keuls test at P≤0.01.

The ESP of the 2 soils, T_1 and T_2, after a 4-year irrigation with saline-sodic water has been on average 7.07% and 6.40% respectively. In particular, the ESP average of the whole soil profile increased significantly with the increase in salinity of the applied irrigation water, reaching values of 3.15%, 6.28% and 11.77% for soil T_1 and 2.50%, 6.11% and 10.61% for soil T_2, when using water with salt concentrations equal to 0.01 M, 0.032 M and 0.064 M, respectively (Figure 5). With the increase in the irrigation water sodium level, the ESP increased from 5.43% to 7.62% and 8.04%, for soil T_1 and from 5.09% to 6.32% and 7.81% for soil T_2, respectively, when using water with SAR equal to 5, 15 and 45. In all cases, the soil ESP was more affected by irrigation water salinity than by its sodium level.

Increasing values of the ESP result in a severe deterioration of the
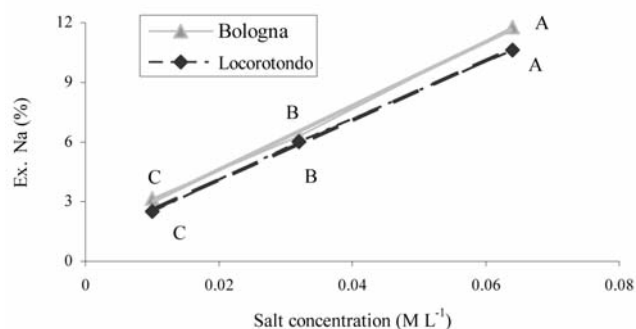

Figure 5. Exchangeable (Ex.) sodium percentage of the 2 soils after a 4-year irrigation period with saline-sodic water, as related to the salt concentration of the applied irrigation water. For each effect considered, the values followed by the same letter are not significantly different, according to the Student-Newman-Keuls test at P≤0.01.

structure. In the *terra rossa* (T_2), rich in organic matter, the structure is kept more stable (stability index=38.3%). This is not the case in the calcareous greyish soil (T_1) (stability index=29.3%) (Figure 6). Illite and kaolinite contribute to stabilise the structure, notably in the soils rich in sesquioxides (Cavazza *et al.*, 2002). In both soils, the increase in irrigation water salt concentration resulted in stability indices of structural aggregates that reflected those of the ESP.

The tests of stability of the aggregates differentiate soils according to their physical properties, but little is known about the relationship between indicators of aggregate stability and soil response to specific destabilising factors. In this context, great importance is attached to the sodium ion for its effects on soil physical properties (porosity, permeability, hydraulic conductivity), but very little is known about the time needed for the onset of soil degradation or to reclaim the degraded soils. This is due to the various factors involved, such as soil type and geomorphology, climate conditions, crop rotation (Lavini *et al.*, 2002; Tedeschi and Dell'Aquila, 2005). The stability index of structural aggregates decreased on average by over 12%, ranging from the soils previously irrigated with water of salt concentration equal to 0.01 M L^{-1} to the soils irrigated with water of 0.064 M L^{-1} (Figure 6). The low structural stability of non-pre-treated samples was always shown to increase after pre-treatment with alcohol (Figure 6). The first result represents the condition at the soil surface (pouring rain effect), whereas the other expresses the effect below the soil surface (Cavazza *et al.*, 2002).

Conclusions

The results of a research of four consecutive years on the effects of irrigation with saline-sodic water on 2 soil types, both rich in clay materials, one with vermiculite and illite and a poor content of iron and aluminium sesquioxides (Bologna soil, T_1), the other with illite and kaolinite and a high content of iron and aluminium sesquioxides (Locorotondo soil, T_2), enable to some conclusions to be drawn: i) the
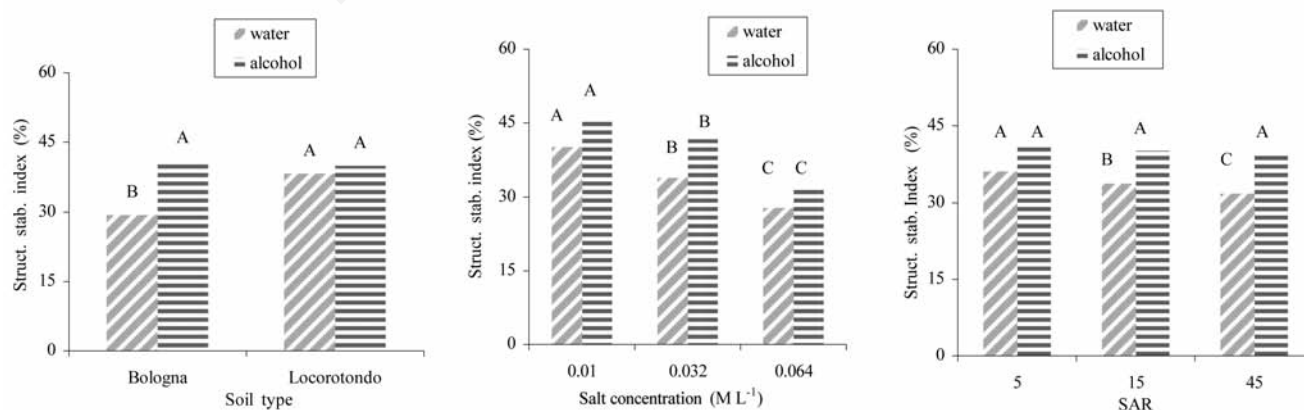

Figure 6. Variation in the stability index of structural aggregates with or without pre-treatment with alcohol as related to the soil type, salt concentration and sodium adsorption ratio (SAR) of irrigation water. For each effect considered, the values followed by the same letter are not significantly different, according to the Student-Newman-Keuls test at P≤0.01.

effects of irrigation water salinity and sodium level and of leaching fractions on the two soil types have not been different; ii) the increase in salt concentration and sodium level of irrigation water resulted in a progressive salinisation and sodification of both soils, with decreasing values from the top to the deep layer of the soil under analysis; iii) the application of leaching water has not mitigated soil salinisation and sodification that have even increased under the higher application (20% of watering volume). Therefore, the amounts of solute accumulated in the soil increased as the salt concentration of irrigation water increased; on the other hand, there was a slight variation with the higher leaching requirement and between the two compared soils. In the Mediterranean areas, where the long-term average annual rainfall is not less than 450-500 mm, winter precipitation could effectively leach the solutes applied with saline water, thus reducing the amounts of irrigation water and the solutes applied to the soil; iv) the pH has been little influenced by the use of saline or saline-sodic water: the highest values have been observed in the top layer and when using irrigation water with SAR equal to 45; v) in the two soils, the exchangeable sodium percentage has been more influenced by salinity than by the sodium level of irrigation water; it increased on average by over 10% using water with higher salt concentration; vi) the stability index of structural aggregates has progressively decreased with the increase in salinisation and sodification of the 2 soil types. In the red soil of Locorotondo, with clay minerals rich in illite and kaolinite, and rich in organic matter and iron and aluminium sesquioxides, the structural aggregates remained more stable.

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