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Full Length Research Paper

Reclamation of saline and saline-sodic soils using gypsum and leaching water

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The results of a two-year research aiming to evaluate the effects of corrective treatments on two saline-sodic soils are reported. The trial was carried out in cylindrical pots (high 0.6 m and with a diameter of 0.4 m), provided with a bottom control device to collect drainage water, and located under shed, to avoid rain leaching effect. The two clay soils: Saline and saline-sodic resulting from a four-year experiment in which different crops had been irrigated with 9 solutions obtained by dissolving in distilled water the appropriate amounts of NaCl and $CaCl_2$ by the factorial combination of three salt concentrations and three SAR levels (5, 15 and 45). During the subsequent two-year period, the soils were cropped to barley and borlotto bean and irrigated with freshwater (ECw = 0.5 dS m^{-1} and SAR = 0.45) whenever the soil contained in the pots lost by evapotranspiration 30% of the maximum available water (MAW). The corrective treatments were carried out by applying $CaSO_4$ to the soils with ESP>6% and leaching fractions equal to 20% of the watering volume to the most saline soils and proportionally lower fractions to the less saline soils, in order to reach, in the drainage water, electrical conductivity (EC) and sodium absorption ratio (SAR) values of 3 dS m^{-1} and 9, respectively. The reclamation treatments reduced significantly soil salinity and sodicity: Electrical conductivity of the saturation extract (ECe) decreased on average from 12.34 to 3.66 dS m^{-1}; the exchangeable sodium percentage (ESP) dropped by 50.93 and 41.41% respectively for Bologna and Locorotondo soils.

Key words: Soil reclamation, gypsum requirement, saline soils, saline-sodic soils.

INTRODUCTION

Salinity-induced land degradation is one of the major obstacles to sustainable agricultural production in many arid and semi-arid regions of the world (Bossio et al., 2007). Based on Szabolcs' estimates (1989) of salt-affected areas all over the world (including rainfed- areas) 340 million ha (23%) of cultivated lands are saline and 560 million ha (37%) are sodic.

As known, high salt concentration favours the flocculation of colloids, while a high percentage of exchangeable sodium causes colloids' dispersion (Hanson et al., 1999; Bauder, 2001; Bauder and Brock, 2001). Another process, somehow reversible, associated with the high percentage of exchangeable sodium is the high expansion of soils (Saskatchewan, 1987; Hanson et., 1999). Moreover, the soil type (mineralogical composition of clay), the irrigation techniques and the rain may influence the flocculation and dispersion of colloids (Shainberg and Letey, 1984; Saskatchewan, 1987; Levy et al., 1999; Bauder, 2001; Bauder and Brock, 2001). The most evident physical effect of the increasing level of sodium in the soils is its reduced permeability that is more severe in soils containing montmorillonitic clays than in the soils with illite-vermiculitic clays and kaolinitic-sesquioxides (Saskatchewan, 1987).

Saline soils are usually formed in hot-arid climate areas, in coastal regions involved by sea-water intrusion and irrigation with brackish water. The reclamation of

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these soils necessitates the removal of excess soluble salts from the plant root-zone. The methods reported in literature include the mechanical removal of the salts accumulated in the topsoil; the washing out of salt build-up by horizontal flux of water; leaching by irrigation in the presence of natural or artificial active drainage system (Bastiaansen et al., 2007; Corwin et al., 2007). In the latter case, a water depth unit is reported to leach almost 80% of salts from a soil depth unit (Abrol et al., 1988).

The leaching efficiency of applied water increases under unsaturated flow conditions (Oster et al., 1972). The reclamation of saline-alkaline soils, instead, involves the removal of excess salts and sodium by an efficient drainage system and the application of calcium sulphate or chloride, sulphuric acid or acid-forming amendments, in the presence of carbonates in the soil. Gypsum is the most largely used amendment, as it is cheaper and readily available (Ardakani and Zahirnia, 2006). Bio-reclamation is another possible means to reclaim saline-sodic and sodic soils (Qadir et al., 2001).

Overstreet et al. (1980) compared gypsum, sulphur and sulphuric acid for the reclamation of sodic soils of the Fresno series in California, USA. For two consecutive years, the best production response of irrigated pasture was observed in the soils corrected with sulphuric acid rather than in those corrected with sulphur and gypsum.

Verma and Arbol (1980) compared the corrective effect of chemically equivalent quantities of five levels of gypsum (85% purity) and pyrite (31% purity) on soil proprieties and on rice and wheat yield in a highly sodic soil. Results have indicated a pyrite efficacy of 25% compared to gypsum. The amount of amendment needed to reclaim a sodic soil depends on the total amount of sodium to be replaced as well as the soil depth to be reclaimed that is related to the crop type (Abrol et al., 1988).

Qadir et al. (2003) observed that the release of H^+ by nitrogen-fixing crops might increase the NA removal from sodic calcareous soils. To gain further insight on this topic, the Agricultural Faculty of the University of Bari (Italy), started up a research aimed to assess the effects of gypsum and leaching water application for the reclamation of saline and saline-sodic soils.

MATERIALS AND METHODS

The research was conducted for two years at the Campus of Bari University on two types of saline and saline-sodic soils, contained in cylindrical pots (0.4 m in size and 0.6 m high) supplied with a bottom valve for the discharge of drainage water, located under shed to avoid the rain leaching effect.

The two soils were saline and saline-sodic because they had been cropped for four consecutive years with different species in succession (borlotto bean, capsicum, sunflower and wheat), irrigated with 9 types of brackish water obtained dissolving in deionised water appropriate amounts of NaCl and $CaCl_2$, combining factorially three salt concentrations (0.001, 0.01 and 0.1 M for bean irrigation in the first year and 0.01, 0.032 and 0.064 M for capsicum, sunflower and wheat irrigation in subsequent years) with three sodium levels (SAR=5, 15 and 45) and subject to two different leaching fractions (10 and 20% of the watering volume). In the text, graphs and tables, is found the salt concentrations (0.01, 0.032 and 0.0064 M) of the irrigation water applied in the three-year period. The research has been conducted on 72 pots following a split-plot experimental design with two replicates, with the soil types in large plots (18 containers), the leaching levels in sub-large plots (9 containers) and the types of water in plots (single containers).

The 2 soil types, both rich in clay, were characterized as follows (Cavazza et al., 2002; Patruno et al., 2002): (1) Bologna soil (T_1) with clay mineral, rich in vermiculite and illite, poor in iron and aluminium sesquioxides, resulting from an AP horizon of a *Udertic Ustochept* (fine, mixed, mesic) soil, Montefalcone series, of the soil map of *Emilia Romagna* region; (2) Locorotondo soil (T_2) with clay mineral rich in illite and kaolinite, rich in iron and aluminium sesquioxides, resulting from horizon AP *Pachic Hapoxeroll* (fine, mixed, thermic), Cutino series, of the Apulia soil map; this soil type is common in the area south-east of Bari.

The research involved the following steps:

1. Characterization of the soils to be reclaimed (b.r.), using the official methodologies (Violante, 2000).
2. Correction of saline and saline-alkaline soils.
3. Soil cropping during reclamation with a barley (*Hordeum Vulgare* L.) followed by borlotto bean (*Phaseolus vulgaris* L.).
4. Characterization of the soils after reclamation (a.r.).

For soil correction calcium sulphate was applied. The gypsum requirement was determined for each soil type on a mean sample of the whole 0.60 m soil profile, considering the ESP, CEC and the quantity of sodium to be exchanged with calcium (cmol of Na kg^{-1} of dry soil) so as to obtain an exchangeable sodium percentage equal to 6. The gypsum requirement was calculated using the methodology indicated by Nyle et al. (1996), the estimated quantities are reported in Table 2.The applied calcium sulphate had 98% purity and was incorporated in the top 0.2 m soil layer. The amount of the corrective was split so that the quantity at each application foreseen could not exceed 2.0 Mg ha^{-1} equivalent. In all cases, the corrective was applied prior to the seeding of the two crops (barley and borlotto bean).The leaching of the salts already built-up in the soils and of the salts (sodium sulphate) formed after the application of the corrective has been favored increasing by 20% the watering volume applied to barley and bean crops, as leaching fraction for the soils with an EC (electrical conductivity) above 18 dS m^{-1}, and by a lower percentage for the soils with an EC below 18 dS m^{-1}.During the irrigation season, the leaching fractions were reduced proportionally to the reduction of the drainage water EC, until the EC and the SAR were respectively 3 dS m^{-1} and 9. During the growing season both crops were irrigated with tap water (EC 0.5 dS.m^{-1} and SAR 0.79) whenever 30% of the maximum available water was lost by evapotraspiration from each pot (80%), applying the volume of water needed to bring to field capacity (evaluated directly in the containers) the full mass of soil contained in each pot plus the leaching fraction calculated every time.During the growing season of the two crops, each container was tested for the following parameters: water requirement, volume of drainage water, EC and pH of drainage water. At the end of the second crop (borlotto bean) along the 0.6 m soil profile, soil samples were taken, by 0.2 m increments, for the following determinations: saturation extract; electrical conductivity and pH of the soil saturation extract, soluble bases (Na, K, Mg, Ca) exchange bases (Na, K, Mg, Ca), cation exchange capacity (CEC), exchangeable sodium percentage (ESP); mineralogical and chemical characteristics of two soils, calculated by X-ray fluorescence.

All detected and calculated parameters were submitted to the variance analysis using the SAS (S.A.S. INSTITUTE INC.-USA) software, and the differences between the means were evaluated

Table 1. Electrical conductivity and pH of the saturation extract and ESP as related to soil depth, salt concentration and SAR of irrigation water.

Parameter	ECe (dS m^{-1})		pH		ESP (%)	
	T_1	T_2	T_1	T_2	T_1	T_2
Soil depth (m)						
0.0 - 0.2	13.84	19.39	7.85	7.86	-	-
0.2 - 0.4	10.94	11.79	7.79	7.77	-	-
0.4 - 0.6	8.97	9.67	7.77	7.69	-	-
average	11.25	13. 61	7.80	7.77	7.07	6.40
Quality of irrigation water used in the preceding four years (M)						
0.01	5.47	6.22	7.77	7.86	3.15	2.50
0.032	10.04	12.32	7.81	7.77	6.28	6.10
0.064	18.23	22.30	7.83	7.69	11.77	10.61
Average	11.25	13.61	7.80	7.77	7.07	6.40
SAR						
5	13.02	15.67	7.73	7.72	5.45	5.09
15	10.94	13.32	7.78	7.73	7.72	6.32
45	9.78	11.85	7.89	7.86	8.04	7.80
Average	11.25	13.61	7.80	7.77	7.07	6.40

Table 2. Gypsum requirement of the two soils.

Treatments		Soil of Bologna (T_1)	Soil of Locorondo (T_2)
Salt concentration (M)	SAR	Required $CaSO_4$ Mg ha^{-1}	Required $CaSO_4$ Mg ha^{-1}
	5	-	-
0.01	15	-	-
	45	-	-
	5	-	-
0.032	15	1.55	-
	45	1.71	2.18
	5	1.97	1.93
0.064	15	5.00	4.39
	45	5.75	4.86

by Student-Newman- Keuls' test.

RESULTS AND DISCUSSION

The characteristics of the reclaimed soils are reported in Table 1. The average values for the soils of Bologna (T_1) and Locorotondo (T_2) concerning the ECe (electrical conductivity of the saturation extract), pH and ESP were respectively 12.25 and 13.61 dS m^{-1}, 7.80 and 7.07 and 6.40% with decreasing values, shifting from the top to the deeper layers, and increasing values with higher salt concentration and SAR of the irrigation water applied in the four previous years.

The ECe, however, decreased as the SAR of irrigation water decreased (Table 1). The gypsum requirement increased, as the salt concentration and the SAR of the irrigation water applied in the four previous years increased (Table 2). When applying the leaching water and the corrective ($CaSO_4$ - $2H_2O$) the salinity and the ESP decreased significantly in both soils. In particular, the amounts of salts in the two soils decreased from 18.72 to 28.66 and 36.1 to 7.78 to 9.07 and 13.76 cmol kg^{-1} for the soil T_1 and from 18.89 to 25.95 and 30.34 to 8.06 7.53 and 13.02 cmol kg^{-1} for the soil T_2 (Figure 1). The time required for the reclamation of salt-damaged soils depends on many factors related to the soil type, such as the geomorphology, climate conditions, crop rotation etc.. The fine-textured soils with high clay contents and elevated salinity and sodium levels are difficult to reclaim due to the problems associated with water flow along the soil profile (Qadir et al., 2008). The correction of these soils gets even more complicated if the clay mineral fraction is mostly constituted by swelling-

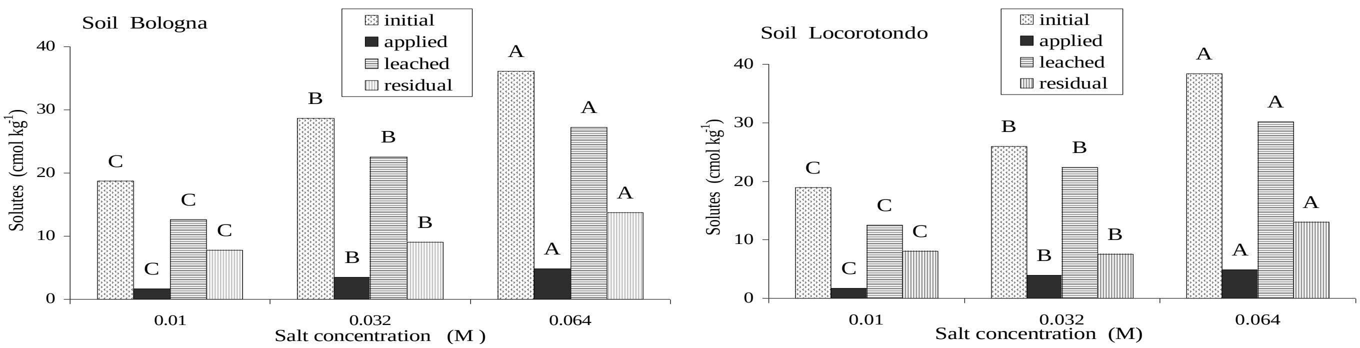

Figure 1. Initial salts in the two soils, salts applied during reclamation, leached and residual salts vs. the salt concentration of the irrigation water applied in the four-year period before reclamation. For each effect considered, the values followed by the same letter are not significantly different, according to the SNK test at P≤ 0.01.

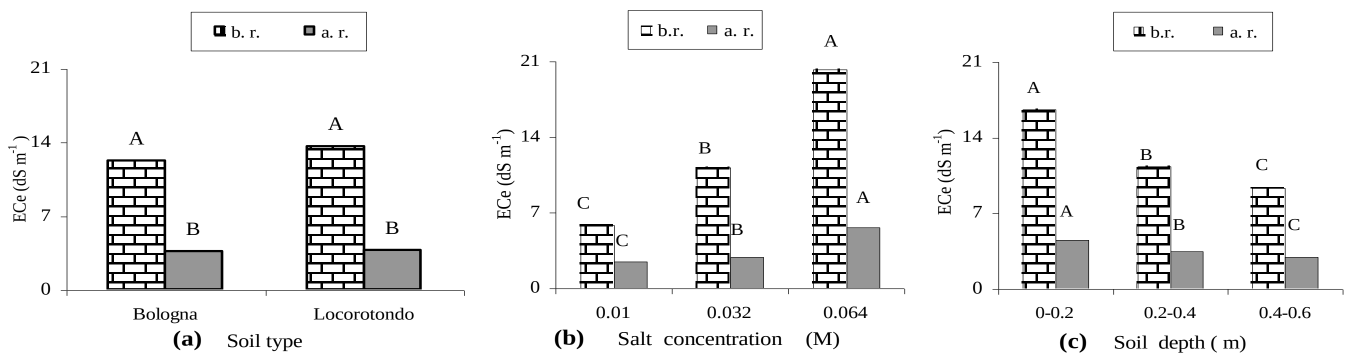

Figure 2. Electrical conductivity of the saturation extract for the soils irrigated with saline-sodic water in the four-year period before reclamation (b.r.) and after reclamation (a.r.), as related to: (a) soil type; (b) salt concentration of the irrigation water applied before reclamation; (c) soil depth (0-0.60 m). For each effect considered, the values followed by the same letter are not significantly different, according to the SNK test at P≤ 0.01.

type montmorillonite. As a result of leaching application, the clay mineral swells quickly, the hydraulic conductivity drops and the macropores that constitute the main drainage path are destroyed. Gypsum application contributes to increase calcium concentration in leaching water thus reducing swelling, dispersion and clay migration, and favouring the reclamation of saline-sodic soils in few years' time (Bahçeci, 2009). Therefore for both soils that showed the lowest ECe values (6 dS m^{-1} on average) at the end of barley cycle, after a drainage of 5 liters per container, the EC of the latter decreased from 8 to 3 dS m^{-1} (pre-established level), while for the soils with intermediate ECe values (around 11 dS m^{-1}) the pre-established value of the EC of leached water (3 dS m^{-1}) was achieved at the end of the bean cropping cycle, after a drainage of 10 liters per container. Finally, for the soils with higher salinity (ECe around 20 dS m^{-1}) at the end of the two-year reclamation, after a drainage of about 13.6 liters per container, the EC of the leached water decreased from the initial values around 24 to 25 dS m^{-1} to values around 6 dS m^{-1}, without reaching the pre-established limit.

After the leaching treatment of the soil, the average ECe decreased from the initial value of 12.34 to 3.66 dS m^{-1} (Figure 2). As expected, the trend of the final ECe values reflected the initial values, and the average of the two soils decreased from 5.84 to 11.19 and 20.27 to 2.49 to 2.88 and 5.63 dS m^{-1} respectively for the soils irrigated before with water with a salt concentration equal to 0.01, 0.032 and 0.064 M (Figure 2).

Along the profile the ECe values for the two soil types decreased on average from 16.61 to 4.55 dS m^{-1} in the top layer, from 11.37 to 3.47 dS m^{-1} in the intermediate layer and from 9.62 to 2.97 dS m^{-1} in the deepest layer (Figure 2), with reductions of 72.6, 69.5 and 68.1%, respectively. Shifting from the top to the deepest layer, the decreasing percentage of leached salts is to be associated with the salt concentration along the profile and with the amounts of water that have flown across different layers: higher on the surface and lower in the deeper layer.

The pH of the soils has changed slightly, presumably due to the high buffer power of the soil; after two-year reclamation it decreased from 7.82 to 7.69. Leaching and

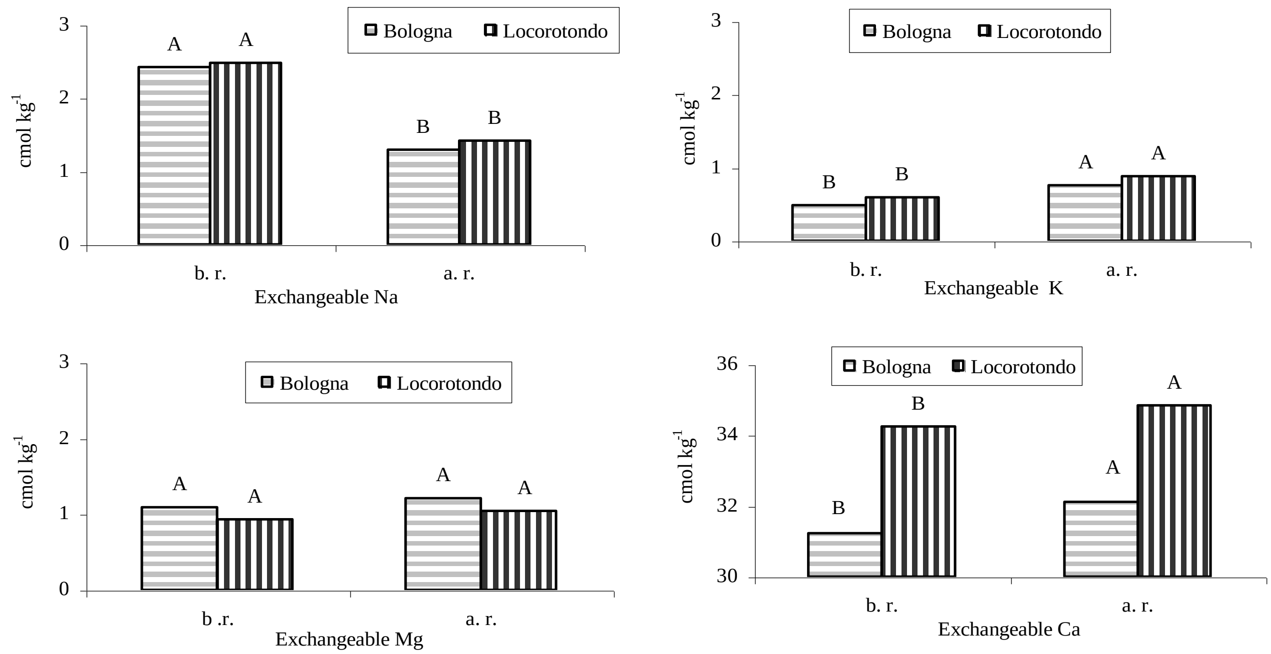

Figure 3. Cation exchange bases (Na, K, Mg and Ca) in the two soils irrigated with saline-sodic water in the four-year period before reclamation (b.r.) and after reclamation (a.r.). For each effect considered, the values followed by the same letter are not significantly different, according to the SNK test at P≤ 0.01.

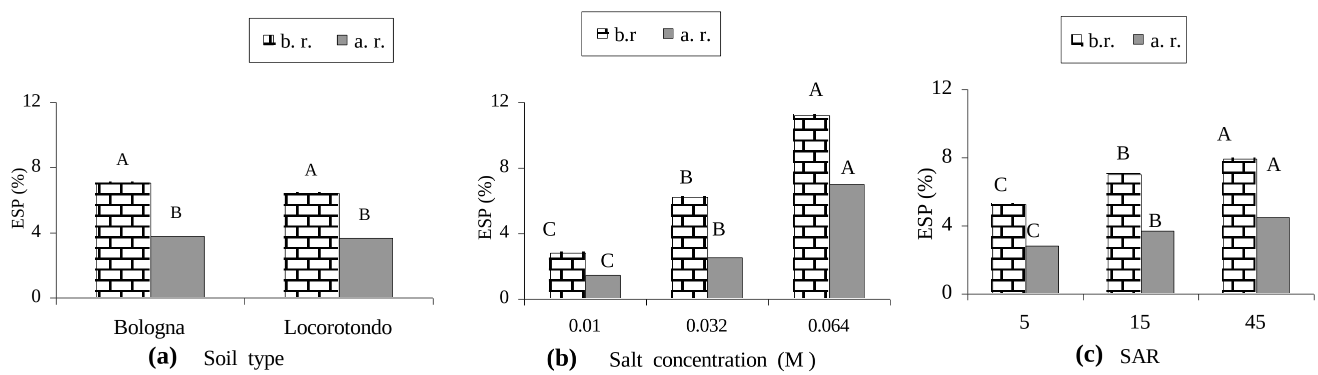

Figure 4. ESP of the two soils irrigated with saline-sodic water in the four-year period before reclamation (b.r.) and after reclamation (a.r.), as related to: (a) soil type; (b) salt concentration and (c) SAR of the irrigation water applied before reclamation. For each effect considered, the values followed by the same letter are not significantly different, according to the SNK test at P≤ 0.01.

correction actions caused significant variations of exchangeable bases; in particular, for the two soils, the exchangeable sodium decreased by 55%, shifting from 2.47 to 1.35 cmol kg^{-1}; the exchangeable calcium increased by 2.2%, shifting from 32.74 to 33.48 cmol kg^{-1}, while the exchangeable potassium increased by 0.20 cmol kg^{-1} and the exchangeable magnesium experienced non-significant variations (Figure 3).

As a consequence, the exchangeable sodium percentage in both soils decreased significantly, shifting, on average, from the initial value of 6.74 to 3.67% after reclamation (Figure 4). Since the ESP in the soil, during the four-year irrigation with saline-sodic water, increased proportionately to the salt concentration and to the SAR of irrigation water, after two years of reclamation, the ESP of the soil irrigated with the water of higher salinity (0.064 M) still had a value around 7.01 %.

To reach the desired ESP level (<6%) and EC of leached water (<3 dS m^{-1}) further reclamation actions are needed in those soils. The studies conducted to compare the effects of chemical treatments and bio-reclamation on the reduction of soil sodicity has pointed out a higher efficacy of gypsum application (Qadir and Oster, 2004). Within bio-reclamation the species with a higher biomass

Table 3. Mineralogical and chemical properties of the 2 soils after reclamation.

Soil types	Salt conc. (M)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO (mg kg^{-1})	MgO	CaO	Na_2O	K_2O	P_2O_5	L.O.I.*
	0.01	59.10	0.89	15.83	6.37	0.08	1.56	4.70	0.77	1.75	0.21	8.78
Bologna	0.032	58.85	0.90	16.37	6.37	0.07	1.58	4.39	0.91	1.81	0.21	8.54
	0.064	58.33	0.89	16.10	6.22	0.07	1.57	4.99	0.98	1.81	0.22	8.85
	0.01	49.50	1.06	22.46	8.31	0.21	1.21	2.04	0.48	2.48	0.27	12.00
Locorotondo	0.032	49.77	1.06	22.54	8.32	0.21	1.21	1.83	0.54	2.51	0.24	11.77
	0.064	48.42	1.03	22.15	7.99	0.20	1.21	2.17	0.77	2.41	0.24	13.44

* Limiting Oxygen Index

yield and a higher tolerance to soil salinity and sodicity and to warterlogging are more effective in soil reclamation (Qadir et al., 2002; Kaur et al., 2002).

The chemical analyses by X-ray fluorescence showed in both soils, after reclamation, very low variations of sodium content, shifting from the soil irrigated with water of lower concentration to the soil of higher salt concentration (Table 3).

The series of Bologna's samples resulted more reactive than the samples of Locorotondo, due to the presence, in the former, of higher swelling clay concentrations (smectite and/or vermiculite) (Table 3). Many research works have documented the following positive effects of calcium sulfate applications on the physico-chemical properties of saline-sodic soils: increasing permeability and leaching (Baumhardt et al., 1992; Ilyas et al., 1997); increasing flocculation and soil macroporosity (Chartres et al., 1985; Greene et al., 1988) and reduction of surface crusting.

Conclusion

The results of two years of research on the reclamation by gypsum and leaching water of the two types of saline and saline-sodic soils, cropped with barley and borlotto beans, respectively, enable formulating some final considerations.

The two-year application of calcium sulfate to alkaline soils, of leaching water to both soils, equal to 20% of the full watering volume for more saline soils and to lower fractions for less saline soils until the electrical conductivity and the SAR of drainage water were respectively 3 dS m^{-1} and 9, caused a sharp reduction of salinity and alkalinity of both tested soils, in particular:

1. The salt content decreased by over 63 % in Bologna soil and by 65.6% in Locorotondo soil.
2. The electrical conductivity of the saturation extract of the two soils decreased, on average, by 70.5% with a 72.6% reduction in the top layer (0.20 to 0.40 m), 60.5% in the intermediate layer and 68.1% in the deeper layer.
3. The pH of the saturation extract of both soils decreased by 1.7%.
4. The soil exchangeable sodium, decreased, on average, by 55%.
5. The ESP decreased on average by 50.9% for Bologna soil and by 41.4% for the soil of Locorotondo.
6. The soil of Bologna resulted to be more reactive than that of Locorotondo, due to the presence of a higher concentration of swelling clay minerals (smectite and/or vermiculite).

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