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Amelioration of a saline sodic soil through cultivation of a salt-tolerant grass *Leptochloa fusca*

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SUMMARY

Reclamation of saline lands seems difficult for climatic and economic reasons, but cultivation of salt-tolerant plants is an approach to increasing productivity and improvement of salt-affected wastelands. A five-year field study was conducted to evaluate the effects of growing a salt-tolerant species *Leptochloa fusca* (L.) Kunth (kallar grass) on chemical properties of a saline sodic soil irrigated with poor quality groundwater. Soil salinity, sodicity and pH decreased exponentially by growing kallar grass as a result of leaching of salts from surface (0–20 cm) to lower depths (>100 cm). Concentrations of soluble cations (Na^+, K^+, Ca^{2+} and Mg^{2+}) and anions (Cl^-, SO_4^{2-} and HCO_3^-) were reduced through to greater soil depths. A significant decline in soil pH was attributed to release of CO_2 by grass roots and solublization of $CaCO_3$. Both soil salinity and soil pH were significantly correlated with Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^- and sodium adsorption ratio (SAR). Significant correlations were found between soluble cations (Na^+, Ca^{2+} and K^+), soluble anions (Cl^-, SO_4^{2-} and HCO_3^-) and the SAR. In contrast, there were negative correlations between soil organic matter content and all chemical properties. The ameliorative effects on the soil chemical environment were pronounced after three years of growing kallar grass. Cultivation of kallar grass enhanced leaching and interactions among soil chemical properties and thus restored soil fertility. The soil maintained the improved characteristics with further growth of the grass up to five years suggesting that growing salt-tolerant plants is a sustainable approach to biological amelioration of saline wastelands.

Keywords: biological amelioration, soil chemical environment, remediation, salinization, *Leptochloa fusca*, saline sodic soil

INTRODUCTION

Soil salinity is a widespread environmental problem, particularly in arid and semi-arid regions of the world. In Pakistan, about 6.3 million hectares of land are affected by salinity, and groundwater in most of these saline areas is brackish and thus unfit for irrigation (Qureshi & Barrett-Lennard 1998). Reclamation of large areas of saline lands seems difficult for many climatic and economic reasons, such as shortage of fresh water for leaching of salts, poor natural drainage, and high costs of construction and maintenance of drainage systems. However, salt-affected lands and brackish water could be used for cultivation of salt-tolerant plants, because halophyte species that accumulate salt, such as *Suaeda fruticosa*, *S. calceoliformis* and *Atriplex prostrata*, have been reported to improve saline sodic soils (Chaudhari *et al.* 1964; Keiffer & Ungar 2000). Sandhu and Malik (1975) proposed a plant successional scheme in which kallar grass (*Leptochloa fusca* [L.] Kunth), a highly salinity-tolerant species, is used as a primary colonizer for plant establishment and biomass production on saline sodic lands. The growth of kallar grass not only provides biomass to be used as forage, but also ameliorates soil conditions, thus facilitating the growth of other species in succession and improving the general environment (Mahmood *et al.* 1989, 1994).

Saline sodic soils have an excess of sodium and are impermeable, and therefore salts cannot be leached from them into the deeper soil layers. Irrigation with saline and sodic water introduces both salts and sodium into the soil system and may impose stress on growing plants resulting in decreased yields (Kern & Shainberg 1984). The chemical properties of soils determine soil structure (Carter *et al.* 1977; Goldberg *et al.* 1988). The growth of kallar grass improves the soil physical conditions and accelerates leaching of salts. However, systematic studies (see Mahmood *et al.* 1989, 1994) of successive changes in soil properties of saline lands after kallar grass planting are scanty. Sustainability of growing plants on saline sodic soils with saline water irrigation has not been thoroughly investigated. The question of how long-term use of saline irrigation water will affect, deteriorate or ameliorate, the chemical environment of soils already degraded due to excess salts remains unanswered. We therefore monitored the changes in physical, chemical and mineralogical properties of a saline sodic soil profile in reclamation fields under kallar grass cultivation, which were irrigated with brackish water. This paper reports on the changes in chemical properties at different depths of saline sodic soil over a five-year period after planting kallar grass.

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MATERIALS AND METHODS

A field experiment was carried out at the Biosaline Research Station, Nuclear Institute for Agriculture and Biology, Faisalabad situated near Dera Chahl, 30 km from Lahore, Pakistan (74°7′ E, 31°6′ N). A two-factor factorial experiment was laid out in a randomized complete block design (RCBD) with three replicates. A preliminary survey using a four-electrode electrical conductivity probe established eighteen 30 m × 30 m plots with similar soil salinity and texture. Soil was highly saline (EC = 18.9 dS m^{-1}), sodic (SAR = 163) and alkaline (pH = 10.4) with sandy clay loam texture (sand 550 g kg^{-1}; silt 240 g kg^{-1}; clay 210 g kg^{-1}) up to one metre depth. Brackish irrigation water (EC 1.4 dS m^{-1}; SAR 19.3; residual sodium carbonate 9.8 me l^{-1}) was used to grow kallar grass.

Kallar grass was planted on 15 plots, while three plots were preserved as unplanted controls (T_0). Initially, three unplanted plots were also kept as irrigated controls. However, we abandoned these unplanted irrigated controls, as irrigation water did not penetrate in the soil. The saline sodic soils cannot be leached simply by water because of their extremely low permeability (Akhter *et al.* 1988; Mahmood *et al.* 1994). Flood irrigations of about 75 mm were applied (mainly during dry months, October–June) when the soil moisture dropped to about 50% of available water (AW) at soil field capacity as indicated by neutron moisture-meter readings. Cumulative irrigation water was applied at 172 ± 5.6 cm yr^{-1}. Rainfall during the five-year study period was 49.7 ± 0.86 cm yr^{-1} (standard error), most of which (≥80%) occurred in the monsoon (July–September) season. Kallar grass being a perennial species was continuously grown for five years and 3–4 cuttings were taken per year. Three plots were randomly selected at the end of the growing season (during November) for soil sampling and to measure the soil physical properties *in situ*. Soil properties were determined at the end of the first (T_1), second (T_2), third (T_3), fourth (T_4), and fifth (T_5) years. Average values of different soil properties, determined at the end of each year, for the unplanted plots were used as controls (T_0) to compare the combined effects of kallar grass growth and irrigation. Soil samples were collected from preselected depths of 0–20 cm (D_1), 40–60 cm (D_2) and 80–100 cm (D_3). Salt efflorescences were scraped from the surface before sampling the soil profiles. Three profiles were sampled up to preselected depths from each plot and composite samples for each depth were obtained. Soil samples were air-dried and ground to pass through a 2-mm sieve. A saturated soil paste extract was obtained from sub-samples of each soil (US Salinity Laboratory Staff 1954).

Electrical conductivity (EC) and pH of saturated paste extracts were determined for each sample with a WTW conductivity meter LF-530 and a Corning pH meter 130, respectively. Soil saturation extracts were analysed for cations (Na^+, Ca^{2+}, Mg^{2+} and K^+); the Na^+ and K^+ ions were determined with a flame photometer (Model PFP7 Jenway) and Ca^{2+} and Mg^{2+} by titration with ethylene diamine tetraacetate. The anions CO_3^{2-}, HCO_3^- and Cl^- were determined by titration (US Salinity Laboratory Staff 1954), and SO_4^{2-} by turbidimetry (Anon. 1995). Total carbon was determined by a modified Walkly-Black method (Nelson & Sommers 1982). Inorganic carbon (C_i) was determined with a modified volumetric calcimetric method in which soil was treated with 4N HCl in the presence of $FeCl_2$ in a closed system and the volume of CO_2 released was determined. Organic matter was calculated by multiplying the organic carbon by 1.72. These data were subjected to analysis of variance (ANOVA). An F test was used to identify treatment main effects and interactions and if significant differences were found these were followed by least significant difference (LSD) tests at the 0.05 probability level (Steel & Torrie 1980). Data were also subjected to simple linear and nonlinear regression analyses. The regression coefficient (b) and correlation coefficient (r) were verified at the $p \leq 0.05$ and 0.01 levels. The standard error of estimate (SEE) and coefficients of determination (R^2) were also calculated.

RESULTS

Soil salinity, sodicity and organic matter

Irrigation and kallar grass growth for one to five years significantly ($p \leq 0.05$) reduced the soil salinity (EC) by 71.4% over controls (Table 1). A maximum reduction of 87.3% was

Table 1 Mean (n = 3) electrical conductivity, pH, sodium adsorption ratio, and organic matter content at different depths (D) of saline sodic soil with kallar grass growth for different periods (T).

Growth year (T)	*Soil depth*		
	D_1 *(0–20 cm)*	D_2 *(40–60 cm)*	D_3 *(80–100 cm)*
Electrical conductivity (dS m^{-1})			
0	22.0	22.2	12.5
1	12.6	14.0	6.3
2	7.4	9.7	3.1
3	3.2	3.8	2.4
4	2.8	3.8	4.8
5	2.0	2.1	3.2
Soil pH			
0	10.4	10.5	10.4
1	9.3	9.2	9.5
2	9.1	9.4	9.3
3	9.2	9.5	9.4
4	9.1	9.6	9.7
5	8.9	8.9	9.0
Sodium adsorption ratio			
0	185.5	187.2	114.7
1	70.6	97.6	78.7
2	65.9	91.5	74.1
3	32.5	53.0	35.8
4	25.8	47.5	25.0
5	20.7	41.2	25.4
Organic matter (g kg^{-1})			
0	3.3	1.9	1.8
1	3.2	8.9	2.8
2	5.5	11.7	3.4
3	7.3	10.7	2.6
4	6.3	11.9	2.9
5	7.4	13.3	3.8

observed in T_5 followed by 79.9, 83.6, 64.6 and 41.8% reduction after the fourth, third, second and first years, respectively, as compared with T_0 (uncropped plots). Regression analysis showed that the EC exponentially decreased with increased growing time of kallar grass (Table 2). A 91.7% reduction in EC resulted because of the increase in cropping time. The predicted values of soil salinity decreased markedly from 16.2 to 2.1 dS m^{-1}.

The effects of growing grass on soil EC varied significantly with depth. Over all growing periods of kallar grass, the values of soil EC were 8.3, 9.3, and 5.4 dSm^{-1} for the soil depths D_1, D_2 and D_3, respectively (Table 1). There were considerable differences in the EC of soil depth D_3 for all treatments (T_1 to T_5) as compared to upper soil depths D_1 and D_2. The highest reduction of 41.9% was recorded at soil depth D_3 followed by 10.8% at soil depth D_1 as compared with soil depth D_2. Analysis of variance (ANOVA) of these data indicated a significant interaction in EC data between the growing period of kallar grass and soil depth (Tables 1 and 3).

Soil pH statistically decreased in all treatments tested by cropping kallar grass as compared to soil pH of uncropped plots (Table 1). The maximum decrease in soil pH relative to T_0 of 14.4% was observed after five years. The cultivation of kallar grass had a significant linear effect on pH, the decrease averaging 0.229 units for each year of growing kallar grass (Table 2). The soil pH differed significantly among depths in the soil profile; in general, soil pH gradually increased with increase in soil depth. The highest reduction of 2.5% in soil pH was recorded in the upper soil (D_1) compared with that in deeper soil D_2 (Table 1).

A significant decrease in SAR of soil was recorded with all the treatments of growing kallar grass for five years (T_1 to T_5). The maximum reduction of 82.1% in soil SAR was observed after 5 years (T_5) followed by 79.8, 75.1, 52.5 and 49.4% in T_4, T_3, T_2, and T_1, respectively, after successive growing periods of kallar grass as compared with uncropped plots (Table 1). The SAR of soil decreased in an exponential pattern as the growing time was increased, the rate of reduction being 0.343 me l^{-1}year^{-1} (Table 2). Reduction of the soil SAR was due mainly to the cropping system employed. These data also revealed that the SAR of the upper soil (0–20 cm) was significantly reduced by 27.3% when compared with the mean SAR of depth D_3 (Tables 1 and 3).

The effect of cropping practices on soil organic matter (OM) was highly significant (Tables 1 and 3). The maximum soil OM content of 8.2 g kg^{-1} was found after 5 years and 2.3 g kg^{-1} was recorded in uncropped soil (T_0). The maximum increase of 3.6 fold was recorded at five years followed by 2.1, 2.9, 3.0 and 3.0 fold increase through years 1–4. The soil OM increased linearly when growing periods were increased (Table 2). The growth of kallar grass caused 83% of the observed variability in soil OM content, which increased by a rate of 1.026 g kg^{-1}yr^{-1} in kallar grass treatments compared with uncropped soil.

There were significant differences in the OM content among the soil depths (Table 1). Higher OM content (9.6 g kg^{-1}) was found at soil depth D_2 as compared with 5.6 and 2.9 g kg^{-1}, respectively, at soil depths D_1 and D_3.

Table 2 Relationship between soil chemical properties (y) and cropping time of kallar grass (x) for all depths combined. SEE = standard error of estimate, EC = electrical conductivity, SAR = sodium adsorption ratio, OM = organic matter; *, ** = significant at 0.05 and 0.01 probability levels, respectively.

Variable	*Regression equation*	*SEE*	*r*
EC	$\ln y = 2.783 - 0.408x$	0.23	0.958**
pH	$y = 10.038 - 0.229x$	0.29	0.854*
SAR	$\ln y = 4.926 - 0.343x$	0.21	0.968**
OM	$y = 3.452 + 1.026x$	0.97	0.911*
Na^+	$\ln y = 5.110 - 0.418x$	0.26	0.958**
Ca^{2+}	$y = 2.329 - 0.371x$	0.49	0.845*
Mg^{2+}	$y = 1.152 - 0.134x$	0.30	0.687
K^+	$y = 1.438 - 0.249x$	0.14	0.962**
Cl^-	$\ln y = 3.996 - 0.449x$	0.10	0.982**
SO_4^{2-}	$\ln y = 4.077 - 0.435x$	0.20	0.977**
HCO_3^-	$\ln y = 4.206 - 0.467x$	0.25	0.970**

Table 3 Mean squares and least significant difference of effect of growing kallar grass for different time periods (T) on chemical properties of soil at different depths (D). SOV = source of variation, df = degrees of freedom, EC = electrical conductivity, SAR = sodium adsorption ratio, OM = organic matter content; *,** significant at 0.05 and 0.01 probability levels, respectively.

	Mean squares of effects of					*Least significant difference*		
SOV	*Replicate*	*Growth year*	*Soil depth*	*T × D*	*Error*	*T*	*D*	*T × D*
df	2	5	2	10	34	5	2	10
EC	0.64	261.6**	74.42**	83.85**	0.90	0.9	0.7	1.6
pH	0.05	2.377**	0.210**	0.240**	0.026	0.3	0.2	0.4
SAR	258.3*	22834.9**	3581.1**	767.47**	55.84	7.2	5.1	12.4
OM	0.13	31.41**	207.89**	11.56**	0.08	0.27	0.19	0.47
Na^+	120.13*	37480.8**	7647.02**	1155.42**	17.01	4.0	2.8	6.8
Ca^{2+}	0.167	6.024**	1.325**	0.354**	0.098	0.3	0.2	0.5
Mg^{2+}	0.041	1.792**	0.540**	0.23**	0.019	0.1	0.1	0.2
K^+	0.003	2.142**	1.135**	1.546**	0.015	0.1	0.1	0.2
Cl^-	67.23*	3096.6**	542.3**	107.68**	13.10	3.5	2.5	6.0
SO_4^{2-}	59.66	3505.7**	2342.6**	348.25**	14.65	3.8	2.7	6.3
HCO_3^-	41.25	8856.9**	801.5**	398.98**	16.26	3.9	2.7	6.6

Further, analyses of variance (ANOVA) of these data showed a significant interactive effect of kallar grass growth on soil organic matter with a maximum increase at the soil depth D_2 (Tables 1 and 3).

Soluble cation concentrations

A significant reduction of Na^+ content was found as the time of growth of kallar grass increased on highly salt-affected soil (Table 4). Agronomic practices of growing kallar grass significantly reduced (70.5%) the mean Na^+ content in soil solution through T_1 up to T_5 compared with uncropped control plots. The Na^+ concentration significantly decreased by 38.0, 62.0, 81.3, 86.6 and 84.5% as compared to controls (T_0) at 1, 2, 3, 4 and 5 years, respectively. Na^+ concentration declined exponentially (Table 2). The highest Na^+ concentration (98 me l^{-1}) over all years was at D_2 (40–60 cm); it was reduced (56 me l^{-1}) at soil depth D_3 as compared to that at the soil surface D_1. In general, the results showed significant interactive effect of growing kallar grass on Na^+ with soil depth (Tables 3 and 4).

Growing kallar grass had a significant effect on the Ca^{2+}, Mg^{2+} and K^+ concentrations in the solution phase of the soil (highly saline sodic). The Ca^{2+}, Mg^{2+} and K^+ contents significantly decreased after five-year growth of kallar grass (Table 4). Levels of Ca^{2+}, Mg^{2+} and K^+ were 2.8, 1.4, and 1.5 me l^{-1} in uncropped control plots (T_0) and then gradually decreased to 1.0, 0.3 and 0.3 me l^{-1} after five years of cropping. The maximum reductions relative to T_0 values in Ca^{2+}, Mg^{2+} and $K^+$of 64.3, 78.6 and 80% were recorded after five years of cultivation.

Under the cropping system, increasing the period of kallar grass growth from one to five years resulted in a linear reduction in the concentration of Ca^{2+}, Mg^{2+} and K^+ (Table 2). The Ca^{2+}, Mg^{2+} and K^+ decreased by constant rates of 0.371, 0.134 and 0.249 me l^{-1} in each year of cropping (Tables 2 and 4), predicted values decreasing gradually from 2.33 to 0.47 me l^{-1} (Ca^{2+}), 1.15 to 0.48 me l^{-1} (Mg^{2+}) and 1.44 to 0.24 me l^{-1} (K^+). There were significant differences in the cation contents of deeper soil D_3 for all treatments (T_1–T_5) as compared to upper soil D_1 and D_2 (Table 4). Reductions of 35.3, 40.0 and 45.5% were recorded at soil depth D_3 followed by 11.8, 20.0 and 36.4% at soil depth D_2 in the concentrations of Ca^{2+}, Mg^{2+} and K^+, respectively, as compared with the surface layer (0–20 cm). Analysis of variance (ANOVA) of these data indicated significant interactive effects of cropping between cations and soil depth (Tables 3 and 4).

Table 4 Mean ($n = 3$) concentrations of soluble cations (Na^+, Ca^{2+} and K^+) in saturation extracts of soil at different depths (D) as a function of growing kallar grass for different time periods (T).

Growth year (T)	*Soil depth*		
	D_1 (0–20 cm)	*D_2 (40–60 cm)*	*D_3 (80–100 cm)*
Na^+ (me l^{-1})			
0	207	226	128
1	116	136	96
2	73	101	40
3	26	38	40
4	18	38	16
5	23	46	18
Ca^{2+} (me l^{-1})			
0	3.7	2.6	2.0
1	2.0	2.0	1.9
2	1.3	1.4	0.4
3	0.9	0.7	1.2
4	0.6	1.0	0.5
5	1.4	1.0	0.6
Mg^{2+} (me l^{-1})			
0	1.8	1.3	1.0
1	0.5	1.0	0.6
2	1.2	1.1	0.2
3	0.4	0.3	1.3
4	1.1	1.5	0.4
5	0.4	0.3	0.3
K^+ (me l^{-1})			
0	1.3	1.8	1.3
1	3.0	0.5	0.5
2	0.7	0.7	0.7
3	0.7	0.7	0.7
4	0.3	0.5	0.3
5	0.4	0.2	0.2

Soluble anion concentrations

There were significant effects of cropping on concentrations of soluble anions in solution phase of the highly saline sodic soil (Table 5). All treatments of kallar grass growth (T_1–T_5)

Table 5 Mean concentrations ($n = 3$) of soluble cations (Cl^-, SO_4^{2-} and HCO_3^-) in saturation extracts of soil at different depths (D) as a function of growing kallar grass for different periods (T).

Growth year (T)	*Soil depth*		
	D_1 (0–20 cm)	*D_2 (40–60 cm)*	*D_3 (80–100 cm)*
Cl^- (me l^{-1})			
0	62.1	72.5	40.7
1	32.7	44.7	33.6
2	20.3	29.3	16.6
3	9.7	12.6	9.0
4	8.2	11.6	7.5
5	6.0	8.0	6.0
SO_4^{2-} (me l^{-1})			
0	46.7	76.0	28.8
1	55.2	71.3	24.2
2	22.2	39.4	13.5
3	12.5	16.2	9.4
4	10.2	13.8	10.0
5	5.6	10.1	4.7
HCO_3^- (me l^{-1})			
0	103.4	101.4	68.3
1	36.1	50.5	15.4
2	23.1	37.8	11.0
3	12.3	15.8	14.8
4	6.8	8.0	13.4
5	6.2	3.6	15.0

significantly reduced the levels of soluble Cl^-, SO_4^{2-} and HCO_3^- ions (Table 5), the maximum reductions relative to T_0 being 88.4, 88.6 and 90.9% in Cl^-, SO_4^{2-} and HCO_3^- after 5 years of kallar grass cultivation (T_5). The concentrations of anions Cl^-, SO_4^{2-} and HCO_3^- decreased exponentially with increase in growth period (Table 2).

Concentrations of Cl^-, SO_4^{2-} and HCO_3^- in soil solution decreased at rates of 0.449, 0.435 and 0.467 me l^{-1} yr^{-1}. Predicted levels of Cl^-, SO_4^{2-} and HCO_3^- decreased substantially from 54.4 to 5.8, 59.0 to 7.0 and 67.1 to 6.0 me l^{-1}, respectively. These data showed significant differences in Cl^-, SO_4^{2-} and HCO_3^- concentrations at different soil depths (Table 5). Reductions in Cl^-, SO_4^{2-} and HCO_3^- concentration by 36.9, 60.1 and 36.7% were observed at soil depth D_3 (80–100 cm) followed by 22.1, 32.8 and 13.5% at soil surface D_1 as compared with depth D_2. Statistical analysis of these data clearly confirmed the interactive effects of cropping practice between soluble anions and soil depths (Table 3).

Relationships between chemical properties

Both soil salinity (EC) and soil pH were significantly correlated with Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^- and HCO_3^- concentrations and the SAR (Table 6). Significant correlations were found between soluble cations (Na^+, Ca^{2+}, and K^+), soluble anions (Cl^-, SO_4^{2-} and HCO_3^-) and the SAR. Meanwhile, the SAR had a high correlation with most of the soil chemical properties. In contrast, there was a negative correlation between soil organic matter content (OM) and all chemical properties.

DISCUSSION

Cropping of kallar grass increased organic matter content of the soil, which was initially negligible (mean 2.3 g kg^{-1}) and increased linearly at 1.026 g kg^{-1} yr^{-1} (Table 1); 83% of the observed variability in organic matter was attributed to kallar grass growth. The inverse relations of organic matter with soil EC, pH, SAR and most of the soluble ions indicated that the binding of organic matter with soil particles released most of the ions including Na^+, which subsequently leached to lower depths. The marked enhancement in the soil organic matter content may be due to rapid addition of organic matter by plant roots. In many studies similar effectiveness of cropping systems in improving organic carbon content of soil has been reported (Carter 1984; Wallace & Wallace 1986; Perfect *et al.* 1990; Haynes & Francis 1993).

Nelson *et al.* (1996, 1997) observed that mineralization of carbon appreciably decreased with increasing soil sodicity and they suggested that retention of organic matter would be enhanced if added after reducing the exchangeable sodium percentage (ESP) of the soil. Barzegar *et al.* (1997) found that addition of plant residues improved the stability of soil aggregates due to increase in organic matter content and decrease in soil sodicity. The soil salinity significantly declined by growing kallar grass on highly saline sodic soil compared to unplanted controls. The EC exponentially decreased at 0.408 dS m^{-1} yr^{-1} of cropping period; 91.8% of the EC variation was attributable to cropping time (Table 2). The effects of growing grass on soil EC varied significantly with depth mainly due to leaching of salts. Using ^{22}Na and ^{36}Cl as tracers, Bhatti and Wieneke (1984) reported that most of the salt taken up by kallar grass plants was excreted by the leaves or extruded to the nutrient solution by roots. Further, concentrations of cations (Na^+, K^+ and Ca^{2+}) in kallar grass shoots were affected neither by the presence of competing species nor by different soil salinity and moisture levels (Mahmood 1997; Mahmood *et al.* 1993). Accumulation and removal of salts from soil by harvested kallar grass plants were negligible (1.65%) compared to the total salts leached from the 0–25 cm zone; major proportions of salts were washed with irrigation water down to the deeper (below 100 cm) soil layers (J. Akhter *et al.*, unpublished data 2003). The saline sodic soils cannot be leached simply by water because of their extremely low permeability; water may not penetrate even 2 cm into such soils (Akhter *et al.* 1988; Mahmood *et al.* 1994). However, cultivation of salt-tolerant plants, like kallar grass, helps to restore soil structure and permeability through penetration of their roots and solubilization of native-soil calcium carbonate and thus enhanced leaching of salts. Growth of perennial grasses and other plant species have helped to reduce the salinity and alkalinity problems (Zartman & Gichuru, 1984; Akhter *et al.* 1988; Costa *et al.* 1991; Hussain *et al.* 1994; Chang & Leghari 1995).

Table 6 Correlation coefficients among different soil chemical properties: EC = electrical conductivity, SAR = sodium adsorption ratio, OM = organic matter; *,** = significant at 0.05 and 0.01 probability levels, respectively (n = 6).

Variable	pH	OM	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}	HCO_3^-	SAR
EC	0.924**	−0.989**	0.994**	0.965**	0.751	0.929**	0.996**	0.919**	0.974**	0.988**
pH		−0.965**	0.898*	0.860*	0.791	0.862*	0.905*	0.773	0.953**	0.927**
OM			−0.966**	−0.946**	−0.805	−0.945**	−0.974**	−0.901*	−0.961**	−0.950**
Na^+				0.976**	0.684	0.946**	0.913**	0.935**	0.965**	0.978**
Ca^{2+}					0.592	0.931*	0.969**	0.912*	0.939*	0.923**
Mg^{2+}						0.621	0.709	0.564	0.776	0.762
K^+							0.952**	0.968**	0.870*	0.890*
Cl^-								0.919**	0.961**	0.970**
SO_4^{2-}									0.819*	0.861*
HCO_3^-										0.983**

In the present study, three years of kallar grass cropping were sufficient to improve the soil to a level suitable and safe for introducing moderate salinity-tolerant agricultural crops. However, leaching of soluble salts continued during five years of cultivation on saline sodic soil and the EC of the soil was significantly reduced (Amundson & Lund 1985; Mahmood *et al.* 1989; 1994). Rasmussen *et al.* (1972) observed a significant reduction in the EC and ESP of a saline sodic soil by alfalfa–wheat rotation with 3–4 years of deep tillage. Chang and Leghari (1995) found that growing sorghum, maize and sudan grass on a moderately saline sodic calcareous soil for three years considerably reduced soil salinity and sodicity.

Here, cultivation of kallar grass reduced the soil pH at a rate of 0.229 units for each year of cultivation. This study is in agreement with many others (Zaidi *et al.* 1968; Gupta *et al.* 1984; 1989; Hussain & Ali 1989; Chang *et al.* 1994) where economic crops and native species cumulatively removed soil exchangeable sodium. Mobilization of native insoluble $CaCO_3$ lowered the soil pH because of increased solublization and release of CO_2 by plant roots. Cultivation of grasses and other plants helped to reduce soil salinity and alkalinity through various mechanisms (Gupta *et al.* 1984; 1989; Amundson & Lund 1985; Hussain *et al.* 1994; Chang & Leghari 1995).

The SAR of the soil decreased exponentially with the growth of kallar grass. The cropping system significantly reduced the soil SAR near the surface compared with greater depth. Saline water in a saline sodic soil increased soil SAR at depth as a result of leaching of sodium from surface layers and its subsequent accumulation in the middle soil depth D_2 (Tables 1 and 4). Several workers have reported similar results for SAR (Zaidi *et al.* 1968; Khalid *et al.* 1972; Chaudhry *et al.* 1985; Costa *et al.* 1991; Hussain *et al.* 1994; Chang & Leghari 1995). The growth of kallar grass for three years significantly reduced soil SAR and can be continued to reduce the SAR of highly saline sodic soils. Growing kallar grass is an effective means of replacing and leaching the sodium from the soil exchange complex and soil solution, respectively.

Agronomic practices of growing kallar grass significantly reduced the average Na^+ content in soil solution at all the studied soil depths. Na^+ accumulated initially in the middle depth (98 me l^{-1}) and followed a sharp reduction (56 me l^{-1}) in the deepest soil depth. Sodium was reduced due to improvement in some physical properties of the soil through an enhancement of soil structural stability, porosity, hydraulic conductivity and drainage (Quirk & Schofield 1955; McNeal *et al.* 1968; Giovannini & Sequi 1976; Acharya & Abrol 1978; Goldberg *et al.* 1988). Kallar grass and other plants grown effectively ameliorates saline sodic soils (Zaidi *et al.* 1968; Sheikh & Irshad 1980).

Growing kallar grass had a significant effect on the Ca^{2+}, Mg^{2+} and K^+ concentrations in the solution phase of the soil system, which decreased, respectively, by rates of 0.371, 0.134 and 0.249 me l^{-1} yr^{-1}. Salt-affected lands can be effectively used and ameliorated through judicious use of various plant species (Chaudhry *et al.* 1985; Robbins 1986; Chang *et al.* 1994; Crescimanno *et al.* 1995). The amounts of Cl^-, SO_4^{2-} and HCO_3^- in soil solution also decreased exponentially as a result of kallar grass growth. Maximum reductions in Cl^-, SO_4^{2-} and HCO_3^- were observed after five years of cultivation as compared with controls. Ameliorative effects were more pronounced after three years of growing kallar grass. Cultivation of kallar grass enhanced leaching and interactions among soil chemical properties and thus restored soil fertility. Soil maintained the improved characteristics with further growth of the grass up to five years suggesting that growing salt-tolerant plants is a sustainable approach for biological amelioration of saline wastelands.

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