Arid Land Research and Management, 16:161–176, 2002

1532-4982/02 $12.00 + .00

Spectral Reflectance Characteristics of Na-carbonate Irrigated Arid Secondary Sodic Soils

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In the arid region of Rajasthan, India, saline ground water containing elevated residual Na-carbonate (RSC) is frequently used for raising winter crops. Relationships between spectral reflectance characteristics of RSC water irrigated sodic soils under differential management with their physicochemical and crust characteristics have been investigated. Studies have been carried out at four sites irrigated with saline/high RSC water (EC 4.0 to 10.1 dS m^{-1}, Na adsorption ratio (SAR) 21.8–45, adjusted SAR 45.8–98.1 and RSC nil to 19 $mmol_c$ L^{-1}) for more than 10 years. Some of the parcels have received gypsum for amelioration and have received differential management. The spectral values were higher at Site 2 (32.3–42.1%) followed by Site 1 (18.2–23.2%), and Site 3 and Site 4 (11.1–20.5%). Higher reflectance values were obtained at 800 nm and 1,000 nm wavelengths, followed by 460 nm, and the lowest at 620 nm. At Site 1 and Site 2 low penetration values (0.05–4.24 kg cm^{-2}) were associated with higher soil water content. At Site 3 and Site 4 large penetration resistance (29.06–46 kg cm^{-2}) was attributed to low water content. The multiple regression analysis involving eight soil parameters could predict spectral reflectance to the extent of 99.7% of total variance. The spectral reflectance shows a negative relationship with soil water status, and positive relationships with soil salinity and pH value. For the remote sensing of soil salinity and sodicity in the area, the fallow season of May and June is suggested.

Keywords penetration resistance, remote sensing, residual Na-carbonate, saline soils.

Received 21 February 2001; accepted 28 June 2001.

This research was made possible under the Indo-Hungarian intergovernmental collaborative program for the years 1998–2000. We are grateful to the Department of Science and Technology, Government of India, New Delhi, and the Hungarian National Science Foundation for funding under grant nos. T023271 and T030738. We are also grateful to Dr. A. S. Faroda, then Director CAZRI, Jodhpur, and Prof. Tamas Nemeth, Director, RISSAC, Budapest, for providing necessary facilities and to Mr. P. C. Bohra for technical support.

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Due to lack of sufficient rainfall and river water, farmers use groundwater for irrigation in western Rajasthan, India. The groundwater contains high residual Na-carbonate (RSC). Increased RSC of irrigation water causes development of high sodicity leading to dispersion of soil particles. After repeated irrigation, the dispersed particles settle on the surface forming hard clods and surface crust. This leads to decreased infiltration and limited soil workability. This irrigation water is not reaching roots, but largely evaporates on the surface. This is also manifested in greater penetration resistance and modulus of rupture. The result is a compact sodic surface (Toth et al., 1995).

The surface reflectance value of a soil is related to several factors, physical and chemical properties of the soil, and also to the condition of the surface (Baumgardner et al., 1985; Post et al., 1994). In the earlier studies (Kalra & Joshi, 1994, 1996; Csillag et al., 1993), it has been shown that there is great difference in reflectance values of sodic and normal soils. In the soils irrigated with water dominated by bicarbonate or carbonate, the high pH values were accompanied by high compactness and about 60% higher reflectance values, than in the case of normal soils. Among factors potentially contributing to the reflectance values, most important were pH and electrical conductivity (EC) (Toth et al., 1998a). Reflectance properties of cultivated secondary sodic soils are also determined by the smooth surface layer made up by dispersed soil material, which is enhanced by the related low infiltration rate, also resulting in a bright surface. Knowledge on sodicity status of irrigated soils is crucial to their reclamation (Joshi & Dhir, 1994). After establishing the relationship of surface reflectance with sodicity and surface crust strength, we could delineate the plots affected by high RSC on remotely sensed images and plan their reclamation accordingly (Toth et al., 1998b, 2000). Therefore, our objective was to describe the relationship between soil characteristics and crust strength with the spectral reflectance behavior of soils irrigated with brackish water.

Materials and Methods

Environment

The study area is located in the western part of India (Figure 1), in an arid region of Rajasthan (24°37′00″ N to 30°10′48″ N and from 69°29′00″ E to 76°05′33″ E). It is bounded by Punjab and Haryana states in the north, and Gujarat state in the south. There is a distinct east to west gradient of rainfall and temperature in the region. Along the eastern margin, the mean annual rainfall is 500 mm, and in the westernmost part it is 100 mm. The rainfall is largely monsoon-driven and received between June and September. Large coefficient of variation (40–60%) and erratic distribution during the monsoon are characteristic features of rainfall. The mean maximum air temperature in May and June varies from 40° in the east to 42°C in the west, but it is not uncommon to experience 48°–50°C. The mean minimum air temperature of 6°–10°C prevails during December–January. The annual potential evapotranspiration (PET) values range from 1,600 mm to above 2,000 mm. In winter season because of lower temperature, the PET values in these regions vary from 3 to 8% of the above value. The mean daily wind speed of 6 to 8 m sec^{-1} is normally recorded from April to June but, during dust storms in these months, wind speed often reaches 17 to 30 m s^{-1}. High wind speed during summer leads to wind erosion and sand deposition in agricultural fields, on roadsides, and other infrastructures. During summer months the atmospheric humidity reaches as low as 2–3% which starts increasing, and in rainy seasons it can reach 60–70%.

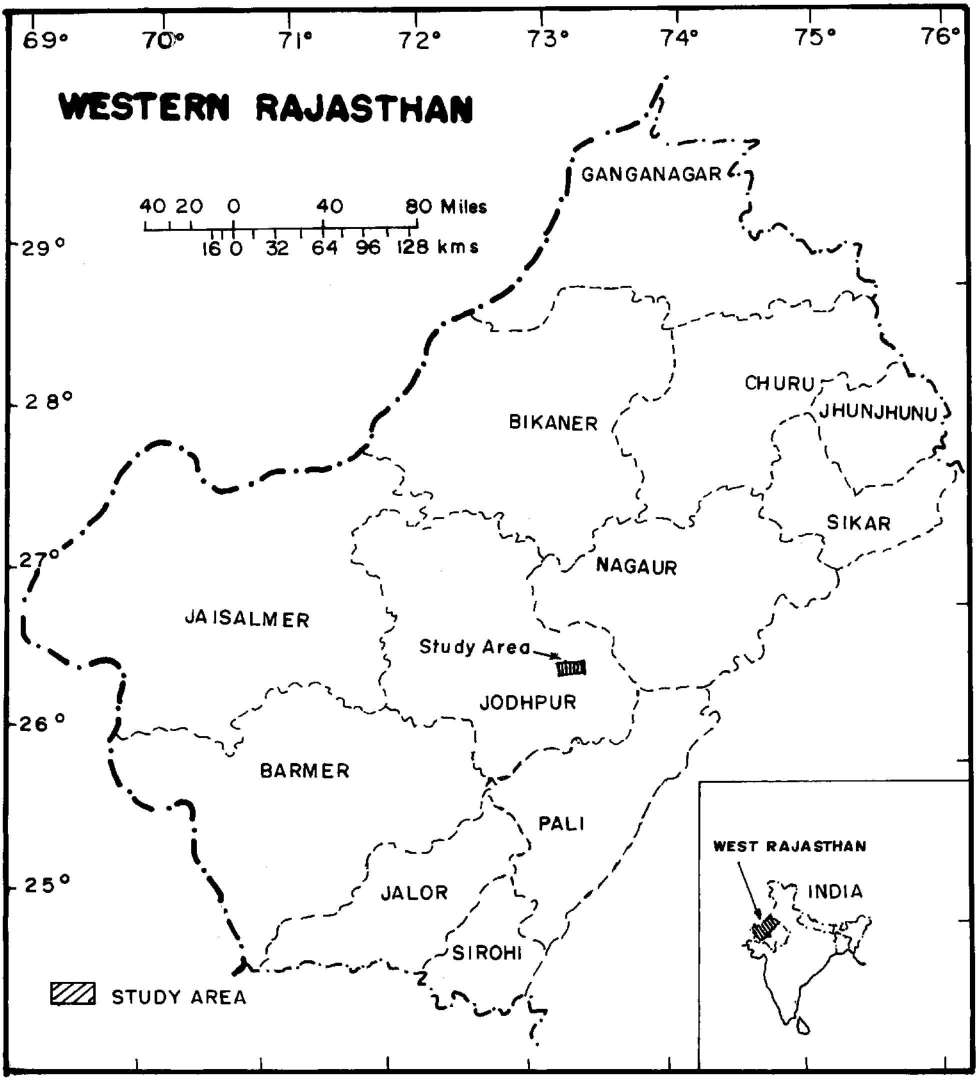

FIGURE 1 Location of study area.

Because of high atmospheric temperature and low humidity, a large part of the rainwater is lost as evaporation. In sandy and alluvial areas groundwater is 100 to 150 m deep, and in hard rock areas the groundwater is encountered in fissures, joints, and cavities. Very often the groundwater is saline/sodic, unsuitable for drinking and irrigation purposes. Despite severe water constraints, the arid region has a high density of human and animal populations. The inhabitants have developed techniques for harvesting and storing rainwater to meet their annual demands. The ephemeral rivers flow at the northern, eastern, and southern fringe of the region. The western-central area is devoid of an integrated drainage system, and surface water resources are meager. Soils in this region are coarse-textured and covered with sand dunes. Low available water capacity, vulnerability to aeolian hazards, and low fertility are major soil constraints. High salinity, calcareousness, and the gypsiferous nature of the soil add other dimensions to these constraints. Rained agriculture supporting animal husbandry is the major stake of livelihood. Frequent droughts result in failure of crops and, at times, mitigation of animal and human populations.

Study Sites

The study was carried out in the eastern part of the arid Rajasthan, at village Sathin (26°27′ N and 73°35′ E) located 75 km east of Jodhpur, and four sites on farmers' fields (Figure 2) were selected. The soils at the farms of Mangi Lal (Site 1) and Hari Prasad (Site 2) are sandy loam to loam, and at Sita Ram (Site 3) and Pema Ram (Site 4) they are clay loam, 50 to 70 cm deep underlain by soft lime concretionary horizon. The soils have been classified as fine loamy Typic Haplocambids (Soil Survey Staff, 1992). Specific site characteristics are presented in Table 1. On these farms, saline/high residual sodium carbonate (RSC) water (EC 4.0 to 10.1 dS m^{-1}, SAR 21.8 to 45, and RSC nil to 19 $mmol_c\ L^{-1}$) has been used for irrigation for more than 10 years, and some of the parcels have received gypsum for amelioration of salinity and sodicity. The soil was treated with gypsum in 1997 before monsoon. In each farm, 0.5 ha plots of the following three kinds of treatment were available for study:

G0. control without gypsum treatment,
G1. 0.5 amount of soil gypsum requirement (GR) determined by Schoonover's method (Richards, 1954) for the soil depth of 20 cm + quantity of gypsum required to neutralize RSC in excess of 5 $mmol_c\ L^{-1}$, and
G2. full amount of soil GR + quantity of gypsum required to neutralize RSC in excess of 5 $mmol_c\ L^{-1}$.

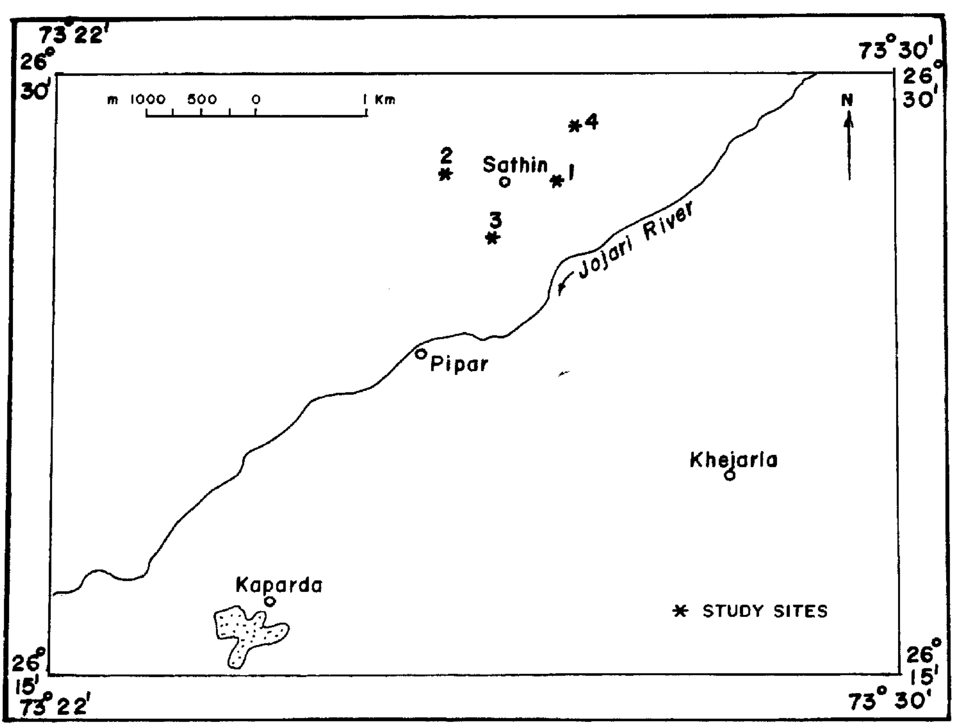

FIGURE 2 Locations of study sites.

TABLE 1 Physicochemical Characteristics and Moisture Status of Soils at the Four Sites

Gypsum treatment	Depth (cm)	pH	EC ($dS\ m^{-1}$)	$CaCO_3$ (%)	Moisture status (%)	Moisture equivalent (%)	Soil texture	Soil color
Site 1								
G2	0–5	8.90	2.22	5.80	19.60	18.50	sl	10YR5/3
	5–10	9.16	1.27	6.36	17.10		sl	10YR6/2
	10–30	9.30	1.35	10.23	19.40	31.80	sl	10YR6/2
G1	0–5	8.50	1.91	7.60	13.20	10.30	sl	10YR6/2
	5–10	9.05	0.83	9.20	13.30		sl	10YR6/2
	10–30	9.33	0.27	15.10	15.00	23.20	sl	10YR6/2
G0	0–5	9.80	0.99	6.40	21.10	10.80	sl	10YR6/2
	5–10	9.58	2.43	6.40	17.70		sl	10YR6/2
	10–30	9.48	0.67	5.90	14.20	23.50	sl	10YR6/2
Site 2								
G2	0–5	8.43	1.40	0.42	5.90	11.70	sl	10YR5/3
	5–10	8.59	0.56	0.27	9.90		sl	10YR5/3
	10–30	8.48	0.56	0.14	10.60	12.70	sl	10YR5/3
G1	0–5	8.73	0.94	1.38	7.90	12.04	sl	10YR5/3
	5–10	8.78	0.77	1.56	9.90		sl	10YR5/3
	10–30	9.12	0.53	3.68	12.11	14.65	sl	10YR5/3
G0	0–5	8.62	0.86	0.71	9.99	11.14	sl	10YR5/3
	5–10	8.77	0.71	0.46	12.24		sl	10YR5/3
	10–30	9.05	0.64	1.53	12.92	27.60	sl	10YR5/3
Site 3								
G2	0–5	8.70	0.37	1.75	8.50	33.40	cl	10YR5/2
	5–10	8.80	0.43	1.64	14.50		cl	10YR5/2
	10–30	8.60	0.76	1.69	13.70	37.00	cl	10YR5/2
G1	0–5	8.53	0.38	1.05	10.70	19.81	cl	10YR5/2
	5–10	8.74	0.41	1.29	12.8	21.45	cl	10YR5/2
	10–30	8.91	0.40	0.70	13.10	23.02	cl	10YR5/2
G0	0–5	8.85	0.32	1.47	6.70	20.92	cl	10YR5/2
	5–10	9.05	0.38	2.76	13.40		cl	10YR5/2
	10–30	9.03	0.47	4.22	14.20	31.10	cl	10YR5/2
Site 4								
G2	0–5	8.87	0.89	1.37	9.9	24.60	cl	10YR5/3
	5–10	9.25	0.76	0.43	6.2		cl	10YR6/2
	10–30	9.16	0.86	0.47	14.9	43.20	cl	10YR6/2
G1	0–5	8.69	0.91	0.10	1.4	26.50	cl	10YR6/2
	5–10	9.07	0.72	0.75	12.3		cl	10YR6/2
	10–30	9.17	0.83	0.45	16.2	43.20	cl	10YR6/2
G0	0–5	8.85	0.50	0.50	2.1	28.50	cl	10YR6/2
	5–10	9.27	0.62	1.28	12.3		cl	10YR6/2
	10–30	9.33	0.68	1.14	16.2	34.80	cl	10YR6/2

These sites are under differential management and therefore manifest variation in their characteristics. Specific site characteristics of individual farms are given below.

Site 1. Soil was ploughed, wheat sown, and 50 mm water applied as irrigation two days before spectral reflectance measurement and soil sampling. Soil surface was bare but smooth with occasional soft clods.

Site 2. Mustard was sown and irrigation applied seven days before spectral reflectance measurement and soil sampling. The surface was dry and crusted with some protruding clods, but subsoil was wet. Young mustard plants had emerged. The penetrometer cylinder required push on the surface, but below 2 cm depth, it slipped easily into the soil, because under the hard crust there was a wet layer.

Site 3. The field was ploughed 30 days before spectral reflectance measurement and soil sampling. Surface was smooth and dry with large clods. There were some dry stalks of the previous mustard crop, and weeds were emerging. Penetration resistance and reflectance were measured on the newly established bare smooth surface as well as on the surface of exposed clods.

Site 4. The field was ploughed seven days before spectral measurement and soil sampling, but due to high sodicity, there were large dry clods on the surface mixed with small, loosely arranged soil aggregates. Penetration resistance measured on the clod surface was very high, which means that the instrument could not penetrate into the clods. The maximum value, therefore, was multiplied by 10 in order to show that there was no penetration.

Sampling Design

Four sites were sampled, each having three treatments, measuring two replicates in each treatment plot. The number of replicates was kept low, because the plots proved to be homogeneous during previous sampling (Joshi & Dhir, 1991). Altogether there were four farms $\times$ three treatments $\times$ two replicates. All samplings and field observations were made within a few days in November, 1997. The well, which is a source of irrigation, is located on one corner. A higher amount of irrigation water was available to the pacels located nearer to the well than to those located at a distance, which helps in efficient leaching of salts and maintains moist surface. This resulted in development of low salinity/sodicity in surface soils and the associated low reflectance values.

Measurement of Spectral Reflectance

Reflectance was measured with a field radiometer, Hindhivac Spectro-Radiometer 101 as described by Kalra and Joshi (1994). Optics is and f/3 Newtonian telescope, angle of view is 10°, and width of band is variable from 400 nm to 1,000 nm. The instrument was held in hand, and measurements were made after a previous checking of the view at about 70–80° with the top of instrument at about 1.3 m height. The recorded values have been normalized by comparing a $BaSO_4$ reference plate. Surface reflectance of a particular wavelength has been given as percent reflectance. Based on previous experience (Figure 3) four bands were selected, two in the visible region at 460 nm (blue), 620 nm (orange), and another two in the infrared spectral region at 800 nm and 1,000 nm. In each plot, two measurements were made, since the difference of the repeated measurements was small, on average 3.1, 0.9, 1.2% of the total mean of the reflectance at the 460, 620, 800, and 1,000 nm wavelengths, respectively (see difference between sites and treatments shown in Table 3).

Measurement of Penetration Resistance

We used a CL-700 type pocket penetrometer (Soil Test Inc., Chicago, USA). The diameter and the calibration mark distance are 6 mm. Readings are given in kg cm^{-2} for unconfined compressive strength of the surface. There were extreme values, such

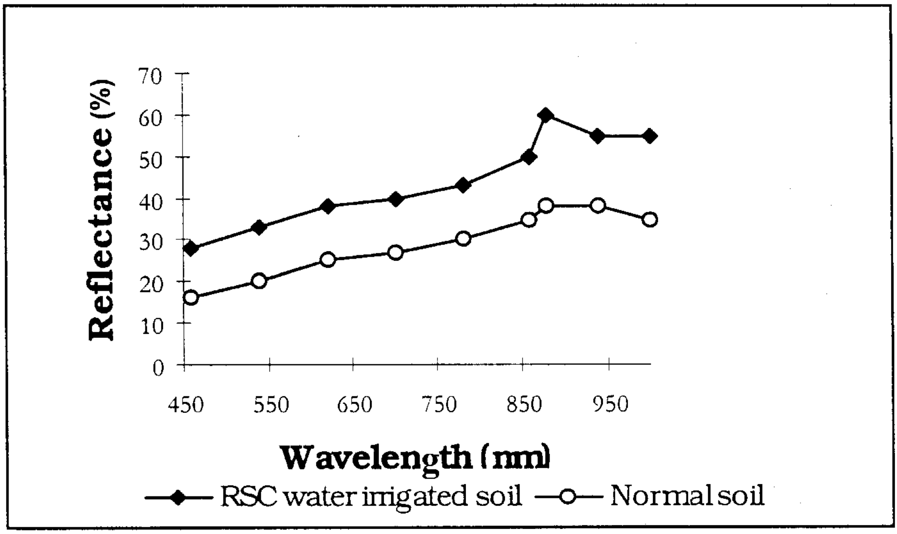

FIGURE 3 Typical reflectance curve of a normal and secondary sodic soil.

as "butter" soft soil surface when the full length of the cylinder was pushed with small force. On the other hand, in Site 4 every measurement attained the maximum value. Despite pushing the cylinder to the maximal 46 kg^{-2} value, the "stone hard" crust on the surface was not broken. In order to distinguish readings made in soft irrigated soil from the rest, the measured values in those plots were divided by 10, and in this way separate intervals were received for irrigated and nonirrigated soils. In each plot, 20 replicate measurements were made.

Soil Sampling

Soil samples were taken at 0–5, 5–10, and 10–30 cm intervals for soil water content measurements and chemical analysis, in duplicates per plot. Soil color was estimated with moist samples on the 10 YR sheet by comparison with the chips of Munsell's soil color chart (Munsell Soil Color Charts, 1954), and soil texture was estimated by hand rubbing. For statistical analysis, soil texture ratings were numerically coded (with increasing particle size: clay loam-1, sandy clay loam-2, loam-3, sandy loam-4, coarse sandy loam-5, and loamy sand-6). Measurements of soil EC and pH were made in 1:2.5 soil water suspension, $CaCO_3$ by calcimeter and soil water content according to standard procedures (Richards, 1954).

Statistical Analysis

The measured properties were subjected to analysis of variance using statistical package (SAS, 1985) regarding three factors: (1) the four sites, because these represented different soil salinity/sodicity status due to differential agricultural management and variation in quality of irrigation water, (2) distances of observation points from the irrigation wells, and (3) three gypsum treatments.

An SAS (1985) statistical package was used for multiple and step down regression equations between the spectral reflectance and associated soil parameters. The factor analysis was used to identify the relatively small number of factors that can be used to represent relationships among sets of many interrelated variables. For this purpose, principal component analysis was used. The first component indicated the combination of the observable variables which account for the largest amount of variance, and this was followed by the second and third component. Rotation phase of the component matrix was calculated to explain variance due to initial factors. The factor analysis, principal component analysis, and rotation were calculated using the same SAS (1985) computer package.

Results and Discussion

The physicochemical characteristics and water content of soils at the four sites in different gypsum treatment plots showed that (Table 1) the control plots generally have higher pH values than the gypsum-treated plots. The $CaCO_3$ content was higher (0.058–0.151 kg kg^{-1}) at Site 1 than at other sites (0.001–0.038 kg kg^{-1}, Table 1). At Site 1 the soil water content was more in plots not treated with gypsum (0.142–0.211 kg kg^{-1}) than in the gypsum-treated (0.133–0.196 kg kg^{-1}) plots. At the other three sites, the dry surface (0.014–0.107 kg kg^{-1}) was followed by a wet subsoil (0.099–0.157 kg kg^{-1}).

The analysis of soils used for irrigation showed EC values between 4.0 and 10.1 dS m^{-1}, SAR from 21.8 to 45, adjusted SAR from 45.8 to 98.1, and RSC from nil to 18.9 $mmol_c$ L^{-1} (Table 2). Compared to the limits of 1.25 (marginal) and 2.5 $mmol_c$ L^{-1} RSC (not suitable for irrigation) of waters set up by Eaton (1950), the waters in the study area were of poor quality. Apparently the water available at Site 1 was most hazardous to soil and plants.

Reflectance Values

The spectral reflectance values in the four wavelengths in different treatment plots are reported in Table 3 and their mean values and statistical analysis in Table 4. The spectral values were in higher ranges at Site 2 (32.3–42.1%) followed by Site 1 (18.2–23.2%) and Site 3 and Site 4 (11.1–20.5%). Higher reflectance values were obtained at 800 nm and 1,000 nm, wavelengths followed by 460 nm, and lowest at

TABLE 2 Groundwater Characteristics of the Sites

	Sites			
Groundwater attributes	1	2	3	4
EC (dS m^{-1})	7.9	7.1	10.1	4.0
Cations ($mmol_c$ L^{-1})				
Na^+	79.4	76.1	86.9	43.5
K^+	0.1	0.2	0.1	0.1
Ca^{2+}	1.6	2.2	6.0	2.2
Mg^{2+}	4.8	9.2	17.6	5.8
Anions ($mmol_c$ L^{-1})				
Cl^-	50.0	65.3	86.5	28.6
CO_3^{2-}	3.2	3.3	0.8	2.2
HCO_3^-	22.1	12.5	2.4	14.2
SO_4^{2-}	10.5	6.6	20.9	6.6
SAR	44.6	31.8	25.4	21.8
Adj. SAR	98.1	66.8	48.3	45.8
RSC ($mmol_c$ L^{-1})	18.9	4.4	Nil	8.4

TABLE 3 Spectral Reflectance Values (%) in Different Gypsum-Treated Plots at the Four Sites

		Wavelength (nm)			
Location	Treatment	460	620	800	1,000
Site 1	**G2**	22.7	19.6	24.1	23.2
	G1	22.7	19.6	23.3	23.2
	G0	18.2	13.6	16.1	16.1
Site 2	**G2**	37.5	30.4	42.9	42.1
	G1	37.5	34.5	35.7	42.1
	G0	32.3	32.6	30.9	39.5
Site 3	**G2**	11.1	7.4	18.0	20.5
	G1	22.2	12.9	18.0	15.9
	G0	22.2	11.1	16.0	13.6
Site 4	**G2**	11.1	7.4	18.0	20.5
	G1	11.1	12.9	18.0	15.9
	G0	11.1	11.1	16.0	13.6

G0, control (without gypsum treatment).
G1, 0.5 amount of soil gypsum requirement (GR) determined by Schoonover's method for the soil depth of 20 cm + quantity of gypsum required neutralizing RSC in excess of 5 $mmol_c\ L^{-1}$.
G2, full amount of soil GR + quantity of gypsum required to neutralize RSC in excess of 5 $mmol_c\ L^{-1}$.

TABLE 4 Average Reflectance Values (%) of Studied Plots and the Significance of Means Inside Individual Farms

	Gypsum treatment			
Location	**G0**	**G1**	**G2**	Significance of *F*
Site 1	14.9	19.7	21.7	0.001
Site 2	33.6	38.9	32.7	0.560
Site 3	30.2	20.5	16.3	0.058
Site 4	13.5	14.5	14.6	0.483

G0, control (without gypsum treatment).
G1, 0.5 amount of soil gypsum requirement (GR) determined by Schoonover's method for the soil depth of 20 cm + quantity of gypsum required to neutralize RSC in excess of 5 $mmol_c\ L^{-1}$.
G2, full amount of soil GR + quantity of gypsum required to neutralize RSC in excess of 5 $mmol_c\ L^{-1}$.

620 nm. Due to the differences in the farming practices and actual phases of cultivation, there were differences in their significance values between gypsum treatments (Table 4). At Site 1, differences in reflectance were due to higher water content.

Lower mean reflectance value was at sites near to the well (19.6%) and this increased with distance from the irrigation well (intermediate 23.9%, farthermost 24.3%), which might be due to frequent and higher amounts of water available for irrigation to the sites nearer to the well. This helps in leaching down the salt and maintains a moist surface, resulting in development of low salinity/sodicity in

TABLE 5 Results of the Global Analysis of Variance of the Average Reflectance (%)

Source of variation	Sum of squares	*DF*	Mean square	*F*	Significance of *F*
Main effect	1,900.9	7	271.6	18.5	0.000
Farm	1,677.3	3	559.1	38.1	0.000
Gypsum treatment	136.9	2	68.5	4.7	0.025
Distance from well	167.9	2	83.9	5.7	0.013
Explained	1,900.0	7	271.6	18.5	0.000
Residual	234.9	16	14.7	—	—
Total	2135.8	23	92.9	—	—

DF (Degrees of freedom) = Number of observations − Number of constraints.
F = Treatment mean square/Error mean square.

surface soils and the associated low reflectance values. The results of global analysis of variance (Table 5) showed that the order of the importance of factors, which caused different reflectance, was: farm, distance from well, and gypsum treatment, all in acceptable significance. Joshi et al. (2000) have observed wide variation in the image characteristics of salt-affected soils due to land use practices.

Penetration Resistance Values

Average penetration resistance values (kg cm^{-2}) of studied plots and significance of means between sites (Table 6) showed low penetration values (0.05–0.13 kg cm^{-2}) at Site 1 because of higher water content in surface soil (0.13–0.21 kg kg^{-1}). The instrument tip slipped into the soil without substantial resistance. There was increase in penetration resistance value with decrease in water content in surface soil, and at Site 3 and Site 4 larger penetration resistance value (29.06–46 kg cm^{-2}) was attributed to low soil water content (0.014–0.107 kg kg^{-1}). However these sites did not show the effect of gypsum treatment. The average penetration was not much different when compared in relation to the distance from well (closest 20.2%, intermediate 24.4%, and farthermost 19.9%). Although large penetration resistance was

TABLE 6 Average Penetration Resistance Values (kg cm^{-2}) of Studied Plots and the Significance of Means Inside Individual Farms

	Gypsum treatment			
Location	**G0**	**G1**	**G2**	Significance of *F*
Site 1	0.08	0.13	0.05	0.000
Site 2	1.71	20.58	4.24	0.000
Site 3	29.06	30.88	33.06	0.687
Site 4	46.00	46.00	46.00	NO

G0, control (without gypsum treatment).
G1, 0.5 amount of soil gypsum requirement (GR) determined by Schoonover's method for the soil depth of 20 cm + quantity of gypsum required for neutralizing RSC in excess of 5 $mmol_c$ L^{-1}.
G2, full amount of soil GR + quantity of gypsum required for neutralizing RSC in excess of 5 $mmol_c$ L^{-1}.

TABLE 7 Results of the Global Analysis of Variance of the Average Penetration Resistance (kg cm^{-2})

Source of variation	Sum of squares	*DF*	Mean square	*F*	Significance of *F*
Main effect	159,901.7	7	22,843.1	144.0	0.00
Farm	157,090.5	3	52,363.5	330.2	0.00
Gypsum treatment	790.0	2	395.0	2.4	0.084
Distance from well	562.6	2	281.3	1.7	0.171
Explained	159,901.7	7	22,843.1	144.0	0.00
Residual	74,845.3	472	158.5	—	—
Total	234,747.1	479	490.1	—	—

DF (Degrees of freedom) = Number of observations − Number of constraints.
F = Treatment mean square/Error mean square.

expected at Site 1, which has structure degradation (Toth et al., 1995), it was low because of higher soil water content. Results of global analysis of variance (Table 7) showed that the order of importance of factors which caused difference in spectral reflectance was in the order: farm, gypsum treatment, and distance from well, all in acceptable significance.

Interrelationship between Spectral Reflectance, Penetration Resistance, and Soil Characteristics

The reflectance and penetration resistance values of the four sites were distinctly different (Figure 4). In this figure, the ratio of the measured water content to the "moisture equivalent" (Loret & Mathieu, 1991) is shown as "relative water content," since it makes for a more meaningful comparison of water content.

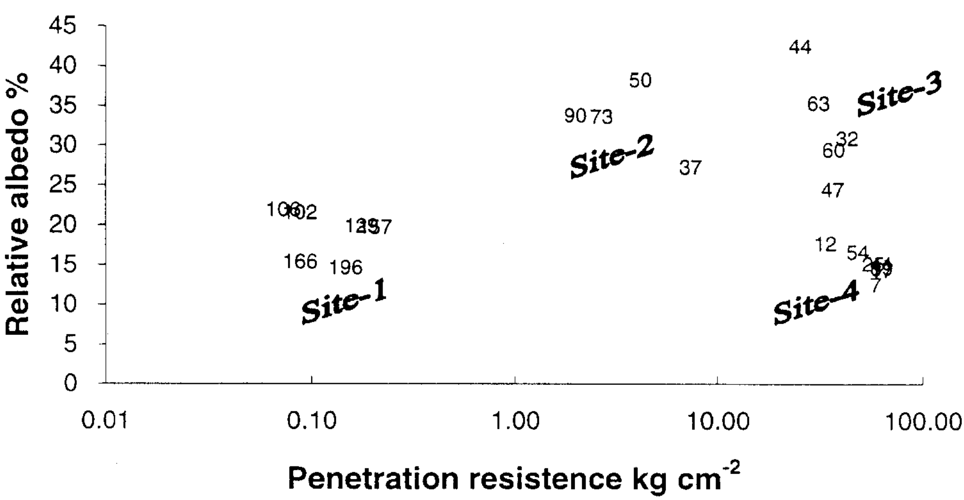

FIGURE 4 Relationship between the penetration resistance and relative albedo. The numbers indicate the percent of the actual soil water content to the "moisture equivalent."

In the gypsum-treated plots at Site 1, water infiltration and percolation improved, but in the control plot, the infiltration did not improve and that resulted in oversaturation (0.211 kg kg^{-1} water content). The oversaturated plot had low values for spectral reflectance as well as penetration resistance. Due to relatively dry surface (0.059–0.099 kg kg^{-1} water content) at Site 2 the gypsum-treated and control plots had relatively higher reflectance and intermediate penetration resistance values. Low water content in 0–10 cm depth (0.067–0.045 kg kg^{-1} water content) at Site 3 was also associated with larger spectral reflectance and higher penetration resistance, because after plowing and the original subsurface clods were turned, the altered surface had high resistance to penetration. Due to its unequal surface roughness, the lowest water content (0.014–0.099 kg kg^{-1} water content) at Site 4 was accompained by lower spectral reflectance and uniformly large penetration resistance.

Multiple and step down regression equations were set up between the spectral reflectance and associated soil parameters at the four sites (Table 8). The multiple regression involving eight soil parameters could predict spectral reflectance to the extent of 99.7% of the total variance. The signs of regression coefficients for $CaCO_3$ (negative), EC and pH (positive), the wet chroma (positive), and wet value (negative) were rather consistent with the results of Kalra and Joshi (1994) and indicated that salinity and sodicity caused higher reflectance compared to normal soils. Note the negative correlation with wet value. The spectral reflectance had a negative relationship with soil water content (Myers, 1983). The negative sign of the regression coefficient for texture, and the same for moisture equivalent showed that maximum reflectance was provided by loam soil, which is consistent with the findings of Johannsen and Baumgardner (1968). In the sodic soils, the mechanism of texture deterioration is manifested in the disruption of (normal, nonsodic) structural aggregates and the formation of a densely packed surface crust (Toth et al., 1998b). This phenomenon causes an increase in the reflectance, as is shown by the positive sign of the regression coefficient of pH in Table 8. Correlation coefficients in the present study are larger than those of Kalra and Joshi (1994) and indicate that, within the category of secondary sodic soils, the reflectance is strongly determined by the soil physicochemical properties (Toth et al., 1991), namely sodicity and salinity.

The step down regression equation (Table 8) indicated that elimination of $CaCO_3$ at one stage and water content at another stage markedly decreased the predictability of spectral reflectance and shows the importance of mineralogical components of the soil in the spectral reflectance (Bauer et al., 1979; Mulders, 1987). On the other hand, field operations, such as irrigation and plowing, had an overriding effect on both reflectance and penetration resistance.

The precision of the regression equation was very large and therefore, for testing the consistency and stability of the database and its suitability for prediction of spectral reflectance, we performed ‘‘data reduction’’ by factor analysis resulting in three principal components (Table 9). The components are groupings of the studied variables, which affect the spectral reflectance. The most important is component 1 (texture, moisture ratio, $CaCO_3$, and penetration resistance), this is followed by component 2 (albedo and Munsell's value) and by component 3 (pH, EC, and Munsell's chroma). These components extracted 81% of the total variance. A plot of the variables in the rotated space of the three extracted components shown in Figure 5 indicated that texture, moisture ratio, and $CaCO_3$ content are located closely and albedo separately. Albedo was in close correlation with component 2.

Conclusions

A characteristic feature of sodic soils is that their physical properties are dependent on their composition (Sumner & Naidu, 1998; Toth, 1998). Some of those properties

TABLE 8 Multiple Regression Analysis Relating Spectral Reflectance (Y) with Soil Parameters

Dependent variable (Spectral reflectance)	Intercept (a)	Independent variables (Soil parameters)									
		ME X_1	Value X_2	Moisture X_3	Texture X_4	pH X_5	Chroma X_6	EC X_7	$CaCO_3$ X_8		
		Regression coefficients									
		b	c	d	e	f	g	h	i	R^2	Adj. R^2
Y	−206.24	−3.55	−10.54	−1.23	2.81	48.92	−37.32	17.98	−3.45	0.99	0.997
	(17.22)	(0.14)	(0.41)	(0.06)	(0.21)	(2.59)	(1.95)	(0.97)	(0.29)	9	
Y	15.73	−0.82	−7.70	−0.38	−0.96	6.81	1.51	0.61	—	0.69	0.55
	(92.64)	(0.34)	(3.48)	(0.35)	(1.34)	(12.0)	(2.96)	(2.96)			
δ	25.03	−0.80	−7.36	−0.35	−0.88	5.41	1.94	—	—	0.69	0.58
	(78.74)	(0.31)	(2.99)	(0.31)	(1.23)	(9.64)	(3.80)				
Y	21.41	−0.90	−7.64	−0.44	−0.56	6.69	—	—	—	0.68	0.59
	(76.8)	(0.22)	(2.88)	(0.26)	(1.04)	(9.11)					
Y	77.27	−0.86	−7.66	−0.38	−0.31	—	—	—	—	0.67	0.61
	(10.83)	(0.21)	(2.84)	(0.24)	(0.36)						
Y	77.20	−0.82	−8.03	−0.38	—	—	—	—	—	0.67	0.62
	(10.59)	(0.17)	(2.53)	(0.24)							
Y	77.80	−0.68	−9.60	—	—	—	—	—	—	0.63	0.59
	(10.96)	(0.16)	(2.42)								
Y	36.30	−0.70	—	—	—	—	—	—	—	0.35	0.33
	(4.10)	(0.20)									

Data in parenthesis indicate the standard error.
Note: Equation of the type $Y = a + bX_1 + cX_2 + dX_3 + eX_4 + fX_5 + gX_6 + hX_7 + iX_8$.
R^2 = Regression sum of square/Total sum of square.
R^2 (Adjusted R^2) = $1-(1-R^2)(n-1)/(n-k)$, where k is the number of independent variables and n is the number of observations.

TABLE 9 Rotated Component Matrix

	Variable component		
	1	2	3
pH	0.493	0.268	−0.537
EC	0.134	0.261	0.875
Munsell's value	0.114	0.865	0.246
Munsell's chroma	0.437	−0.315	0.680
Texture	0.799	0.143	0.441
$CaCO_3$	0.800	0.267	2.72E-02
Penetration	−0.771	0.447	−0.317
Albedo	2.30E-02	0.921	0.205
Moisture ratio	0.93	−9.67E-02	−1.75E-02

Note: EC is electrical conductivity of soil water (1:2.5 soil water suspension); soil texture ratings numerically coded as clay loam-1, sandy clay loam-2, loam-3, sandy loam-4, coarse sandy loam-5, and loamy sand-6.

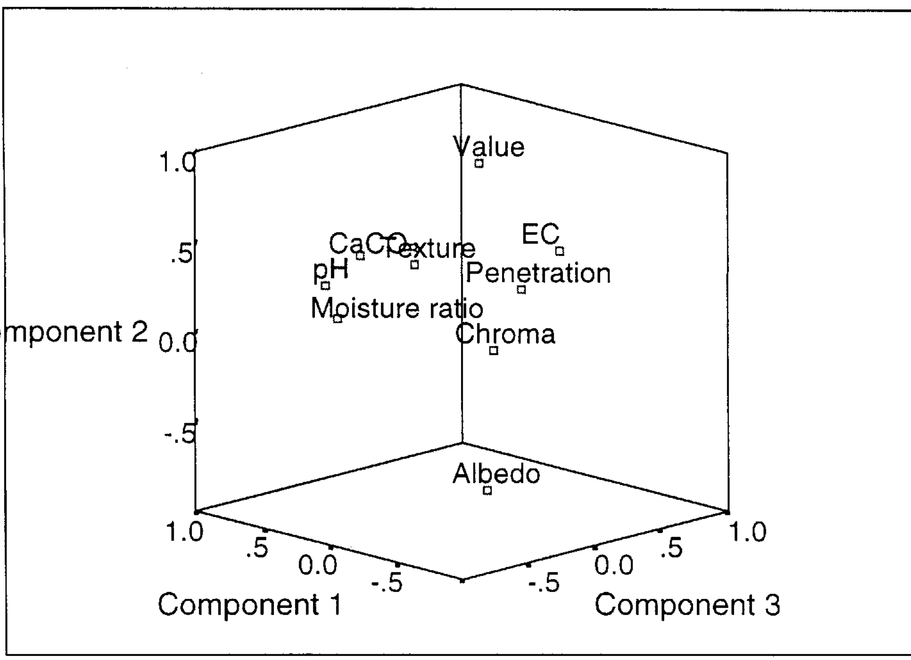

FIGURE 5 Plot of the variables in the rotated space of the three extracted components. Abbreviations: EC= electrolytic conductivity of soil water (1:2.5 soil water suspension). (Soil texture ratings numerically coded: clay loam-1, sandy clay loam-2, loam-3, sandy loam-4, coarse sandy loam-5, loamy sand-6.)

are readily available for the rapid estimation of salinity and sodicity status of soils (Toth et al., 1998a).

The reflectance of irrigated saline and sodic fields is determined by several conditions. In our study, though emphasis was put on salinity and sodicity, agronomic practices modifying the surface characteristics, like plowing and irrigation, were also considered. Nevertheless, the occasional importance of other soil parameters arose as well. According to information shown in Figure 4, the large scatter in the reflectance values of Site 4 was caused by the roughness of the surface. Roughness is known to be a strongly influential parameter of soil reflectance (Mulders, 1987), but its quantification is not easy. One important finding of this study is the mutual relationship of physical, chemical, and agronomic practices with spectral reflectance, penetration resistance, sodicity, texture, and soil water content. The empirical regression equation between albedo and soil parameters provides opportunity for precise prediction. It should be emphasized that the relationship deduced should not be taken as universal for other areas and times, and rather must be considered as an example for identifying the soil characteristics that cause the specific reflectance of the plots.

For the assessment of the salinity and sodicity with remote sensing of the irrigated plots of arid Rajasthan, the fallow months of May and June (before the onset of the rainy months) are suggested, when the fields are not cultivated, the surfaces are similar, and the soil is dry. Moreover, it is the time of the year when the sodicity and salinity reaches its maximum value due to the intensive evaporation.

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