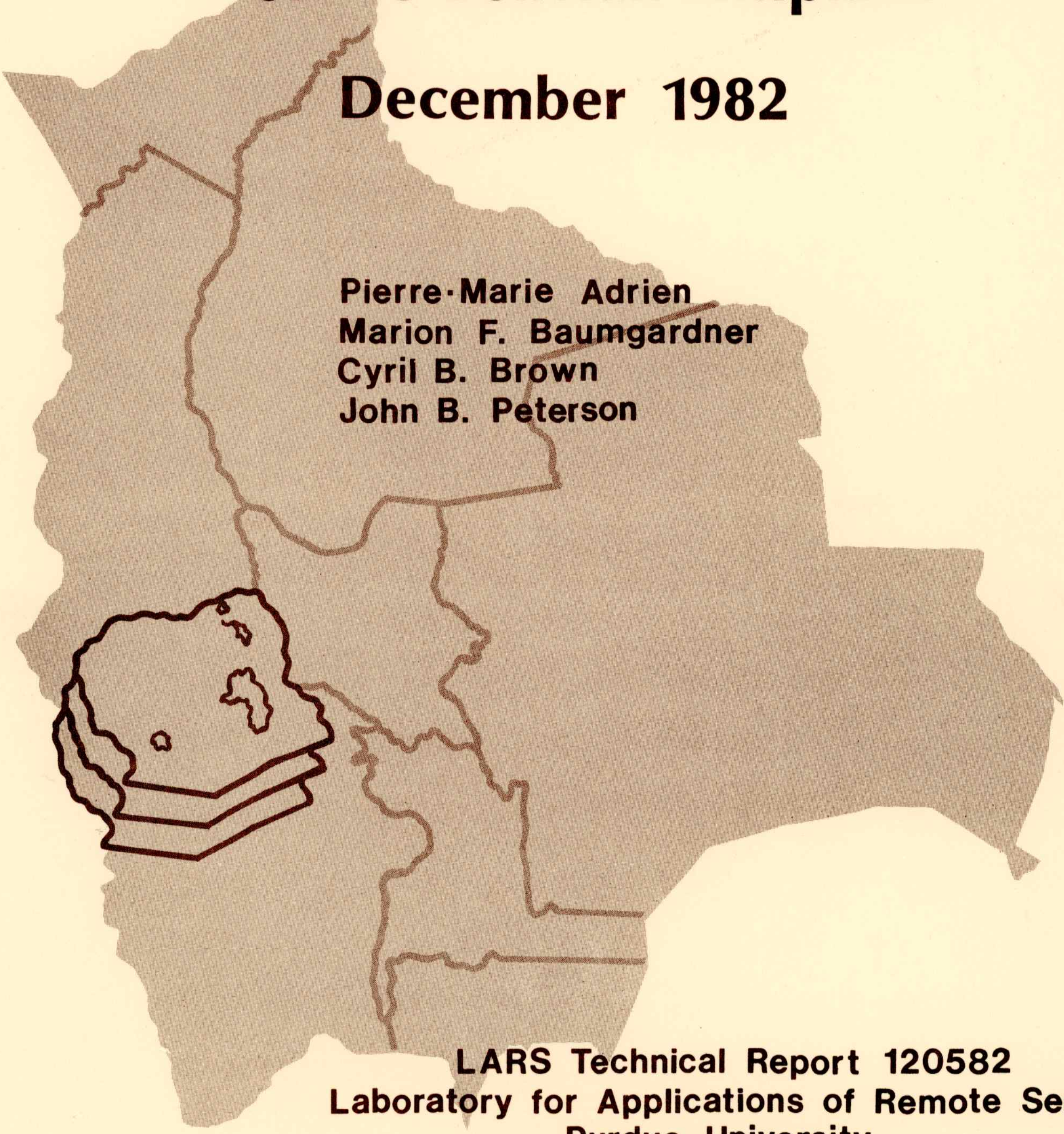
Characteristic Variations in Reflectance of Saline and Alkaline Soils of the Bolivian Altiplano

December 1982



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ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Inter-American Development Bank (Project ATN/SF-1812-BO) and President Antonio Ortiz Mena for supporting the research described in this report and for making the opportunity possible through the Bank's policy on sabbatical leave. The authors are also grateful to the Programa ERTS/Bolivia for providing soil samples used in this study.

An expression of gratitude is also extended to professors and scientists in the Agronomy Department, the Laboratory for Applications of Remote Sensing, Purdue University, and the National Soil Survey Laboratory, Lincoln, Nebraska, for their many contributions to this research effort. Individuals whose counsel, administrative support and service warrant special mention include:

- Dr. Carlos E. Brockmann, former Director of the Programa ERTS, Geological Bureau of Bolivia, and Ing. Carlos Valenzuela, Soil Scientist, Programa ERTS - strong and tedious cooperation in collecting and sending the soil samples from Bolivia to Purdue University;

- Ing. Alexis Vasquez, Soil Scientist in the Ministry of Agriculture, Costa Rica - consideration for suggesting different suitable methods for soil sample collection;

- Mr. Michael E. Curtin, Executive Vice President of the IDB; Mrs. Myrtha Valdez, Messrs. Mauricio Thomae, Luis Fernando Jaramillo, Luciano E. Barraza and Alberto Gomez of the Bank.

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ABSTRACT

Physical and chemical properties of soils contribute significantly to variation of their spectral characteristics within both the visible and infrared regions of the electromagnetic spectrum. Practically, little is known about the specific impact of different types of salts on the spectral characteristic variations of salt affected soils.

A research project was undertaken to investigate the relationship between the chemical and physical properties of some salt affected soils of Oruro in the Altiplano Boliviano and their spectral characteristics. Fifteen salt affected samples from the Alfisol, Aridisol, Entisol and Inceptisol orders were selected. These samples were collected from the (Ap) horizon, at an altitude of about 3800 meters above sea level within a 400 square kilometer area located in the semi-arid climatic zone of Bolivia. All soil samples were prepared and analyzed under similar laboratory conditions.

Stepwise regression analysis reveals that the most important chemical properties affecting the spectral reflectance of these soils seem to be calcium carbonate ($CaCO_3$), nitrate (NO_3^-) concentration, base saturation and sodium adsorption ratio (SAR). It was observed that for Band 1 (0.52-0.62 μm) and Band 2 (0.62-0.72 μm) calcium carbonate and base saturation had the best and most obvious statistical correlations due to the maximum R^2 improvement obtained for dependent variables included in the regression model; whereas for Band 3 (0.72-0.82 μm), it was calcium carbonate and clay; Band 4 (0.82-0.92 μm), Band 5 (0.92-1.02 μm) and Band 6 (1.02-1.12 μm), show ($CaCO_3$) and (SAR) as having the best correlations for soil parameters with reflectance. For Band 7 (1.12-1.22 μm) and Band 8 (1.22-1.32 μm), (NO_3^-) and calcium measured from extractable soil water display the strongest correlations and for Band 9 (1.55-1.32 μm) and Band 10 (2.08-2.32 μm) the values were best correlated between NO_3^- and base saturation in the case of the former and exchange sodium percentage (ESP) and moisture (H_2O) for the latter. Statistical analysis also indicated that there exists a strong correlation between sodium and organic matter in bands 4 and 5. Their interaction within the range of these two spectral bands demonstrated that high organic matter combined with sodium does not necessarily produce low reflectance. A medium range of values falling fairly well between high and low sodium and organic matter content seems to be around 0.55 meq/100 g of soil for sodium and 2% organic matter.

These data suggest a definite relationship between the laboratory spectral reflectance versus soil properties. Such an observation suggests that large areas affected by salt could be identified and mapped by various remote sensing techniques such as earth orbiting satellite systems and others.

INTRODUCTION

Salt affected soils have undermined the effectiveness of agricultural development in many areas of the world since the very early days of civilization. Fertile lands have gradually lost their productivity while the formation of deserts combined with decreases in fertility have drastically decreased agricultural production on a national and global basis. At the beginning of this century, soil scientists and agronomists around the world became more concerned about the necessity of in depth familiarization with the chemical and physical properties of saline and alkaline soils.

Within the past fifty years, the rapid expansion of irrigated agriculture coupled with the presence of inadequate drainage systems have increased the burden of scientists and policymakers concerned with a rational utilization of the soil, water and plant resources in a productive environment. Irrigation engineers and agricultural development project managers soon discovered that the development and maintenance of successful irrigation projects pertain not only to the supply of irrigation water but also to the control of salinity and alkalinity. Effective methods of controling saline and alkaline conditions require a good analysis of the quality of irrigation water, a sound assessment of irrigation practices by the farmers and a careful evaluation of the needs for establishing new or improving existing drainage conditions. Failure to maintain an adequate balance between water quality, its application rates and the soil drainage status may cause soils that were initially nonsaline-nonalkaline to become unproductive whenever excess of soluble salts or exchangeable sodium are allowed to accumulate in the soil profile. Such an accumulation may bestow on the soil significant tonal differences which are often detectable by the human eye.

These differences can also be detected by aerial photographs and by the use of multispectral scanner (MSS) devices onboard earth-orbiting satellites designed to monitor the natural resources and their rates of changes around the globe. In order to derive meaningful and valuable information from the data provided by the MSS and other more sophisticated scanning devices such as the Thematic Mapper (TM) currently placed onboard earth resources satellites, it appears necessary or, perhaps, indispensable to acquire reliable laboratory measurements of soil reflectance properties so as to grasp a better understanding of the multispectral nature of soils in general and salt affected soils in particular as they are viewed by the four spectral bands of the MSS, the proposed seven bands of the TM, and other sensors.

This study describes the scope of the research, the digital analysis procedures and the statistical correlations used to investigate the relationships between reflectance characteristics and the physicochemical properties of saline and alkali soils of the semi-arid regions of the Altiplano Boliviano. Numerous soil parameters were studied and the reflectance measurements of the soil sample were obtained at a uniform moisture tension to minimize the impact of differences in reflectance values triggered by varying water tension in the soils.

The investigation of reliable and reproducible soil reflectance measurements under carefully controlled laboratory conditions provides not only a quantitative measure of soil spectral properties in different regions (visible, near and middle infrared) of the electromagnetic spectrum but also may be extended to spectral measurements made by satellite sensing devices. Such investigations will pave the way for scientists involved in remote sensing research and applications to establish practical procedures to identify, inventory and monitor on a global basis the salt affected regions of the earth presently estimated at more than 400 million ha.

LITERATURE REVIEW

Saline and Alkali Soils: Their Origin, Nature, and Distribution

Since the very early days of civilization society has been confronted with problems of salinization and alkalization. At the end of the 19th century, K. Murakozy (1902) wrote "In order to fight against soil salinity and alkalinity, one has to be familiar first of all with the nature of this phenomenon." And today, even though it is well known that water soluble salts, particularly sodium salts, are the main cause of saline and alkali soil formation, the complex chemical and physical processes affecting such soils are far from being well understood. A lack of adequate knowledge about their properties and management combined with misuses of irrigation and inappropriate drainage systems has contributed to the salinization of fertile areas and the formation of deserts and has destroyed many ancient civilizations.

The various concentrations of the cations calcium, magnesium and sodium and the chloride and sulfate anions represent the principal soluble salts which occur in soils. Also, other constituents are found in smaller amounts: they are the cation potassium, the anions bicarbonate, carbonate and nitrate. A significant portion of these compounds comes from the primary minerals found in soils and the exposed rocks of the earth´s crust. It has been estimated that the average chlorine and sulfur content of the earth´s crust is 0.05 and 0.06%, respectively, while calcium, magnesium and sodium each occur to the extent of 2-3% (Clarke, 1924). It must also be mentioned that the salt source might be seawater, surface or underground saline water or even wind. In certain areas such as in Haiti or South America where coastal areas are constantly pounded by the sea, salinity is generated by direct inundation by salt water and by upward or lateral movement of groundwater.

Processes of Soils Salinization and Alkalization

Salinization

Salinization is considered as a process of accumulation of soluble salts in the soil whereas alkalization is a process which consists of increases of the exchangeable sodium of the soil.

Salinization is more commonly found in arid or semiarid regions than in humid areas of the world. This difference is partially justified in terms of the more pronounced downward movement of soluble salts encountered in humid regions where the rates of evaporation are much lower than those of arid climates. High evaporation combined with low rainfall tend to concentrate the salts near the surface. Furthermore, unfavorable soil texture created, for instance, by a claypan or a silica hardpan might prevent adequate downward movement of water. In certain cases, the presence of an impermeable soil layer is essential for the formation of saline soils (De Sigmond, 1924). In more recent years, the development of irrigated agriculture has brought about an increase in salinization problems, mainly due to excessive uses of water and insufficient drainage or both. This situation has been observed in Mexico and the western U.S. where a substantial expansion of irrigation projects over the past fifty years has also generated an increase in salinization. Irrigation waters may contain from 0.1 to as much as 5 tons of salt per acre-foot of water, and the annual application of water may amount to 5 feet or higher (USDA - Handbook No. 60, 1954).

Alkalization

Alkalization constitutes a process of accumulation of exchangeable sodium in the soil. The surface of soil particles carries electrical charges which are responsible for adsorption and exchange of cations. This is essentially a surface phenomenon; it involves primarily the clay micelles, organic and fine silt matter fractions of soils. The combination of soil particles, water and cations creates a closely run environment in which cations like calcium, magnesium and sodium may be removed from their adsorbed position on the soil particle and replaced by other cations in the soil solution. While these cations are readily exchangeable others are far more difficult to be exchanged. They are rather tightly fixed on the soil particles. The ease with which the adsorbed cations are freely interchanged with those in the soil solution determines their respective concentrations both on the soil particles and soil solution. When environmental conditions such as high evaporation in arid regions coupled with the upward capillary movement of water force the precipitation of calcium and magnesium compounds, sodium tends to become the predominant cation not only in the soil solution but also in the upper horizons and surfaces of the soil. If the excess of soluble salts are mostly chlorides and sulfates of sodium, such soils are sometimes called "white alkali"; on the other hand, extreme cases of alkalinity resulting from the presence of sodium carbonate (Na_2Co_3) commonly show a discoloration of the soil surface provoked by the dispersed humus transported upward by capillary water movement. These soils are often named "black alkali" (Brady, 1974). Russian soil scientists refer to the "white alkali" as "Solonchaks" and the "black alkali" are identified as "Solonetz."

Classification Characteristics of Saline and Alkali Soils

The classification of salt affected soils is essentially based on the soluble salt content and the exchangeable sodium of the exchange site. The chemical and physical characteristics of these soils determine their classification as saline non sodic, non saline sodic, and saline sodic. These soils are also referred to in the literature as saline, saline-alkali and non saline-alkali, respectively. These groupings are derived from the measurements of pH, the electrical conductivity of the saturation extract at 25°C and the exchangeable - sodium percentage (USDA Handbook No. 60). An overview of the essential differences in physicochemical features among these three classes of salt affected soils is provided in Table 1. These characteristics were taken into account to classify the soils of Oruro as described in Table 2.

Table 1. Summary of Criteria for Classification of Salt Affected Soils.

Electrical Conductivity (mmhos/cm)

Exchangeable Na

	0	4
	Normal (nonsaline/nonsodic)	Saline Saline nonsodic (pH < 8.5)
15	Nonsaline-alkali Nonsaline-sodic (pH ≥ 8.5)	Saline alkali Saline sodic (pH = 8.5)

Worldwide Distribution of Saline and Alkali Soils

Salt affected soils are found in practically all continents. The exact and accurate extent of these soils is not very well known. Estimates pertaining to their quantification and distribution vary greatly. Ponnamperuma and Bandyopadhya (1980) estimate that about 380 million ha of soils on the earth's land surface are saline. But, Kovda and Szabolcs (1979), interpreting the FAO/UNESCO Soil Map of the World (on a scale 1:5,000,000) and the maps of salt affected soils of various continents prepared by the Subcommision on Salt Affected Soils of the International Society of Soil Science (ISSS) projects that the total area covered by these soils is in excess of 950 million ha. The extent of salt affected soils over the world is summarized in Table 3.

Historical Profile of Remote Sensing Applications in Soil Mapping

The use of the common black and white panchromatic aerial photograph as a tool for mapping and studying soils was first introduced in the state of Indiana in 1929 (Bushnell, 1951). Subsequently, the United States Department of Agriculture developed interest in such techniques and substituted the use of plane tables in preparing base maps for aerial photographs which became a key component in most detailed and large scale surveys (Soil Survey Staff, 1951). Furthermore, Rust et al. (1976) assessed the usefulness of high-altitude photography in preparing medium to small-scale soil maps through the use of soil associations as the delineated unit.

Table 2. Physicochemical Classification of the 15 Soil Samples of Oruro, Bolivia

Sample No.	Soil Order	pH	Electrical Conductivity mmhos/cm (E.C.)	Exch. Sodium % (E.S.P.)	Classification*
0121	Aridisol	8.5	101	100	Saline-alkali
0131	Entisol	7.5	94.7	100	Saline-alkali
0441	Inceptisol	6.9	47.0	52	Saline-alkali
0551	Aridisol	6.6	86.50	100	Saline-alkali
0911	Alfisol	7.5	8.30	22	Saline-alkali
0921	Inceptisol	8.0	6.66	14	Saline
1011	Inceptisol	6.2	0.54	1	Nonsaline-Nonalkali
1041	Entisol	6.4	0.58	0	Nonsaline-Nonalkali
1051	Entisol	7.0	0.41	3	Nonsaline-Nonalkali
1131	Entisol	6.3	0.86	1	Nonsaline-Nonalkali
1231	Entisol	6.6	0.24	1	Nonsaline-Nonalkali
1251	Inceptisol	7.3	0.86	2	Nonsaline-Nonalkali
1321	Inceptisol	6.3	0.93	1	Nonsaline-Nonalkali
1351	Inceptisol	7.0	0.86	4	Nonsaline-Nonalkali
1381	Inceptisol	6.7	1.71	5	Nonsaline-Nonalkali

*The saturation extracts of the nonsaline-nonalkali soils have low sodium-adsorption-ratios (between 1 and 6). Sodium-adsorption-ratio (SAR) is defined as a ratio for soil extracts and irrigation waters used to express the relative activity of sodium ions in exchange reactions with the soil; or

$$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{++} + Mg^{++})}{2}}}$$

where the ionic concentrations are expressed in milliequivalents per liter.

Table 3. World Extension of Salt Affected Soils (Kovda and Szabolcs, 1979)

Country/Continent	Area (thousand ha)
Africa	80,538
Australasia	357,330
Europe	50,804
Mexico and Central America	1,965
North America	15,755
North and Central Asia	211,686
South America	129,163
South Asia	87,608
South East Asia	19,983
Total	954,832

These soils contain large amounts of Carbonates, Chlorides and Sulphates.

Even though the development of color aerial films, color infrared emulsions and multi-lens camera systems proved quite valuable in carrying out aerial photographic surveys, some experts began to advocate the need to introduce instruments in implementing those studies (Cihlar and Protz, 1972). Then, in the early 1960's the development of sophisticated optical-mechanical scanner systems capable of measuring visible, reflective and thermal infrared radiation strengthened by the advent of computer pattern recognition techniques paved the way for preliminary studies of soil organic matter content, surface conditions or erosion problems using remote sensing techniques (Baumgardner et al., 1970; Kristof, 1971; Weismiller and Kaminsky, 1978).

Utilization of Landsat Data in Soil Studies

The launch of the first satellite of the Landsat family in July 1972 provided scientists, for the first time, with a broad synoptic view of the earth's surface in a consistent 18 day repetitive cycle in four spectral bands ranging from 0.5 to 1.1 μm. The smallest mapping unit of the satellite known as a pixel corresponds to approximately 0.5 ha; whereas, its scanning devices provide images which cover about 34,000 km^2. Once the data are gathered by Landsat, various photographic products and computer compatible tapes can be obtained.

Kristof and Zachary demonstrated in 1974 the feasibility of mapping soil types from multispectral scanner data. Westin and Frazee (1976) established the relationships between certain features of Landsat images and the delineation of soil association boundaries. In a parallel manner, other researchers were able to conclude that such associations can be interpreted from visual analysis of the satellite image patterns (Lewis et al., 1975).

The development of computer-aided analysis techniques and their utilization in soil studies led to the delineation of important soil differences, vegetation complexes, surface drainage patterns, erosion hazards, and land use (Adrien and Baumgardner, 1977). The intensive use of digital analysis techniques for processing and interpreting Landsat data enabled scientists at the Laboratory for Applications of Remote Sensing (LARS)/Purdue University to generate spectral maps at 1:20,000 scale which displayed certain drainage features. These results encouraged the United States Soil Conservation Service to experiment with such techniques in Jasper County, Indiana as a tool for soil surveyors (Kirschner et al., 1978). A spectral map at 1:15,840 scale was prepared in which close correlations among soil drainage classes were observed (Weismiller et al., 1979). Even though the work is preliminary in nature, such achievements came about some 50 years after black and white aerial photographs were first introduced in soil survey projects in the United States. Present and future research in digital analysis of remotely sensed data will continue to provide a better understanding of the spectral properties of the soil scene being mapped. The contribution from this research is likely to add some knowledge to this process of using remote sensing techniques for the understanding of soil properties.

Bidirectional Reflectance Factor as a Tool for Measuring Soil Spectral Properties

The measurement of reflected solar radiation accounts for a significant amount of the data acquired in remote sensing. This normally occurs in a field situation. However, data acquired under laboratory conditions must be correlated with those gathered under field conditions in order to derive meaningful relationships. To properly establish such correlations, meticulous and accurate procedures pertaining to bidirectional reflectance factor (BRF) measurements must be followed (Dewitt and Robinson, 1976).

The measurement method used to obtain BRF, thus allowing for direct comparison of field-collected data with laboratory-collected data, is based upon the concept of a perfectly diffuse, entirely reflecting surface as a reference. Nicodemus et al. (1977) defines reflectance factor as the ratio of flux reflected by a target under specified conditions of irradiation and viewing to that reflected by an ideal, completely reflecting, perfectly diffuse surface, identically irradiated and viewed. The concept of perfect diffusion suggests that the surface reflects equally in all directions. It is also referred to in the literature as a Lambertian reflector. Robinson and Biehl (1979) describe the angular reflectance properties of reference surfaces used in practice.

On a reasonably clear day, most of the radiant flux incident on the surface of the earth comes from within 15 degrees of the solar disc (Herman et al., 1979). A soil sample is not considered a Lambertian reflector due to the presence of shadows generated by the grainy surface of the soil, its lumps and clods (Dewitt and Robinson, 1976). In the laboratory environment, the angle of incidence is chosen to minimize the shadowing of the surface by irradiating the sample from 10 degrees off normal (Fig. 1). The sample is viewed along the normal to the surface. A collimated light source is used and its rays are transmitted to the soil samples in a parallel path to insure that all the rays come more or less from the same direction. In addition, the BRF reflectometer used in conjunction with a field spectroradiometer provides appropriate conditions to handle variations in incident irradiance for horizontally placed soil samples having a 3.2 cm diameter (Dewitt and Robinson, 1976). Such an instrument set up facilitates quantitative measurements of soil spectral properties (Fig. 2). Several researchers have confirmed the technical soundness and usefulness of this laboratory simulation in determining many important soil properties (Montgomery and Baumgardner, 1974; Beck et al., 1976; Stoner and Baumgardner, 1980).

Effect of Soil Parameters on Reflectance

Characteristics of Soils

Moisture

Among the numerous soil properties which influence reflection and/or emission of electromagnetic energy, soil moisture has been found to create increasing or decreasing patterns in soil reflectance. Researchers have noticed certain linear relationships between absorbance and percentage of soil moisture (Bowers and Smith, 1972). Stoner and Baumgardner (1980), having evaluated results of statistical analyses as well as a qualitative evaluation of soil reflectance/absorption characteristics of 481 benchmark soil samples of different United States Soil Taxonomy orders, concluded that the region of the electromagnetic spectrum which displayed the highest correlations with soil moisture corresponds to the range of 2.08 to 2.32 μm. Other relationships were observed between the loss of reflectance from the oven dry state to field capacity for 15 surface Mollisols and Alfisols from central Indiana. Peterson et al. (1979) estimated that such a loss in reflectance is related to the absence of water in these soils. They also discovered that the same relationships existed throughout the visible, near and middle infrared reflective bands.

Strong water absorption bands at 1.45 and 1.95 μm are known to affect the shape of soil reflectance curves. This suggests that the water molecules are specifically located in clearly defined ordered sites. Hunt and Salisbury (1970) first identified the cause of the absorption band at 1.45 μm as a factor which is conditioned by the behavior of the hydroxyl ion. Such a pattern was also confirmed in the case of liquid water but not for the absorption band at 1.95 μm which was absent. Therefore, it became appropriate to conclude that the hydroxyl groups and not free water were found in the soil samples examined by Hunt and Salisbury (1970).

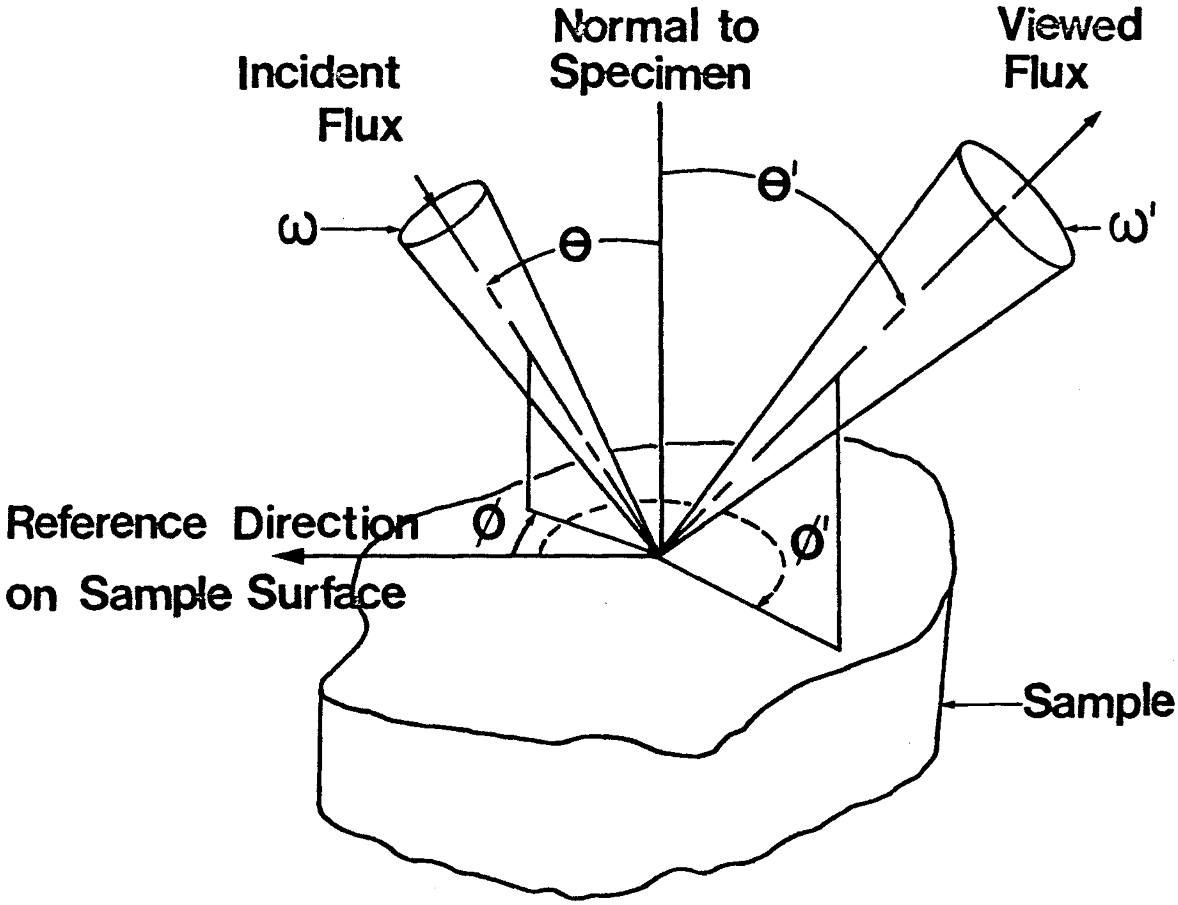
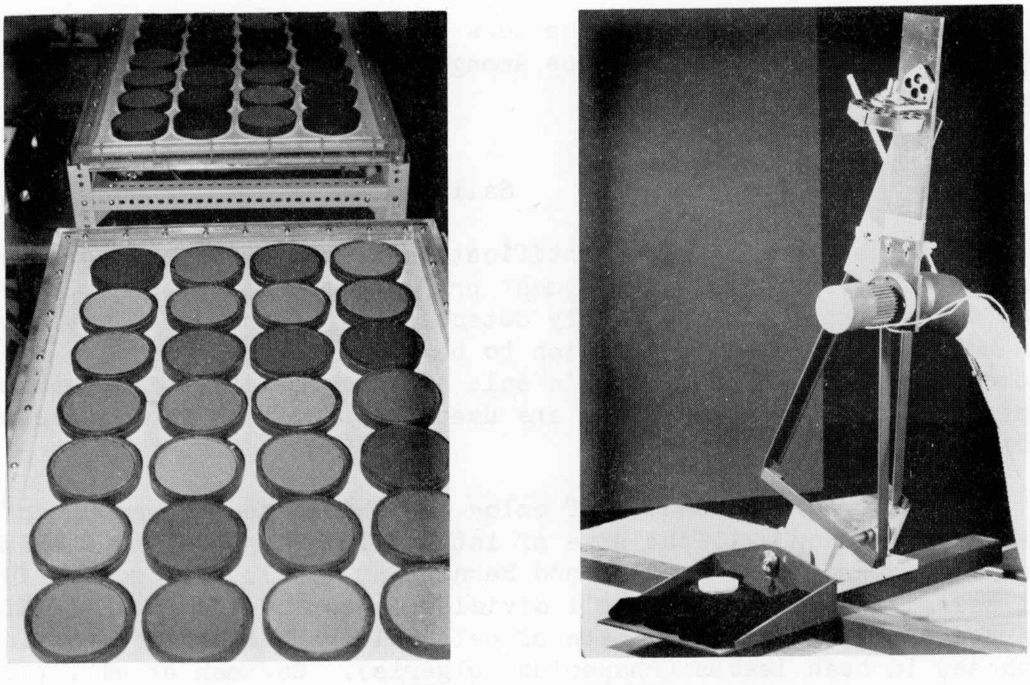


Figure 1. Geometric parameters describing reflectance from a surface.



Fifty-six soil samples ready for spectral measurement after 24 hours equilibration at 100 cm H_2O tension.

BRF reflectometer positioned for soil sample detection by the Exotech 20C spectroradiometer.

Figure 2. Set up for laboratory spectral measurements of soils (reprinted from Stoner and Baumgardner, 1980).

The work of these researchers in pinpointing the role of the hydroxyl ions established the need to carry out carefully controlled moisture tension equilibria and soil moisture content determination in soil reflectance studies (Beck et al., 1976). Prior to this period and, even though it had been demonstrated that moist soils had lower reflectance values than dry soils in the 0.4 to 2.6 μm wavelength region (Hoffer and Johannsen, 1969), some researchers organized their soil spectral measurement experiments and reported their findings without paying attention to or at least discussing the impact of fluctuation in soil moisture content for their samples (Condit, 1970, 1972).

As previously mentioned, the work of Peterson et al., (1979) revealed marked and distinct relationships among soil moisture tensions and soil reflectance values.

Salinity

The identification and quantification of saline areas are of considerable interest to agricultural development projects around the world. Myers and Allen (1968) point out that early detection of saline areas may permit preventive measures or corrective action to be taken before significant crop damage becomes apparent. Crops grown in salt affected soils exhibit marked visual symptoms of moisture stress and are used frequently as good indicators of soil conditions.

Salinity may influence leaf color and thickness, the amount of chloroplasts and chlorophyll, the size of intercellular spaces and the number of stomata (Harter, 1908, Hayward and Bernstein, 1958). Strogonov (1962) found that salinization depressed cell division in cotton leaves while Nieman (1965) observed a reduction in the rate of cell enlargement and of protein and RNA syntheses in bean leaves (Phaseolus vulgaris). Gausman et al., (1969) performed spectrophotometric studies which showed that individual plant leaves affected by salinity have reduced reflectance and increased transmittance compared with unaffected leaves of the same age.

Remote sensing of plant canopy temperatures has been determined to be feasible for detecting soil salinity problems (Myers et al., 1966). Water thermodynamic activities are reduced whenever dissolved salts are present in the soil solution. Therefore, plants are unable to absorb the soil water which becomes somehow less available. Other researchers have used microdensitometry on 70 mm color-infrared (CIR) aerial film to distinguish saline from nonsaline sites on a rangeland in Starr County, Texas (Everitt et al., 1981). However, these research efforts seem to be geared towards indirect measurements of soil salinity problems (Cordova, 1981) rather than attempting to measure directly characteristic variations in reflectance of salt affected soil samples.

Organic Matter

Organic matter not only influences soil color but also cation exchange capacity, water holding capacity, structure, heat capacity, erodibility of soils and soil reflectance characteristics. Hoffer and Johannsen (1969) demonstrated that within the 0.4 to 2.5 μm wavelength range an increase in organic matter content was accompanied by a corresponding decrease in soil reflectance values. Kristof (1971) and Baumgardner et al., (1970), using digital analysis for processing remotely sensed data, were able to delineate and map five different ranges of organic matter content for mineral soils which contained from 1.5 to 7 percent organic matter. Different soils series were used in this study which included soils formed under both deciduous hardwood forests and tall prairie grasses.

Stoner and Baumgardner (1979) indicated that the green wavelength region (0.52 to 0.62 μm) showed high correlations with the organic matter content of 481 benchmark soil samples belonging to different taxonomic classes. The organic matter content of these soils varied from amounts lower than 3 percent to 10 percent. Earlier studies in the 1960's had also detected certain degrees of influence of organic constituents like humic and fulvic acids on soil reflectance (Obukhov and Orlov, 1964). Bowers and Hanks (1965) noticed that the oxidation of soil organic matter with hydrogen peroxide (H_2O_2) provoked an increase in reflectance in the range from 0.4 to 2.4 μm.

Although there remains no doubt about the impact of organic matter on soil reflectance characteristics, researchers maintain different opinions with respect to the region of the electromagnetic spectrum most suited for measuring spectral properties of soil organic matter content (Beck et al., 1976; Montgomery, 1976; Stoner and Baumgardner, 1980; Latz et al., 1981). Therefore, it appears appropriate to emphasize the need to design more effective techniques for studying organic constituents and their influence on soil spectral properties.

Parent Material

Soil parent material constitutes another important parameter whose effect on soil reflectance has been recognized by several researchers (Stoner and Baumgardner, 1980; Mathews et al., 1973). For instance, the presence of limestone or sandstone in soil samples bestowed unique characteristic shapes to their spectral curves. Weismiller et al., (1979) noted that drainage classes were best separated if they were spectrally studied on a separate basis in the context of their specific geographic locations. Latz et al. (1981) also found that a variety of parent materials such as loess over glacial outwash, lacustrine, calcareous loam till and limestone residuum affected soil reflectance.

Particle Size

The amount and texture of different soil particles seem to influence spectral response. The direct effect of particle size on reflectance has been identified by several scientists through spectrophotometric analysis (Bowers and Hanks, 1965; Orlov, 1966; Shockley et al., 1962). One of the principal conclusions drawn from their studies relates to a decrease in reflectivity as the diameter of the soil particles increases. Stoner and Baumgardner (1980) also noted that a decrease in particle size increases soil reflectance among coarse textured soils; whereas, the inverse was noticed for medium to fine textured soils. Furthermore, they reported that higher moisture contents associated with increasing clay content cause a decrease in reflectance in the 2.08 to 2.32 μm band as textures vary from silt loam to clay. In other studies of silty soils, spectral variations were observed to be greatly conditioned by the amount of silt present (Montgomery, 1974, 1976) and the suitability of the spectral readings for mapping clay content in surface soils were best assessed within the 1.50 to 1.73 μm wavelength region (Beck et al., 1976).

Clay Mineralogy and Iron Oxides

Both clay mineralogy and iron oxides constitute additional parameters which affect soil reflectance. The chemical and physical properties of montmorillonite and kaolinite group clay minerals exhibit different spectral characteristics. Lindberg and Snyder (1972) attribute these differences to the presence of water molecules. They also observed that a general decrease in reflectance took place with decreasing wavelength starting around 0.7 μm. It is difficult to study specifically as an isolated factor the impact of soil clays on reflectance since they exist in close association with other soil constituents. This might explain, perhaps, the fact that Montgomery (1976), having studied separately a group of montmorillonitic mineralogy soils, did not find any significant and meaningful statistical correlations between reflectance and soil properties for these clays vis a vis soil characteristics in general. Stoner and Baumgardner (1980) characterized the 1.0 μm wavelength as critical for identifying hydroxyl gibbsite and ferrous iron.

As far as ferric iron is concerned, they labeled the 0.7 μm and 0.9 μm ranges as the key absorption wavelengths for properly identifying the spectral properties of such a compound in soils. Schreier (1977) pointed out that percent iron in iron-organic complexes as well as the percent of carbon and exchangeable magnesium and potassium were very much correlated with spectral measurements. Montgomery (1976) also remarked that the significance of free iron oxide increased with increasing wavelength particularly in the visible and infrared regions of the electromagnetic spectrum. All these studies seem to reinforce the belief and confirm the observation that infrared iron absorption bands are rather narrow in nature.

DESCRIPTION OF THE AREA

Geographic Setting

Bolivia is a South American country which includes nine Departments covering 1,098,581 square kilometers. The area of study is limited to a 400 square kilometer zone within the Oruro Department (57,000 square kilometers) located approximately between the parallels 17°30'45" and 19°50'10" South and the meridians 66°30'50" and 69°00'15" West (Fig. 3). The area is more specifically confined in the Abaroa Province with an elevation of about 3800 meters above sea level and belongs to the Altiplano Central Watersheds.

Geology and Geomorphology

The specific area where the samples were collected has a highly complex geomorphologic feature. It is formed by an old pediment on top of which an alluvial fan has developed. The sandy material present in the pediment has been reworked and, due to wind influence, transported over short distances forming accumulation of sand. The area is found in the Altiplano, an interandean depression which constitutes an aggradational plain with a mountain range. It is characterized by a watershed which does not exhibit features of a main drainage system but diverts its resources to the lakes Titicaca, Poopo, the Salt Flats of Uyuni and Coipasa. The area was also influenced by the ancient Lake Minchin. This lake, formed in the Upper Pleistocene, covered an area of about 90,000 km^2, leaving as remnants great amounts of organic carbonates present all over the study area. Lake Poopo is also influencing the area due to seasonal changes in water availability, flooding the area during summer (rainy season). The affected regions are saturated for a short period of time and then exposed to a high evapotranspiration process by which soluble salts (Lake Poopo´s water contains high amounts of soluble salts) are transported by capillary action to the surface, thus forming the salt crusts present in the area.

Precipitation

The area experiences sporadic rainfall during the dry season months from April to November. The mean annual precipitation reaches about 325 mm and maximum precipitation is registered during the months of December, January and February.

Temperature

The mean annual temperature oscillates around 10 degrees centigrade and marked differences are observed during the months of November and March when measurements fluctuate between 12 and 17 degrees centigrade. The months of April through October are usually the coldest ones with temperature values ranging from 6 to 9 degrees centigrade.

Natural Vegetation

Cardenas (1969) characterized by their indigenous and scientific names the predominant species of natural vegetation as follows: "Tola" - *Lepidophyllum quadrangulare*; "yareta" - *Azorella glaba*; "Kota o Yaretila" - *Arozella spp*; "Paja brava" - *Festuca ortophylla*; "Cola de raton" - *Hordeum andicola*; "Chiji blanco" - *Distichlis humilis*. Along with these native species are

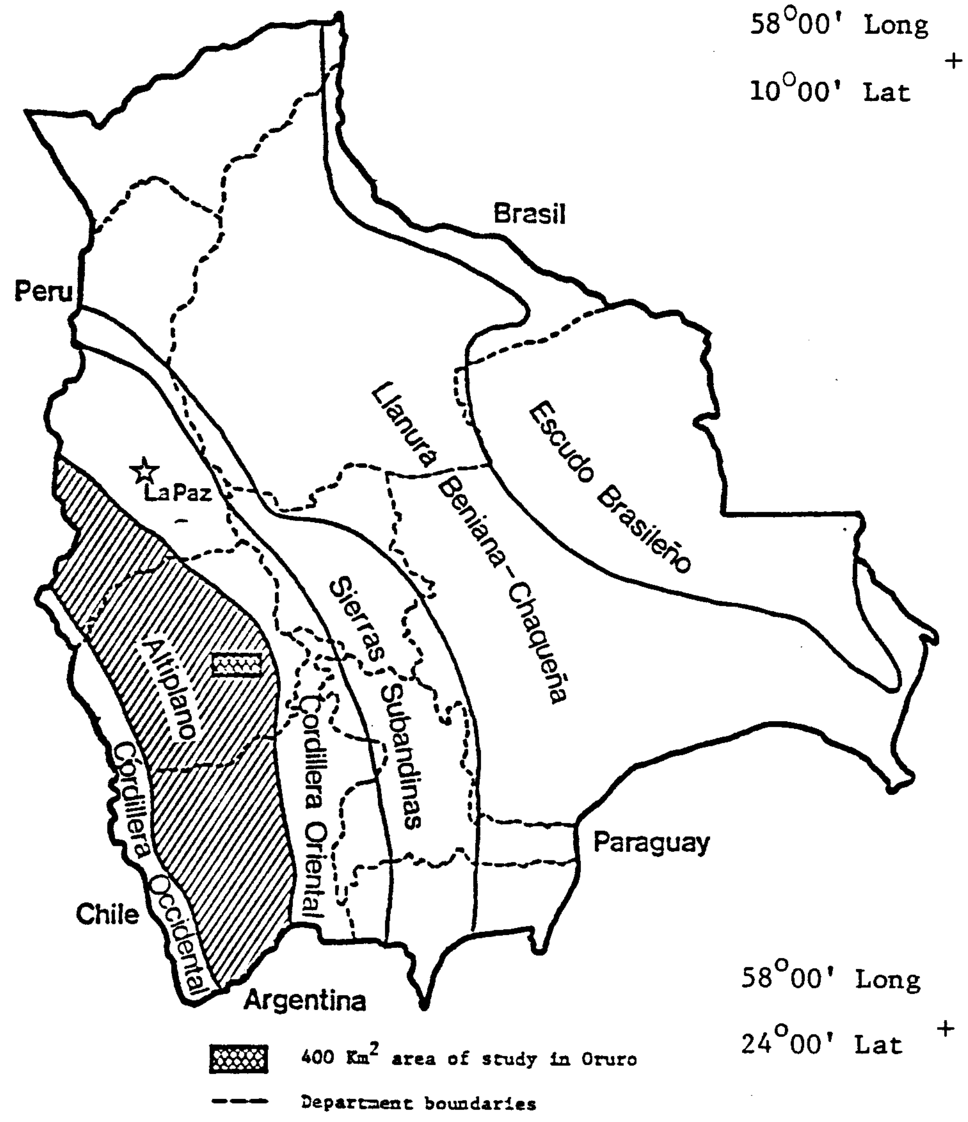


Figure 3. Major morphological zones of Bolivia (1,098,581 km^2) and its nine departments.

found patches of subsistence farming where the most common crops under cultivation are: potatoes (*Solanum tuberosum*), quinoa (*Chenopodium quinoa*), barley (*Hordeum vulgare*), horse bean (*Oxalis tuberosa*), and alfalfa (*Medicago sativa*).

Soils

The sites of interest within the 400 square kilometer area where the soils were obtained are located in Challapata, on the Eastern side of Lake Poopo at an altitude of about 2686 meters above sea level, Oruro Department. Soil samples were collected, described and classified in accordance with the ten orders of the United States Soil Taxonomy. A total of 125 soil samples were gathered including the 15 surface samples having an Ap horizon used in this study. Challapata is one of the few areas of Bolivia known for its large regions of salt affected soils. The following soil orders characterize the area: Alfisols, Aridisols, Entisols, Inceptisols and Vertisols. The 15 soil samples belong to the Alfisol, Aridisol, Entisol, and Inceptisol orders (Table 2). Kovda et al., (1979) estimate that there are nearly 6.0 million ha of salt affected soils in Bolivia.

METHODS AND PROCEDURES

Field Work

Soil scientists at the Programa ERTS (Earth Resources Technology Satellite), dependency of Bolivia Geological Bureau, cooperated with the Laboratory for Applications of Remote Sensing (LARS)/Purdue University by collecting the soil samples in the Oruro Department. These soils were sampled, properly identified and forwarded to LARS for analysis.

The field work involved initially the visual interpretation of seven Landsat images which cover the entire Department of Oruro. Soil maps at the reconaissance level (1:250,000 scale) were produced from the satellite data, and their interpretation enabled the identification of potential areas for agricultural development. Black and white photographs at 1:30,000 scale were used to delineate the soil mapping units with particular emphasis on the areas of salt affected soils. Field checks were conducted to assess the validity and accuracy of the preliminary delineation made on the aerial photographs. Taxonomic classes were identified for a total of 15 profiles (125 samples) collected from the area (400 square kilometers) where salinity problems are known to prevail.

Soil Sample Selection

Soil sample selection was based on the presence of salinity problems in specific locations where it was visually perceived that surface samples would reflect major levels of salinity. Besides, the Bolivian soil scientists knew from experiences acquired through laboratory analyses that significant physical and chemical differences existed among the final 15 sites selected from a total of 125 samples collected at different depths within the soil profile of these sites and a few other ones. Their surface samples represented a good random selection of the major salinity problems encountered within the 400 square kilometers area (Table 2).

The specific site location of each representative surface sample was also determined on the corresponding Landsat image which was generated by a computer compatible tape (CCT) stored at LARS. A Comtal Image Processing Systems Vision One/20 was used as an image display device to project on its screen the area of interest. The salt affected sites were pinpointed by an x-y coordinate system. The size of the area fitted perfectly within the maximum range of 512 lines or x coordinate and 512 columns or y-coordinate of the image display screen. Each site was assigned a line and column value for references that might prove useful in future studies.

Soil Sample Preparation

Upon reception of the 125 soil samples at the Agronomy Department of Purdue University, they were transferred to its soil chemistry laboratory for preparation and identification. First, the 15 surface samples were dried and slightly crushed with a wooden rolling pin to break up clods. Secondly, they were passed through a 10 mesh sieve in order to remove all particles and aggregates larger than 2 mm in diameter. Such an approach helped standardize the procedure for soil reflectance measurements in accordance with the use of similar size particles for most chemical and physical analysis of soils (SCS-USCA, 1972; Franzmeier et al., 1977).

The prepared soil samples were divided into three similar groups and placed in one quart containers. They were identified as to site selection and sampling number. One group was kept at the Agronomy Department for certain chemical and physical analysis while a second group was sent to the National Soil Survey Laboratory, Lincoln, Nebraska for appraising salinity and alkalinity. The third group of quart containers as well as the remaining 110 samples of different soil horizons were stored at LARS for eventual future studies.

Measurements of Physicochemical Properties

The analyses of the chemical and physical properties of the soils were conducted at the Purdue University Agronomy Department and the U.S. Department of Agriculture National Soil Survey Laboratory, Lincoln, Nebraska. The Soil Characterization Laboratory of Purdue determined the particle size distribution following removal of organic matter by H_2O_2. Eight particle size separate classes were used on a weight percentage basis; they were: very coarse sand (2-1mm), coarse sand (1-0.5mm), medium sand (0.5-0.25mm), fine sand (0.25-0.10mm), very fine silt (0.02-0.002mm), and clay (<0.002mm). For the particle size analysis hydrogen peroxide and heat were applied to reduce the presence of organic matter. (Franzmeier et al., 1977; SCS-USCA, 1972). This procedure is followed by a process of filtering, washing and dispersing with sodium metaphosphate to derive the organic matter-free portion of each soil sample. A 300 mesh sieve was used to separate the sand particles from silt and clay by washing the dispersed sample. To break down the sand content in different classes a nest of sieves was used; whereas, the silt and clay contents were determined by sedimentation-pipetting.

Cation exchange capacity (CEC) was determined by the sum of extractable cations of Ca^+, K^+, Na^+, Mg^{++} including extractable acidity (H), all of them expressed in milliequivalents per 100 g of soil. The use of barium chloride combined with a buffer solution of triethanolamine through titration with hydrochloric acid (HCl) permitted the determination of extractable acidity. The values for base saturation were calculated as follows:

a) $CEC - H = X$
b) $Na^+ + K^+ + Ca^+ + Mg^{++} = X$
c) $(X/CEC)(100) = \%$ base saturation

The modified Walkley-Black procedure of acid dichromate digestion with ferrous ammonium sulfate titration was selected to calculate the percentage of organic carbon (Franzmeier et al., 1977). This method facilitates the identification of easily oxidizable organic carbon in a general empirical way. Furthermore, this method has been tested by several researchers who found no significant differences among this procedure and others designed to assess organic carbon content in soils in terms of their impact on fluctuations of soils spectral responses (Beck et al., 1976).

Standardization of Moisture Tension

A number of considerations led to the standardization of the procedure for preparing the soil samples and measuring their reflectance values. First of all, it became desirable to control as much as possible soil moisture deriving from environmental factors in view of the critical role which moisture plays in soil reflectance. Secondly, the set up of the spectroradiometer/reflectometer facilitates a view of a soil sample diameter of about 3.2 cm in such a horizontal position that it was not necessary to use glass slide covers which could have hindered the work. A plexiglass-framed (61 x 91cm) tension table including an asbestos set up was used to equilibrate the 15 soil samples at approximately one-tenth bar moisture tension. The latter is produced by exposing the upper side of a membrane such as the asbestos to atmospheric pressure while a column of water 100cm in height generates the tension to the lower side (Kohnke, 1968). Under field conditions, one-third bar is the upper limit of the range of water availability to plants; whereas, the moisture tension selected here is somehow drier than the aeration-porosity limit of about one-twentieth bar and moister than one-third bar. Elrick and Tanner (1955) recognized that it is difficult to obtain direct comparative correlations between field soil moisture tension and moisture retention of sieved samples which is known to increase over core samples at tensions lower than 0.4 bar.

The asbestos tension table was built by Stoner (1979) who followed the method of Jamison and Reed (1949) in which a more durable asbestos membrane was used in lieu of the blotter paper apparatus discussed by Leamer and Shaw

(1946). Stoner (1979) also added an additional feature to the table by using a plexiglass top which covered the equilibrating soil samples thereby avoiding exposure to room air currents while permitting the upper membrane to be very slightly exposed to atmospheric pressure. Therefore, crusting of the soil surface did not occur.

The soil samples were placed in plastic sample rings which were painted with non-reflecting black paint to reduce undesirable reflectance. The rings were designed to meet the specifications of the spectroradiometer field of view and the modus operandi of the tension table. A filter paper was placed at the bottom of each ring before adding sufficient soil to a depth of about 2 cm. In order to keep the soil samples in direct contact with the asbestos membrane a 60 mesh brass strainer cloth was stretched and fastened in a counter sink grooved at one end of the plastic rings. The filter paper prevented the asbestos from staining while keeping it in good contact with the soil.

The soil samples were carefully placed in a large tray in which deionized water was added to a depth of about 1 cm. Once they became saturated for approximately four hours, they were removed and put on the tension table for 24 hours so as to reach equilibrium. Jamison and Reed (1949) observed that a 24 hour period was quite adequate for most soils at a 100 cm water tension.

At the expiration of the 24 hour period, the samples were removed from the tension table and transferred to the Measurements Research Laboratory at LARS for reflectance measurements.

Measurements of Bidirectional Reflectance Factors

LARS Exotech Model 20C spectroradiometer mounted in an indoor configuration with a bidirectional reflectance factor reflectometer was operated to gather spectral readings in increments of 0.01 m for values ranging from 0.52 - 2.32 µm. A silicon detector was used to measure radiation in the 0.37 to 0.85 µm wavelength range and a lead sulfide detector was used to cover two ranges of the spectrum, 0.65 to 1.3 µm and 1.25 to 2.5 µm (Silva et al., 1971). A circular variable filter (CVF) with a segment which matches each of the previously cited wavelength ranges enables spectral scans to be made by rotation through the optical path in front of the detectors. Leamer, Myers and Silva (1973) have concluded that such filters, through the rapid scan time of 2 complete scans/second, generate enough potential for the instrument to function under natural conditions. A multichannel strip chart recorder and a magnetic tape were used for data recording. Then, the recorded data were reformatted and made available for subsequent digitization and computer analysis.

Each soil sample was kept at a distance of about 2.5 meter away from the sensing head of the spectroradiometer, mounted in a vertical and stable position. A 1000 watt tungsten iodide coiled filament lamp was used as an illumination source. It generated a powerful collimated beam through a paraboloidal mirror to the sample-viewing plane. According to Dewitt and Robinson (1976), in similar cases, incident irradiation is off vertical by about 10 degrees and the 3/4 degree field of view of the spectroradiometer helps detect a sample size of approximately 3.2 cm in diameter.

Both before starting the experiment and during the gathering of spectral measurements, pressed barium sulfate ($BaSO_4$) was utilized as a standard to calibrate the Exotech Model 20C spectroradiometer. The $BaSO_4$ was measured 3 times or one reading after every fifth soil sample to adjust the instrument for any change in intensity of the illumination source. The bidirectional reflectance factor data, once corrected, were put on magnetic tapes for digitization and processing. The tapes contained the average values of a total of six complete scans covering the entire wavelength range. The tape (run number 3072) was stored at LARS for possible future analysis.

Digital Analysis Procedure

The LARSPEC software package which is a system of Fortran and assembler computer programs implemented on an IBM 4341 computer was used to access and analyze the spectral measurements obtained by the Exotech Model 20C Spectroradiometer. Fuhs et al. (1979) point out that LARSPEC has three overall capabilities:

- Printing and punching statistics of wavelength bands (DSEL)
- Plotting identification information and spectral data (GSPEC)
- Printing and punching identification record information (IDLIST)

For each spectroradiometer reading, a list of seven computer cards or soil data sheets containing the soils information was prepared. Prior to reformatting the digital computer tape, the information printed on these cards is combined with the spectral values for each of the 15 soil samples and placed on the tape. The processors available in the LARSPEC software permit the graphic displays of the spectral curves as well as specific chemical, physical and other characteristics inherent to the soil samples.

Catalog of Soil Spectral Characteristics

A large quantity of data was stored in the soil data base for each soil sample. However, a format was developed to retrieve from the data base only certain key parameters which were judged relevant to the need to understand the reflectance properties of salt affected soils. The spectral curve of each sample was matched with its corresponding set of data. Bidirectional reflectance factor (%) was plotted on the y-axis and wavelength (0.52 - 2.32 μm) on the x-axis.

Some of the essential soil parameters retrieved from the data base and displayed for each soil sample are: soil order, parent material, horizon, slope and drainage classes, texture class, percent sand, silt and clay, cation exchange capacity, percent organic matter, moisture percentage by weight, moist and dry Munsell colors, percent base saturation, buffer pH, water pH, electrical conductivity (mmhos/cm at 25°C), exchangeable sodium percentage, meg./liter of Ca^{++}, Mg^{++}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, $SO_4^{=}$ and NO_3^{-} measured from the water extracted from the saturated paste, and the sodium adsorption ratio (SAR).

RESULTS AND DISCUSSION

Catalog of Soil Characteristic Variations

The chemical, physical and spectral characteristics of the 15 soil samples have been sorted out and grouped in Appendix 1. Each spectral curve is displayed with its corresponding physicochemical data. In addition, a brief description of the type of natural vegetation as well as the scientific names of the plants found in the salt affected soils of Challapata, Oruro are also listed.

Absorption Bands

As expected, the spectral curves of the 15 surface samples reveal the presence of strong water absorption bands at 1.45 and 1.95µm in all of them (Fig. 4 and 5). Figure 4 contains the reflectance curves of the first 10 samples listed in Appendix 1 and Figure 5 shows the soil curve composite of samples 5-15 (Appendix 1). It can be observed in Figure 4 that the curves of the saline alkali samples 1 and 2 differ significantly from the others. These two samples were the only ones which contained 28% and 19% of calcium carbonate ($CaCO_3$), respectively. These samples show the highest reflectance in the visible and the lowest in the infrared. Most of the curves display a slight dip around 0.7 µm (Figures 4 and 5) and a more pronounced one at 0.87 µm. As previously mentioned researchers have attributed these characteristics to the presence of iron oxide (Montgomery, 1976; Stoner and Baumgardner, 1980). In this particular study a scientific assessment of these findings cannot be made for the iron content of the soils was not determined.

Particle Size Distribution

Montgomery et al., (1974) measured the spectral properties of 71 soils from 26 states within the United States and characterized spectral reflectance curves from 0.5 - 2.6 µm for each of the 10 orders of the United States Soil Taxonomy. The study identified silt and cation exchange capacity as the most important properties used to estimate variations in spectral response by multiple regression. Prior to this investigative work, Condit (1970) had used a similar procedure to measure spectral properties from 0.32 to 1.0 µm for 160 soils from 36 states and classified them by their spectral curve into 3 typical or characteristic types.

Beck et al. (1976) used a similar method to study the variations in characteristic reflectance of 15 mainly silty surface soils gathered from the western part of Tippecanoe County, Indiana. These soils varied predominantly in organic carbon values, and the spectral measurements from 0.53 to 2.32 µm were made after they had been equilibrated at three moisture contents (oven dry, 15 bar and 1/3 bar). Regression analysis results pointed out that moisture content affected the spectral response of soils the most followed by

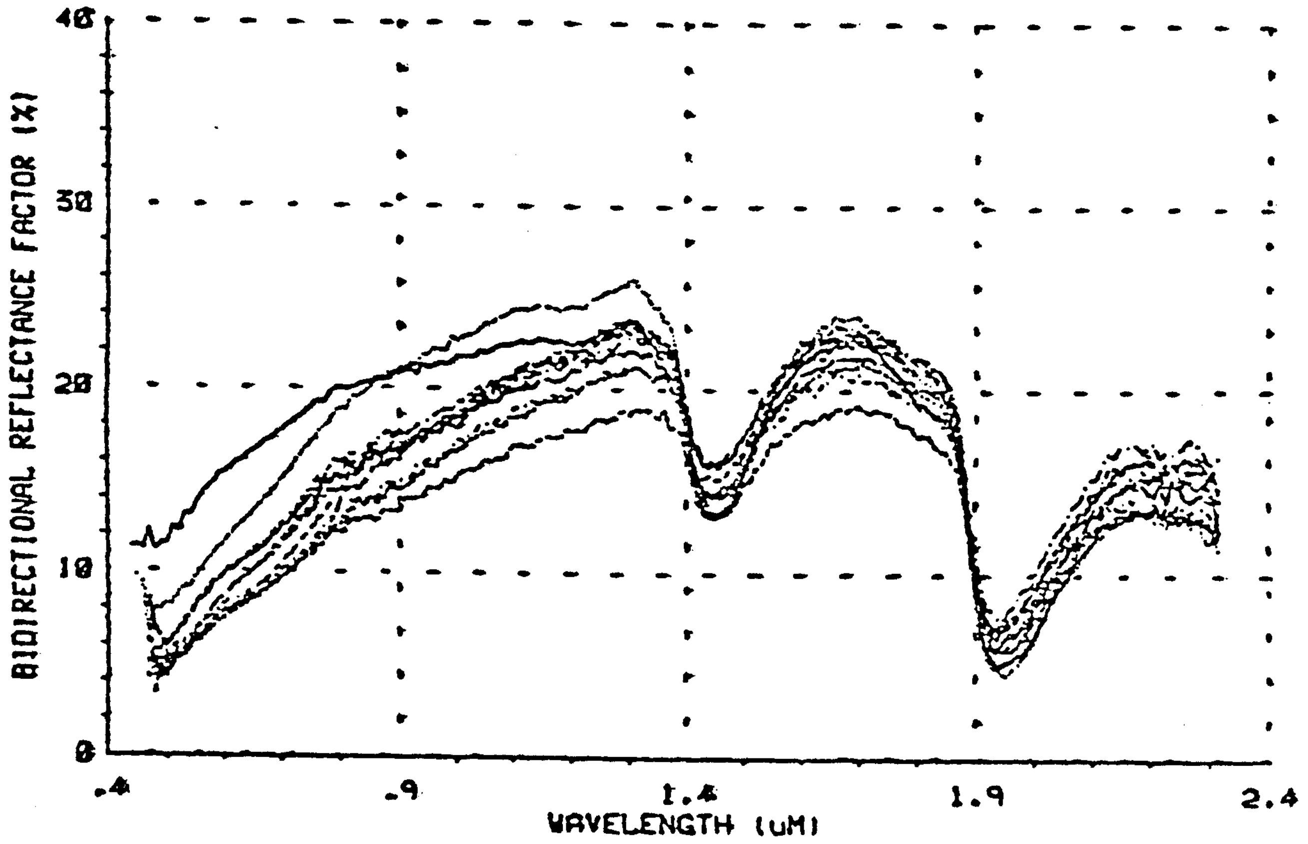


Figure 4. Composite soil curves of 10 soils. (Sample 1-817562 through 10-817571, Appendix 1; dark black solid line represents sample 1 with 28% $CaCO_3$.)

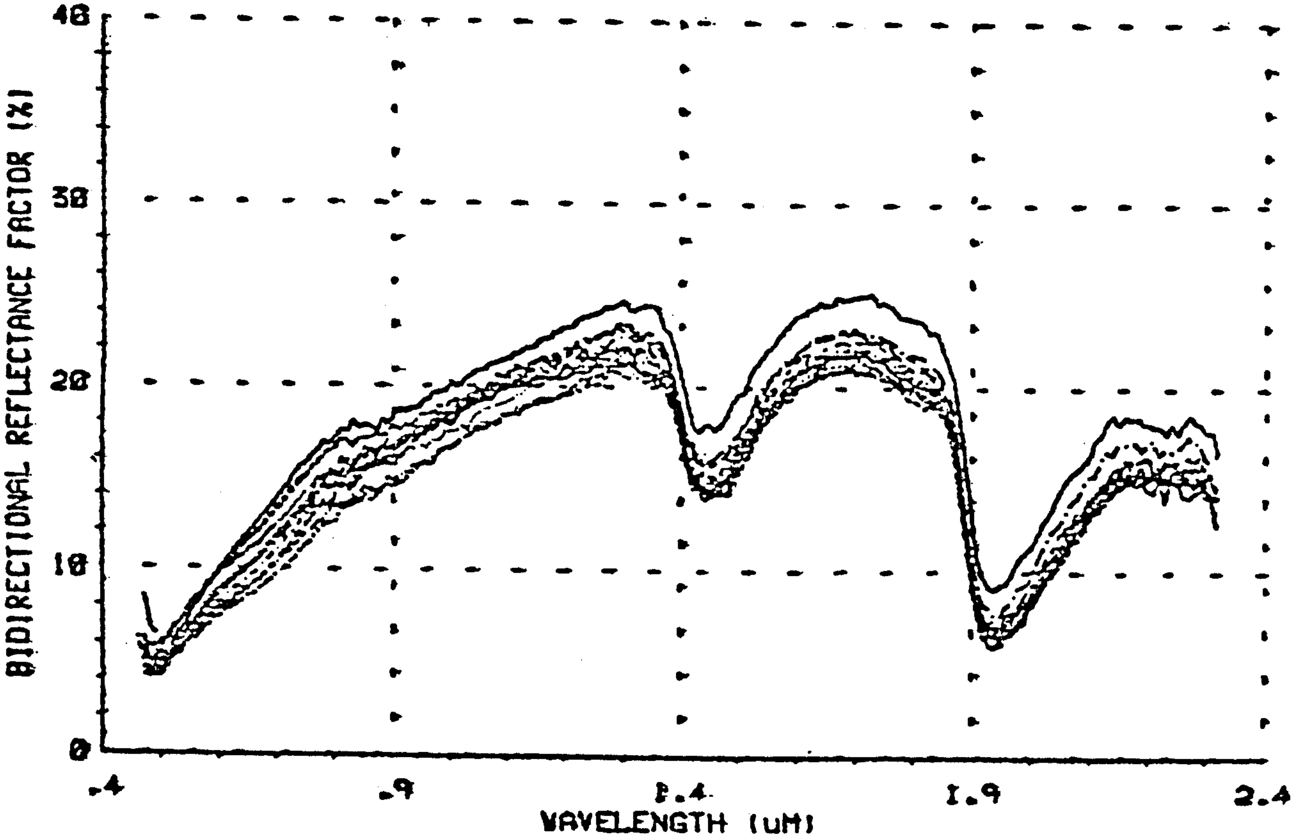


Figure 5. Composite soil curves of samples 5-817559 through 15-817567. (See Appendix.)

organic carbon content, percent silt and percent clay. As previously stated, Stoner et al. (1979) pointed out, after having studied the spectral properties of 481 benchmark soil samples from 39 states of the continental United States as well as Brazil and Spain, that an increase in reflectance among sand textured soils was associated with a decrease in particle size. However, they indicated that the inverse was observed for medium to fine textured soils.

None of the above mentioned studies took into account the possible impact of salts on the spectral characteristics of soils since the samples were not collected from salt affected regions. Figure 6 shows the composite curves of 4 samples of this study classified as nonsaline-nonalkali soils which have a fine sandy loam texture. The closeness of the spectral curves is particularly noticeable in the visible range (0.5-0.6, 0.6-0.7 μm) where they almost overlay one above the other. The respective amounts of clay, sand and silt for each of these samples appear in Appendix 1 where it can be detected that such values for the four soils do not vary significantly.

On the other hand, Figure 7 contains the spectral curves of 3 soils with a similar silty clay loam texture which display very different reflectance curves. The curve of sample 1 corresponds to a saline-alkali soil with 28% calcium carbonate (Appendix 1 - sample 1-817562). It can be noticed that the saline alkali soil curves display the lowest, most pronounced dip in the infrared region of the spectrum; whereas in the visible the spectral curve for sample 1 with 28% calcium carbonate has the highest, bidirectional reflectance factor (BRF%).

It appears reasonable to suggest that spectral curves of salt affected soils with similar texture differ substantially from those of nonsaline nonalkali soils of the same texture.

Comparative Analysis with Munsell Color Chart

Soil colors for the 15 samples were determined by placing a small portion of the soil next to the color chips and comparing colors for the most appropriate match in a Munsell soil color chart.

Moist soil colors were obtained by moistening each sample and reading the color as soon as visible moisture films disappeared. Air dry and moist readings were taken and the resulting data fell for all soils within the Munsell notation range of 10 YR 3/2 to 10 YR 7/2 (Figure 8).

Statistical Analysis

A Fortran program was written to include all the chemical and physical parameters inherent to each of the 15 surface samples. This very preliminary step helped screen out the parameters which displayed high correlation coefficients. Once this phase was completed, a second course of action which can be characterized as exploratory in nature was followed. It consisted in using a stepwise regression model which looks at all the variables already included in the model and deletes any variable that does not produce a significant F sta-

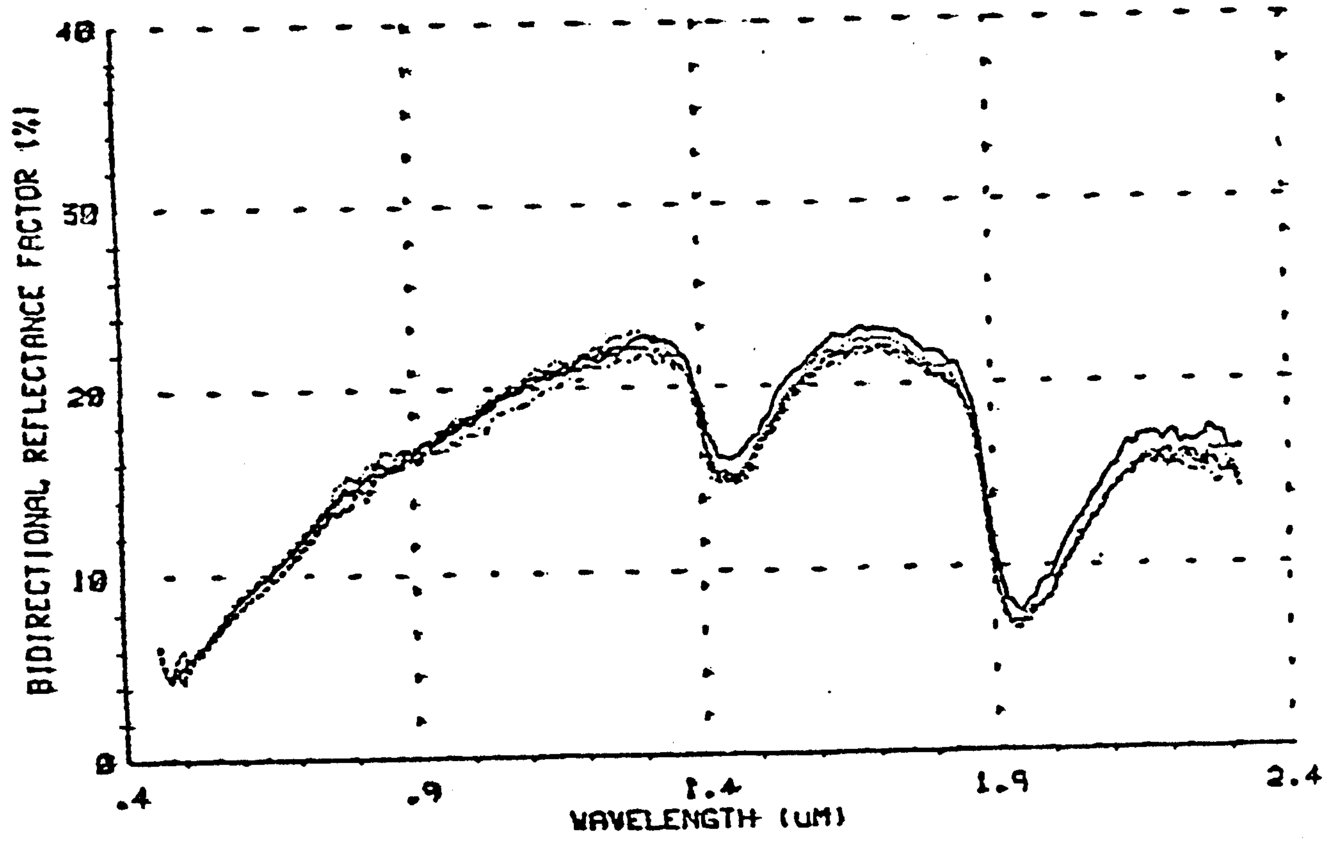


Figure 6. Composite soil curves -- Fine Sandy Loam -- of 4 nonsaline nonalkali soils.

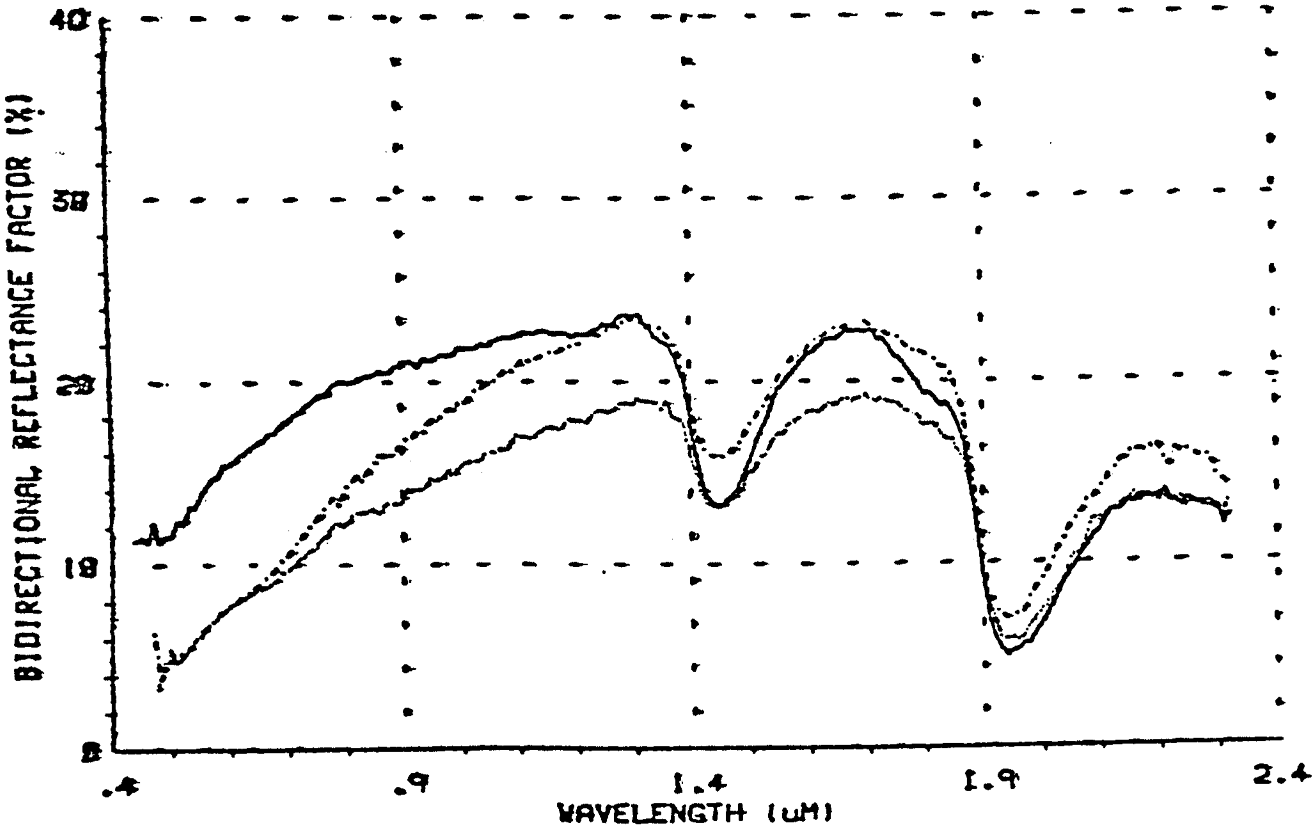


Figure 7. Composite soil curves of 2 saline alkali soils and a nonsaline alkali soil. (Lowest reflectance at 0.9 μm; sample 1 - 28% $CaCO_3$, saline alkali; all have a silty clay loam texture.)

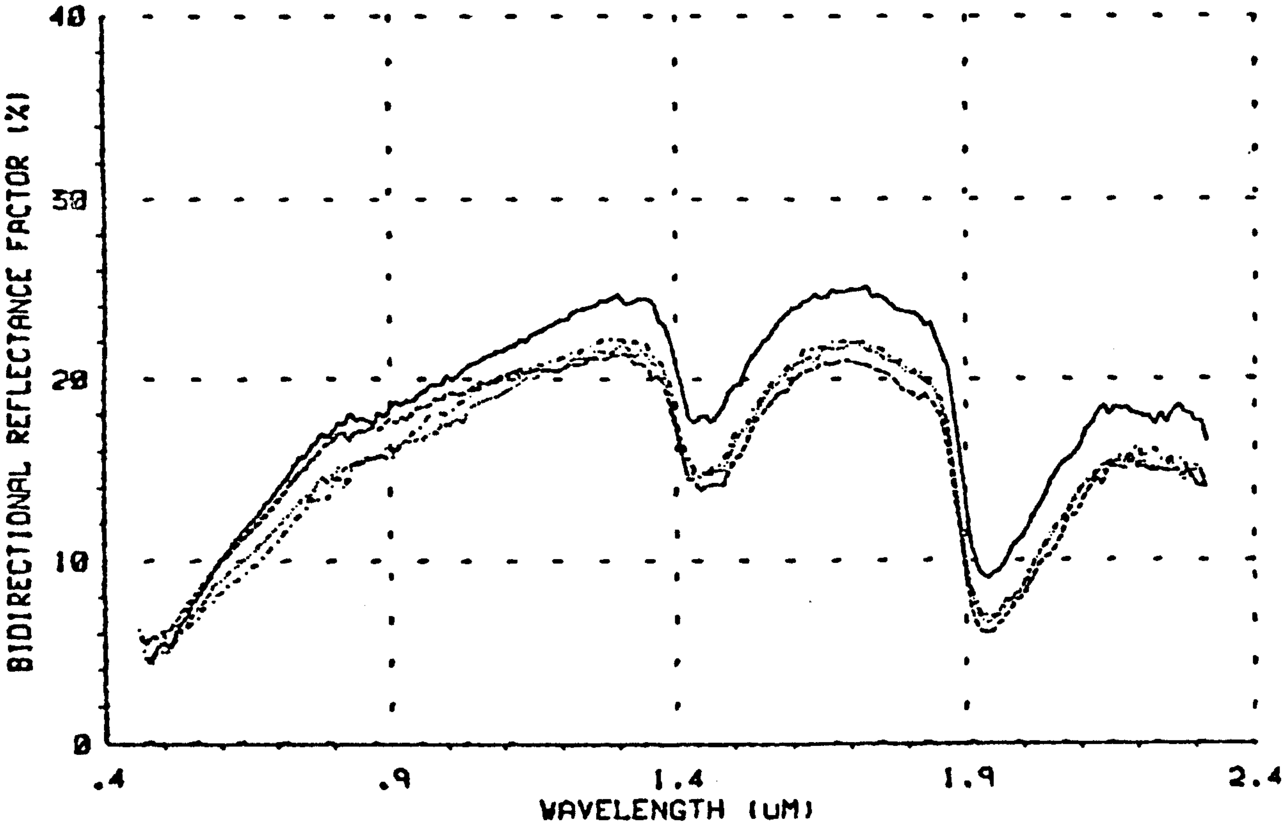


Figure 8. Composite soil curves of 4 nonsaline nonalkali soils with similar Munsell color notations (10 YR 4/4).

tistic. Subsequently, another technique known as the Maximum R^2 Improvement (MAXR) was used. It starts by finding the one variable model producing the highest R^2. Then another variable, the one that would yield the greatest increase in R^2, is added. After the selection of the two-variable model, each of the variables in the model is compared to each variable not included in the model. For each comparative analysis, MAXR determined whether or not excluding one variable and replacing it with the other variable would increase R^2. Upon completing all possible comparisons and switches within the soil parameters as independent variables, the ones that produced the largest increase in R^2 were selected.

One important difference between the stepwise technique and the maximum R^2 improvement method comes from the fact that all possible combinations and switches among parameters are evaluated prior to making any switch in the MAXR method. On the other hand, the stepwise method may facilitate the removal of the "worst" variable without assessing whether or not the addition of the "best" remaining variable may affect the model in anyway.

For each of the 10 spectral bands listed in Table 4, the best 2 variable model was selected. Table 4 was prepared in order to show the distribution of the soil parameters with the highest R^2 values and their respective F values for each of the 10 spectral bands. The overriding observation pertains to the predominance of salts particularly calcium carbonate ($CaCO_3$) and the anion (NO_3^-) in the "best" models produced. Figure 9 and 10 reflect the characteristic variations in the spectral reflectance of four samples of saline alkali soils. Samples 1 and 2 in Figure 9 contains 28% and 19% $CaCO_3$ respectively.

The statistical analysis was carried out one step further to detect whether or not the values listed in Table 4 were not masking certain significant correlations among spectral bands and the chemical and physical properties of the samples. Spectral band 1 (0.52-.62 μm), band 4 (0.82-0.92 μm), band 5 (0.92-1.02 μm), band 9 (1.55-1.75 μm) and band 10 (2.08-2.32 um) were selected and the independent variables chosen were: Na^+, O.M., silt, sand and clay.

The results of the analysis show correlation coefficients pointing out no clear relationships between silt, sand and clay. However, the best correlations were found between O.M. and Na^+ in bands 4 and 5. In spectral band 4 the R^2 value was 0.64 whereas for band 5, it was 0.69. When O.M. was excluded from the model, the R^2 values were 0.61 for band 4 and 0.67 for band 5. Furthermore, an R^2 of 0.90 was obtained when predicting Na on the basis of bands 4 and 5 plus the interaction of these two spectral bands. But, when the interaction between O.M. plus Na^+ was excluded from the statistical model, the R^2 decreased significantly; in band 4, the R^2 was 0.29 and band 5 it went up very slightly to 0.30. The statistical analysis was carried out one step further to determine correlations between bands and samples for all samples having more than 2% organic matter and 20 meg of sodium. The results of the analysis appears in Table 5. Again, bands 4 and 5 show the strongest correlations. A graphic display of the correlations between organic matter and sodium content versus reflectance appears in Figures 11 and 12.

Table 4. Maximum correlations (R^2 values) between the independent variables and spectral bands.

Spectral Band (μm)	Spectral Region	R^2 Value	F Value	Prob. F	Independent Variable
0.52-0.62	visible	0.84	68.44	0.0001	$CaCO_3$
		0.90	56.36	0.0001	Base Sat.
0.62-0.72	visible	0.72	33.89	0.0001	$CaCO_3$
		0.82	26.76	0.0001	Base Sat.
0.72-0.82	near IR	0.62	20.92	0.0005	$CaCO_3$
		0.74	17.08	0.0003	Clay
0.82-0.92	near IR	0.62	20.96	0.0005	$CaCO_3$
		0.78	21.20	0.0001	SAR*
0.92-1.02	near IR	0.57	17.24	0.0011	$CaCO_3$
		0.78	21.95	0.0001	SAR
1.02-1.12	near IR	0.47	11.73	0.0045	$CaCO_3$
		0.75	17.63	0.0003	SAR
1.12-1.22	near IR	0.34	6.56	0.0237	NO_3^-
		0.62	9.68	0.0031	LCa**
1.22-1.32	near IR	0.34	6.88	0.0211	NO_3^-
		0.59	8.52	0.0050	LCa
1.55-1.75	middle IR ****	0.34	6.69	0.0225	NO_3^-
		0.42	4.37	0.0376	Base Sat.
2.08-2.32	middle IR ****	0.61	20.31	0.0006	ESP***
		0.73	16.11	0.0004	H_2O

* Sodium Adsorption Ratio
** Leached Calcium
***Exchangeable Sodium Percentage
****Proposed Thematic Mapper (TM) bands

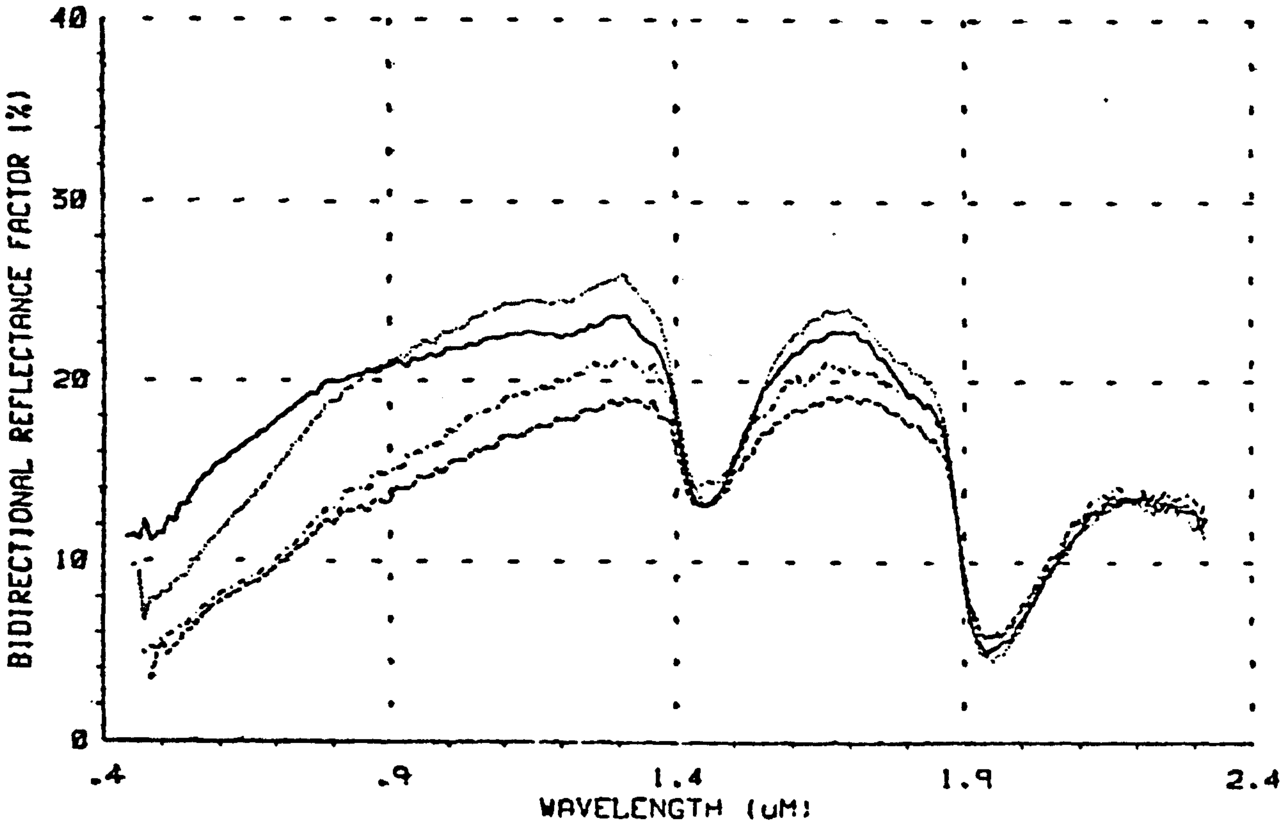


Figure 9. Composite soil curves of 4 saline alkali soils which gave up bromine gas upon the addition of potassium chromate and sulfuric acid during laboratory analysis. (—— sample 1 (28% $CaCO_3$); ---- sample 2 (19% $CaCO_3$)

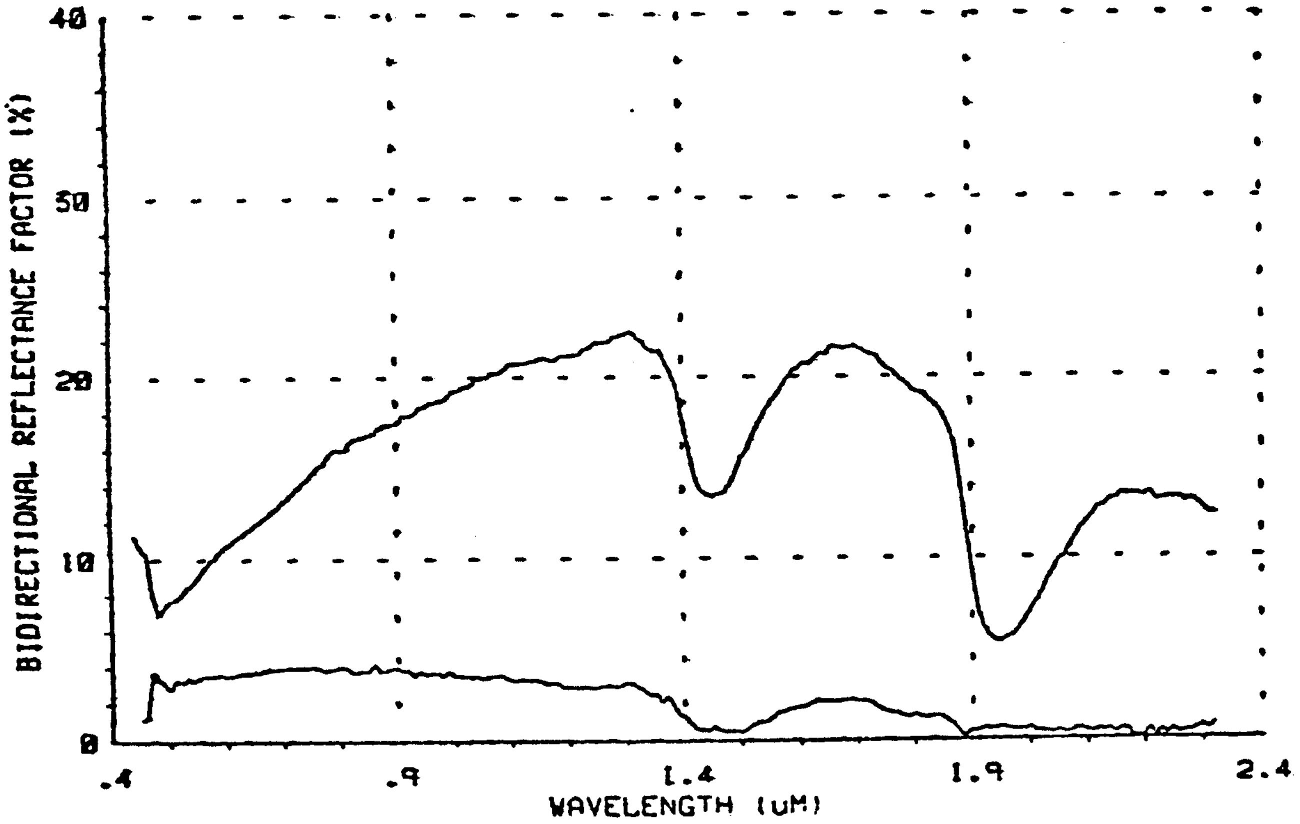


Figure 10. Averaged reflectance spectra for the 4 saline alkali soils listed in Figure 9 and their standard deviation.

Thus, one significant conclusion pertains to the interaction of O.M. and Na^+. Such an interaction appears to be an important factor in predicting reflectance value based on the presence of both O.M. and Na^+.

Table 5. Correlation Coefficients -- Max. R^2 for Samples Having 2.0% O.M. and 20 meq Na^+.

Spectral Region	Na^+	O.M.
Band 1 (0.52-0.62 μm)	0.84	0.41
Band 4 (0.82-0.92 μm)	0.86	0.82
Band 5 (0.92-1.02 μm)	0.89	0.84
Band 9 (1.55-1.75 μm)	0.85	0.25
Band 10 (2.08-2.32 μm)	-0.81	-0.27

SUMMARY AND CONCLUSIONS

Calcium carbonate, base saturation, sodium adsorption ratio and the anion NO_3^- appear to be the most significant parameters which affect reflectance. The effect of organic matter was not noticed even though the 15 salt affected soil samples (surface horizon) contained range of 0.4% to 5.8% organic matter. The results of the statistical analysis indicate that maximum correlations (R^2 values) between the independent variables and 10 spectral bands (0.52-2.32 μm) involve the dominant influence of salts and their effects on spectral characteristic variations. The two samples which contained 28% and 19% $CaCO_3$ showed the highest response in the visible and near IR. The dominance of $CaCO_3$ over the other parameters or independent variables used in the statistical analysis is perceived by both the strength of the R^2 values and the significance of the F values listed in Table 4. The influence of calcium carbonate is also apparent in Figure 9 where four salt affected soils with fairly similar SAR and base saturation show marked differences in spectral responses in the visible and infrared portions of the spectrum. The percentage of bidirectional reflectance factor increases as the content of $CaCO_3$ changes from trace or near zero percent to 28%.

Furthermore, no correlation among silt, clay and sand was found within the range of the spectral bands 1, 4, 5, 9 and 10. These bands were selected to cover a broad range of the electromagnetic spectrum including the thematic mapper bands (1.55-1.75 and 2.08-2.32 μm).

But, the best correlations were observed between Na^+ and O.M. and their interaction within spectral bands 4 and 5. It may be appropriate to speculate an explanation based on this observation that in the case of sodium soils, the higher the organic matter, the greater is the reflectance although in this study one sample with 0.43 meq of Na^+ occurs in high range as compared to a sample with 0.59 meq of Na^+ in lower range. This may also explain why 0.55 meq of Na^+ combined with 2.0% organic matter remains in medium range. This interaction of sodium and organic matter has reversed what had been stated so far that high organic matter implies low reflectance and vice versa (Figure 11 and 12).

RECOMMENDATIONS

In view of the results derived from the chemical, physical, spectral and statistical analyses carried out for the 15 soil surface samples, it can be recommended that:

1. The influence of organic matter and its interaction with sodium on the spectral response of salt affected soils should be further investigated since high organic matter combined with high sodium does not produce low reflectance. In the past, researchers had found that high organic matter alone produces low reflectance and low organic matter is associated with high reflectance.

2. More specifically, research should focus on the specific role of Na^+ and organic matter and their interaction in predicting reflectance values based on the presence of either one or both within the range of spectral bands 4 and 5. Refraction analysis of organic matter should be conducted to determine the types of organic matter constituents such as humic, fulvic acids and their behavior in soils with low and high sodium content. For such an experiment, it would be easier to take a soil of known organic matter, say 2%, and change the sodium saturation gradually and correlate the values with percent BRF.

3. Further spectral analysis should be made for salt affected soils under normal air dry conditions.

4. Spectral measurements should be made for surface samples showing visible salt crust accumulation.

5. These spectral analyses should be conducted over a broader range of salt affected soils including wide fluctuations in salt content.

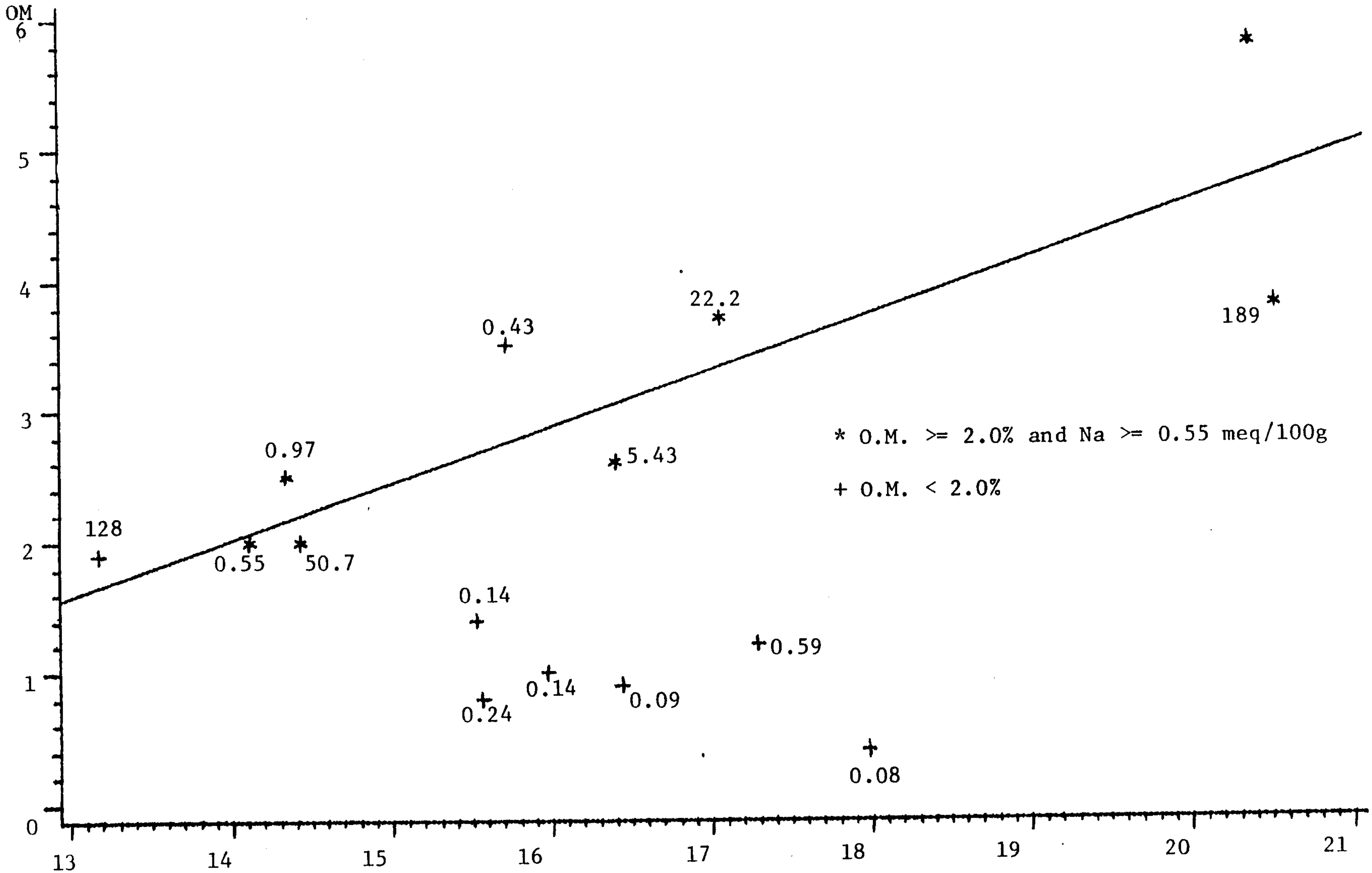


Figure 11. Correlations between % O.M., Na^+ content and % reflectance in band 4.

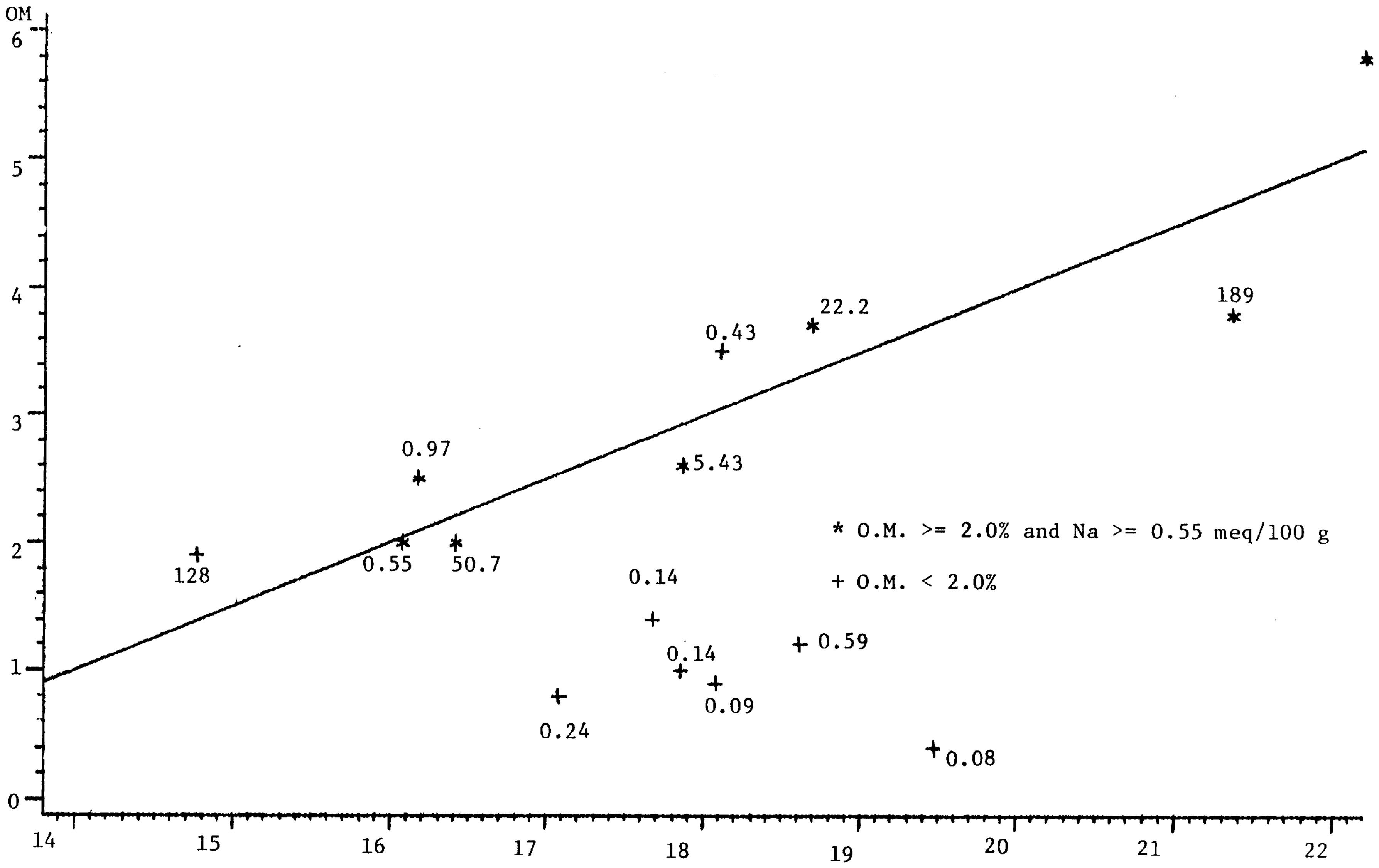


Figure 12. Correlations between % O.M., Na^+ content and % reflectance in band 5.

6. Further analysis of soils rich in calcium carbonate should be made to understand better the influence of $CaCO_3$ on spectral responses.

7. The procedure in future experiments should allow for spectral measurements to be made before saturation of the salt affected samples with the salt crust still present and after standardization of the soil moisture; then the spectral responses should be compared and analyzed in terms of differences due to differences in moisture content of the soil itself and differences among all soils.

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APPENDIX 1

CATALOG OF THE CHEMICAL, PHYSICAL AND SPECTRAL CHARACTERISTICS OF THE 15 SURFACE SAMPLES

ORURO DEPARMENT

BOLIVIA

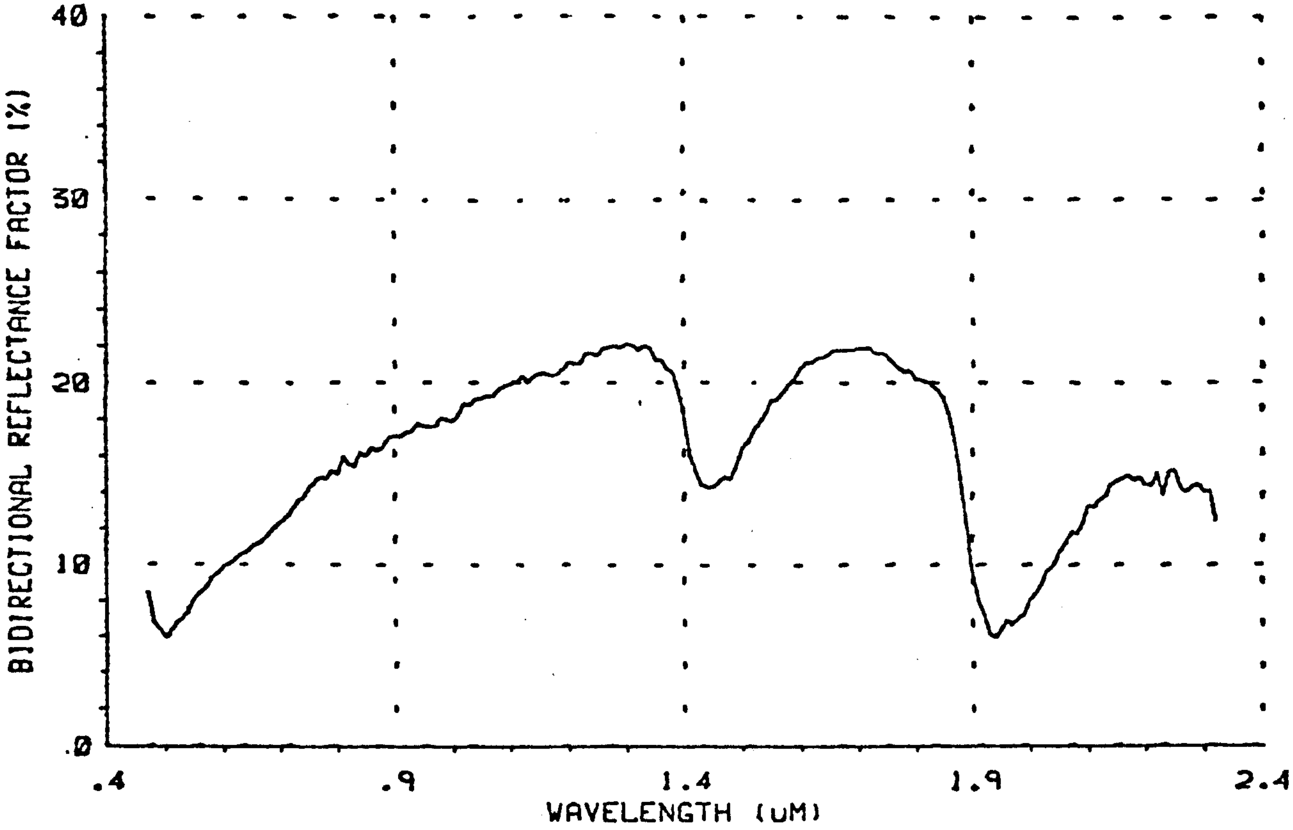
Aridisol
Ap horizon
3.80% O.M.
ph (H_2O) 8.5
28% $CaCO_3$

229 C.E.C.
189 meq/100 g Na^+

10YR 6/2 (moist)
16.4% sand

56.6% silt
27% clay
101 E.C. (mmhos/cm)
100% E.S.P.

SAMPLE 1 817562 SALINE ALKALI



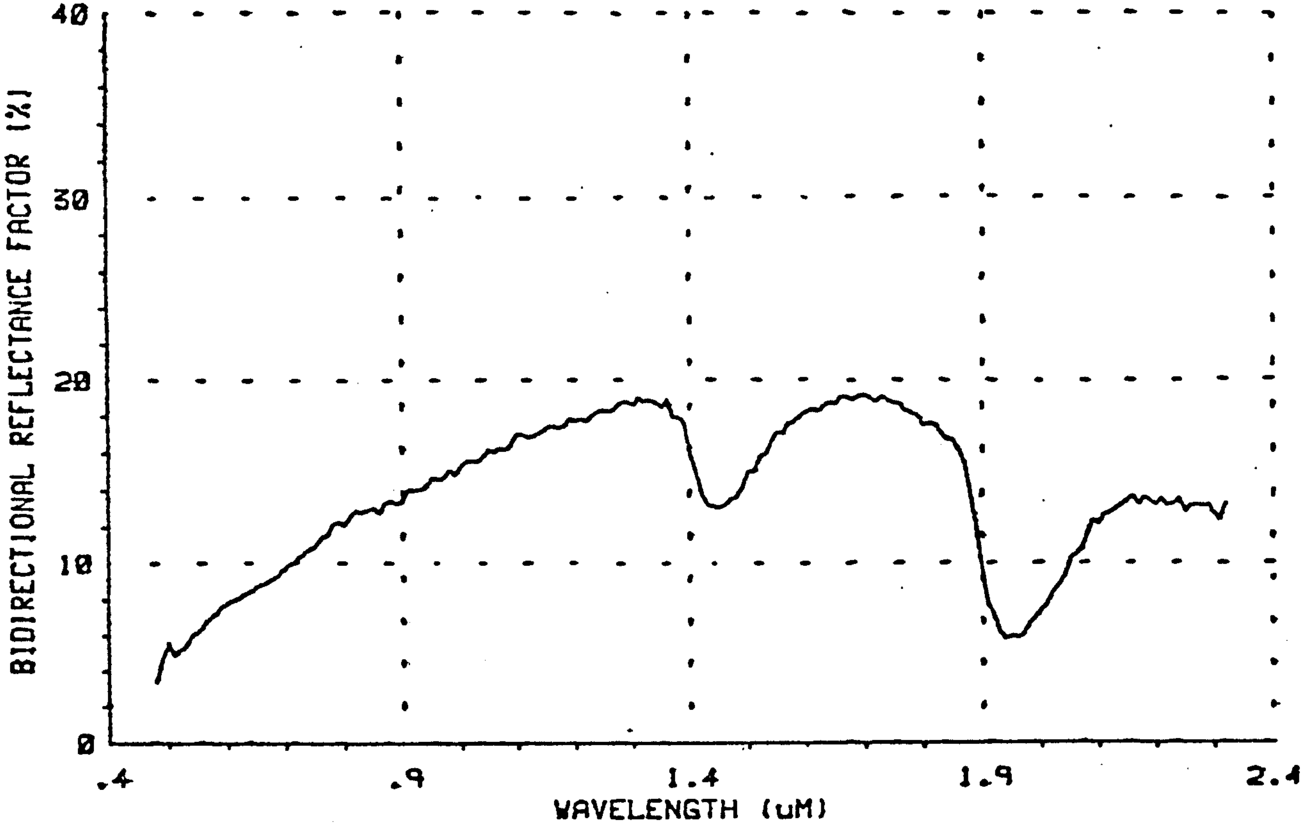
Entisol
Ap horizon
5.80% O.M.
ph (H_2O) 7.5
19% $CaCO_3$

287 C.E.C.
166 meq/100 g Na^+

10YR 4/3 (moist)
17.7% sand

60.7% silt
21.6% clay
94.7 E.C. (mmhos/cm)
100% E.S.P.

SAMPLE 2 817560 SALINE ALKALI



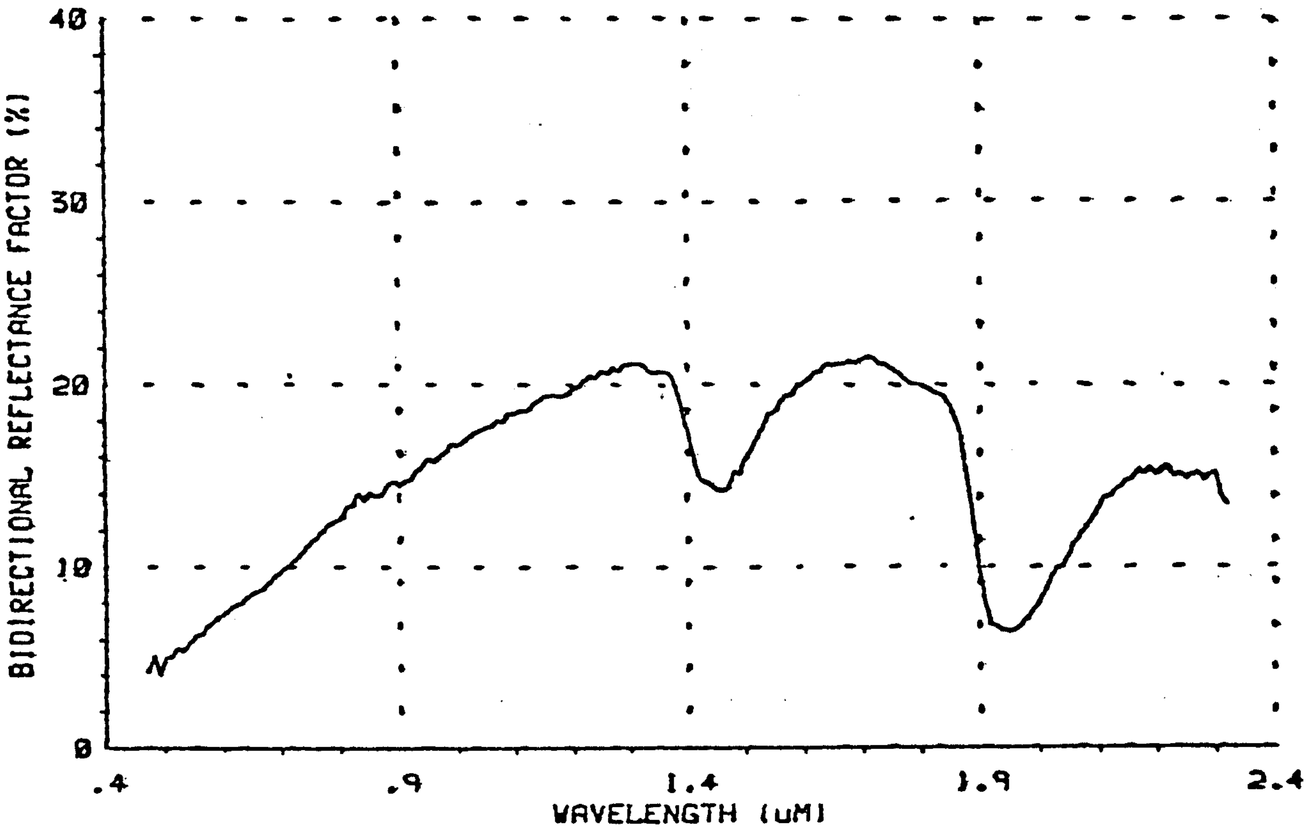
Inceptisol
Ap horizon
2.0% O.M.
pH (H_2O) 6.9

78.40 C.E.C.
50.70 meq/100 g Na^+

10YR 4/3 (moist)
16.4% sand

43.6% silt
40.0% clay
47 E.C. (mmhos/cm)
52% E.S.P.

SAMPLE 3 817565 SALINE ALKALI



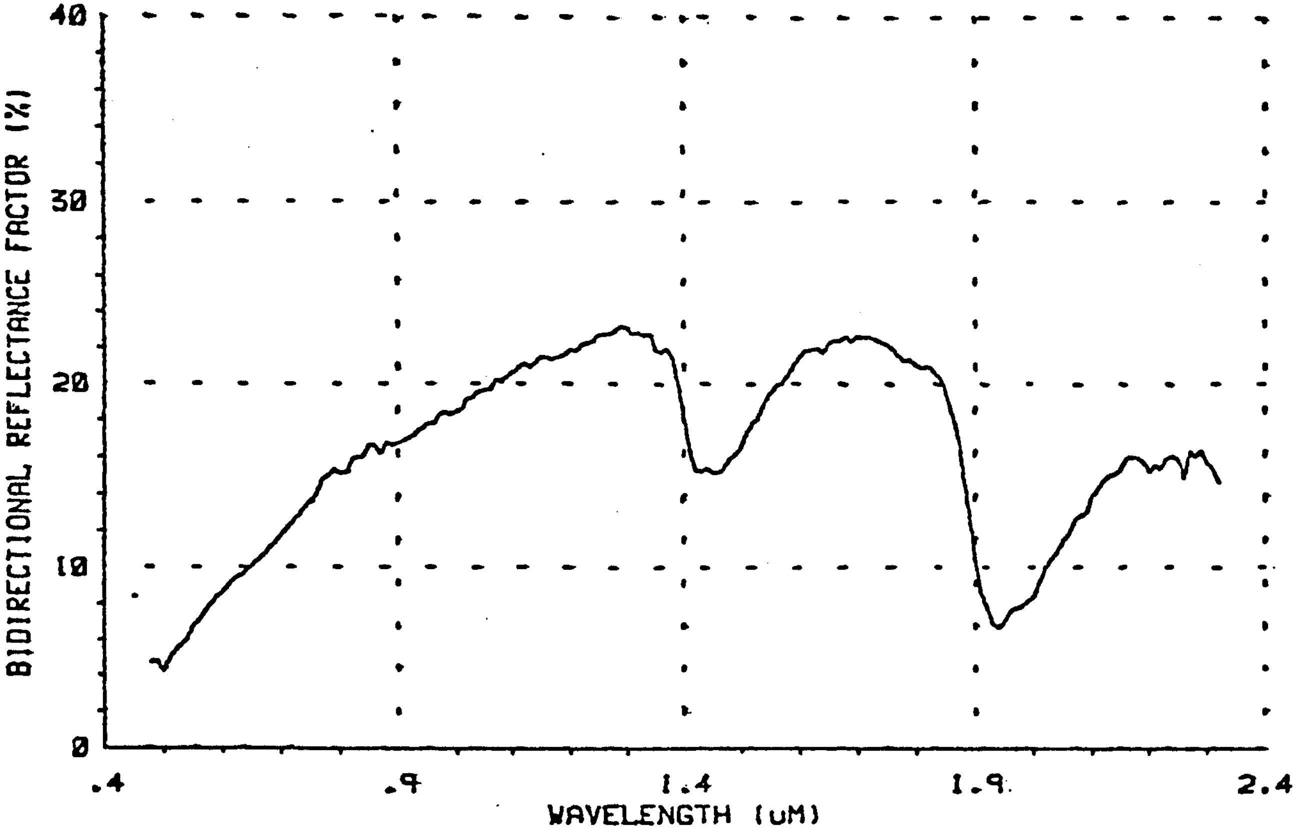
Aridisol
Ap horizon
1.90% O.M.
pH (H_2O) 6.6

185 C.E.C.
128 meq/100 g Na^+

10YR 4/3 (moist)
12.4% sand

57.8% silt
29.8% clay
86.50 E.C. (mmhos/cm)
100% E.S.P.

SAMPLE 4 817566 SALINE ALKALI



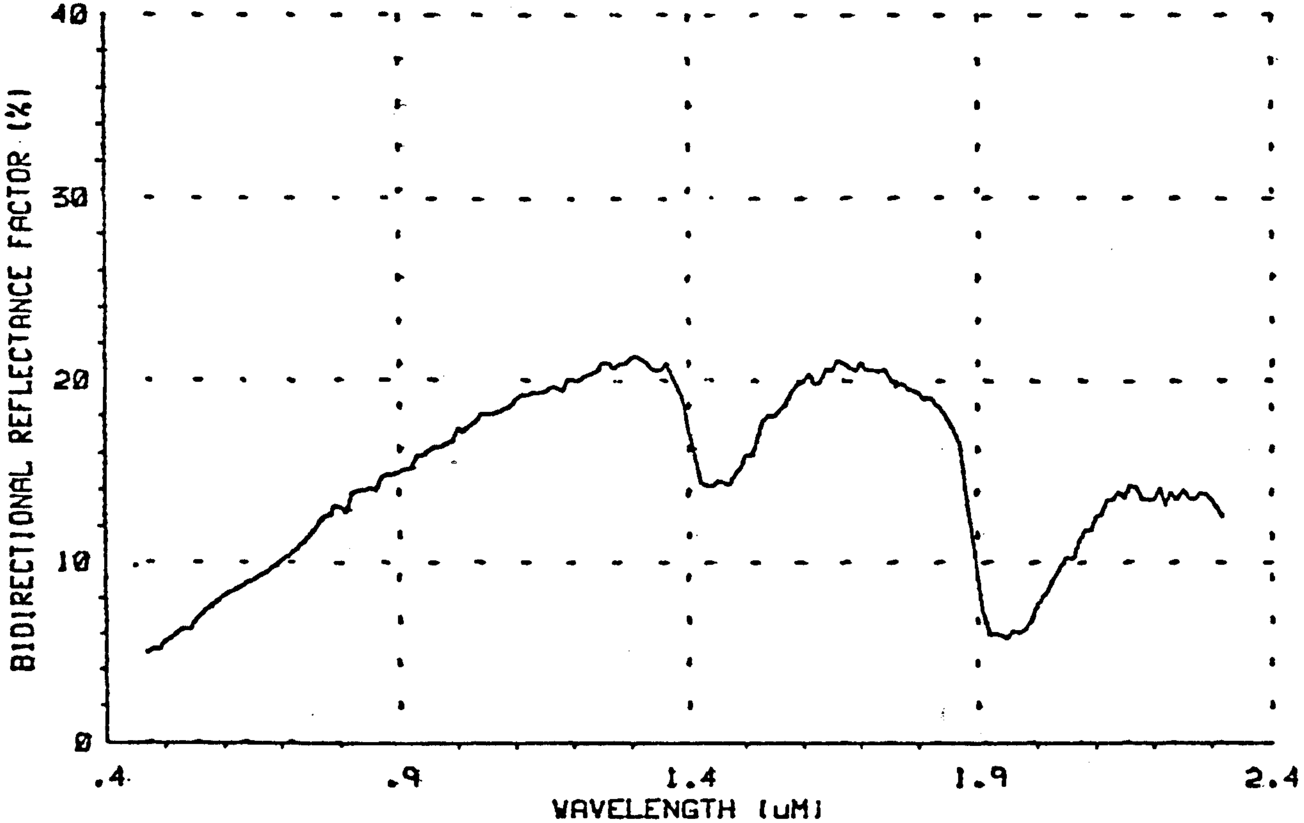
Alfisol
Ap horizon
3.70% O.M.
pH (H_2O) 7.5

37.80 C.E.C.
22.20 meq/100 g Na^+

10YR 4/4 (moist)
1.8% sand

62.7% silt
19.3% clay
8.30 E.C. (mmhos/cm)
22% E.S.P.

SAMPLE 5 817559 SALINE ALKALI

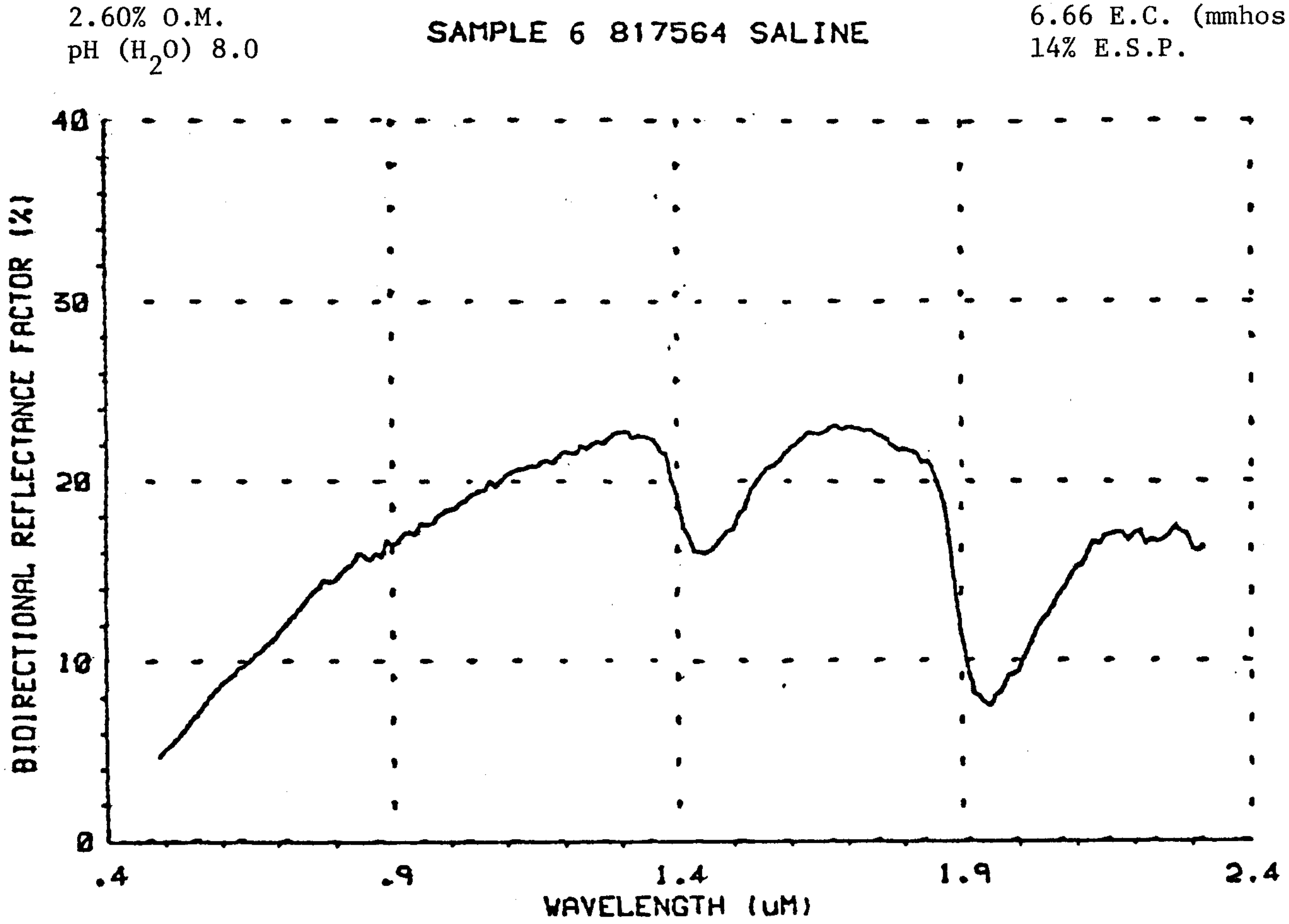


Inceptisol
Ap horizon
2.60% O.M.
pH (H_2O) 8.0

21.60 C.E.C.
5.43 meq/100 g Na^+

10YR 3/3 (moist)
47.8% sand

37.6% silt
14.6% clay
6.66 E.C. (mmhos/cm)
14% E.S.P.



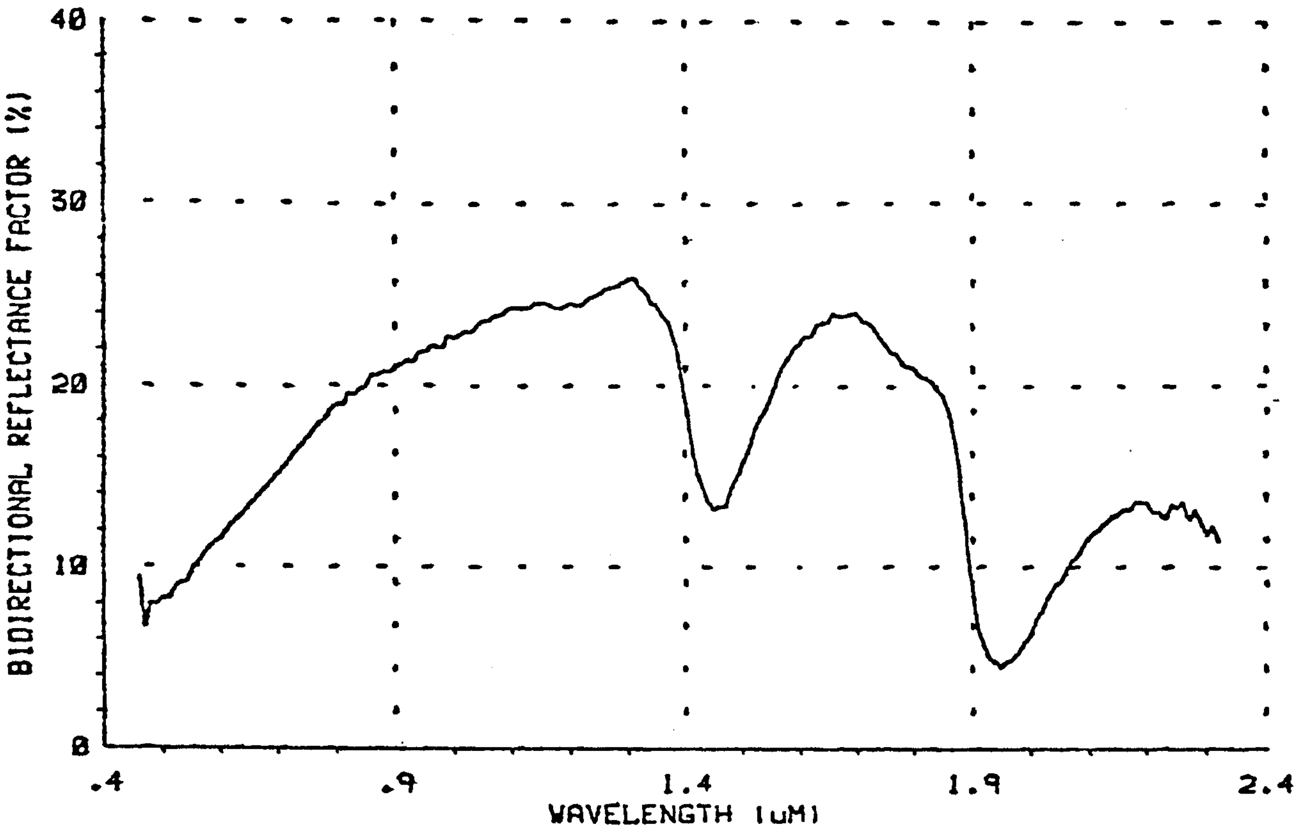
Inceptisol
Ap horizon
3.50% O.M.
pH (H_2O) 6.2

18.90 C.E.C.
0.43 meq/100 g Na^+

10YR 3/3 (moist)
9.2% sand

58.5% silt
32.3% clay
0.54 E.C. (mmhos/cm)
1% E.S.P.

SAMPLE 7 817558 NONSALINE NONALKALI



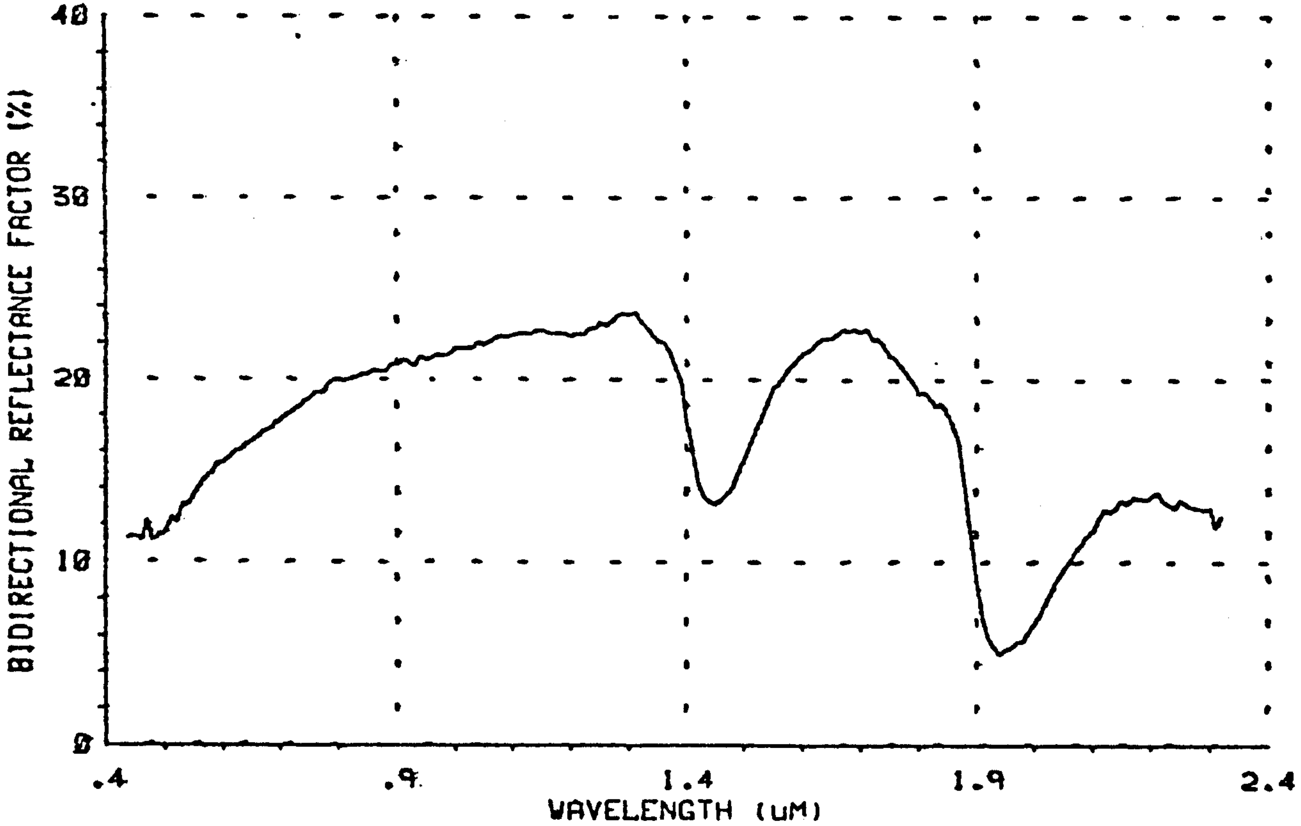
Entisol
Ap horizon
1.0% O.M.
pH (H_2O) 6.4

7.50 C.E.C.
0.14 meq/100 g Na^+

10YR 4/4 (moist)
71.9% sand

17.4% silt
10.7% clay
0.58 E.C. (mmhos/cm)
0% E.S.P.

SAMPLE 8 817557 NONSALINE NONALKALI



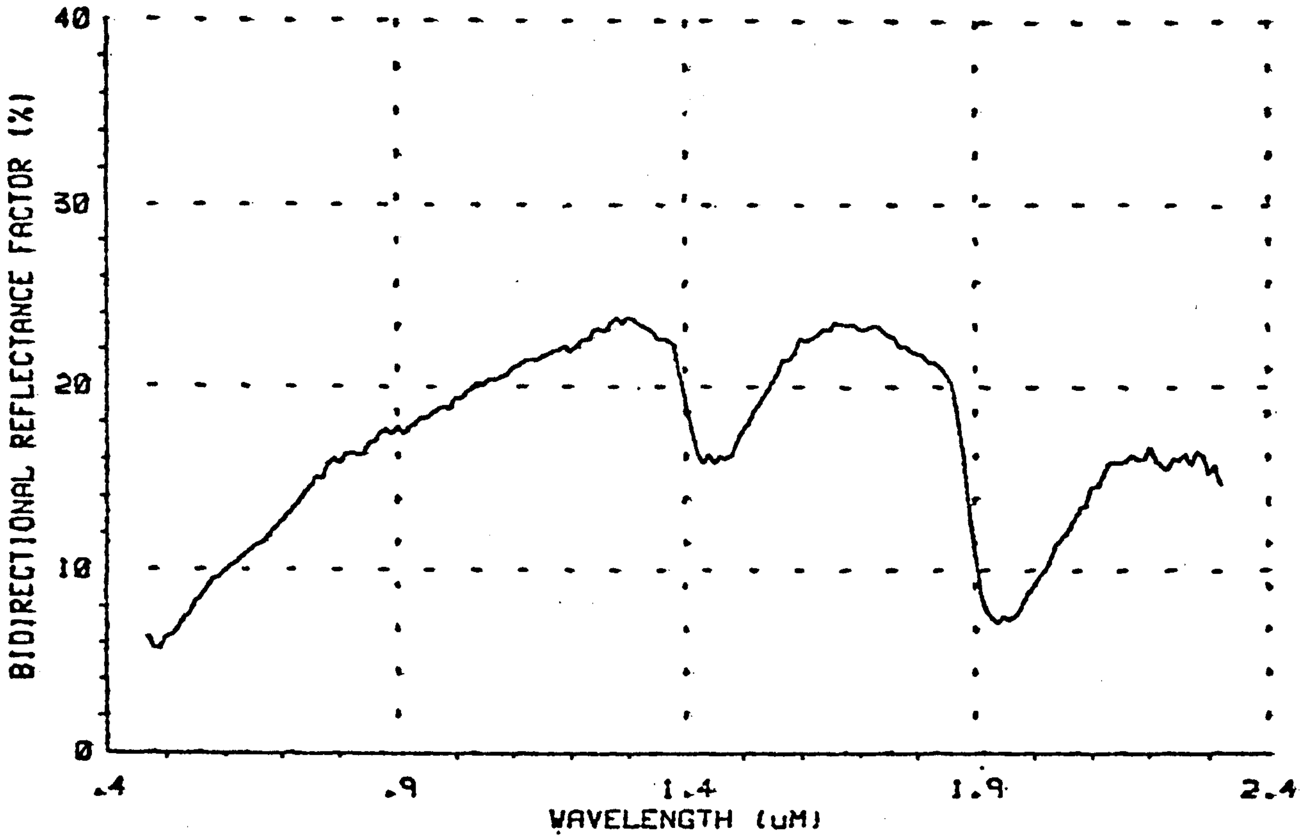
Entisol
Ap horizon
2.0% O.M.
pH (H_2) 7.0

1.41 C.E.C.
0.55 meq/100 g Na^+

10YR 3/4 (moist)
32.9% sand

50.9% silt
16.2% clay
0.41 E.C. (mmhos/cm)
3% E.S.P.

SAMPLE 9 817561 NONSALINE NONALKALI



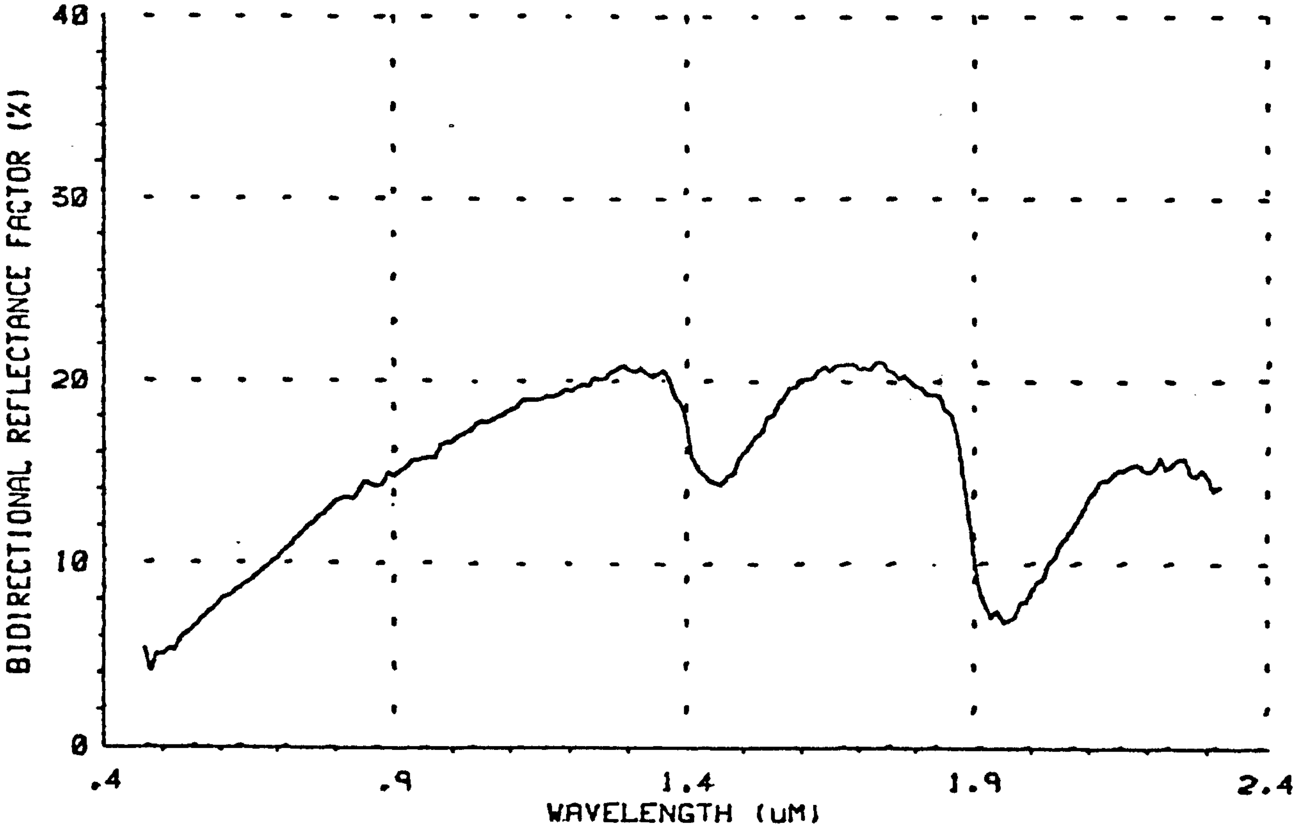
Entisol
Ap horizon
0.9% O.M.
pH (H_2O) 6.3

4.99 C.E.C.
0.09 meq/100 g Na^+

10YR 3/3 (moist)
72.4% sand

21.9% silt
5.7% clay
0.86 E.C. (mmhos/cm)
1% E.S.P.

SAMPLE 10 817571 NONSALINE NONALKALI



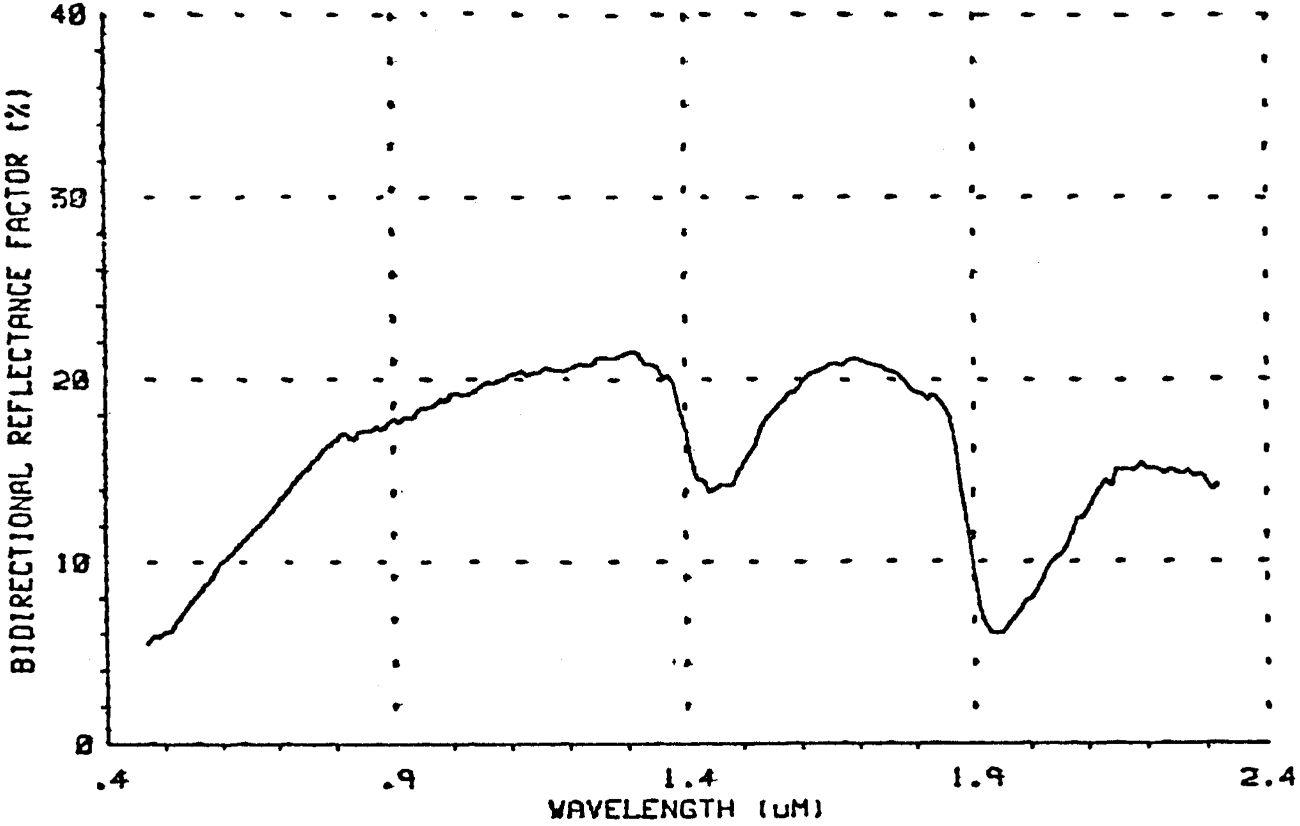
Entisol
Ap horizon
0.4% O.M.
pH (H_2O) 6.6

3.65 C.E.C.
0.08 meq/100 g Na^+

10YR 4/4 (moist)
86.8% sand

8.8% silt
4.4% clay
0.24 E.C. (mmhos/cm)
1% E.S.P.

SAMPLE 11 817570 NONSALINE NONALKALI



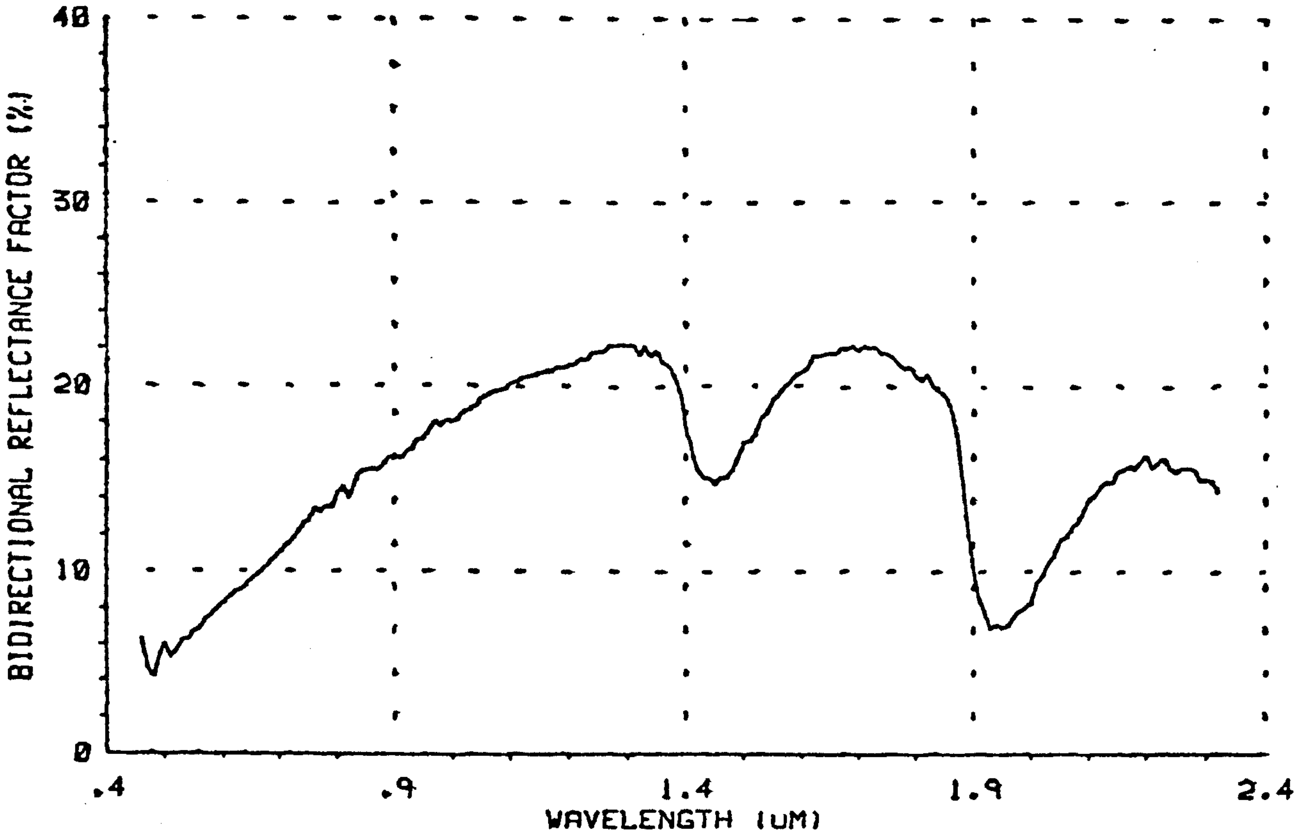
Inceptisol
Ap horizon
0.8% O.M.
pH (H_2O) 7.3

7.64 C.E.C.
0.24 meq/100 g Na^+

10YR 4/4 (moist)
69.8% sand

22.1% silt
8.1% clay
0.86 E.C. (mmhos/cm)
2% E.S.P.

SAMPLE 12 817569 NONSALINE NONALKALI



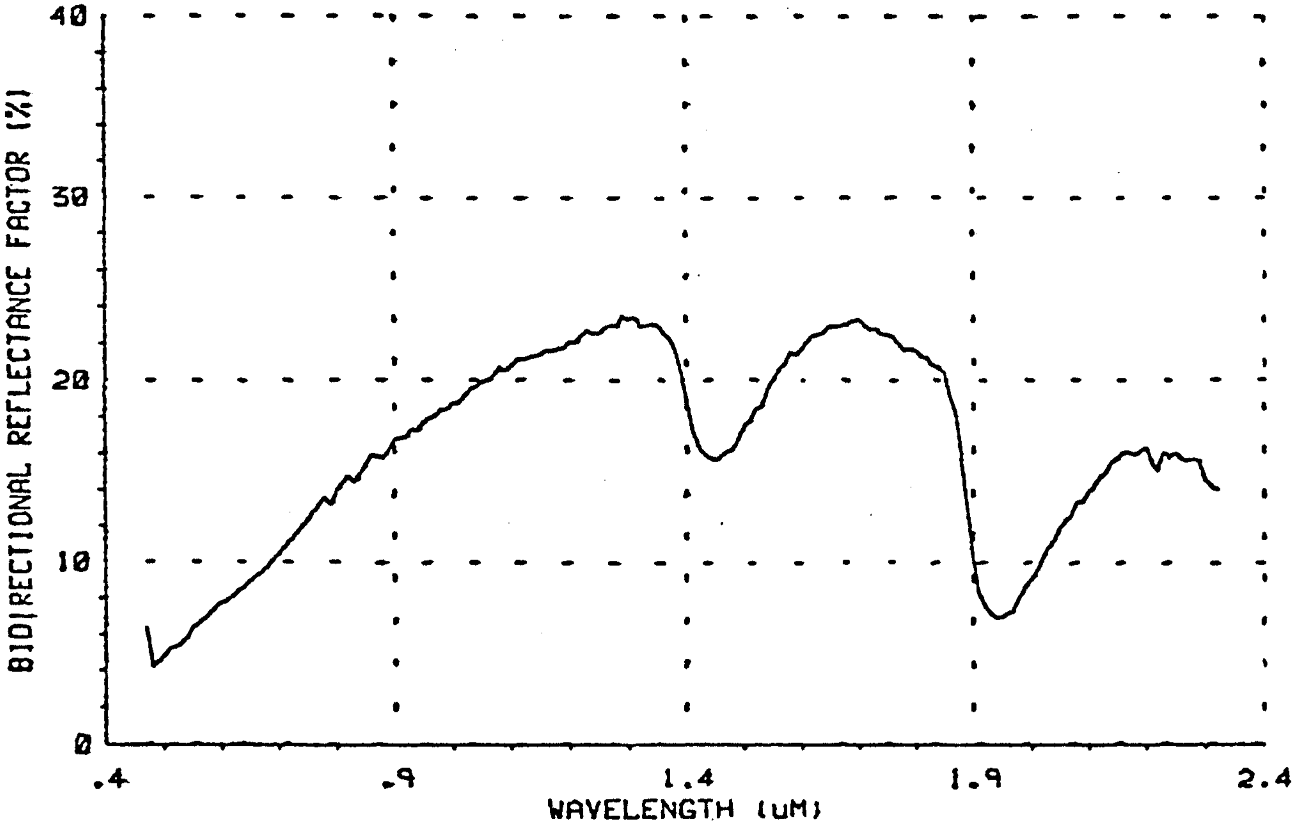
Inceptisol
Ap horizon
1.4% O.M.
pH (H_2O) 6.3

7.24 C.E.C.
0.14 meq/100 g Na^+

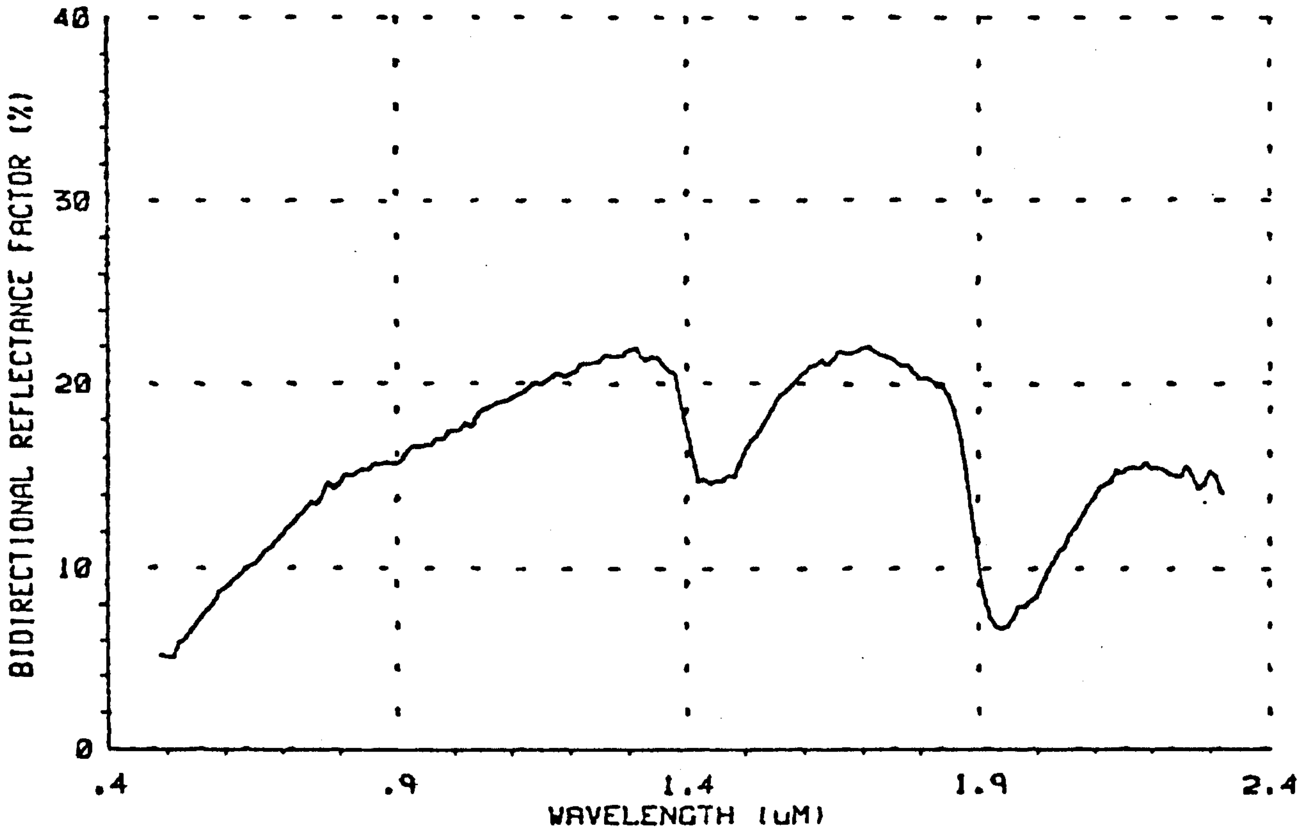
10YR 4/2 (moist)
75.3% sand

17.2% silt
7.5% clay
0.93 E.C. (mmhos/cm)
1% E.S.P.

SAMPLE 13 817563 NONSALINE NONALKALI



Inceptisol 8.61 C.E.C. 10YR 4/4 (moist) 42.9% silt
Ap horizon 0.59 meq/100 g Na^+ 43.7% sand 13.9% clay
1.2% O.M. 0.86 E.C. (mmhos/cm)
pH (H_2O) 7.0 SAMPLE 14 817568 NONSALINE NONALKALI 4% E.S.P.



Inceptisol 10.90 C.E.C. 10YR 4/4 (moist) 34% silt
Ap horizon 0.97 meq/100 g Na^+ 54.2% sand 11.8% clay
2.5% O.M. 1.71 E.C. (mmhos/cm)
pH (H_2O) 6.7 5% E.S.P.

SAMPLE 15 817567 NONSALINE NONALKALI