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Mechanism of clay skin formation and higher B horizon clay content in alkali soils of the semi-arid sub-tropical India

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ABSTRACT:

Large areas in the plains of Indus and Ganges rivers are sodic in nature. In these plains alkali soils occur in patches along with normal (non-alkali) soils in the immediate vicinity. In spite of alkali soils having very poor water transmission characteristics, clay skins are present in both alkali and adjoining normal soils. In alkali soils A horizon has lower clay content than B horizon. However, clay content of the B horizon of alkali as well as adjoining normal soil is almost identical. In order to determine the genesis of clay skins and apparent higher clay content in B horizon, three alkali soils and one adjoining non alkali soil were investigated. Uniformity of parent material of alkali and adjoining normal soils has been indicated through mineral assemblage studies using XRD. Increase in K_2O content of sand and silt fraction with depth indicated lack of in-situ clay formation in B horizon. Absence of decreasing SiO_2 to R_2O_3 ratio in clay fraction of alkali soils and non alkali soil, and lack of total clay to fine clay ratio maxima in the B horizon of alkali soil suggest absence of clay migration in these soils. Occurrence of large number of argillans, and infillings of pure clay in both A and B horizons of these soils suggest the origin of such coatings to be a process other than leaching of clay. Micromorphological investigation indicating presence of pure clay argillans and clay fillings support erosion in A horizon leading to loss of clay. Large scale fluctuations in ground water table, together with ustic soil moisture-regime resulted in deposition of dispersed clay locally on the peds of both alkali as well as normal soils of this region.

INTRODUCTION

Geologically, Indian subcontinent comprises of two parts viz: mountainous region of the Himalayas -the extra-Peninsula and Peninsula. The extra-Peninsula creating the northern parts of India has endured under saline waters of ocean for greater part of the earth history and has thus been covered by succeeding marine deposits [32]. In between the extra Peninsula and Peninsula lie the great alluvial plains of the Indus and Ganges rivers system. North-west India which form a part of these alluvial plains is formed mainly from the debris of extra-Peninsula, which has earlier remained beneath saline waters of Tethyan sea.

There are about 7.4 m ha of salt affected soils in India of which 2.8 m ha are affected with varying degree of sodicity. Of the total alkali soils about 75 per cent of these are concentrated in alluvial plains of the Indus and Ganges rivers. Geologically these plains are of recent origin. Soil moisture regime in general is Ustic. Soils mainly belong to Entisol and Inceptisol orders. In these soils alkali feldspars have been observed to be highly stable at the prevailing pH and soil solution composition [20]. These soils have high pH (9.5 to 10.8 in 1:2 soil water suspension), very high exchangeable sodium percentage (70 to 97), high electrical conductivity and are always clacareous. B horizons of these soils have been considered argillic on the basis of higher clay content and due to the presence of field identifiable clay skins [4,16] or void argillans [12,27]. Illuviation of clay in the sodic environment has been suggested as the mechanism for the enrichment of B horizon and presence of clay skins [19]. Mostly these alkali soils have been classified as Natrustalfs, whereas the normal soils (non alkali) in the immediate vicinity are classified as Typic Ustochrepts [5]. After preparation of resource inventories, large scale reclamation of alkali soils with gypsum was undertaken during nineteen seventies. Since then these are producing bumper crops of rice and wheat. During 1990-1995 we re-examined the alkali as well as the reclaimed alkali soils in this region. Even after 20 years of reclamation soils were still alkali in the sub-surface horizons. This paper attempts to divulge on the genesis of clay skins, clay eluviated A horizon and clay rich B horizon in these alkali soils with very poor water transmission characteristics. A comprehensive analytical approach encompassing ground truth, detailed morphological, physical, chemical, micromorphological data and mineralogical and elemental composition has been made to rule out the contribution of illuviation process in the formation of clay rich B horizon and presence of clay skins in the alkali as well as adjoining normal soil (non-alkali).

MATERIALS AND METHODS

Site characteristic

This study was conducted at the research farm of the Central Soil Salinity Research Institute (CSSRI), Karnal, India, having an elevation of 245 m and located at a longitude of $76^{o}57'$E and latitude of $29^{o}42'$N. Climate of the area is semiarid and subtropical, with an average yearly rainfall of around 711 mm, about 90 per cent of which is received during July to September. These soils qualify for hyperthermic temperature regime. The present investigation was carried on four typical sites of a benchmark soil series-the Zarifa Viran, classified as Typic Natrustalf [16]:

(i) Fenced alkali soil: An original alkali soil, which has been set aside and fenced for around twenty years. Earlier this site was barren but at present it supports luxurious perennial grasses.

(ii) Occasionally cultivated alkali soil: This site was cultivated infrequently once to twice in a year to get rid of weeds.

(iii) Reclaimed alkali soil: In this treatment reclamation was introduced twenty years ago with application of gypsum. Rice-wheat crop rotation is followed every year since then.

(iv) Normal soil: This site is non-alkali (normal) and is under cultivation with irrigation for more than ninety years.

All the sites were within 500m to 700m of each other.

Analytical techniques

Soil profiles were exposed in the field upto about 1.5 m depth. Horizons were demarcated in each profile on the basis of soil characteristics such as color, texture, structure, mottling, reaction, and concretions etc. Macro-morphological description for each profile was studied as per methodology of Soil Survey Division staff [31]. After exclusion of soluble salts, organic matter, carbonates and free iron oxides from the soil, the sand (2000-50µm), silt (50-2µm) and clay (<0.2µm) were separated according to size segregation procedure of Jackson [10]. Soil texture was estimated with the help of USDA soil textural diagram. Hydraulic conductivity was determined on disturbed soil samples [6]. Moisture retention at 0.03 MPa and 1.5 MPa was determined with pressure plate apparatus [24]. Bulk density of the clods was calculated from their mass and volume. Volume was determined by immersing wax coated clods in a specially designed apparatus.

The electrical conductivity and pH of the soil samples were measured in 1:2 soil: water suspension and designated as pH_2 and EC_2 respectively. Organic carbon was estimated by using Walkley and Black's titration method [33]. Calcium carbonate was determined by acid neutralization method of Williams [34] using a calcimeter.

Positive and negative ions in the saturation extract were determined following the recommended procedures. The pH of soil paste (pH_s) and EC of saturation extract (EC_e) were also measured. Saturation paste was prepared according to the procedure outlined by Rhoades [25]. Cation exchange capacity was determined by the procedure recommended for calcareous and sodic soils [3].

For elemental analysis, soil was digested with HF in a closed vessel as recommended by Jackson [10] and Si and Al were determined colorimetrically by molybydosilicate yellow color and aluminon-accetate buffer methods, respectively. Other elements: Na, K, Ca, Mg and Fe were determined by directly feeding the solution on atomic absorption spectrophotometer.

The clay fraction was exposed to X-ray diffraction (XRD) analyses of parallel oriented slide mounts after Mg saturation and Mg-glycolation with ethylene glycol, K saturation and K saturation with heat treatment at 350^{o}C and HCl treatment using a Philips diffractometer with Ni filtered CuK$\propto$ radiation and a scanning speed of 2^{o}2min^{-1}. Semiquantitative estimates of the clay minerals were made following the procedure of Gjems [7].

RESULTS AND DISCUSSION

Soil characteristics

Color of the soils when moist, was dominantly dark yellowish brown (Table 1). Soil texture was dominantly loam with sandy loam in the epipedon of some of the pedons. Soil structure was mostly medium to coarse, moderate to strong, sub angular blocky. Broken cutans ranging from thin patchy to thin were present in the horizon immediately below Ap and in the B horion of all the pedons including the normal soil.

As compared to A horizon, clay content is higher in the B horizon. This difference is more pronounced in alkali soils as compared to the adjoining normal soil. Whether this apparent higher clay content in B horizon is due to illuviation of clay from surface to sub-surface horizons or due to washing out of finer particles from surface horizon is discussed in a subsequent section on clay distribution. Alkali soils have poor transmission characteristics (Table 3). Hydraulic conductivity of all the horizons of alkali soils is almost zero (<0.003µms^{-1}), exception being surface horizon of fenced alkali soil (5.850µms^{-1}). It was due to the self-reclamation by consistent vegetative cover. Reclaimed alkali soils and adjoining normal soil had good water transmission characteristics. The pH_2 of alkali soils, ranged from 8.8 to 10.8 (Table 2). As expected, pH_2 of reclaimed alkali soil and adjoining normal soil was comparatively lower. ESP of alkali soil varied between 52 and 89 with the exception of the surface horizon of fenced alkali soil where it was 12 only. Reclaimed alkali and normal soils had lower ESP values in the range 10-18 and 5-9 respectively. A comparison of ESP (Table 2) and hydraulic conductivity data (Table 3), shows that the ESP adversely affects the water transmission characteristics in these soils. Higher the ESP, the lower is the hydraulic conductivity. Study of ionic composition indicated the dominance of Na^+ and Mg^{++} among the cations and, HCO_3^- and Cl^- among the anions in the three alkali soils (Table 4).

Uniformity of parent material

Zarifa Viran benchmark soil is a part of the vast alluvial plain formed by the Indus and Ganges rivers. To understand the mechanism of clay skin formation and apparent bulge in the clay content of the B horizon as compared to A horizon, it is necessary to first establish the uniformity of parent material of alkali as well as normal soil. X-ray diffraction investigation of clay fraction (<2µm) of these soils showed almost similar amounts of micas, 1.0-1.4 nm mixed layer minerals, smectite, kaolinite, chlorite, vermiculite and small amounts of quartz, feldspars and amphiboles (Table 5). The 1.0 nm peak of mica is more asymmetrical and broader towards low angle in the clay fraction. As such most of these minerals are inherited from different geological formations existing in the catchment [20]. Almost identical mineral assemblage of alkali soils and adjoining

Table 6: Na_2O content of sand fraction and pH of saturation paste

Pedon	**Na_2O* (g kg^{-1})**	**pH_s ***
Fenced alkali soil	21.0	9.80
Occasionally cultivated alkali soil	20.4	9.60
Reclaimed alkali soil	20.8	8.57
Normal soil	20.9	7.46

*weighted average for profile

normal soil do not suggest in-situ formation or transformation of clay as a result of pedogenic activity. Uniformity of parent material of these pedons is further substantiated by almost identical Na_2O content of sand fraction of all the soils even though saturation paste pH_s varied from 7.46 to 9.80 (Table 6). Na_2O content of sand fraction represents the alkali feldspars which has been used as the index mineral for establishing the uniformity of parent material [2].

Clay distribution as a function of depth:

Depth-wise distribution of clay in three alkali soils (Table 7) only literally satisfies the criteria for argillic diagnostic horizon as laid down in Soil Taxonomy [30]. But, an apparent increase in clay content with increasing depth is, in itself, not an evidence of clay movement vis-a-vis an argillic horizon [30]. Based on decreasing clay mica distribution, [4,18] reported the presence of clay illuviation vis-a-vis argillic/natric horizon in the alkali soils of north-west India. However, decreasing trend in clay mica distribution has been observed in most of the normal [27] and alkali soils [21,22] of the Indus plains. In these vast alluvial plains of Indus and Ganges rivers, alkali soils exist in patches and normal soils occur in the immediate vicinity. Most of the earlier studies describe the genesis of alkali soils without taking into account the characteristics of adjoining normal soils and ignoring their genesis from the same alluvium. Point for investigation here is - whether the clay has actually moved from epipedon to B horizon in these alkali soils having almost nil hydraulic conductivity. Poor transmission characteristics of these alkali soils have been discussed in detail [1]. Whether the movement of clay is vertical or horizontal (run off), can be best understood by comparing the clay distribution of alkali soils with the adjoining normal soil (up to 1 m). Clay content of the alkali soils in the A horizon (20 cm depth) is around 8 per cent and that of the adjoining normal soil is around 16 per cent. However, in the B horizon the clay content of alkali and normal soil is similar (21-22 per cent). These soils occur in micro-depression type topography. It appears that beating action of rain coupled with high sodium in the A horizon resulted in the finest particles being carried away through runoff resulting in net loss of clay from A horizon. Loss of clay including fine clay from A horizon by runoff will be significantly higher in alkali soils as compared with the adjoining normal soil. For a given rainstorm in this Zarifa Viran benchmark soil, runoff volume from an unreclaimed alkali soil was four times as high as from a reclaimed alkali soil [29]. Thus, it is the loss of clay from A horizon by eluviation and not the movement of clay by illuviation which results in apparent higher clay in B horizon of alkali soils. Higher loss of clay including fine clay from the epipedon of sodium rich alkali soils also explains the relatively higher content of clay mica in surface horizon of these soils [11,17].

Distribution of K_2O

Micas and potassium feldspars are the common potash bearing minerals present in these soils. In the sand and silt fractions, K_2O content, in general, increased with depth. Such a K_2O distribution in these alkali and normal soils rules out the possibility of clay formation in B horizon at the expense of micas. In clay fraction there is a general decrease in K_2O content with depth in the three alkali soils. Based on such a K_2O distribution in alkali soils [19] suggested clay illuviation as a mechanism for higher clay content in B horizon, however these authors did not take into account a similar K_2O distribution in the adjoining normal soil. Such a K_2O distribution with depth is a common feature in all the Entisols and Inceptisols of Indo-Gangetic plains [27,28]. Moreover, these alkali soils have very high ESP resulting in possible sealing of micropores by dispersed clay leading to almost zero hydraulic conductivity. Thus, free percolation of water which is a pre-requisite for the formation of argillic horizon is lacking in these soils. Had it been so, the adjoining normal soil as governed by similar factors and processes of soil formation and under irrigated cultivation for more than eight decades would have been the first to show the characteristics of an argillic horizon. Moreover, it is a known fact that crop roots mine K from sub-surface horizon in excess of their requirement and clay fraction of the soil is responsible for replenishment of soil solution K following its removal by plants, resulting in lower K_2O content of sub-surface horizon [8,9].

The SiO_2 to R_2O_3 ratio

Clay formation affects mostly the content of alkali and alkaline earth metals, whereas clay migration affects the silica and sesqui-oxide content of the parent material [2]. Clays have lower SiO_2 to R_2O_3 (Fe_2O_3 + Al_2O_3) ratio than the silt and sand fractions (Table 7). The SiO_2 to R_2O_3 ratio of fine earth in these pedons is lower in the B horizon. This is attributed to relatively higher clay concentration in the B horizon as compared to A horizon. However, SiO_2 to R_2O_3 ratio of clay fraction do not show any definite change. Any migration of fine clay into B horizon should have led to a decrease in SiO_2 to R_2O_3 ratio of clay fraction also [30]. Lack of clay migration is also evident from the absence of total clay to fine clay ratio maxima in B horizon of alkali soils (Table 7). This shows that relatively higher clay content in B horizon is not due to clay migration from the epipedon.

Formation of clay skins

Thin patchy clay skins are present in all the three alkali soils and in the adjoining normal soil. Micromorphological investigation in this Zarifa Viran benchmark soil by Kooistra [13] show the occurrence of large number of argillans and infillings of pure clay not only in B horizon but also in A horizon. Investigator suggested such clay coatings in soils with high sodium due to a separate process instead of pure clay illuviation. Further, the occurrence of argillans and infillings of pure clay in top soil, micromorphologically confirms erosion in A horizon [14].

Under ground water table in the study area had been fluctuating from 0.3 m to 3.0 m depending upon the season [5]. It seems quite probable that upon hydration, clay got dispersed locally under sodic environment, which upon dehydration, as controlled by evapotranspiration demand, got flocculated and deposited at the site of dispersion itself. Thus, the fluctuating ground water table could have played a major role in the formation of these argillans as these are also present in large amounts in adjoining normal soil- a Typic Ustochrept [5]. Therefore, these cutans may be better termed as flood cutans only.

CONCLUSIONS

Alkali soils have very high ESP and almost zero hydraulic conductivity. X-ray diffraction and index mineral studies confirm the uniformity of parent material of alkali as well as adjoining normal soils. Apparent higher clay content in B horizon of alkali soils is due to loss of clay from A horizon by eluviation and not due to downward movement of clay (illuviation). B horizon clay content of alkali and adjoining normal soil is similar. Depth-wise distribution of K_2O and SiO_2 to R_2O_3 ratio further supports these observations. Thin patchy clay skins are present in alkali and adjoining normal soils in both A and B horizons. Micro-morphological investigations show these to be infillings of pure clay only, confirming erosion in A horizon. Fluctuating ground water table, under high evapotranspiration demand and dominance of sodium on the exchange complex seem to be responsible for the formation of these localized flood cutans.

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TABLE 1 Morphology of the soils

Depth (cm)	Horizon	Colour (moist)	Mottling	Texture (USDA)	Structure	Consistence (wet)	Cutans	Roots	Coarse Fragments	Reaction with HCl
Fenced alkali soil										
0-8	`	2.5Y 6/4	-	sl	1m,sbk	wss,wpo	-	m,f	-	0
8-18	AB	2.5Y 6/4	-	sl	2m,sbk	wss,wpo	-	mf	-	1
18-33	B1	10YR 5/4	-	sl	2m,sbk	ws,wp	-	c,f	-	2
33-58	B21	10YR 5/4	-	l	2m,sbk	ws,wp	p,tn	c,f	-	3
58-81	B22	10YR 6/4	-	l	3m,sbk	ws,wp	p,tn	c,f	-	4
81-`117	B3	10YR 6/4	-	l	3m,sbk	ws,wp	-	c,f	conir,f	2
117-152	B22	10YR 6/4	-	sl	3m,sbk	ws,wp	-	-	-	3
Occasionally cultivated alkali soil										
0-13	Ap	2.5Y 5/2	-	sl	2m,sbk	wso,wpo	-	c,f	-	1
13-25	AB	2.5Y 5/2	-	l	1f,pl	wss,wpo	-	c,f	-	2
25-56	B21	2.5Y 5/4	-	l	2m,sbk	ws,wp	-	f,f	conir,m	2
56-89	B22	10YR 5/4	-	l	2m,cr	wvs,wvp	b,tn	f,f	-	2
89-119	B23	10YR 5/4	-	l	2m,cr	wvs,wvp	b,tn	-	Conir,m	2
119-135	B3	10YR 5/4	-	l	2m,sbk	wvs,wvp	-	-	-	3

135-155	C	10YR 5/3	-	l	2m,sbk	wvs,wvp	-	-	Conca,c-	4
Reclaimed alkali soil										
0-20	Ap	2.5Y 4/2	-	l	2m,sbk	ws,wp	-	f,f	-	3
20-41	B21	10YR 5/4	-	l	2m,sbk	ws,wp	p,tn	f,f	Conir,m	3
41-73	B22	10YR 5/4	7.5YR5/8 3f,fn,ft	l	2m,sbk	ws,wp	-	-	Conir,m	3
73-100	BC	10YR 5/4	-	sl	2m,sbk	wss,wsp	-	-	Conca,c	4
100-148	C	10YR 5/4	-	sl	massive	wss,wsp	-	-	Conca,c	5
Normal soil										
0-16	Ap	10YR 5/2	-	l	1m,sbk	ws,wp	-	f,vf-f	-	0
16-37	B1	10YR 4/3	-	l	1m,sbk	ws,wp	p,tn	f,f	-	0
37-66	B21	10YR 4/4	-	l	2m,sbk	ws,wp	p,tn	-	-	0
66-99	B22	10YR 4/4	-	l	2m,sbk	ws,wp	p,tn	-	-	0
99-125	B3	10YR 5/4	-	l	2m,sbk	ws,wp	p,tn	-	Conir,m	0
125-160	BC	10YR 5/4	-	l	1m,sbk	ws,wp	-	-	-	0

TABLE 2: Physico-chemical characteristics of the soils

Depth (cm)	Hori-zon	pH_2	EC (dS m^{-1})	O.C. g kg^{-1}	$CaCO_3$ g kg^{-1}	Sand	Silt	CEC ($cmol_c$ kg^{-1})	ESP
Fenced alkali soil (coarse loamy Typic Ustochrept)									
0-8	A1	8.8	0.44	6.0	-	69.6	25.3	5.6	12
8-18	AB	10.4	1.19	0.8	5.5	57.7	32.6	8.6	73
18-33	B1	10.6	2.25	0.9	3.0	55.5	33.9	11.6	83
33-58	B21	10.8	3.83	0.6	6.3	50.6	31.0	13.3	90
58-81	B22	10.7	3.47	0.6	6.7	47.2	33.1	14.4	93
81-117	B3	10.6	2.92	0.6	3.2	48.6	34.8	13.4	93
117-152	BC	9.7	1.83	0.5	15.9	61.8	26.7	11.6	45
Occasionally cultivated alkali soil (coarse loamy Typic Ustochrept)									
0-13	Ap	9.9	0.55	2.2	8.3	55.2	37.2	6.4	52
13-25	AB	10.4	1.59	0.5	10.0	51.3	40.7	7.1	61
25-56	B21	10.5	2.19	0.8	15.0	43.5	37.9	13.3	86
56-89	B22	10.6	2.37	0.6	13.7	32.5	45.8	15.4	90
89-119	B23	10.5	2.01	0.2	12.0	36.8	40.8	15.1	89
119-135	B3	10.3	3.00	0.5	28.0	36.6	44.3	15.3	85
135-155	C	10.3	2.01	0.3	37.8	47.5	38.7	11.8	80
Reclaimed alkali soil (coarse loamy Typic Ustochrept)									
0-20	Ap	8.7	0.38	3.1	31.6	42.0	49.1	7.3	12
20-41	B21	8.9	0.46	0.5	26.1	35.5	45.5	14.7	10
41-73	B22	9.3	0.57	0.2	18.7	38.8	39.9	14.1	18
73-100	BC	9.3	0.37	0.3	67.4	44.1	48.4	4.3	11

100-148	C	9.3	0.39	0.5	97.5	59.6	30.4	5.8	16
Normal soil (fine loamy Udic Ustochrept)									
0-16	Ap	8.6	0.82	5.2	-	46.6	43.6	11.2	9
16-37	B1	8.6	0.48	2.8	-	34.7	45.2	13.4	8
37-66	B21	8.5	0.38	2.4	-	38.4	39.8	12.8	7
66-99	B22	8.5	0.37	1.8	-	36.1	40.0	13.1	6
99-125	B3	8.4	0.35	1.4	-	36.2	39.2	15.3	5
125-160	BC	8.3	0.86	1.0	-	43.4	37.2	17.4	5

TABLE 3 : Some physical characteristics of the soils

Depth (cm)	Coarse fragments %	Water content (kg kg^{-1}) 0.03 Mpa	1.5Mpa	Available	Bulk density Mg m^{-3}	Hydraulic conductivity µm s^{-1}
Fenced alkali soil (coarse loamy Typic Ustochrept)						
0-8	-	0.173	0.052	0.121	1.54	5.850
8-18	-	0.201	0.091	0.110	1.66	<0.003
18-33	-	0.210	0.108	0.102	1.70	"
33-58	-	0.228	0.132	0.096	1.67	"
58-81	-	0.246	0.131	0.115	1.78	"
81-117	<1	` 0.247	0.157	0.090	1.90	"
117-152	<1	0.215	0.112	0.103	1.81	"
Occasionally cultivated alkali soil (coarse loamy Typic Ustochrept)						
0-13	-	0.190	0.081	0.109	1.59	<0.003
13-25	-	0.205	0.105	0.100	1.77	"
25-56	-	0.245	0.178	0.067	1.88	"

56-89	-	0.265	0.187	0.078	1.83	"
89-119	2	0.291	0.203	0.088	1.74	"
119-135	6	0.291	0.208	0.083	1.69	"
135-155	38	0.264	0.177	0.087	1.74	"

Reclaimed alkali soil (coarse loamy Typic Ustochrept)

0-20	-	0.244	0.084	0.160	1.75	2.072
20-41	3	0.235	0.110	0.125	1.63	2.188
41-73	13	0.251	0.159	0.092	1.89	0.008
73-100	32	0.254	0.093	0.161	1.88	1.758
100-148	26	0.235	0.064	0.171	1.58	3.327

Normal soil (fine loamy Udic Ustochrept)

0-16	-	0.246	0.097	0.149	1.75	2.011
16-37	-	0.255	0.122	0.133	1.69	1.333
37-66	-	0.250	0.134	0.116	1.75	1.266
66-99	-	0.244	0.133	0.111	1.79	1.172
99-125	<1	0.253	0.136	0.117	1.54	1.516
125-160	-	0.287	0.105	0.182	1.78	2.558

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TABLE 4:Ionic composition of the saturation extract of soils

Depth (cm)	Satura-tion (%)	pH_s	EC_e dS m^{-1}	Saturation extract analysis (m mol_c L^{-1}) Na^+	Mg^{++}	Ca^{++}	K^+	CO_3^{--}	HCO_3^-	Cl^-	SO_4^{--}	SAR
Fenced alkali soil (coarse loamy Typic Ustochrept)												
0-8	38	8.4	1.8	8.8	3.0	1.5	0.21	1.0	7.4	7.0	1.0	4
8-18	28	9.5	2.9	21.2	3.0	2.5	0.14	1.4	16.1	8.0	3.0	9
18-33	26	10.3	6.6	53.7	5.5	3.0	0.07	19.6	16.8	10.0	3.0	18
33-58	33	10.4	11.9	139.7	2.0	6.0	0.07	37.6	39.2	28.0	4.0	49
58-81	37	10.3	11.1	118.3	2.5	2.0	0.08	30.6	28.2	20.0	5.5	56
81-117	42	10.2	3.6	26.2	1.5	2.0	0.07	4.2	18.2	7.0	1.0	14
117-152	39	8.9	2.9	22.4	2.5	1.5	0.08	0.7	6.3	10.0	7.0	16
Occasionally cultivated alkali soil (coarse loamy Typic Ustochrept)												
0-13	29	9.1	0.8	5.9	1.0	2.0	0.13	0.0	6.8	4.0	-	3
13-25	25	9.6	3.1	22.4	3.5	2.5	0.23	2.8	14.7	11.0	1.0	9
25-56	30	9.7	4.5	36.7	1.5	4.5	0.08	8.4	19.6	10.0	-	15
56-89	34	9.8	4.6	42.2	2.0	3.0	0.28	11.2	12.6	12.0	-	19
89-119	38	9.6	2.9	22.6	3.5	2.5	0.05	2.8	9.1	8.0	5.0	8
119-135	39	9.7	4.1	35.5	4.0	2.0	0.08	5.6	13.3	14.0	6.0	15
135-155	40	9.5	3.6	28.8	0.5	2.5	0.05	5.6	5.6	11.0	5.5	16
Reclaimed alkali soil (coarse loamy Typic Ustochrept)												
0-20	37	8.4	1.5	3.1	4.5	2.0	0.14	0.7	9.5	1.0	0.6	46
20-41	39	8.2	1.3	2.1	2.0	3.0	0.03	0.0	3.5	4.0	3.0	1
41-73	39	8.7	1.5	7.3	3.0	1.5	0.03	1.4	6.3	3.0	1.5	3
73-100	38	8.6	0.9	3.1	2.0	1.5	0.08	0.0	3.5	4.0	0.5	2
100-148	37	8.7	1.2	3.1	4.0	1.0	0.04	0.0	4.2	3.0	3.0	1

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Normal soil (fine loamy Udic Ustochrept)												
0-16	35	8.2	1.5	4.7	8.0	5.0	0.17	0.0	6.8	8.4	1.0	2
16-37	40	8.2	1.5	5.1	8.0	3.0	0.11	0.0	7.0	8.0	2.0	2
37-66	35	7.6	1.2	3.0	6.0	2.0	0.04	0.0	4.2	6.0	2.0	2
66-99	39	7.6	1.3	4.2	7.0	2.0	0.04	0.0	4.2	5.0	4.0	2
99-125	42	7.6	0.9	3.0	3.0	2.0	0.03	0.0	4.9	5.0	1.0	2
125-160	40	7.6	1.1	3.3	4.0	3.0	0.03	0.0	4.9	4.0	0.0	2

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Table 5:Semi-quantitative estimates (%) of clay minerals

Depth (cm)	Smectite	Chlorite	Vermic-ulite	Illite	Mixed layer	Kaol-inite	Quartz	Feldspar	Amphi-bole
Fenced alkali soil (coarse loamy Typic Ustochrept)									
0-8	7	7	4	61	8	8	tr	3	2
58-81	9	5	7	59	7	8	tr	3	2
Normal soil (fine loamy Udic Ustochrept)									
0-16	7	5	2	64	11	8	tr	1	2
66-99	8	4	3	66	10	6	1	1	1
125-160	11	4	3	62	11	7	tr	1	1
Reclaimed alkali soil (coarse loamy Typic Ustochrept)									
0-20	8	10	4	58	9	8	tr	1	1
41-73	11	9	4	57	8	8	tr	2	1
100-148	16	10	4	52	8	7	tr	2	1

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TABLE 6 Changes in soil characteristics due to differential management of an alkali soil

Soil Characteristics	CSSRI-fenced alkai		CSSRI-alkali		CSSRI reclaimed alkali		CSSRI normal	
	1972	1992	1972	1992	1972	1992	1972	1992
Surface horizon								
pH_s	9.0	8.4	10.6	9.1	10.5	8.4	7.9	8.2
EC_e	102.3	1.8	22.3	0.8	19.8	1.5	0.9	1.5
Cations	Na	Na, Mg	Na	Na,Ca	Na	Mg,Ca	Na,Ca	Mg,Ca
Anions	CO_3, HCO_3, Cl	CO_3,HCO_3 Cl	CO_3,HCO_3,Cl	CO_3,HCO_3,	CO_3,HCO_3 Cl	HCO_3, Cl	HCO_3, Cl	HCO_3, Cl
ESP								
Sub surface horizons								
pH_s	9.5-10.3	9.7-8.6	10.2-9.6	9.8-9.5	10.5-9.4	8.2-8.7	8.1-8.5	8.2-7.6
EC_e	2.9-11.9	6.0-0.9	6.3-1.3	3.1-4.6	11.0-0.9	1.3-0.9	0.5- 1.0	1.5-0.9
Cations	Na	Na	Na	Na	Na	Mg,Ca	Na,Ca	Mg,Na,Ca
Anions	CO_3, HCO_3, Cl	CO_3,HCO_3 Cl	CO_3,HCO_3,Cl	CO_3,HCO_3,Cl	CO_3,HCO_3 SO_4,Cl	HCO_3, SO_4,Cl	HCO_3, SO_4,Cl	HCO_3, SO_4,Cl
ESP	24-92	45-93	69-91	61-80	25-96	10-18	11-17	5-8

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TABLE 7: SiO_2 to R_2O_3 and fine clay to total clay ratios in the soils

Depth (cm)	Fine earth fraction (<2mm)				Clay %	Clay fraction (<0.002mm)				Fine clay / Total clay
	SiO_2	Al_2O_3	Fe_2O_3	SiO_2 / $Al_2O_3+Fe_2O_3$		SiO_2	Al_2O_3	Fe_2O_3 / $Al_2O_3+Fe_2O_3$	SiO_2	
Fenced **alkali soil (coarse loamy Typic Ustochrept)**										
0-8	80.0	8.2	2.47	7.49	5.1	51.0	24.2	8.12	1.57	-
8-18	77.5	9.6	2.79	6.26	9.7	49.5	23.5	7.94	1.57	-
18-33	77.0	9.9	2.94	5.99	10.6	51.9	22.2	8.08	1.71	-
33-58	74.9	11.1	3.16	5.25	18.4	52.3	23.4	7.70	1.68	-
58-81	74.1	11.5	3.55	4.92	19.7	53.2	21.7	7.80	1.80	-
81-117	75.0	11.0	3.89	5.04	16.6	53.2	22.1	7.72	1.78	-
117-152	77.7	9.4	3.06	6.23	11.5	51.5	21.5	7.71	1.80	-
Occasionally cultivated alkali soil (coarse loamy Typic Ustochrept)										
0-13	78.1	8.8	2.83	6.71	7.6	49.5	22.9	8.49	1.57	0.31
13-25	78.0	9.1	3.19	6.34	8.0	48.6	23.8	8.56	1.50	0.33
25-56	74.4	10.9	3.94	5.01	19.6	50.9	22.5	8.08	1.66	0.32
56-89	73.0	11.8	4.04	4.60	21.7	49.2	23.1	8.00	1.58	0.28
89-119	72.2	11.6	4.30	4.54	22.4	49.1	23.4	7.55	1.58	0.29
119-135	73.9	11.2	4.36	4.74	19.1	52.9	22.2	7.56	1.77	0.25
135-155	76.2	10.0	4.19	5.36	13.8	51.8	23.9	7.38	1.65	0.23

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Reclaimed alkali soil (coarse loamy Typic Ustochrept)										
0-20	74.7	10.7	3.33	5.32	8.9	52.3	22.2	7.77	1.74	-
20-41	71.8	12.2	3.82	4.48	19.0	50.3	23.1	7.66	1.63	-
41-73	71.7	12.2	4.50	4.29	21.3	51.8	22.9	7.12	1.72	-
73-100	73.2	10.4	4.36	4.96	7.5	49.2	23.4	6.47	1.64	-
100-148	72.4	9.5	4.06	5.34	10.0	50.1	23.1	6.52	1.69	-
Normal soil (fine loamy Udic Ustochrept)										
0-16	74.6	11.5	3.22	5.06	15.8	52.1	22.2	8.68	1.69	-
16-37	72.8	12.4	3.49	4.58	20.1	51.6	22.5	7.92	1.70	-
37-66	77.9	12.2	3.80	4.89	21.8	51.5	22.8	7.61	1.69	-
66-99	72.2	12.6	3.89	4.37	23.9	51.9	23.1	7.35	1.70	-
99-125	70.9	12.2	4.20	4.32	22.6	52.7	22.7	6.77	1.79	-
125-160	73.9	11.6	3.95	4.75	19.4	51.7	22.5	7.08	1.74	-

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