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GROWTH RESPONSE OF RICE AND WHEAT CROPS DURING RECLAMATION OF SALINE-SODIC SOILS

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Abstract

Productivity and internal drainage of saline-sodic soils can be restored by better management practices like combination of physical and chemical treatments. A field experiment was carried out for 3 years at two saline-sodic sites, in Punjab-Pakistan to improve soil physical/chemical properties and increase wheat and rice yields. The site 1 was highly deteriorated (bulk density 1.77-1.86 Mg m^{-3}) followed by site 2 (bulk density 1.6-1.7 Mg m^{-3}). Due to a very low infiltration rate at both sites, vertical drainage through auger holes that extend down to a permeable soil layer was suggested to flush down excess saline water thus minimizing temporary waterlogging and associated hypoxia. Gypsum as a source of calcium was applied @ 3.8-7.2 t ha^{-1} at site 1 and 3.6-11.4 t ha^{-1} at site 2, to all vertical drainage treatments to replace excess sodium on soil exchanger and decrease dispersion. Saline-sodic tube well water, used to irrigate rice and wheat crops, also helped attain a significant decrease in soil salinity and sodicity within a reasonable time period. After harvesting the final wheat crop (6th in sequence), non-significant differences were observed between the vertical drainage/gypsum treatments and the control treatments regarding the final electrical conductivity, sodium adsorption ratio, and yields of crops. Detailed economic analysis indicated that at site 1, combination of gypsum and vertical drainage technique was the best, with benefit cost ratio of 8.0 while at site 2, the vertical drainage + gypsum treatments did not work. As the study was carried out with farmers' participation approach, there seems a need to educate and train the farmers, as well as supply them with quality inputs, in time and space, to maximize the benefits from the projects dealing with the management of saline-sodic groundwater resources and saline-sodic soils.

Introduction

Irrigated agriculture is contributing a major share to provide food, fiber and shelter. With the pressing and increased non-agricultural demands, the supplies of good-quality water are falling short to fulfill the demands of increasing cropping intensities; demanding even more water. To overcome this shortage, tube wells are being installed, which pump groundwater of marginal quality with elevated levels of salinity (excess of soluble salts) and sodicity (excess of sodium ions). This phenomenon is expected to continue and to intensify in less developed, arid regions/countries that already have high population growth rates and suffer from serious environmental problems (Qadir & Oster, 2004). Therefore, the use of saline-sodic waters for irrigation necessitates site-specific management.

The global extent of salt-affected area is about 955×10^6 ha (Szabolcs, 1994). The salt-affected area is mostly characterized by water scarcity and is often underlain by aquifers having elevated levels of salinity and sodicity. In the absence, or limited availability, of good-quality water resources, some area under salt-affected soils has been brought under cultivation by using saline and/or sodic waters as irrigation source (Qadir & Oster, 2004). The inappropriate use of saline-sodic waters and salt-affected soils has complicated the situation by increasing the problems of salinity and sodicity. Recent research has demonstrated that such soils and waters can be used to improve crop productivity without deteriorating the ambient environment (Saifullah *et al.,* 2002; *Murtaza, et al.,* 2002; Ghafoor *et al*., 1997; Qadir *et al*., 2001). The use of high electrolyte waters with low Na^+ concentrations often prove useful during the initial phase of soil amelioration (Muhammed *et al.,* 1969), owing to its favourable effect on infiltration rate, bulk density and soil structure (Oster & Schroer, 1979).

High salt-water dilution method for reclaiming sodic soils is based upon valence-dilution effect. Along with advantages of improvement of soil physical properties of sodic soils by successive dilutions of high-salt water, there are limitations like, the water must have a high ratio of Ca + Mg to total cation concentration (*R*-Value), to decrease the duration of reclamation, and large quantities of water are needed (Reeve & Bower, 1960; Reeve & Doering, 1966; Mohite & Shingte, 1979). The ratio of divalent to total cations in the applied water should be at least 0.3 (Reeve & Doering, 1966). However, the required increase in *R*-Value can be achieved by addition of a small quantity of Ca^{2+} in every step of a successive dilution–leaching series (Muhammed *et al.,* 1969; Misopolinos, 1985).

In Pakistan, salt-affected soils cover an area of about 11.5 million ha (Anon., 2005), of which about 60 % is saline-sodic. Such soils cannot be reclaimed economically by leaching without the application of a Ca^{2+}-source (Ghafoor *et al.,* 1997). Most of the saline-sodic and sodic soils have poor internal drainage which otherwise is a pre-requisite for their reclamation. To facilitate adsorbed sodium replacement with calcium, a good drainage is a pre-requisite because plough pan (dense soil layer) generally exists in saline-sodic heavy textured soils (Hussain *et al.,* 2000). Reclamation of saline-sodic soils involves not only the leaching of soluble salts, but also improvement of the soil physical conditions to enhance the rate of passage of applied water through soils, following soil-application of gypsum. Use of water having high electrical conductivity (EC) and sodium adsorption ratio (SAR) for initial reclamation of saline-sodic/sodic soils has been advocated by researchers due to an improvement in physical properties of soils (Aggasi *et al.,* 1981). Gypsum can maintain electrolyte concentration at levels suitable for better physical and chemical properties of soils over longer periods (Shainberg & Letey, 1984)

Accumulation of exchangeable sodium in saline-sodic/sodic soils often leads to deterioration of soil structure. This results in a low infiltration rate. Under these conditions, irrigation water mostly evaporates at the soil surface, leaving behind its residue of salts. The use of deep ploughing and subsoiling techniques along with the use of gypsum, for the amelioration of saline-sodic/sodic soils have received considerable attention in several parts of the world (Rasmussen *et al.,* 1972; Qadir *et al.,* 2001), but deep ploughing/subsoiling cost, however, makes the practice unacceptable to farmers under ambient farm financial conditions (Grevers & De Jong, 1993).

Keeping in view the above facts and economic aspects, drainage holes were made with the help of an auger, to accelerate vertical drainage of surface water. The idea was that, such a vertical drainage will not only flush down excess saline water within a reasonable time, but will also help to avoid hypoxia/anoxia to wheat crop(s) during early phases of reclamation. If the strategy is successful, then such a practice could be adopted at nominal cost by resource poor farmers, majority of whom possess very limited land holding. The concept of vertical drainage through the drilling of auger holes has been suggested and was proven to be feasible for the removal of soluble salts from a saline-alkali soil (Chahal, 1962); and for the elimination of mosquito population on standing water in low water permeability pastures (Mulligan *et al.*, 1979). Keeping all the above facts in view, a three-year study was designed at two locations with the objectives: (1) To evaluate the potential of saline-sodic groundwater for growing rice-wheat crops on saline-sodic soils, (2) To test more economical methodology for the reclamation of saline-sodic soils, (3) To evaluate the applied treatments in terms of their economic viability

Materials and Methods

Experimental site: This field experiment was conducted at two different locations with a permanent layout in the Fourth Drainage Project Area (FDPA), Faisalabad, Pakistan during June 2001 to May, 2004. The site 1 was situated at Chak 140/R.B., Muthianwala while site 2 at Chak 147/R.B., Chauri, Faisalabad. The FDPA is located in South Western Part of the Rachna Doab including some parts of Faisalabad, Jaranwala and Sumandri Tehsils of the Faisalabad District. For developing water resources in the FDPA, a three pronged strategy i.e., protection, improvement and extension of irrigation and drainage system was proposed in the Revised Action Program for irrigated agriculture. Under this program, an area of about 0.14 mha around Faisalabad was recognized to have severe waterlogging and salinity/sodicity problems. To reclaim this area, a tile drainage project was completed a decade before, designated as the Fourth Drainage Project Area (FDPA).

The FDPA covers a total area of 30364 ha, of which an extensive area of about 40 % is affected by high water table and salinity/sodicity. In the FDPA, a total of 79 sumps have been constructed. The discharged water from these sumps is of hazardous quality, particularly with respect to sodium adsorption ratio (SAR) and residual sodium carbonate (RSC), and is disposed off into surface drains. In the FDPA, 40% area is salt-affected, where this type of water could be used for reclamation with some management practices (Ghafoor *et al.*, 1997). So it is the dire need of the time to develop a technology to use this water for sustainable crop production and reclamation of salt-affected soils. In this regard, farmers' participation approach might serve the purpose better as ultimately they will be the end users of any emerging technology for the reclamation of saline-sodic soils.

Experimental design: Both the experiments were permanently laid out on an area of 0.40 ha following randomized complete block design (RCBD) with 3 replications. This gave a total of 12 individual plots of 13.7 m x 29.2 m. The treatments were; control (no gypsum / auger hole treatment of soil to facilitate vertical drainage of surface water in order to avoid hypoxia/anoxia); G_{50}+AH-S:R (1 auger hole per 50 m^2, of 7.5 cm diameter, up to 1200 mm depth, refilled with a mixture of excavated soil and rice husk in 1:1 ratio, once at the start of experiment, and soil application of gypsum @ 50% soil gypsum requirement (SGR); G_{50}+AH-S:G (1 auger hole per 50 m^2, of 7.5 cm diameter, up to 1200 mm depth, refilled with a mixture of excavated soil and gypsum in 1:1 ratio, once at the start of experiment, and soil application of gypsum @ 50% SGR); G_{50}+AH-S:R:G (1 auger hole per 50 m^2, of 7.5 cm diameter, up to 1200 mm depth, refilled with a mixture of excavated soil, rice husk and gypsum in 1:1:1 ratio, once at the start of experiment, and soil application of gypsum @ 50% SGR). Thus, for each auger hole treatment plot, 8 auger holes were made. Rice and wheat were grown during this study. At both the sites, locally available drainage water from tube wells (EC = 4.5 dS/m, SAR = 28.8, RSC =

14.9 $mmol_c/L$ at site1; EC = 4.1 dS/m, SAR = 20.1, RSC = 8.9 $mmol_c/L$ at site2) was used to irrigate the crops. However, under some unavoidable circumstances (load shedding, mechanical faults in tube well operating systems etc.), few irrigations of canal water (EC = 0.26 dS/m) were given to save the crops. Details of irrigation water applied from various sources for rice and wheat crops are given in Table 2. According to the climatic data obtained from the nearest weather station, this area received a total of about 1083 mm rainfall during 3-year study with a mean annual temperature of 24.6 °C, with an average annual minimum of 18.6 °C and maximum of 30.7 °C.

At both the sites, 3-4 seedlings per hill having age of 45 days, of rice cv. *Super Basmati* were transplanted during the third week of July each year. To achieve a good leaching of salts and avoid any further deterioration of the soil structure, puddling of soil for rice crop(s) was not practiced. Wheat cv. *Wattan* was planted during the last week of November each year after the harvest of rice following the designs of experiments, using seed @ 100 kg/ha. Each, rice and wheat crop was fertilized with urea and diammonium phosphate fertilizer @ 99 and 67 kg/ha. Potassium fertilization (as muriate of potash) was made only, to each rice crop @ 25 kg/ha. All the phosphatic and potassic fertilizer (for rice only) along with half dose of urea were applied at sowing. The remaining urea dose was applied at the 1^{st} or 2^{nd} irrigation in case of wheat while for rice it was applied in two equal splits, i.e. 25 and 40 days after transplanting. Each crop was harvested at maturity to record economic yield.

Measurements: Soil chemical properties were examined to determine the treatment effect on the soil. Composite soil samples were taken from 0-150 and 150-300 mm depth of all the treatment plots. Five soil samples were taken and bulked from each plot for the 0-150 and 150-300 mm depths. The samples were air-dried and sieved to <2 mm. These samples were then used for laboratory determinations of pH of saturated paste (pH_s), electrical conductivity of saturated extract (EC_e), and soluble cations. Samples were taken at the start of studies (2001) and after the harvest of each crop. The summary of the characteristics of original soil at both the sites is given in Table 1.

Chemical analysis of soil: Soluble cations were determined following the methods described by the USSL Staff (Anon., 1954). Clear extracts of the saturated soil pastes were obtained and analysed for soluble cations Ca^{2+} + Mg^{2+}, Na^+, and K^+; and soluble anions CO_3^{2-}, and HCO_3^-. The sodium adsorption ratio (SAR) of the soil was calculated as follows:

$$SAR = \frac{Na^+}{[(Ca^{2+} + Mg^{2+})/2]^{1/2}}$$

where, concentration of all the cations is in $mmol_c\,L^{-1}$

pH and electrical conductivity: Soil pH and electrical conductivity was determined by preparing saturated soil paste. The pH of the saturated paste (pH_s) was recorded on TOA bench-top pH meter. The electrical conductivity (EC_e) measurements of the saturated extracts were made on TOA conductivity meter.

Table 1. Characteristics of original soils at the start of the study.

Characteristics	pH_s	EC_e ($dS\ m^{-1}$)	SAR	SGR ($t\ ha^{-1}$)	CEC ($cmol_c\ kg^{-1}$)	$CaCO_3$ (%)
	0-150 mm depth					
Site 1	8.4-8.7	15.1-17.9	98.6-123	7.7-14.3	6.95-7.81	2.74-3.19
Site 2	8.3-8.4	6.6-10.3	38.9-55.1	7.1-22.7	13.97-15.62	2.85-4.99
	150-300 mm depth					
Site 1	8.5-8.6	15.3-19.1	61.8-84.9		5.22-6.95	1.17-1.65
Site 2	8.2-8.4	9.0-10.0	43.6-55.4		12.20	1.16-1.50

Table 2. Details of irrigation water input from various sources (mm).

Site	crop	tube well	canal	Rainfall	total
Site1	Rice 2001	700	200	326	1226
	Wheat 2001-02	400	100	19	519
Site2	Rice 2001	700	150	326	1176
	Wheat 2001-02	400	100	19	519
Site1	Rice 2002	600	300	250	1150
	Wheat 2002-03	400	100	127	627
Site2	Rice 2002	300	100	250	650
	Wheat 2002-03	400	100	127	627
Site1	Rice 2003	600	400	306	1306
	Wheat 2003-04	200	-	55	255
Site2	Rice 2003	700	300	306	1306
	Wheat 2003-04	200	-	55	255

The weather station was about 30 km away from the study area. As both the sites were only about 5 km away from each other so it was supposed that same amount of rainfall occurred at each site.

Soil gypsum requirement (SGR): Soil was shaken mechanically with saturated gypsum solution (Ca^{2+} concentration > 28 $mmol_c\ L^{-1}$). The suspension was filtered and the filtrate was analysed for $Ca^{2+} + Mg^{2+}$ by titrating against 0.01N EDTA solution to a blue end point. Gypsum requirement was calculated from the difference of $Ca^{2+} + Mg^{2+}$ concentration of gypsum saturated solution and filtrate as follows:

$$\text{SGR (cmol}_c\text{/kg)} = \frac{[\text{Ca}^{2+} + \text{Mg}^{2+} \text{ in gyp.soln.}] - [\text{Ca}^{2+} + \text{Mg}^{2+} \text{ in filtrate}]}{1000} \times \frac{100}{\text{wt. of soil (g)}} \times 100$$

Irrigation water analysis: Samples of irrigation water were collected in plastic bottles at their source. Four drops of 0.1 % $(NaPO_3)_6$ per 100 mL sample were added in each bottle to check the precipitation of salts (like carbonate) during storage. The analytical methods described by USSL Staff (1954) were used. The RSC of the water samples was calculated as follows:

$$RSC = (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+})$$

where, concentration of all the cations and anions is in $mmol_c\ L^{-1}$

Bulk density: Bulk density measurements were undertaken with the help of a core, inserted to a depth of 50 mm. The bulk density was measured on the soil immediately below the apedal surface layer (i.e. ~50-100 mm). The soil extending beyond each end of the core was trimmed with a sharp spatula. The soil sample volume was thus established to be the same as the inner volume of the core. The oven-dried weight of all the samples was measured to calculate bulk density (Blake & Hartge, 1986).

Economic analysis: The methodology proposed by Chaudhry *et al*., (1995) was followed for analyzing adjusted yield, dominance analysis and marginal rate of return (MRR) analysis. For the determination of benefit cost ratio (BCR), net present worth (NPW) and internal rate of returns (IRR), the methods described by Muniraj (1987) were followed, to select the best alternative treatment under different conditions of farms and experiments. Following is some detail of the terms used for economic analysis:

Adjusted yield: The adjusted yield may be defined as the average yield adjusted downward by a certain percentage to reflect the difference between the yield realized on the experimental farm and the yield obtained on the farmers' field while using the same treatment. The concept of adjusted yield stems from the recognition that farmers often cannot realize the same yield as researchers do, even when they apply the same procedures. In the present studies, the average yields were adjusted downward by 10 %.

Dominance analysis: This analysis was carried out by listing the treatments in order of increasing variable costs. Any treatment having net benefits that are less than or equal to those of a treatment with lower costs was considered as dominant.

Marginal rate of return (MRR): Marginal rate of return is an expression in percentage terms of relationship between the marginal net benefit (i.e. the change in net benefit) and the marginal cost (i.e. the change in variable cost). Thus, marginal net benefit divided by marginal cost and expressed as a percentage would give marginal rate of return of moving from one alternative treatment to another in an experiment.

$$\text{MRR} = \frac{\text{(Net benefits of treatment X) - (net benefits of treatment Y)}}{\text{(Costs that vary of treatment X) - (costs that vary of treatment Y)}} \text{ x } 100$$

Benefit cost ratio (BCR): It is widely used as a measure of benefit. It is the ratio between the present worth of benefits and present worth of costs.

$$\text{BCR} = \frac{\text{Present worth of benefits}}{\text{Present worth of costs}}$$

Net present worth (NPW): The net present worth of the project is obtained by deducing costs from the benefits and the resulting net benefits are discounted at the opportunity cost of capital for each year. The sum of the net benefits of the entire life period of the project gives the net present worth.

$$\text{NPW} = \sum_{t=1}^{t=n} \frac{Bt - Ct}{(1+i)^t} = 0$$

where, Bt is benefit in each year; Ct is cost in each year; t is No. of years; and i is interest (discount) rate.

Internal rate of return (IRR): It is that rate of interest, which makes the net present worth of an investment equal to zero. It is a measure of the earning capacity of a project or an investment. Interpolation method was used to estimate the IRR (Ahmad & Ali, 1997).

$$\text{IRR} = \text{Difference between LDR \& HDR} \left[\frac{\text{NPW of cash flow at LDR}}{\text{Absolute diff. b/w NPW of cash flow at LDR \& HDR}} \right]$$

where, LDR is lower discount rate at which NPW is positive; HDR is higher discount rate at which NPW is negative.

Statistical analysis: The data gathered from both the studies were analysed statistically following appropriate methods. The Analysis of Variance technique (ANOVA), and Duncan Multiple Range (DMR) test, was applied to differentiate the treatment effects using MSTAT package (Steel & Torrie, 1980). The graphs were plotted in EXCEL package.

Results and Discussion

Electrical Conductivity: The electrical conductivity of the saturated extract (EC_e) is a measure of soluble salts present in soil-water system. The initial EC_e values were very high and it ranged from 15.1 to 19.1 dS m^{-1} at site 1 while the corresponding range was 6.6-10.3 dS m^{-1} at site 2. Analyses of soil three years after treatment application indicated a consistent and gradual decrease (52.4-74.7%) in EC_e at site 1 while this decrease ranged from 21.9-63.2% at site 2 (Fig. 1). There were non-significant differences among treatments at both sites and both soil depths. After 6 crops, maximum decrease in EC_e was recorded with G_{50}+AH-S:R (74.7%) followed by control, G_{50}+AH-S:R:G and G_{50}+AH-S:G (52.4%) at 0-150 mm soil depth, and G_{50}+AH-S:R:G (65.5%) followed by G_{50}+AH-S:R, G_{50}+AH-S:G, and control (55.6%) at 150-300 mm soil depth at site 1. Treatment effectiveness at site 2 was in decreasing order of G_{50}+AH-S:G (49.9%) > control > G_{50}+AH-S:R > G_{50}+AH-S:R:G (21.9%) at 0-150 mm soil depth, and G_{50}+AH-S:R:G (63.2%) > G_{50}+AH-S:G ≈ G_{50}+AH-S:R > control (51.7%) at 150-300 mm depth. The results are in line with those of Ghafoor (1984), who reported non-significant differences between gypsum and control treatment (only leaching with low quality water) for soil EC_e, after harvest of three rice and three wheat crops during reclamation of saline-sodic soils of Gandhra and Khurrianwala soil series.

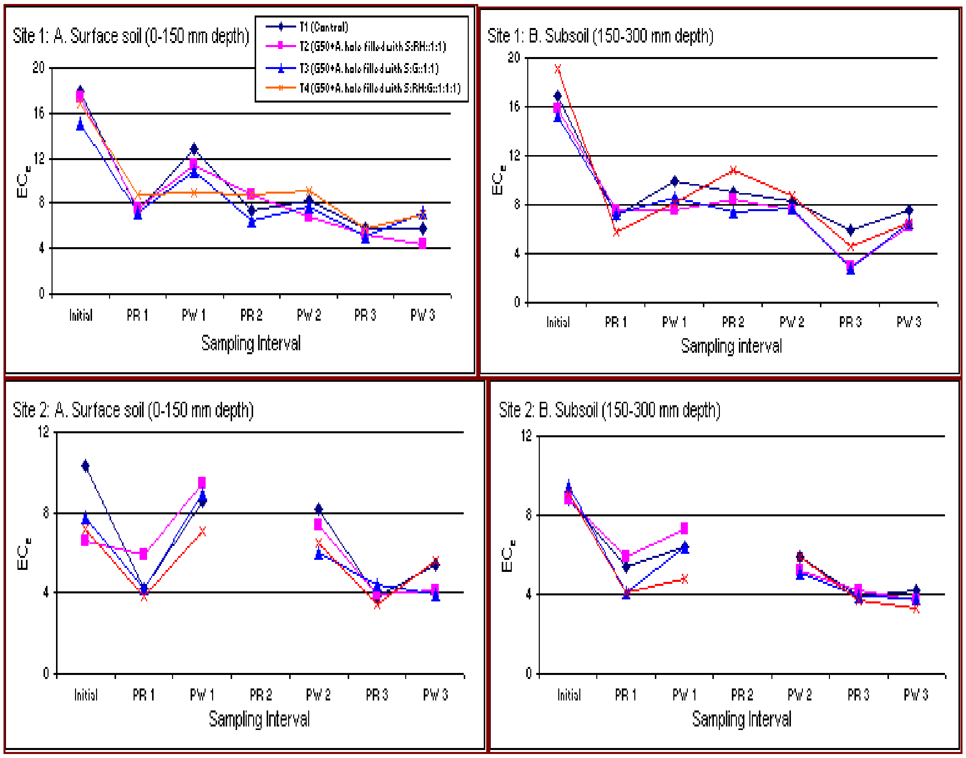

Fig. 1. Effect of treatments on EC_e of a saline-sodic soil after the harvest of each crop; PR1=Post rice 2001, PR2=Post rice 2002, PR3=Post rice 2003 PW1=Post wheat 2001-02, PW2=Post wheat 2002-02, PW3=Post wheat 2003-04; At site 2, rice (2002) could not grow, so the soil was not analyzed.

After the harvest of rice 2001 (1st crop in sequence), soil EC_e decreased sharply up to a range of 6-8 dS m^{-1}. The decrease in EC_e was 48-69% at site 1, and 11-59% at site 2, over the initial values at both the soil depths. Actually, high leaching fraction during rice growth, contributed to sharp decline in soluble salts at both the sites. This sharp declining trend in soil EC_e clearly advocates that rice crop should be preferred as the first crop during reclamation program of saline-sodic soils. After the harvest of wheat 2003-04 (6th crop in sequence), all the treatments decreased EC_e up to 75%, and 63%, at site 1, and 2, respectively, at both the soil depths. Relatively less decrease in EC_e after wheat than that after rice crops appears mainly because of the time laps between the last irrigation and the time of soil sample collection during the hot months of April and May each year during which high evaporation caused concentration of soil solution (Tyagi, 2003). However, the treatment differences leveled off after three-year study period. Ghafoor (1984) also reported similar trend, i.e. slight increase in EC_e after 2nd and 3rd wheat crops during reclamation of saline-sodic soils under farmer field conditions.

Initially the higher EC_e levels probably helped the leaching process during the 1st rice crop of 2001 under submerged conditions, but the decrease in SAR lagged behind. Leaching of salts was more during rice compared with that during wheat, because rice provided more drainable surplus. Rice is grown under flooded conditions, while wheat grows under unflooded conditions. For decrease in EC_e, some contribution of applied irrigation water having high RSC can not be over-looked for decreasing the soluble salts during reclamation of saline-sodic soils at both the sites. According to Muhammed & Rauf (1983) waters containing residual sodium carbonate (RSC) caused less salts built up in the soil at a given EC, SAR and leaching fraction perhaps through promoting precipitation of $CaCO_3$, $CaSO_4$ or $MgSiO_3$. Overall, the leaching of soluble salts from root zone to lower soil depths with irrigation and/or rain water, in excess of the moisture deficit of the root zone, remained the main cause for decreasing EC_e in soil.

Relatively less decrease in EC_e at site 2 compared to that at site 1 might be due to the reason that rice 2002 could not grow at site 2, and no nursery was available at the time for 2nd time transplantation. Thus, relatively less leaching of soluble salts took place since rice was to be grown under submerged conditions and ultimately high leaching fraction could be achieved, which is very beneficial for decreasing EC_e. At site 1, G_{50}+AH-S:R and, at site 2, G_{50}+AH-S:G performed relatively better, and the decrease in EC_e was faster compared to rest of the treatments. The observed values of EC_e, especially at site 2 at both the depths, decreased near to the critical level of 4 dS m^{-1} with all the treatments under study. It appears that relatively less decrease in soil EC_e with gypsum especially at site 2 could be through its slow dissolution, which is otherwise helpful for better soil infiltration and ultimately for soil amelioration. In addition, initially low EC_e at site 2 also allowed slow decrease in EC_e. Upon addition of gypsum, a slight increase in soil EC_e has also been reported by Hussain *et al.,* (1981) under field conditions.

It appears that soil at site 2 responded better to all the treatments compared to that at site 1, which might be due to its relatively low initial EC_e. To sustain soil health at last stage of reclamation, good quality water irrigation is pre-requisite, especially for fine textured soils as in the present study. At termination of the study, there were non-significant differences among the treatments, which showed that vertical drainage strategy through augur holes, for saline-sodic soils, might be of little use, regarding significant decrease in soluble salts level from the surface soil. Several factors might be responsible for this, like number of holes per unit area and illuviation of clay particles, which plugged the soil pores etc. Our results are in contradiction with those of Chahal (1962), who in a lysimeter study noted that leaching of soluble salts was accelerated from a saline-alkali soil after filling the auger holes with porous material like sand.

Sodium adsorption ratio: It is a measure of sodicity of soils and waters, and indirectly indicates gypsum requirement of soils and waters as well as deterioration in the physical properties of soil. Soils under study at both the sites had SAR much higher than 13, a limit for sodic soils prescribed by the United States Salinity Laboratory Staff (Anon., 1954). Since the soils under study had been lying barren for the last many decades during which salinization was followed by sodication (Muhammed, 1983) due to the formation of $CaCO_3$, leading to the dominance of sodium ions in soil solution and consequently on soil exchange sites.

At site 1, a maximum decrease in SAR was noted with G_{50}+AH-S:R (82.6%) followed by G_{50}+AH-S:R:G, control, and G_{50}+AH-S:G (65.1%) for 0-150 mm depth; and G_{50}+AH-S:G (62.3%) followed by G_{50}+AH-S:R:G, G_{50}+AH-S:R, and control (47.7%) for 150-300 mm depth. Treatment effectiveness at site 2 was in the decreasing order of G_{50}+AH-S:G (56.5 %) followed by control > G_{50}+AH-S:R:G > G_{50}+AH-S:R (34.7%) at 0-150 mm depth; and G_{50}+AH-S:R:G (67.9%) followed by G_{50}+AH-S:R > G_{50}+AH-S:G > control (64.6%) at 150-300 mm depth at site 2. The soil surface had almost double SAR than that of lower depth (150-300 mm) at site 1 while at site 2, both the depths had SAR around 50 (Fig. 2). After harvest of rice 2001 (1st crop in sequence), the SAR decreased by about 50% in surface soil at site 1, i.e. higher the initial SAR, greater and faster was the decrease in SAR due to statistical probability of Na-Ca exchange (Bresler *et al.,* 1982; Ghafoor, 1999).

After the harvest of wheat 2003-04 (6th crop in sequence), a decrease in SAR at both the sites was natural since a decrease in exchangeable sodium needs external supply of calcium, which was made available through gypsum in treatments G_{50}+AH-S:R, G_{50}+AH-S:G, and G_{50}+AH-S:R:G. A decrease in SAR with simple leaching, especially in control plots was likely due to *in-situ* mineral weathering (Oster & Shainberg, 1979), naturally present Ca^{2+} + Mg^{2+} in irrigation water, valence dilution (Eaton & Sokoloff, 1935), and partially due to dissolution of native lime from soil under the influence of CO_2 released by roots (Qadir & Oster, 2002, 2004). Ghafoor (1984) also reported similar results during reclamation of saline-sodic soils, i.e. 56% and 42% decrease in SAR by simple leaching in Khurrianwala and Gandhra soil series, respectively. In the same field study, a decrease in SAR with gypsum addition @ 100 SGR was 64% in Khurrianwala soil series. However, reclamation was accomplished faster in all the treatments except control at both the sites. This clearly favors well-established efficiency of gypsum to sustain soil health within a reasonable time. Soil improvement with respect to SAR was more at site 1 than that at site 2, which could have been due to the reason that initial SAR was higher at site 1 (61.8-123.3) than that at site 2. For further decrease in SAR, at both the sites, there was only a need of irrigation with good quality water. The irrigation with good quality water would also enhance the lasting effect of reclamation treatments (Ghafoor *et al.,* 1997).

The rate of decrease in SAR was higher during the initial phases of reclamation at both sites. The removal of soluble salts as well as replaced cations from the root zone to deeper soil layers acts as a sink, resulting in promotion of Na^+-Ca^{2+} exchange reaction. The occupation of exchange sites by Ca^{2+} also acts as a sink to increase the dissolution of applied gypsum and native soil lime. At lower SAR, the efficiency of Na^+-Ca^{2+} exchange decreased due to a decrease in the statistical probability of exchange between adsorbed Na^+ and soluble Ca^{2+} (Anon., 1954; Shainberg *et al.,* 1980). The integrated effect of these factors resulted in a rapid reduction in SAR, initially at both sites. The rate of decrease in SAR was also greater for the upper soil layer than for the lower one, with all the treatments at both sites. This might have been due to the decreasing ratio of soluble Ca^{2+} to Na^+ in the water as it moved downward. Since the Na^+ replaced from the surface soil would move downward, thereby increasing the SAR of downward moving water, this should result in less replacement of adsorbed sodium. Greater decrease in SAR occurred during the cultivation of rice crops than that of wheat. The anaerobic conditions during rice growth also provide higher CO_2, which could increase the amount of soluble Ca^{2+} for soil reclamation (Ponnamperuma, 1972). A slight increase in SAR was also observed during the growth of wheat 2003-04 (6th crop in sequence) over that after the former rice crop at both the sites. This slight increase have been due to less leaching fraction during this wheat crop as well as time lapse in sampling after wheat harvest during hot summer as was earlier observed by (Armstrong *et al.,* 1996).

Final EC_e and SAR values indicated that reclamation of saline-sodic soils starts as soon as agricultural operations are initiated (Ghafoor *et al.,* 1997), but to expedite the Na^+-Ca^{2+} exchange, external source of calcium like gypsum is useful. It could be concluded that application of gypsum @ 50% SGR could affect soil reclamation even using highly saline-sodic water within a reasonable time. Ghafoor (1984) concluded that saline-sodic soils of Khurrianwala series became productive after simple leaching with marginal quality water, after three years of rice-wheat cropping with moderate management of soil, water and crops.

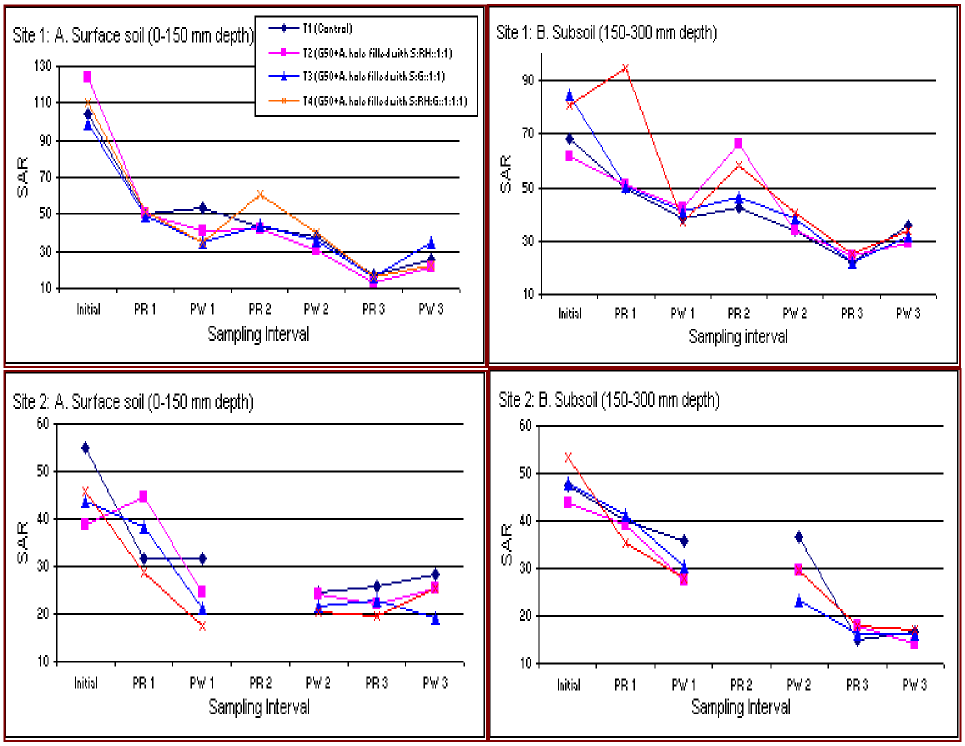

Fig. 2. Effect of treatments on SAR of a saline-sodic soil after harvest of each crop; PR1=Post rice 2001, PR2=Post rice 2002, PR3=Post rice 2003 PW1=Post wheat 2001-02, PW2=Post wheat 2002-03, PW3=Post wheat 2003-04; At site 2, rice (2002) could not grow so the soil was not analyzed.

Crop yields: The data regarding economic crop yields is presented in Table 3. At site 1, on the basis of three wheat crops, the treatments ranked as G_{50}+AH-S:R > G_{50}+AH-S:G > G_{50}+AH-S:R:G > control, while for the three rice crops, the treatment sequence was G_{50}+AH-S:R > G_{50}+AH-S:R:G > G_{50}+AH-S:G > control. At site 2, on the basis of three wheat crops, the treatments ranked as G_{50}+AH-S:G > G_{50}+AH-S:R:G > control > G_{50}+AH-S:R, while for the two rice crops, the treatment sequence was control > G_{50}+AH-S:R:G > G_{50}+AH-S:G > G_{50}+AH-S:R. Regarding the yields of grain crops, the auger hole treatments did not differ significantly from control treatment, since the leaching of soluble salts and final SAR values of the soils has non-significant differences for all the treatments including control (Figs. 1 and 2). Rice proved a better crop for soil reclamation but wheat produced better grain yields. This could be attributed to differential genetic make up of these crops, as well as differences in moisture condition prevailing in the crop plots.

There are reports that 50% reduction in yield of rice paddy occurs at soil SAR of 60 (Gupta & Abrol, 1990) or soil EC_e of 6-7 dS m^{-1} (Maas & Grattan, 1999). The EC and SAR of soils were much higher than these limits and impaired grain filling of rice. Similarly, wheat grain yield is reduced by 50% at soil SAR of 30 (Gupta & Abrol, 1990) or EC_e of 13 dS m^{-1} (Ayers & Westcot, 1985; Maas & Grattan, 1999). The EC_e and SAR of soils under study (Table 1) were much higher than their respective threshold limits, at the start of the experiment. Thus high SAR caused low yields of wheat during first year and high EC that of rice throughout the study period. Especially the yields of first three crops were not satisfactory at site 1 which was highly deteriorated with respect to its physical and chemical characteristics as compared to site 2. The economic yields of the following wheat and rice crops at site 1 improved gradually owing to the advancement in soil reclamation. In the past similar findings had been reported by Ghafoor *et al*., (1997), Niazi *et al*., (2000), and Mahmood *et al*., (2001). Moreover, very little rainfall (722 mm only at each site) was received during the growth period of the first four crops, which, otherwise, could have helped salt dilution in soils, to favor crop performance along with soil reclamation.

Table 3. Economic yields of rice and wheat (kg ha-1) during the study.

Site/Treatment	rice 2001 Paddy	wheat 2001-02 grain	rice 2002 paddy	wheat 2002-03 Grain	Rice 2003 paddy	Wheat 2003-04 Grain
				Site1		
Control	0	645	124	1915	944	1732
G_{50}+AH-S:R	0	1193	109	2511	2263	2861
G_{50}+AH-S:G	0	1119	482	2377	1762	2891
G_{50}+AH-S:R:G	0	1075	514	2399	1814	2471
l.s.d. (P = 0.05)		n.s.	n.s.	n.s.	n.s.	n.s.
				Site2		
Control	1517	3361	-	4082c	848	2081
G_{50}+AH-S:R	1265	3531	-	4114bc	983	1740
G_{50}+AH-S:G	1233	3805	-	4589ab	1023	1957
G_{50}+AH-S:R:G	1072	3768	-	4631a	1263	1740
l.s.d. (P = 0.05)	n.s.	n.s.		477*	n.s.	n.s.

*$P < 0.05$; n.s., not significant.
Within rows, values followed by the same letter(s) are not significantly different at $P = 0.05$.
At site 1, first rice crop could not grow successfully due to very high initial EC_e and SAR values of the soil. At site 2, second rice crop could not grow successfully and rice nursery was not available for second time transplantation

Better crop growth gave the added benefit of cleaning the environment through sequestration of atmospheric CO_2 (Lal, 2001) as 1 mole of CO_2 consumption yields 1.4 g of biomass and the consumption of 70 moles of CO_2 in photosynthesis affects simultaneously a net release of 100 moles of O_2 (Monteith, 1981). Consideration of this aspect makes the soil reclamation programs even more attractive, environment friendly and cost-effective. The amelioration of salt-affected soils could help remove the rural to urban migration through providing farm employment, which in turn will help rural poverty alleviation.

Bulk density: Since the experimental sites were lying barren for at least more than 25 years, the physical properties (bulk density only) for whole of a field under each site are presented in Table 4, assuming a uniform degree of soil deterioration. Both the sites were badly deteriorated. Overall, the soil at site 1 was the worst followed by site 2. Since the improvement in physical properties is time-dependent, these were again measured after three years at the termination of study in May 2004, to evaluate effectiveness of treatments. Bulk density measured after harvest of wheat 2003-04 (6^{th} crop in sequence) depicted non-significant differences among the treatments, except at 200-250 mm depth at site 1, and 100-150 mm depth at site 2 (Table 4).

Table 4. Effect of various treatments on soil bulk density (Mg m^{-3}) after 3 years.

Treatment	100-150 mm depth		200-250 mm depth		300-350 mm depth	
	Site1	**Site2**	**Site1**	**Site2**	**Site1**	Site2
	At start					
	1.86	1.59	1.77	1.66	1.82	1.70
	After 6 crops					
Control	1.65	1.55b	1.82ab	1.86	1.83	1.69
G_{50}+AH-S:R	1.58	1.81a	1.71b	1.77	1.81	1.70
G_{50}+AH-S:G	1.60	1.70ab	1.93a	1.81	1.89	1.64
G_{50}+AH-S:R:G	1.62	1.68ab	1.83ab	1.74	1.85	1.69
l.s.d. ($P = 0.05$)	n.s.	0.21*	0.18*	n.s.	n.s.	n.s.

Within columns, values followed by same letter(s) are not significantly different at $P = 0.05$, *****$P < 0.05$; n.s., not significant.

The increase in bulk density could be attributed to, continuous use of high SAR and RSC irrigation waters from tube wells and, decreased EC_e to SAR ratio in soil solution since decrease in EC_e was faster than that of SAR (Ayers & Westcot, 1985). Waldron *et al*., (1970) found a 5% decrease in void ratio for soils permeated with solutions of NaCl vs. $CaCl_2$. A gradual increase in bulk density with soil depth, especially at site 1, appears to be due to migration of Na^+ from upper to lower soil layers, causing dispersion of soils and thus high bulk density (Minhas & Gupta, 1993; Qadir *et al*., 2002). However, similar trend was not recorded at site 2, which might be due to low levels of SAR at this site compared to that at site 1. Bauder & Brock (1992), in a greenhouse experiment observed that soil bulk density after three barley crops decreased significantly from 1.07 Mg m^{-3} to 1.24 Mg m^{-3} while there was non-significant increase in the uncropped treatment. In the same study, gypsum amendment increased bulk density of soils cropped to sordan. It was hypothesized that increase in bulk density could be the result of combined effects of aggregate dispersion and pore collapse followed by consolidation of the soil during successive wetting and drying cycles. Emdad *et al*., (2004) proposed that increase in bulk density and decline in infiltration, where moderate and high EC-SAR water was applied could be due to an increase in clay tactoid swelling reducing the size of conducting micropores. Sharma (1971) examined the profile of a sodic soil, forty-months after gypsum application, and revealed that gypsum did not significantly affect the bulk density of the soil profile. The measured bulk densities for depth intervals viz., 0-75-300-450 mm, were 1.46, 1.52, 1.55, and 1.59 Mg m^{-3} for the gypsum treated plots and 1.49, 1.51, 1.54, and 1.58 Mg m^{-3} for the untreated plots, respectively.

Economic evaluation of treatments: The stress-land agriculture is generally discouraged because of relatively high initial treatment costs of soils and irrigation waters. Keeping in view the fact, efforts are required to evolve some economical strategy, which could be adopted by farmers having small land holdings. Moreover, Knapp (1999) have asserted to also consider the benefits of reducing the damage from salinity/sodicity to the ecological systems. This aspect is another added benefit that the net income will be further realized at much higher rates for several years. The objective of economic analysis is to compare costs with benefits, to decide which alternative, yields greater returns to the investment. When the experiments last more than one year or have different life span, they have to be compared by taking into account the present worth of future cost and benefit streams. Following assumptions were followed to appraise the study: i) Before the start of the experiment, the land was not suitable for normal growth of rice and wheat crops ii) Benefits of the study will continue for 8 years iii) The investment starts generating income from the first year onwards iv) The farm budget presented here indicates the future income of the proposed investment v) Yields have been adjusted downward by 10 percent for farmers' fields.

Economic evaluation of the best treatment: The expenditure and income were calculated for the quantities of amendments at actual cost but for the produce at support prices. Other costs on cultural operations, common to all the treatments (fertilizers, ploughing, weeding, irrigation etc.) were not considered. For 6 crops, on per hectare basis (Table 5a), G_{50}+AH-S:R gave maximum net benefit of US $ 1617 followed by G_{50}+AH-S:G (US $ 1508), G_{50}+AH-S:R:G (US $ 1399) and control (US $ 1022) at site 1. Net benefit was maximum with control (US $ 1701) followed by G_{50}+AH-S:G (US $ 1634), G_{50}+AH-S:R:G (US $ 1626), and G_{50}+AH-S:R (US $ 1479) at site 2. In order to calculate the benefit cost ratio (BCR), net present worth (NPW) and internal rate of returns (IRR), the respective variable costs and gross benefits were multiplied with area reclaimed each year. Variable costs and gross benefits were also calculated accordingly for 8 years. The interpolated data about the area under each best treatment is not shown here. It was assumed that after 8-year period, the yield would decrease if necessary measures were not taken at proper time. Net benefits were determined by subtracting variable costs from gross benefits. Benefit cost ratio was calculated for each best treatment at the respective site. At site 1, the MRR was 635 % for G_{50}+AH-S:R treatment over the investment (details not shown here), which was higher than the minimum rate of return of 100 %, indicating this treatment as the best. At site 2, MRR calculation was not possible as control treatment was dominant. The final summarized results (Table 5b) indicated that the BCR was highest at site 2 followed by site 1. Thus for site 1, G_{50}+AH-S:R was the best treatment with BCR value of 8.0.

The cost of reclamation treatments was recovered from the first three crops at site 1, and from first two crops at site 2. More income was received from wheat crop than that of rice, as paddy yield was low due to very high EC_e and SAR at the time of transplanting of the first rice (Table 1). The EC_e and SAR decreased considerably during the first crop (rice 2001) to favor better yields of the following wheat and rice crops. If appreciation in land value, provision of farm employment, and impact of environment cleaning are considered, the reclamation of salt-affected soils becomes much more attractive.

Table 5a. Economics (US $ per ha) of various treatments tested during the study.

Site/Treatment	Variable cost	Gross benefit	Net benefit
		Site1	
Control	161	1183	1022
G_{50}+AH-S:R	408	2025	1617
G_{50}+AH-S:G	391	1900	1508
G_{50}+AH-S:R:G	400	1798	1399
		Site2	
Control	244	1944	1701
G_{50}+AH-S:R	425	1904	1479
G_{50}+AH-S:G	432	2065	1634
G_{50}+AH-S:R:G	434	2060	1626
		Mean of both the sites	
Control	202	1564	1361
G_{50}+AH-S:R	417	1964	1548
G_{50}+AH-S:G	411	1982	1571
G_{50}+AH-S:R:G	417	1929	1513

Table 5b. Economics (US $ per ha) of various treatments tested during the study.

Best treatment	Variable cost	Gross benefit	Net benefit	BCR
		Site 1		
G_{50}+AH-S:R	59608	479175	419567	8.0
		Site 2		
Control	41777	354061	312284	8.5

Prices: Gypsum @ US $ 0.48 per bag; Daily paid labour charges for broadcasting of gypsum @ US $ 1.67 per day per 20 bags of gypsum; Cost of making 200 holes per hectare @ US $ 11.5; Cost of gypsum per hectare for filling auger holes @ US $ 1.15; Support price of super basmati variety (Paddy) @ US $ 7.67 per 40 kg; Support price of wheat grain @ US $ 5.0 per 40 kg for first 2 crops while for last wheat crop the price was @ US $ 6.17; Wheat straw value at farm @ US $ 1.33 per 40 kg.

On the basis of the results from this study, it is possible to conclude that low quality water can successfully reclaim saline-sodic soils within a reasonable time period, provided agricultural grade gypsum @ 50% SGR is soil-applied. Rice-wheat crop rotation appears promising, as rice crop seems to be better for soil reclamation, while wheat crop(s) produced better yields than rice, thus contributed more towards net benefit. The provision of vertical drainage through auger holes was not promising in order to flush down soluble salts from the surface layer of the saline-sodic soils, as depicted from the final $EC_{e,}$ and SAR values. Similarly, non-significant differences among all the treatments were also noted for paddy and wheat grain yields. The vertical drainage strategy through auger holes did not help to flush down excess saline water towards deeper soil layers. Detailed economic analysis indicates that G_{50}+AH-S:R treatment offered the highest cost: benefit ratio at site 1, while at site 2, control treatment was the dominant one.

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