032391

corrected version

SALINITY AND SPECTRAL REFLECTANCE OF SOILS

A. Szilagyi and M.F. Baumgardner
Department of Agronomy, Purdue University
West Lafayette, IN 47907

ABSTRACT

In support of remote sensing applications for monitoring processes of the Earth system, this research analyzed the basic spectral response related to salt content of soils in the visible and reflective infrared wavelengths. BRF (Bidirectional Reflectance Factor) was determined at 10 nm increments over the 515-2325nm spectral range. The effect of salts on reflectance was analyzed based on 162 spectral measurements. The high spectral dimensionality (181 bands) was reduced to a few bands using the first few eigenvectors derived by principal component analysis. Three sets of 7, 12 and 22 bands were selected (excluding 2 water absorption bands) representing the spectral variability of approximately 99.6%, 99.9% and 99.93% of the original data set. Additionally, MSS and TM bands were simulated within the measured spectral region. High R^2 values (0.966-0.997) of ANOVA indicated a strong relationship in variations of reflectance and soil characteristics related to salinization and desalinization. It was found that although the individual MSS bands had high R^2 values and 75-79% of soil/treatment combinations were separable, there was a large number of soil/treament combinations not distinguished by any of the four highly correlated MSS bands. Out of the 5 sets, a set of 12 bands was chosen for further separability studies. Using this set, an overall 92.9% of all possible combinations of the 6 soils and 9 treatments were separable.

INTRODUCTION

During the past decade numerous programs and projects have been initiated to study changes which are occurring in the Earth environment. One of the major thrusts of research in the 1990s supported by the U.S. National Aeronautics and Space Administration is termed "Mission to Planet Earth" (NASA, 1988, 1990). Numerous agencies within the United Nations and committees of the International Council of Scientific Unions are addressing global change issues. All of these efforts require complex data sets and interdisciplinary approaches to understand and model the Earth system. Collaboration among meteorologists, oceanographer, biological scientists, earth scientists, statisticians and engineers is essential in these research efforts.

One of the essential and very important components of the terrestrial ecosystem is soil, a dynamic, often highly buffered and variable system which is an important source and sink of organic and inorganic solid and fluid constituents within the Earth system.

Manuscript prepared for presentation at Annual Meeting of ASPRS/ACSM, Baltimore, Maryland USA, 23-29 March 1991.

Soil is also one of the components of the Earth system, which is highly susceptible to human-induced change, such as accelerated processes of erosion, salinization, nutrient decline, and accumulation of toxins.

This paper addresses questions of soil variability related to the quantity and quality of soluble salts in the soils and the use of measured soil reflectance to monitor and predict the status of soil salinity.

To analyze the basic relationship between spectral and physical-chemical properties of soils, laboratory spectral measurements have been used in numerous studies (Beck et al.,1976; Stoner and Baumgardner, 1981; Henderson, 1990). In spite of that, very few references were found which examined the effects of quantity and quality of salts on soil spectral reflectance. Stoner and Baumgardner (1981) observed that minimally altered Aridisols, which are generally high in soluble salts, had the greatest reflectance of the 10 analyzed soil orders. Al-Mahawili (1983) analyzed the spectral properties of saline and gypsiferous soils from Iraq. Within the 515-2325nm region, the NIR and MIR bands were found to be superior for detecting different soil salinity levels. Increasing the moisture content decreased the spectral separability related to the quantity and quality of salts in the soils. After leaching the salts from 12 soils, the overall reflectance increased. It was concluded that saline soils have lower reflectance than non-saline (normal) and gypsiferous soils. This observation needs further study, because higher reflectance after leaching the water soluble salts from the soil system may also be related to other factors, such as removal of water soluble organic compounds, or change in the composition of salt content, or dispersion of the soil aggregates.

In this study, we aimed to reduce the high spectral dimensionality while maintaining the original information content of the data set for modeling and predicting the effect of salinization and desalinization using soil reflectance.

MATERIALS AND METHODS

Data Source

The experiment was conducted on six soils from the Carpathian Basin (Hungary). Three soils (HM4-HM6) were from a salt-affected area, and three (HM1-HM3) from a salt-free environment (Table 1).

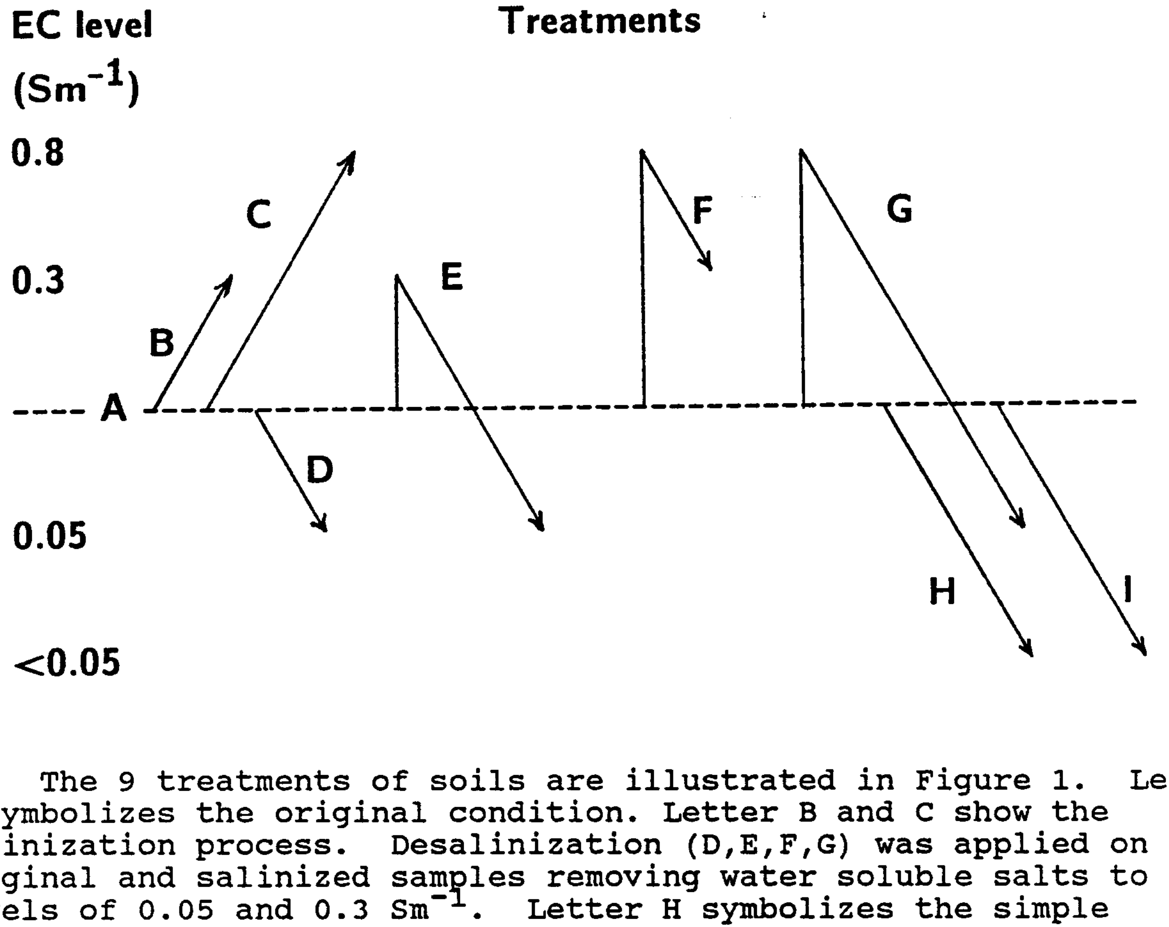
Table 1. Some properties of soils used in this experiment

Soil#	Classification	OC (%)	EC (Sm^{-1})	ESP (%)	Texture
HM1	Typic Calciustoll	1.7	.10	5	silt loam
HM2	Typic Haplustoll	2.8	.12	2	silty clay
HM3	Aquic Haplustoll	2.7	.26	2	silty clay
HM4	Typic Natraquoll	2.7	.10	6	silt loam
HM5	Typic Natraquoll	4.8	.09	6	silt loam
HM6	Aquic Natrustoll	2.1	.21	30	silty clay

None of these soils has a great amount of water soluble salt in the surface horizon as the low EC indicates, although the subhorizons of HM4-HM6 soils are high in salt. The HM6 soil is very sodic as shown by the very high ESP.

Some samples of the original soils were salinized with addition of NaCl (sodium chloride) in solution to an EC level of 0.3 and 0.8 Sm^{-1}. Some samples were desalinized with deionized water using vacuum filtering to a lower EC level (Figure 1). To investigate the dramatic removal of water soluble cations, water soluble organic compounds, and the effect of waterdispersing the aggregates, some of the original samples were leached to an EC level of less than 0.05 Sm^{-1}. Some samples of these soils were also saturated with calcium before leaching. The purpose of Ca (calcium)-saturation was to exchange Na^+ from soils, to prevent removal of organic compounds by the more stable Ca-organic complexes, and to protect the soil structure. It was done with addition of $CaCl_2$ solution, and the excess amount of $CaCl_2$ was rinsed from the samples.

Figure 1. Schematic experimental treatments



The 9 treatments of soils are illustrated in Figure 1. Letter A symbolizes the original condition. Letter B and C show the salinization process. Desalinization (D,E,F,G) was applied on some original and salinized samples removing water soluble salts to EC levels of 0.05 and 0.3 Sm^{-1}. Letter H symbolizes the simple leaching, and letter I stands for leaching after Ca-saturation.

In laboratory conditions, spectral reflectance was measured for 162 samples (6 soils x 9 treatments x 3 replications). To control the effect of moisture and the development of organic film, cracks or crust, all spectral measurements were taken in air dry condition. The samples were crushed and sieved (aggregates less than 2mm). The BRF of the soil samples was determined using an Exotech Model 20C spectroradiometer in 10 nm increments along the spectral range of 515-2325 nm. A pressed barium sulfate surface was used as the reflectance calibration standard.

Spectral data compression

Principal component analysis was used for determining important spectral regions in the data set. However since there were fewer observations (162) than spectral bands (181), the entire data set would not be analyzed as a whole. One need more observations than spectral bands to obtain a valid estimates of the mean and covariance matrix. Two approaches were used to reduce the spectral dimensionality of the data. First, the spectral bands (1375-1695nm; 1915-2035nm) representing the atmospheric water absorption bands were excluded, since the water absorption bands are not used in spaceborn remote sensing. These bands were determined based on a study of moisture effect on reflectance of the same six soils.

Secondly, the data set was divided into three ensembles. The principal component analysis (SAS program) was run on each of the ensembles separately. Therefore there was 162 observations for 86, 22, and 29 bands in calculation of the covariance matrices of the ensemble 1., 2. and 3. respectively. The number of eigenvectors was the number required to represent the spectral variability of 99.6%, 99.9% and 99.93% uniformly for each ensemble (Table 2). The threshold of 99.6% spectral variability was proposed by Price (1990). The threshold of 99.9% and 99.93% were used in this study to test whether the narrower spectral bands contain additional important soil information.

Table 2. Number of eigenvectors and bands for each threshold value

Set (No. bands)	Cumulative % of variation	Ensemble 1 515-1375nm (86)	Ensemble 2 1695-1915nm (22)	Ensemble 3 2035-2325nm (29)
	%	no. eigenvectors / no. bands		
BE	99.6	2 / 2	1 / 1	2 / 4
BF	99.9	4 / 3	2 / 2	10 / 7
BG	99.93	6 / 8	4 / 4	14 / 10

The importance of a wavelength region for the purpose of accurately representing the ensemble of functions is indicated by the magnitude of the eigenvectors in that region. It was hypothesized and shown by Chen and Landgrebe (1987) that the importance of a wavelength region in an ensemble-representational sense is positively correlated with (though not identical to) its importance with respect to classification accuracy. The band selection algorithm which they developed was applied for classification of soil organic matter content by Henderson et al. (1989) in reducing spectral dimensionality tenfold with no loss of classification accuracy. The average of the first several eigenvectors associated with the largest eigenvalues accounts for the cumulative effect of the important spectral regions. Hence, the band intervals were determined by the zero-points of the average of the first few eigenvectors, whenever transition in sign occurred. Additionally, the reflectance values corresponding to the Landsat MSS and TM bands were calculated to simulate possible observations by these satellite sensors. Related to the upper and lower boundary of the data set, the TM1 band was not considered, and the MSS1 and TM7 bands were modified as MSS1m and TM7m respectively (Table 3).

To test the information content of sets of spectral bands, and to analyze the separability of soils and treatments, ANOVA (Analysis of Variance, SAS) and the Tukey method of multiple mean comparison were used at the 0.05 significance level. This multiple mean comparison was applied instead of a multispectral classification because of the small sample size of only 3 replications for each soil/treatment combinations.

RESULTS AND DISCUSSION

The band selection described above resulted the designation of 7 bands in the BE set, 12 bands in the BF set and 22 bands in the BG set. In Table 3, 5, 6, and 7 the R^2 values from ANOVA, the percentage of separable pairs and the number of single cases are given for each set of bands included in the study. In general, R^2 measures how much variation in the reflectance can be accounted for by the model. The larger the R^2 value, the better the model fits the data.

Table 3. Simulated Landsat MSS and TM data sets

Band	Midpoint (nm)	Bandwidth (nm)	R^2	Separable pairs (%)	Single cases
MSS1m	555	80*	.9964	79	22
MSS2	645	100	.9966	78	6
MSS3	745	100	.9951	77	6
MSS4	945	300	.9891	76	61
TM2	555	80	.9964	79	24
TM3	655	60	.9965	79	3
TM4	825	140	.9931	77	2
TM5	1645	200	.9741	65	3
TM7m	2195	240*	.9753	65	4

* modified, shorter than the original bandwidth

In this study, the high R^2 values (0.966-0.997) indicate a strong relationship between reflectance and soil characteristics related to salinization and desalinization processes. The first two bands in the visible and near infrared showed the highest R^2 values and gave the best results in the spectral separation of all combinations of soil/treatment pairs. As a tendency, the number of separable pairs at the 0.05 significance level declined similarly to the decreasing R^2 values from the shorter to the longer wavelengths (Table 3,5,6,7).

High R^2 values alone do not characterize the total separability in the data sets. The higher correlation between bands (Table 4), as with MSS bands, meant less additional information, and less capability for spectral separability of soil/treatment classes. When the MSS bands were used individually, it was possible to separate between 76% and 79% of all possible combinations of soils and treatments. However, there were 129 pairs among the total combinations of samples which were not separable by any of the 4 highly correlated MSS bands.

Table 4. Range of band correlation and number of non-separable pairs for each set

Set	Range of band correlation	Number of non-separable pairs
MSS	.9944 - .9021	129
TM	.9936 - .5721	112
BE	.9986 - .5556	125
BF	.9987 - .5125	102
BG	.9988 - .5090	101

The bands of the BE set showed a less effective performance in separation. The number of non-separable pairs for this set of bands was between those of the MSS and TM (Table 5).

Table 5. Data set BE

Band	Midpoint (nm)	Bandwidth (nm)	R^2	Separable pairs (%)	Single cases
1E1	615	200	.9965	78	121
1E2	1045	660	.9859	75	4
2E	1805	220	.9749	65	1
3E1	2095	120	.9748	65	2
3E2	2190	70	.9764	67	3
3E3	2265	80	.9749	65	2
3E4	2305	20	.9706	63	

The BF and BG bands contained a greater spectral variability than the other band sets (Table 6,7 respectively). It was expected since these bands were chosen based on the high cumulative % of variation represented by their eigenvectors, and it was demonstrated by the widest range of correlations between bands (Table 4). Hence, there were 27-28, and 10-11 additional cases separated by MSS and TM sets respectively.

Table 6. Data set BF

Band	Midpoint (nm)	Bandwidth (nm)	R^2	Separable pairs (%)	Single cases
1F1	570	110	.9966	79	101
1F2	745	240	.9949	77	8
1F3	1120	510	.9830	72	7
2F1	1790	190	.9740	65	2
2F2	2000	230	.9798	70	2
3F1	2045	20	.9755	65	
3F2	2110	110	.9746	65	
3F3	2190	50	.9762	67	
3F4	2250	70	.9765	67	2
3F5	2285	10	.9689	61	
3F6	2305	20	.9689	61	
3F7	2320	10	.9700	63	

Table 7. Data set BG

Band	Midpoint (nm)	Bandwidth (nm)	R^2	Separable pairs (%)	Single cases
1G1	580	130	.9966	79	122
1G2	780	270	.9942	77	6
1G3	920	10	.9879	73	
1G4	930	10	.9881	74	
1G5	950	30	.9883	75	1
1G6	970	10	.9887	74	
1G7	1165	380	.9814	70	1
1G8	1365	20	.9755	66	
2G1	1745	100	.9736	64	2
2G2	1800	10	.9739	64	
2G3	1850	90	.9747	65	
2G4	1905	20	.9805	70	1
3G1	2050	30	.9752	65	
3G2	2110	90	.9745	65	
3G3	2180	50	.9756	66	
3G4	2210	10	.9765	67	
3G5	2225	20	.9758	67	1
3G6	2255	40	.9759	66	2
3G7	2285	20	.9722	63	
3G8	2300	10	.9664	60	
3G9	2310	10	.9692	62	
3G10	2320	10	.9700	57	

There were some single bands in which the separability of soil/treatment combinations was unique, i.e. the Ca-saturated condition of soil HM1 (1I) differed from the desalinized HM5 (5D) just only by the 3G6 band. No other band of the BG set was useful. A minimum number of bands which could account for all spectrally separable soil/treatments was determined. At first, the single bands were ranked based on their R^2 values. Then, one of the single bands, which was the best according to its R^2 rank, was assigned to each observation. It was found that all cases were covered by the so called single bands which uniquely separated one or more of the soil/treatment combinations.

In all cases, these single bands were found to be sufficient in differentiating between all separable pairs for each set. In the MSS and TM sets, all bands were included in the minimum number of bands. Of the BE, BF and BG sets, only 6 and 8 bands were necessary. Some of them are narrow 20 or 30 nm bands, some of them are broad (Table 5,6,7). Although for separability analysis, 6 or 8 bands would be sufficient for the soils and treatments used in this study, we are planning to employ all bands in modeling, and model inversion research for predicting soil characteristics from spectral reflectance.

The BF bands presented a meaningful improvement compared to the BE set in terms of total separability. In contrast, there is only one pair difference between BF and BG sets (Table 4). Increasing the representation of the overall variation improved the fits of the model at some spectral regions, but decreased it in other cases. The analysis with the BG set of 22 bands required significantly more computer time than did the separability analysis with the BF set of 12 bands. Since the differences in the capability of separating soil/treatment combinations were minimal, the decision was made to use the BF set for further separability studies. In modeling studies for use of spectral data in predicting the salinity status of soils, all spectral bands with relatively high R^2 values will be tested.

ACKNOWLEDGEMENT

The authors wish to acknowledge with gratitude the support of this research by NASA (Grant # NAGW-925), the NSF (Grant # INT-8721949), and the Hungarian Academy of Sciences. We would also like to thank Dr. G. Varallyay and his staff at RISSAC (Hungary) for their field work and laboratory measurements, Mr. L.L.Biehl (Purdue Univ.) for his technical assistance in the spectral measurements, and Dr. L.J.Cote (Purdue Univ.) for his statistical advice.

REFERENCES

Al-Mahawili, S.M.H. 1983. Satellite Image Interpretation and Laboratory Spectral Reflectance Measurements of Saline and Gypsiferous Soils of West Baghdad, Iraq, M.S. thesis, Purdue Univ., West Lafayette, IN.

Beck, R.H., B.F.Robinson, W.W.McFee and J.B.Peterson. 1976. Spectral characteristics of soils selated to the interaction of soil moisture, organic carbon and clay content. LARS Info. Note 081176, Laboratory for Applications of Remote Sensing, Purdue Univ., West Lafayette, IN.

Chen, C.C.T. and D.A. Landgrebe, 1987. Spectral feature design for data compression in high dimensional multispectral data. Proc. IEEE Int. Geosciences and Remote Sensing Symposium, Ann Arbor, MI. May 18-21, 1987.

Henderson, T.H. 1990. Use of high-dimensional spectral data to evaluate organic matter-reflectance relationships in soils. M.S. Thesis. Purdue Univ., West Lafayette, IN.

Henderson, T.H., A. Szilagyi, M.F. Baumgardner, C.C.T. Chen and D.A. Landgrebe 1989. Spectral band selection for classification of soil organic matter contents. Soil Sci. Soc. J. 53:1778-1784.

NASA. 1988. Earth system science: a closer view. Earth System Science Committee, NASA, Washington, D.C.

NASA. 1990. EOS: A mission to Planet Earth. NASA, Washington, D.C.

Price, J.C. 1990. On the information content of soil reflectance spectra. Remote Sens. Environ. 33:113-121.

Stoner, E.R. and M.F.Baumgardner. 1981. Characteristic variations in reflectance of surface soils. Soil Sci. Soc. Am. J. 45:1161-1165.