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Characteristics of major soils of Banni mudflat in arid western India and their relationship with topography

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Studies on the soil properties of the apparently flat-lying, but salt-affected Banni mudflat region of arid Kachchh in western India revealed the influence of subtle topographic variations on soil texture and nature and distribution of salts. Six master pedons were investigated to an average depth of 150 cm. The pedons on the upper surfaces showed an abundance of fine sand and a gradual impoverishment of silt and clay, as also lesser amounts of salts in the profiles. Pedons on the successively lower surfaces showed more silt and clay contents, as well as higher amounts of salts. The findings helped to identify the areas suitable for pasture development in this vast degraded rangeland, and to suggest some management practices for improvement.

Keywords: Mudflat; topography; soils; physico-chemical characters; salt composition; fertility; management needs

Introduction

The Banni is a huge mudflat that lies in the arid western part of India. It is also a vast degraded rangeland that traditionally was a dependable grassland for cattle rearers in the Kachchh region. Over 2525 km^2 in area, it is bounded to the north by the marshy salt flat of the Great Rann of Kachchh and the rocky Pachham island. The southern boundary is defined by the Kachchh mainland (Fig. 1). Rainfall in the area is erratic and low (mean 288 mm), with a coefficient of variation between 60 and 80%. More than 80% of the rains come during the monsoon from June to September. The maximum summer temperature varies from 42° to 44°C, but it sometimes reaches 47°C. Average winter temperature is ~ 11°C, but often dips down to freezing point. The annual evapotranspiration is 1887 mm and relative humidity between 50 and 60% (Rao *et al.*, 1996). Groundwater in the Banni is highly saline (> 8 dS m^{-1}). This, together with the high salinity of the soils over large areas, precludes crop production anywhere in the Banni, but a number of shrubs and grasses grow in selective areas. The nearest opening to the Arabian Sea is from the western end, via the Great Rann of Kachchh and the Kori Creek.

The thick Banni sediments were deposited in the tectonically disturbed northern margin of the Kachchh mainland under a fluvio-marine environment. A gradual uplift of the terrain and a recession of the Arabian Sea during the late Quaternary period has

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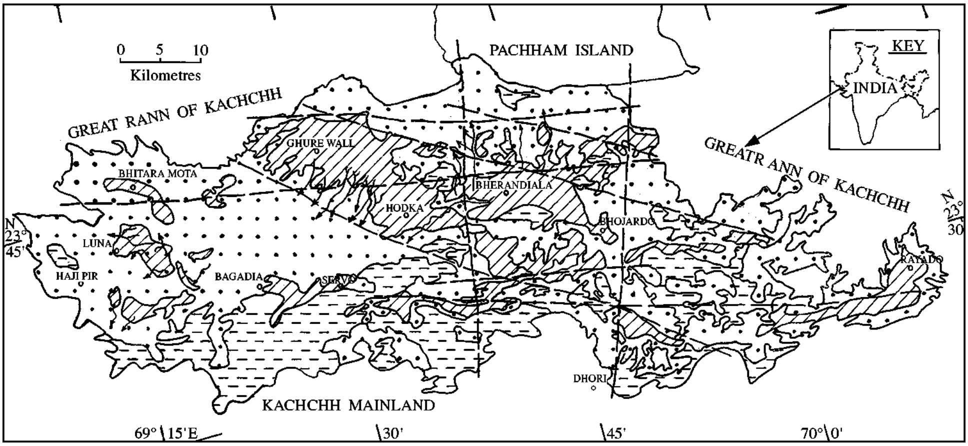

Figure 1. Banni mudflat: landforms. High-level mudflats (▨); mid-level mudflats (⊡); low-level mudflats with saline depressions (⊟); lineaments (◸); shallow gullies (◩).

brought much of the Banni beyond the tidal range of the sea, although its lower western margin is periodically flooded by tidal surges (Biswas, 1974; Kar, 1993*a*).

The aim of the present paper is to show how the soil properties in this apparently flat-lying mudflat terrain are related to topo-sequences, and the implications of this relationship for development activities.

Methods and materials

Subtle topographic variations across the Banni surface were enhanced through trend surface analysis of the height information provided in 1:50,000 scale topographical sheets (Kar, 1993*a*). Soils were identified at series level through auger hole and profile pit inspection at ~4-km-intervals, and mapping was done at 1:50,000 scale. The spatial extent of the identified soil series were checked from the tones provided in the standard False Colour Composites (FCCs) of large-scale satellite images of dry, cool seasons. Soil morphological characteristics were studied in field, following methodologies described in Soil Survey Staff (1951) and Anonymous (1971). Horizonwise soil samples from the master profiles of each series were air-dried and then analysed for particle size, physico-chemical characters, CEC and fertility status, following procedures in Piper (1950) and Jackson (1967). Salt composition, SAR and ESP were determined using procedures described by Richards (1954). The identified series level soils were taxonomically grouped according to the classifications of FAO (Anonymous, 1978) and USDA (Soil Survey Staff, 1975, 1994).

Results and discussion

Topographic variation

The elevation across the Banni ranges mostly from 2 to 10 m a.s.l. Although the gradient varies from 1 in 3000 to 1 in 6000, a fourth order trend surface analysis of the height information from topographical sheets revealed some east-west-oriented higher surfaces across the Banni, separated by lower surfaces. On the higher surfaces the slope is steeper towards the north and gentler to the south. Similar north-facing steeper slopes and south-facing gentle slopes occur repeatedly in the hilly terrain of the Kachchh mainland in the south and the Pachham island in the north at an amplified scale, and provide examples of a cuesta topography (Kar, 1988, 1996). Repeated earth movements along a series of east-west lineaments during the Tertiary and Quaternary periods were responsible for the development of cuesta topography in the mainland and Pachham island. The Banni mudflat was influenced by continued slow earth movement after it emerged out of a shallow marine environment during the Quaternary period (Biswas, 1971). As a result of such movement higher mean surfaces occur in Bherandiala-Bhojardo area. The increased gradient of the lower surfaces westward from this locality and association of the features with a set of N–S running fault systems through Bherandiala-Bhojardo and Pachham island suggested a gradual tilting of the land westward (Biswas, 1974; Kar, 1993*b*). Based on the trend surface analysis, slope configuration and tonal pattern on the satellite images, Banni area has been classified into the following landform units: (1) high level mudflat; (2) mid-level mudflat; and (3) low level mudflat (Kar, 1993*a*; Fig. 1).

Physical characteristics of the soils

Six major soil series have been identified in the Banni. These are: Bhojardo (Pedon 1, or P1); Bherandiala (P2); Dadhiya Mota (P3); Haji Pir, normal (P4); Haji Pir, water inundated (P5); and Saline depression (or Rann; P6). The last one (P6) is a very ill-developed soil on a stratified near-shore deposit of sand, silt and clay. The equivalent nomenclature of the soils under FAO and USDA systems of classification, as well as the extent and topographic locations of the soils are given in Table 1. The spatial distribution is shown in Fig. 2. The P1 and P2 soils occur in close proximity of each other, and are difficult to map as separate series. Therefore, these two soils have been mapped as an association feature. All the characteristics of the soils will be discussed here on the basis of one typical profile for each series, whose locations are shown in Fig. 2. The morphological characteristics of the soil profiles are summarised in a schematic diagram of the pedons along a N–S transect of land surface across the Banni (Fig. 3). The physico-chemical characteristics of the soils are provided in Table 2.

Table 1. *Soils of Banni mudflat, their extent and topographic location*

Soil classification			Pedon identifier	Area		Topographic location
Soil series	FAO	USDA		(Km^2)	(%)	
Bhojardo*	Cambic Arenosol	Coarse loamy, Typic Haplocambid	P1	581*	23·0*	High level mudflat
Bherandiala*	Calcic Yermosol	Coarse loamy, Typic Haplocalcic	P2			High level mudflat
Dadhiya Mota	Solonetz	Fine loamy, Typic Haplonetrargid	P3	562	22·2	Mid-level mudflat
Haji Pir, normal	Solonchack	Fine loamy, Typic Haplosalid	P4	769	30·5	Low level mudflat
Haji Pir, water inundated	Gleyic Solanchak	Fine, Typic Haploaquicsalid	P5	441	17·5	Low level mudflat
Saline depression	Gleyic Solanchak	Fine, Typic Haploaquicsalid	P6	172	6·8	Low level mudflat

*Soil association.

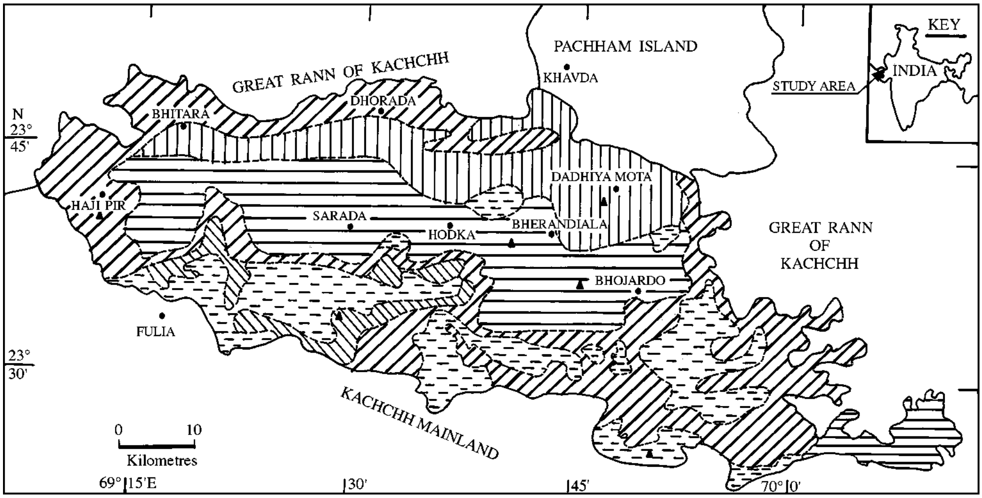

Figure 2. Soils of Banni mudflat. ▤; Bhojardo (P1) – Bherandiala (P2) Association: S-LS; ▥; Dadhiya Mota (P3): CL-SCL; ▨; Hajipir, normal (P4): SICL; ▧; Hajipir water inudated (P5): SICL-SIC; ⊟; Saline depression (P6): CL-SICL - SIC-C ▲; Sample location S: Sandy; LS: Loamy sand; SL: Sandy loam; CL: Clay loam; SCL: Sandy clay loam; SICL: Silty clay loam; SIC: Silt Clay; C: Clay

Bhojardo and Bherandiala series (P1 and P2, respectively) are developed on fine sand and silt, and have uniform 2·5 Y hue throughout the profile. These are also strongly calcareous throughout the profile. The $CaCO_3$ content increases with depth. P1 soils occur on the highest land surface, and have a loamy sand texture throughout the profile (Fig. 3), with very weak blocky structure. Silt and clay contents decrease down the profile, but fine sand and $CaCO_3$ contents increase with depth. P2 soils, on the other hand, are located at a slightly lower level (Fig. 3). These are dominantly silt loam, and have a weak subangular blocky structure. Although the silt and clay contents are higher

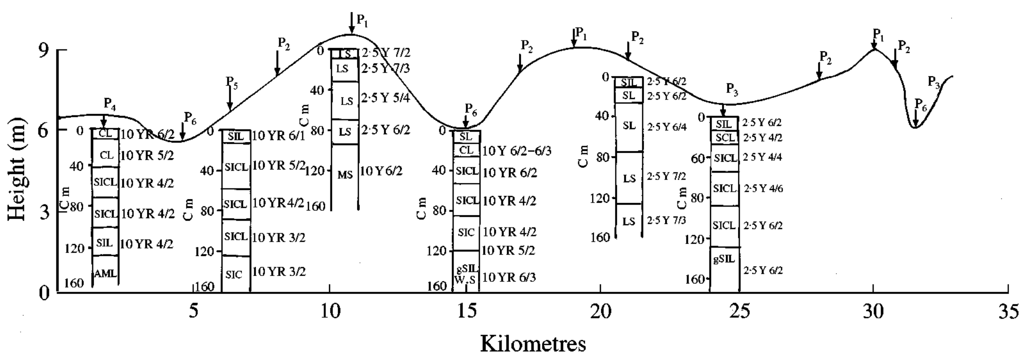

Figure 3. Schematic of Banni mudflat pedons along topo-sequence. (P_1) - Bhojardo Series (P_2) - Bherandiala (P_3) - Dadhiyamota (P_4) - Hajipir (normal) (P_5) - Hajipir (water inundated) (P_6) - Saline Depression. LS - Loamy sand, SL - Sandy loam, SIL - Silt, Loam, SICL - Silty Clay Loam, SIC - Silty Clay, g - Gravelly, AML - Amorphous Lime, W.S. - Water-Saturated, MS - Medium sand.

Table 2. *Physico-chemical characteristics of Banni mudflat soils*

Horizon		Depth (cm)	Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)	$CaCO_3$ (%)	ME (%)	pH (1:2)	EC $dS\ m^{-1}$	CEC C mol (P +) $kg\ ha^{-1}$
					Bhojardo (P1)						
A1		0–10	0·0	69·6	23·3	7·1	13·4	9·1	8·4	0·32	6·2
A2		10–35	0·0	79·5	11·8	8·7	10·8	7·1	8·6	0·29	4·8
C1		35–80	0·0	83·0	13·3	3·7	10·0	6·2	8·9	0·29	3·9
C2		80–105	0·0	88·0	9·4	2·6	17·9	6·7	9·0	0·31	2·6
C3			0·0	88·6	8·7	2·7	18·2	6·6	9·2	0·35	2·6
					Bherandiala (P2)						
A1		0–10	0·0	61·3	26·6	12·1	6·8	13·9	8·0	0·54	10·3
A2		10–30	0·0	64·7	23·9	11·4	12·1	11·5	8·4	0·46	8·4
AB		30–70	0·0	59·6	26·0	14·4	12·9	12·8	8·6	0·44	10·6
C1		70–130	0·0	73·0	21·6	5·4	18·7	9·3	8·7	0·68	6·6
C2		130–150	0·0	78·9	17·4	3·7	19·2	8·2	8·8	0·68	5·4
					Dadhiya Mota (P3)						
A1		0–15	0·0	43·3	32·2	24·5	0·8	20·8	8·5	5·38	21·0
B1		15–28	0·0	45·4	23·7	30·9	0·5	19·7	8·8	5·88	26·4
B21	tsa	28–65	0·0	28·1	38·3	33·6	15·0	17·8	9·1	2·18	31·2
B3	tsa	65–95	0·0	26·1	41·0	32·9	18·3	19·8	8·9	2·34	28·0
Ck	tsa	95–130	0·0	28·1	41·4	30·5	22·0	21·5	8·8	4·05	18·0
Ckm	tsa	130–150	0·0	32·8	42·8	24·4	26·5	21·0	8·8	3·50	16·0
					Haji Pir, normal (P4)						
A1		0–10	0·0	40·4	25·3	34·3	5·5	13·1	7·9	9·04	30·6
B1		10–30	0·0	39·6	23·6	36·8	9·1	18·0	7·8	6·50	32·0
B22	tsa	30–70	0·0	30·1	30·6	39·3	18·1	19·0	8·0	35·80	36·2
B23	tsa	70–100	0·0	37·1	33·6	29·3	22·8	22·0	8·0	29·80	24·6
Ck	tsa	100–160	0·0	39·6	34·1	26·3	27·9	21·0	8·4	27·80	23·3
					Haji Pir, water inundated (P5)						
A1	tsa	0–12	2·1	34·0	38·3	25·6	2·9	20·7	7·9	24·67	22·7
B1	tsa	12–60	0·4	32·7	37·6	29·3	6·3	28·9	7·9	19·02	27·6
B22	tsa	60–90	0·0	28·4	31·7	39·9	13·0	27·4	8·0	14·13	38·4
B23	tsa	90–130	0·2	33·6	31·8	34·4	21·9	28·0	8·1	13·20	34·2
Ckw		130–160	0·5	25·0	32·6	41·9	28·1	27·7	8·1	11·80	39·4
					Saline depression (P6)						
A1	tsa	0–12	24·8	21·6	28·8	24·8	2·5	14·0	8·2	34·20	8·8
C		12–25	28·5	20·7	24·9	25·9	3·4	18·4	8·0	31·19	9·0

than in the case of P1, these decrease down the profile, while fine sand and $CaCO_3$ contents increase. Both the profiles are non-saline to the examined depth of 150 cm, but are moderately sodic. The EC and pH increase with depth.

Dadhiya Mota (P3) soils occupy the mid-slope areas (Fig. 3), and have 2·5 Y hue in all the horizons, with minor variations in chroma. The texture varies from silt loam in the A horizon to silty clay loam down the profile, while the structure varies from platy, moderate angular blocky to prismatic, angular blocky in the same direction. The lower horizons show signs of illuvial clay accumulation and weak argillic characters. In contrast to the P1 and P2 profiles, both silt and clay fractions increase down the profile. Maximum clay accumulation is in B horizon, and silt in the ill-drained Ckm horizon.

Haji Pir, normal (P4) soils are found in the areas of lower relief, especially in the southern and western parts of Banni (Figs 2 & 3). These soils are strikingly different from the soils in upper slopes in that the colour varies from 10YR 3/2 to 10YR 6/2 throughout the profile, and the texture is clay loam in A horizon. It changes to silty clay loam and silt loam down the profile. The structure varies from moderately subangular blocky in the A horizon to strongly angular blocky and columnar in B and C horizons. The soils are moderately calcareous in the upper horizons, but have a very high content of amorphous lime in the subsoil.

Haji Pir, inundated (P5) soils occur dominantly in the west where a topographic low favours long period of flooding after the monsoon (Figs 2 & 3). The texture varies from silt loam to silty clay with moderate to strongly developed angular blocky structure. Otherwise, these soils are almost similar in character to the P4 soils. Both the pedons have a dominance of clay and silt. Carbonate content increases with depth. While B horizon contains the maximum clay, Ckm horizon has the maximum concentration of silt and calcium carbonate percentages.

The Saline depressions, occupying the lowest topographical positions in the Banni (Fig. 3), have a poorly developed soil (P6) on a stratified sequence of sand, silt and clay. The top 30 cm shows a faint sign of soil development, where the texture in A horizon ranges from silt loam to loam and sandy loam, and the colour is light greyish browm (10YR 6/1–6/2–8/2). This is usually followed by clay loam in the subsoil. Further down the profile, laminated deposits of coarse sand, silt loam and silty clay are noticed, with a dominance of silt and clay. Upon drying, the surface exhibits a salt-enriched platy structure with curled margins, bounded by polygonal cracks. Columnar to strong subangular blocky structure is noticed in the subsurface.

Summing up the textural variations in the soils, a high degree of influence of the topographic variation is noticed in the preponderance of sand in the elevated P1 and P2 soils. As one descends the slopes from P1–P2 association, there is a general decreasing trend in the sand content of the pedons, at least to a depth of 40 cm, except in the case of poorly developed P6 which shows near-surface abundance of coarse sand fraction due, perhaps, to wash from the higher slopes in the Banni, as well as from the Kachchh mainland. Silt contents vary little among the pedons, but P1 and P2 still show lesser contents. The minimum clay contents are in P1, followed by P2. There is little variation in clay contents of the other pedons, although the general tendency is an increase in the enrichment of clay within B horizon of the topographically lower pedons. There is also a general down-slope declining trend in the $CaCO_3$ content within the upper horizons of the pedons.

Nature of clay minerals

It was possible to infer the dominant clay minerals from the moisture equivalence percentages and CEC contents of the soils (Table 2). In P1 and P2 soils the clay percentage is very low ($<15\%$), where the moisture equivalence (ME) of ~ 6–14% and CEC of 2·6–10·6 c mol (P +) kg^{-1} suggest a mixture of kaolianite-illite type clays. The P3 soils have higher clay content (24–34%), where the ME varies from 24 to 33%, and CEC from 16 to 31 c mol (P +) kg^{-1}. These values indicate the dominance of smectite clay mineral. In P4 and P5 soils clay fraction varies from 26 to 42%, where the ME ranges from 18·1 to 28·1% and CEC from 22·7 to 39·4 c mol (P +) kg^{-1}, suggesting a dominance of montmorillonite-smectite clay minerals. On the other hand, P6 soils have $\sim 25\%$ clay, where ME and CEC values suggest a illite-smectite combination. Similar results were also obtained from other parts of arid Gujarat (Dubey & Sharma, 1984, 1987).

Salt composition and salt dynamics

The distribution and composition of salts in the pedons are catalogued in Table 3. It is apparent that P1 and P2 soils have lower EC and ECe values, and that down-profile

Table 3. *Salt composition in Banni mudflat soils*

Horizon	Depth (cm)	ECe ($dS\ m^{-1}$)	Cations ($me\ l^{-1}$)				Anions ($me\ l^{-1}$)				SAR
			Na	K	Ca	Mg	CO_3	HCO_3	Cl	SO_4	
					Bhojardo (P1)						
A1	0–10	0·94	2·8	0·9	3·4	3·6	0·0	3·5	5·0	2·2	0·9
A2	10–35	0·83	3·7	0·7	2·2	2·8	0·0	4·0	4·5	0·9	1·8
C1	35–80	1·32	8·9	0·4	1·8	3·3	0·0	3·5	8·0	2·9	6·5
C2	80–105	1·13	8·9	0·8	1·3	0·8	0·0	2·3	4·0	4·5	10·6
C3		1·20	9·0	0·9	1·4	0·8	0·0	2·6	5·0	4·5	10·7
					Bherandiala (P2)						
A1	0–10	1·78	8·0	0·8	3·0	6·0	0·0	2·5	13·2	2·1	3·9
A2	10–30	1·47	6·0	0·6	2·5	4·0	0·0	2·5	8·2	2·4	4·2
AB	30–70	1·87	8·0	0·6	4·0	5·1	0·0	2·5	26·0	10·7	5·2
C1	70–130	4·09	17·3	0·9	12·5	8·5	0·0	2·5	26·0	10·7	5·7
C2	130–150	3·72	18·8	0·8	10·0	8·0	0·0	1·5	25·4	10·6	6·8
					Dadhiya Mota(P3)						
A1	0–15	29·82	24·3	2·2	37·5	26·5	0·0	1·7	278·0	27·8	38·1
B1	15–28	25·68	173·9	1·2	45·5	44·5	0·0	2·7	260·0	12·5	39·7
B21 tsa	28–65	10·23	78·9	0·3	1·3	2·8	2·0	3·5	30·5	47·3	43·9
B3 tsa	65–95	8·32	77·7	0·8	1·2	2·7	1·0	3·5	48·5	23·4	42·2
Ck tsa	95–130	15·22	129·4	1·1	5·0	9·0	1·0	7·5	126·0	11·1	41·8
Ckm tsa	130–150	16·15	147·4	1·1	4·0	8·0	2·1	4·1	140·0	18·5	43·8
					Haji Pir, normal (P4)						
A1	0–10	32·15	100·0	1·5	175·1	55·0	0·0	3·0	320·0	8·2	11·1
B21	10–30	23·55	86·9	0·7	95·3	49·3	0·0	2·2	220·0	9·4	12·1
B22 tsa	30–70	164·24	128·7	0·4	24·0	20·7	0·0	2·2	106·5	64·2	27·5
B23 tsa	70–100	136·26	108·7	0·4	16·4	10·2	0·0	2·1	102·5	50·0	29·6
Ck tsa	100–160	129·00	110·4	0·6	7·3	3·0	0·0	2·0	97·5	21·5	41·5
					Haji Pir, water inundated (P5)						
A1 tsa	0–12	119·82	527·3	1·8	376·2	215·8	0·4	1·8	1077·5	41·4	30·7
B21 tsa	12–60	84·68	399·5	1·8	186·4	144·4	0·4	3·8	665·5	62·8	30·6
B22 tsa	60–90	57·57	494·7	2·0	23·2	44·8	0·4	1·9	487·5	74·9	55·2
B23 tsa	90–130	56·53	400·0	2·2	31·6	69·4	0·0	3·4	447·5	52·3	44·8
Ckw	130–160	54·64	465·2	2·4	37·2	82·8	0·0	4·1	500·0	63·5	46·5
					Saline depression (P6)						
A1 tsa	0–12	166·68	1305·0	5·8	120·0	158·0	0·5	3·0	1344·0	241·3	61·8
C	12–25	158·56	1158·0	4·4	115·5	226·3	0·5	2·2	1300·0	200·7	56·4

increases in the values are less. The maximum accumulation of salts, nevertheless, takes place in the C horizon. Since pH (1 : 2) and pHs values range from 8·4 to 9·2, and show similar increasing trends down the profile, a saline-sodic environment in the C horizon is suggested. The A and B horizons have sodicity problem, but not salinity. This is reflected more in the relative abundance of Ca and Mg ions over Na in A and B horizons, while the reverse is true for C horizon. The trends of cations and anions in A and B horizons are: Mg > Ca > Na > K, and Cl > HCO_3 > SO_4, respectively. The pattern changes to Na > Ca > Mg > K, and Cl > SO_4 > HCO_3 in C horizon. In both the pedons SAR and ESP values are less than 10, but the values increase with depth.

In P3 soils the silt loam to silty clay loam of A1 and B21 horizons have high EC and ECe values. When read with pH (8·1, 8·8) and pHs (7·5, 7·9) values, these suggest a salic character. In B22 and B23 horizons with high clay contents (> 32%), the low values of EC and ECe, as well as high pH (9·1, 8·9) and pHs (8·3, 8·2), suggest natrargid-argillic characters. Below these horizons, the CK and Ckm horizons have high EC, ECe, pH (~ 8·8) and pHs (~ 8·0) values, characteristic of saline-sodic horizons. In the whole pedon sodium ions are dominant. The trend in cations is Na > Mg > Ca > K, while in anions it is Cl > SO_4 > HCO_3. Calcium and magnesium contents decrease with depth, but sodium ions have an irregular downward trend. The values of SAR and ESP also show irregular downward trends.

The fine textured P4 and P5 soils have high clay content in the B and C horizons, but the salt composition and the trends of salt movement in them are quite different, although both of them occur in a low relief situation. The P4 soils are without the risk of inundation. Here A1 and B21 horizons with clay loam texture have comparatively low EC, ECe. The pH (7·9, 7·8) and pHs (7·0, 7·1) values are low, suggesting salic character. In contrast, the B22 and B23 horizons with silty clay loam texture have high EC and ECe. The pH (8·0, 8·1) and pHs (7·6, 7·8) are low. These values suggest a salic-argillic character. In the whole pedon SAR and ESP values increase with depth. Ca is the dominant salt in A horizon, followed by Na and Mg, but down the profile Na shows an increasing trend and dominates over Ca and Mg which register progressive decline. Among the anions the trend is Cl > SO_4 > HCO_3 (CO_3 is absent). The Ck horizon shows a slight decline in salt concentration than that in B horizon.

In contrast to the P4 soils the P5 soils are water-inundated, although both have similar texture. The type of salinity in P5 is almost similar to that in P4, but in P5 salinity decreases with depth. The maximum concentration is in A horizon, suggesting an upward mobility of the salts. EC and ECe values are comparatively low in Ckw horizons, but maximum in A horizon. Na is the dominant ion in A horizon and maintains its dominance down the profile over other ions, although its concentration slightly decreases with depth. The other two major ions, Ca and Mg, show sharp decline in B22 horizon and downward, the decline in Ca being more pronounced with depth. Among the anions the trend is Cl > SO_4 > HCO_3 > CO_3. The SAR and ESP values show irregular trends. Thus, unlike the P4 pedon, P5 has a salic A horizon, but the salic-argillic character of P4 is repeated in the lower horizons of P5.

The saline depressions (P6) have irregular trends of salt movement down the profile. The character suggest a salic A horizon, followed by a salic-argillic C horizon (with higher clay contents, as in P4 and P5). Because of the stratified nature of the deposits, both EC and ECe values showed stepwise decline down the profile.

Similar trends in salt composition and salt dynamics have been found in other salt-affected soils of arid coastal tracts of Gujarat (Dubey & Sharma, 1984, 1987). The variation in composition and mobility pattern of the salts in different pedons of Banni appear to be related to the topographic situations in which these exist. While the pedons on relatively higher land surfaces (P1 and P2) have low concentration of salts throughout the soil profiles, those on the successively lower surfaces have increasing salt concentration at surface or subsurface horizons, depending upon their location on the slopes and inundation character. Thus, the concentration of Ca and Mg ions gradually increase downslope through P3 and P4, unless one comes to the waterlogged P5 and P6 soils that occur in the lowermost segments of the topography. The dominance of Ca and Mg is dramatically replaced in these two last mentioned soils by Na that shows very high surface concentration and very little down-profile dilution. The pattern is also reflected in the trends of ECe values. Although A horizons register increasing ECe values from P1 to P6 pedon, there is a gradual increase of ECe values in the surface and subsurface horizons of P1 to P3. In P4, which occurs on the lower middle slope, there is a sharp increase in the values at B horizon, but no further down the profile, while in the waterlogged P5 and P6 A horizons register very high values. In other words, imperfect leaching of the salts on lower slopes is causing increased salt concentration at or near the surface.

Fertility status

All the pedons have poor organic C and available P_2O_5, but available K_2O is high (Table 4). Because of their locations on higher surfaces, the P1 and P2 soils are perhaps limited by water availability (moisture equivalence varies from 6·2 to 13·9%), and hence have lower average organic C than the pedons further downslope, except the highly saline and waterlogged P6 which has very low organic C. The organic C content generally shows a downward trend in the individual profiles, but in P6 soils the trend is variable due to stratified nature of the deposits. The high content of available K_2O in the Banni soils may be related to the abundance of K-bearing minerals, including mica and feldspar, in the soils, as well as to an anaerobic condition. Similar situations have been reported from some other parts of the country also (Ramamurthy *et al.*, 1952).

Management needs

The Banni area is essentially a degraded pasture that is inhabited by several pastoral communities in its 46 small villages. The human population density is $\sim 8\ km^{-2}$, but the livestock density is $\sim 20\ km^{-2}$, and includes mostly cattle (19%), buffalo (45%), sheep (25%) and goats (8%). Animal husbandary is the dominant occupation, followed by some rural handicrafts to generate additional income. Traditional cattle breeding has earned a name for the inhabitants of the Banni (Bharara, 1987). There is no crop cultivation because of the salinity of soil and water. In spite of its dry climate the natural pasture of the area flourishes with little monsoon showers and attracts hoards of cattle rearers from other parts of Gujarat and Rajasthan states for seasonal grazing, but no census is available about their numbers. The district planners consider that the open, uncontrolled grazing is a major factor of pasture degradation, but villagers of the area opine that rainfall is the major constraint, and admit that some restriction on grazing, as well as encouragement to the severely degraded species may help in improving the situation. The very fast spreading of *Prosopis juliflora*, a perennial thorny bush that has high tolerance to salinity, is considered to be a menace by both villagers and planners. The plant is an aggrasive colonizer, and has invaded large tracts of the grasslands through seed dispersal and animal litter, replacing the existing grass species. The rate of spread in the 1980s was calculated as 2673 ha y^{-1} (Jadhav *et al.*, 1993). Although the species is fast-growing and has a high value for fuelwood, there is hardly any other benefit from it for the cattle rearers. During drought years consumption of the seeds of *P. juliflora* by cattle is reported to have caused high mortality. Considering the potentiality of the area, the local authorities have felt the need for development and management of grassland and promote livestock-based farming. For any plan of grassland development in the area, however, its landscape peculiarities and the catenary development of soil need serious consideration.

As we have analysed, the Banni soils have many limitations but some pedons have qualities that can be exploited for improving the overall resource use pattern in the

Table 4. *Fertility status of Banni mudflat soils*

Horizon		Depth (cm)	Organic C (%)	Available P_2O_5 (Kg ha^{-1})	Available K_2O (Kg ha^{-1})
			Bhojardo (P1)		
A1		0–10	0·40	13·0	443·0
A2		10–35	0·30	9·0	269·0
C1		35–80	0·20	4·0	188·0
C2		80–105	0·06	4·0	190·0
C3			0·08	4·0	
			Bherandiala (P2)		
A1		0–10	0·48	16·0	437·0
A2		10–30	0·40	14·0	287·0
AB		30–70	0·30	8·0	188·0
C1		70–130	0·20	6·0	177·0
C2		130–150	0·20	6·0	168·0
			Dadhiya Mota (P3)		
A1		0–15	0·58	40·0	777·0
B1		15–28	0·48	33·0	1048·0
B21	tsa	28–65	0·28	14·0	487·0
B3	tsa	65–95	0·29	18·0	497·0
Ck	tsa	95–130	0·28	12·0	627·0
Ckm	tsa	130–150	0·20	12·0	625·0
			Haji Pir, normal (P4)		
A1		0–10	0·38	32·0	941·0
B21		10–30	0·26	19·0	1004·0
B22	tsa	30–70	0·24	18·0	525·0
B23	tsa	70–100	0·18	10·0	605·0
Ck	tsa	100–160	0·20	9·0	600·0
			Haji Pir, water inundated (P5)		
A1	tsa	0–21	0·67	30·0	840·0
B21	tsa	12–60	0·37	28·0	1155·0
B22	tsa	60–90	0·28	15·0	746·0
B23	tsa	90–130	0·21	22·0	941·0
Ckw		130–160	0·28	19·0	1089·0
			Saline depression (P6)		
A1	tsa	0–12	0·02	5·0	355·0
C		12–25	0·01	4·0	190·0

region. The P1 and P2 soils occur on a slightly higher relief, have medium to coarse texture, and are well drained. Their main limitations are moderately high pH and the presence of some soluble salts. Yet, the surfaces are found to have supported a variety of grass species, including *Cenchrus setigerus*, *Desmostachya bipinnata* and *Eleusine compressa* during good rainfall years, in spite of the fact that these grasses are grazed quickly because of their nutritious quality. Encouragement given to these species, as well as to the degraded halophytic grasses like *Sporobolus marginatus* and *Dichanthium annulatum*, and to the bushes and trees like *Capparis decidua*, *Salvadora oleoides* and *S. persica*, may help to improve the biomass production (Saxena, 1996). Compartmentalization of the areas selected for development into silvo-pastoral blocks, weeding out the *P. juliflora* stocks, and practicing rotational grazing may help to develop the grassland. However, the relationship between monsoon rainfall, plant cover and animal performance need to be established.

The moderately fine textured P3 soils on the sloping midlands can be brought under good pasture if the sites are deep ploughed, and gypsum is applied to the soils for reducing the effects of sodicity. Salt-tolerant grasses like *Dichanthium annulatum*, *Desmostachya sp*. and *Sporobolus marginatus* can be grown. Ponding of rainwater through low field embankments will help to leach the salts. The P4 soils are very much in need of deep ploughing and rain water harvesting to partially leach the high salt contents in their profiles. Salt-tolerant shrubs and grasses like *Suaeda fruticosa* and *Sporobolus pallidus* can be encouraged.

Waterlogging and high salinity make pasture development a difficult proposition on the P5 and P6 soils. Considering the value of *P. juliflora* as a fuelwood species, and the need of the villages, P5 surfaces can be developed as woodlands of *P. juliflora*. The species may also be encouraged on P4 soils.

Conclusions

The following broad conclusions can be drawn from our study.

(1) Although the Banni mudflat has a gentle gradient, its topography is controlled by lineament-controlled earth movements. Over the millennia, the distribution pattern of soils in the area, as well as the distribution pattern of salts, has been influenced in the manner a catenary sequence is developed.
(2) The soils and ground water of Banni are saline-sodic, to the extent that crop cultivation is difficult. However, the higher surfaces with relatively well-drained and non-saline soils provide the best sites for pasture development. The potentiality of pasture development decreases in the downslope direction, as soils become progressively more ill-drained, and salt contents increase.
(3) Some management practices, including soil and water conservation practices, will be required to establish the pastures and to improve the yield from these degraded lands.

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