LARS Technical Report 111679

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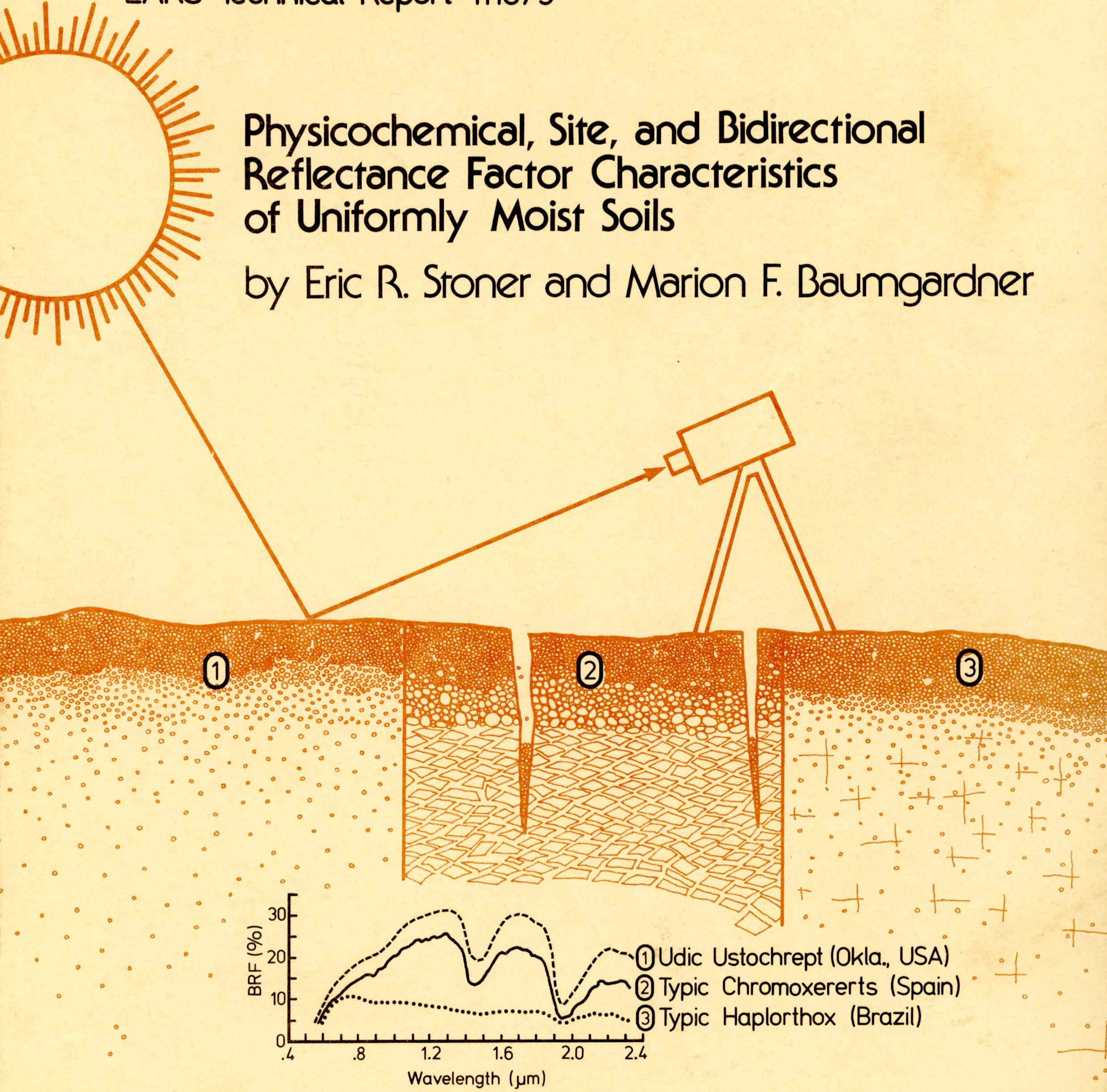
by Eric R. Stoner and Marion F. Baumgardner



Laboratory for Applications of Remote Sensing
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1980

80-10134

AgRISTARS

SR-P9-00431
NAS9-15466 NASA CR-
160571

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A Joint Program for Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing

Supporting Research

February 1980

Technical Report

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(E80-10134) PHYSIOCHEMICAL, SITE, AND N80-26721
BIDIRECTIONAL REFLECTANCE FACTOR
CHARACTERISTICS OF UNIFORMLY MOIST SOILS
(Purdue Univ.) 104 p HC A06/MF A01 CSCL 02C Unclas
G3/43 00134

Purdue University
Laboratory for Applications of Remote Sensing
West Lafayette, Indiana 47907

UNITED STATES DEPARTMENT OF AGRICULTURE

NASA

DEPARTMENT OF COMMERCE UNITED STATES OF AMERICA

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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1. Report No
SR-P0-00431

2. Government Accession No.

3. Recipient's Catalog No

4. Title and Subtitle
Physicochemical, Site, and Bidirectional Reflectance Factor Characteristics of Uniformly Moist Soils

5. Report Date
February 1980

6. Performing Organization Code

7. Author(s)
Eric R. Stoner and Marion F. Baumgardner

8. Performing Organization Report No.
111679

9. Performing Organization Name and Address
Laboratory for Applications of Remote Sensing
Purdue University
1220 Potter Drive
West Lafayette, Ind. 47906

10. Work Unit No.

11. Contract or Grant No.
NAS9-15466

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Johnson Space Center
Houston, Tex. 77058 (J.D. Erickson, technical monitor)

13. Type of Report and Period Covered
Technical Report

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The bidirectional reflectance factor (0.5 to 2.3 μm wavelength interval) and physicochemical properties of over 500 soils from 39 states, Brazil and Spain were measured. Site characteristics of soil temperature regime and moisture zone were used as selection criteria and parent material and internal drainage were noted for each soil.

At least five general types of soil reflectance curves were identified based primarily on the presence or absence of ferric iron absorption bands, organic matter content and soil drainage characteristics. Reflectance in 10 bands across the spectrum was found to be negatively correlated with the natural log of organic matter content. Regression models showed that site characteristics such as climate, parent material, and drainage are important variables along with organic matter, moisture content, texture, and iron oxide content in explaining reflectance differences.

17. Key Words (Suggested by Author(s))
soil parameters, remote sensing, reflectance measurements

18. Distribution Statement

19. Security Classif. (of this report)
unclassified

20. Security Classif. (of this page)
unclassified

21. No. of Pages

22. Price*

NASA - JSC

*For sale by the National Technical Information Service, Springfield, Virginia 22161

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the National Aeronautics and Space Administration, Johnson Space Center (Contract NAS9-15466) for supporting the research described in this report and to the U.S. Department of Agriculture, Soil Conservation Service for providing soil samples used in the study.

An expression of gratitude is also extended to colleagues in the Agronomy Department and the Laboratory for Applications of Remote Sensing, Purdue University, for their many contributions to this research effort. Individuals whose counsel and service warrant special mention include:

- Profs. Virgil L. Anderson, Donald P. Franzmeier, Marvin W. Phillips and LeRoy F. Silva -- members of the senior author's doctoral advisory and examining committee;
- Drs. John B. Peterson and Richard A. Weismiller -- assistance in project management and technical logistics;
- Barrett F. Robinson and Larry L. Biehl-- careful attention to spectro-radiometric measurements and software programming for data logging and retrieval;
- Lou M. Nash -- determination of organic matter and iron oxide contents and cation exchange capacities of 500 soil samples.

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ABSTRACT

A variety of soil parameters and conditions individually and in association with one another contribute to the visible as well as the infrared reflectance of soils. Quantitative reliable measurements of these reflectance properties are vital to an understanding of relationships between reflectance and physicochemical and site characteristics of soil upon which the use of remote sensing technology for soil survey is based.

An experimental procedure was developed for measuring the bidirectional reflectance factor of soils at the uniform moisture tension of approximately one-tenth bar. The soil fraction less than 2mm diameter was equilibrated for 24 hrs prior to spectral measurement on an asbestos tension table apparatus. Bidirectional reflectance factor of soils illuminated by a collimated beam from a 1000 watt tungsten iodide lamp was measured in 0.01μm increments over the 0.52-2.32μm wavelength range using a field spectroradiometer adapted for indoor use.

Surface soil samples from two representative sites for each of over 240 widely occurring soil series from 39 states of the continental United States as well as Brazil and Spain were available for this study. Physicochemical characteristics measured were organic matter content, particle size distribution (8 fractions), cation exchange capacity, and iron oxide content. Site characteristics of soil temperature regime and moisture zone were used as selection criteria for soils included in the study, while parent material and internal drainage were noted for each soil.

At least five general types of soil reflectance curves can be identified based primarily on the presence or absence of probable ferric iron absorption bands at 0.7 and 0.9μm, but also based upon organic matter content and soil drainage characteristics. Partially because of contrasting reflectance properties in the infrared wavelengths, soils with similar Munsell color designations have been seen to possess very different reflectance curves.

Averaged reflectance curves for soils with similar organic matter content reveal the dominant role of organic matter in determining both curve form and reflectance magnitude in the visible and near infrared wavelengths. Decreasing particle size is seen to increase soil reflectance among sand textured soils while the inverse is true for medium to fine textured soils. Averaged soil reflectance curves also show a trend of higher reflectance with increasing soil temperature and decreasing rainfall as a result of decreased organic matter levels.

Statistical correlation of soil parameters with reflectance for 481 soil samples shows that reflectance in each of ten wavelength bands is negatively correlated with the natural logarithmic transformation of organic matter content. Reflectance in the 2.08 to 2.32μm middle infrared band is also negatively correlated with moisture content, clay content, cation exchange capacity, and iron oxide content while it is positively correlated with fine and medium sand contents.

Prediction models indicate that site characteristics such as climate, parent material, and drainage are important variables along with organic matter, moisture content, texture, and iron oxide content in explaining reflectance differences among 481 soil samples. Regression equations using reflectance data in ten wavelength bands as the independent variables show high predictive values for organic matter content, moisture content, content of specific particle size classes, iron oxide content, and cation exchange capacity when inferences are drawn among soils from specific climatic zones.

The proved repeatability of quantitative bidirectional reflectance factor measurements of soil using the described procedure has important implications both as an aid to soil characterization and as a tool for understanding reflective response from soils as measured by remote sensing devices.

INTRODUCTION

Modern soil surveys are essential to planning and management for effective use of soil resources for food and fiber production in the face of ever-increasing population pressures on the land. Only a small fraction of the soils of the world have been mapped in sufficient detail for adequate planning for future land needs. Recent advances in remote sensing technology applied to soil survey may help to accelerate the pace of future mapping efforts.

Comprehensive soil classification provides a basis for relating observable soil properties to the factors responsible for their character, thus permitting extension of soil survey research experience in well-understood soils to unmapped areas of similar soil parent material, climate, relief, age of formation, and biotic factors. Differentiation of soils requires quantitative information about certain physicochemical and site characteristics. Although most of the differentiating characteristics selected as diagnostic criteria in the soil classification process are verifiable by field or laboratory procedures, quantitative spectroradiometric methods have not been adopted to measure soil reflectance properties. In spite of this lack of an instrumental procedure for measuring soil spectra, soil visible reflectance, or soil color, is a differentiating characteristic for many classes in all modern soil classification systems as an essential part of the definitions for both surface and subsurface diagnostic horizons. Aside from soil comparisons to standard color charts, characterization of soil reflectance properties has no standard measurement procedure for obtaining reproducible quantitative visible and infrared reflectance spectra.

Soil surveyors have made wide use of visible wavelength aerial photographs since the 1930's, not only as a base map, but also as an aid in delineating soil patterns largely from visible reflectance properties of soil landscapes. The development of infrared sensitive films as well as calibrated sensor systems, both of which show promise in soil survey research, suggests the need for some reliable laboratory measure of soil reflectance properties in order to understand better the multispectral nature of soils as they are viewed by these sensors.

This study describes the development of a procedure for spectroradiometric measurement of soil reflectance at the uniform moisture tension of approximately one-tenth bar. The method involves the use of large asbestos tension tables for equilibration of sieved, saturated soil samples and evolved out of the necessity to measure a large number of disturbed surface soil samples while improving on sample preparation techniques reported in previous studies. A reflectometer provided parallel beam illumination of the samples from an artificial source, allowing for measurement of percent bidirectional reflectance factor over the 0.52 to 2.32μm wavelength range using a field spectroradiometer adapted for indoor use. Soil reflectance measurements under these controlled laboratory conditions are reliable and reproducible and provide a quantitative measure of soil spectral properties not only in the visible, but also in the near and middle infrared wavelength regions.

Spectroradiometric studies of soils under laboratory and field conditions have contributed to an understanding of the factors influencing soil reflectance. A variety of soil parameters and conditions individually and in association with one another contribute to the spectral reflectance of soils. These parameters include the physicochemical properties of moisture, organic matter, particle and aggregate size, iron oxide content and soil mineralogy. Conditions affecting the radiation of soils in their natural state are green vegetative cover, non-soil residue, surface roughness and crusting, and shadows, all of which vary according to tillage operations, cropping or grazing systems, or naturally occurring plant communities. While both field and laboratory studies of soil reflectance deserve attention, the ability to control more carefully soil conditions in the laboratory favors this approach for studying the contribution of individual soil parameters to soil reflectance.

Soil reflectance is a cumulative property which derives from inherent spectral behavior of the heterogeneous combination of mineral, organic, and fluid matter that comprises mineral soils. This study did not attempt to quantify single component contributions to soil reflectance as isolates from the soil system, but rather attempted to describe the contribution of important physicochemical characteristics of surface soils as they would be viewed by airborne sensors. As far as possible the extraneous contribution of soil moisture to soil reflectance was controlled by maintaining uniform moisture tension. In this manner, differences in moisture content among soils could be attributed to differences in soil component amounts, just as would be expected in the field situation.

Remote sensing systems such as the four-band multispectral scanner on the present Landsat series of satellites and the proposed seven-band thematic mapper are designed for obtaining synoptic, repetitive views of the earth's surface at varying ground resolutions. It is important to remember that the usefulness of any remote sensing system for earth resource survey purposes depends on characteristic spectral response of ground features, whether or not there are seasonal or spatial differences of importance. The design of spectral bands for future sensor systems should therefore take into consideration the results of field and laboratory spectroradiometric studies of earth surface features. Results of this study point to the importance of spectral bands in the near and middle infrared as well as the visible portions of the spectrum for characterization of diverse soil reflectance properties. Observations of soil reflectance curves indicate that narrow wavelength bands in the near infrared may be critical for specific iron determinations in soils.

Reflectance characteristics of soils from within homogeneous climatic zones vary greatly in response to the genetic influence of parent material, relief, and biotic factors over the period of soil formation. In spite of this great variability in soil reflectance, there does appear to be order in the relationships between soil reflectance and physicochemical properties within climatic zones. Prediction models can be developed to relate soil reflectance to some or all of the parameters of organic matter, moisture, iron, and particle size distribution of soils depending on the specific climatic zone where the soils are found. This is possible because of the contribution of these individual soil components to reflectance in specific wavelength regions. Development of multispectral remote sensing as a tool in soil survey builds on these relationships of soil reflectance to soil physicochemical and site characteristics and provides a quantitative basis for soil delineation.

REVIEW OF LITERATURE

Remote Sensing as a Tool in Soil Survey

Early Work

Black and white panchromatic aerial photographs have been a standard soil study and mapping tool since their introduction in 1929 in the state of Indiana (Bushnell, 1951). Aerial photographs were first recognized as an improvement over the use of plane tables in preparation of a base map, and 1:20,000 scale single-lens vertical photographs with stereoscopic coverage became the standard for most detailed, large-scale United States Department of Agriculture surveys (Soil Survey Staff, 1951). Photographs increased both the speed and accuracy of soil scientists because of the wealth of ground detail shown, the availability in areas of difficult access, and the three dimensional view of the soil landscape. Soil boundary delineation was possible largely from tonal characteristics with the understanding that the same land area could vary in appearance from one date to another (Bushnell, 1951).

High-altitude photography was found useful in the preparation of medium- to small-scale soil maps using soil associations as the delineated unit (Rust, et al., 1976). The broad synoptic view from high-altitude photographs more nearly corresponded to the level of detail of soil units occurring together in an individual and characteristic pattern over a geographic area. Development of color aerial films, black and white and color infrared emulsions, and multi-lens camera systems further expanded the possibilities for aerial photographic surveys (Carroll, 1973a). Still, photo interpretation techniques were not conducive to maximum extraction of tone information from aerial imagery, leading some to suggest the use of instruments to perform this task (Cihlar and Protz, 1972).

Optical-mechanical scanner systems capable of detecting visible, reflective and thermal infrared radiation came into civilian use in the 1960's along with computer pattern recognition techniques for sorting and classifying quantified multispectral data (Carroll, 1973b; Weismiller and Kaminsky, 1978). Preliminary studies of soil mapping using airborne multispectral scanner data indicated that soil surface conditions could be mapped with reasonable accuracy by computer techniques (Kristof, 1971). Areas with special drainage, runoff, or erosion problems could be mapped in detail. Similar airborne multispectral scanner data were used to produce maps showing the locations of five levels of organic matter content (Baumgardner, et al, 1970). Further studies indicated that clay content in surface soils could be delineated from statistical modeling of multispectral scanner data, although it was felt that the relationship between clay content and relative reflectance might be secondary as a result of the high correlation between organic matter and clay content (Al-Abbas, et al., 1972).

Surface reflectance properties of nonvegetated fields as determined from airborne multispectral scanner data were sufficient to characterize soil of limestone, shale, sandstone, and local colluvial parent materials (Mathews, et al., 1973a). Delineation of soil patterns from cultivated land showed that although soil patterns became less distinct as maize canopy increased, they remained discernible even with a ground cover of 85% (Kristof and Baumgardner, 1975).

Landsat Imagery

The availability of visible and near infrared multispectral scanner data from 0.45ha resolution elements within a 34,000 square kilometer image frame presented new possibilities and challenges in soil mapping in the 1970's. The Landsat series of satellites obtain spectral data in four bands ranging from 0.5 to 1.1μm in 18-day repetitive cycles. These data are processed to provide imagery in the form of various photographic products as well as numerical format magnetic tapes for digital analysis.

Certain unique characteristics of Landsat imagery were recognized as advantageous in low intensity soil surveys for delineation of soil association boundaries (Westin and Frazee, 1976). Among these were the synoptic view of almost 3.4 million ha on which the condition of soils and stage of vegetative growth were recorded at the same moment; the near-orthographic character of the scenes; and the temporal aspect, allowing study of multispectral changes in the soil/vegetation complex with time. Landsat scene mosaics at the scale of 1:1,000,000 were found useful as base maps for publishing thematic soil maps. Lewis, et al. (1975) concluded that soil associations within the Sand Hills of Nebraska can be interpreted on the basis of image patterns resulting from differences in vegetation and related drainage conditions, as well as from topography enhanced by low elevation solar illumination of snow covered terrain.

Computer-aided analysis of Landsat multispectral scanner data was used to produce a spectral map based on drainage characteristics at a scale of 1:20,000 (Kirschner, et al., 1978). These quantitative data generated by digital analysis could be used to determine if inclusions exist within a map unit, and could serve as a kind of quality control by providing the soil scientist with some prior knowledge of the soils. A procedure of partitioning the area into different parent material areas based on photointerpretation of Landsat false color imagery together with computer-aided spectral classification within parent material groupings led to the preparation of 1:15,840 scale spectral map sheets of Jasper County, Indiana intended for use in the soil survey of this county (Weismiller, et al., 1979). Again, spectral classes displayed were most closely correlated with soil drainage classes.

Remote sensing as a mapping tool in soil survey will continue to develop with further improvements in sensors and automatic data processing techniques, providing that the spectral properties of the soil scene being mapped are understood in their relation to important physicochemical and site characteristics.

Soil Color Standards

For most soil scientists and even laymen, the color of a soil is one of its most obvious characteristics. Relatively slight differences in the color or color pattern of only one horizon in the profile may be significant in classifying soils into different groups. Thus, soil color is one of the most useful and important characteristics for soil identification, especially in combination with soil structure (Soil Survey Staff, 1975).

The human eye recognizes a rather narrow range of electromagnetic waves as light. The wavelength of human physiological perception of visible reflectance extends from about 0.4 to 0.7μm (Wyszecki and Stiles, 1967). Intensities of light at various wavelengths within this range impart different impressions called color. Soils, as most other objects, reflect light of many wavelengths. Although it is possible to distinguish many different soil colors, it is difficult to describe them accurately.

The color imparted to a material may be due to specific absorptions in the visible region, or the color may be caused by intense absorptions in either or both the ultraviolet and near infrared, the shoulders of which may extend forward or back into the visible. This will impart a color to the material without its having any specific chromophoric group absorbing in the visible. Red colors in many soils may be attributable to just such a phenomenon of near infrared absorption of the ferric ion (Hunt and Salisbury, 1970).

After experimentation with numerous methods of soil color determination including briquetting soils of appropriate colors to serve as standards, whirling standard color disks for color matching, and even spectrophotometry, the U.S. Department of Agriculture in 1941 developed a set of soil color name charts based on the Munsell notation system (Pendleton and Nickerson, 1951). Standardized common color names and Munsell color standards continue as the most widely used system for describing soil colors (Soil Survey Staff, 1975).

Munsell soil color charts consist of some 175 colored chips systematically arranged according to their Munsell notations on cards mounted in a loose-leaf notebook. Notations of hue, value, and chroma designate the three variables that combine to represent all colors. Hue is the dominant spectral, or wavelength dependent, color. Value refers to the relative lightness of color while chroma is the relative purity or strength of the spectral color. Soil colors are determined by placing soil next to the color chips and comparing colors for the best match. The soil color is then described by the number of the chip to which it corresponds or by interpolating the number between two chips. Rarely does the color of the sample perfectly match any color in the chart. The probability of a perfect match of the soil color with the standard is less than one in one hundred (Soil Survey Staff, 1975).

Reproducible color standard comparisons are obtained at two soil moisture levels: air dry and field capacity. Moist soil colors are obtained by moistening a sample and reading the color as soon as visible moisture films have disappeared. In most notes and soil descriptions colors are given for moist soils, although the convention for soils from semiarid and arid regions is the dry soil color. Both the dry and moist soil colors are important, however, and official descriptions for technical use should include Munsell color designations for both conditions (Soil Survey Staff, 1975).

A modified Munsell color chart was prepared by Alexander (1969) for help in estimating the organic matter content in the surface of medium to fine textured cultivated soils in Illinois. Use of this five-chip color chart proved valuable in matching herbicide application rates to five levels of organic matter in the soil. Page (1974) related reflectance measurements from a color-difference meter to organic matter in Atlantic Coastal Plain soils. Within the 0 to 5% range, reflectance measurements provided a reliable estimate of organic matter in soils from this region at a considerably faster and cheaper rate than traditional methods. Shields, et al. (1968) converted spectrophotometric measurements of soils at different moisture contents to Munsell renotation color designations in order to relate soil color to organic matter. Munsell renotation value was most highly correlated to organic matter content, although relationships differed between Borolls and Boralfs based on the organic constituents of the organic matter.

Other studies indicated that soil color standards could be related to soil parameters other than soil moisture and organic matter. Krishna Murti and Satyanarayana (1971) found titanium and ferrous iron to be responsible for soil Munsell hue, while clay and organic matter were found to influence soil Munsell value. Soileau and McCracken (1967) observed a general trend of increasing free iron oxide content with increasing Munsell chroma in various size fractions of well-drained Coastal Plain soils. The form of the iron oxide (its degree of hydration or neutralization) was felt to be the dominant factor in influencing Munsell hue of the subsoils in this region. McKeague, et al. (1971) also found chroma and dithionite Fe to be significantly correlated for several groups of surface soil samples. As in the study of Shields, et al. (1968), Karmanov and Rozhkov (1972) found the more promising way of determining soil color characteristics to be from spectrophotometric coefficients calculated on the basis of variations in reflectance values for definite wavelength intervals, rather than notations based on the Munsell system. Spectrophotometric measurements were seen to provide a basis for establishment of quantitative relationships between color characteristics and soil composition.

Bidirectional Reflectance Factor as a Quantitative Measure of Soil Spectral Properties

Variations in reflectance, defined as the ratio of the reflected flux to the incident irradiation as a function of wavelength provide the basis for characterization of target scenes, as is the case in spectroradiometric measurements of soil reflectance. The directional characteristics of the reflection process are crucial to remote sensing studies. For example, aside from the effect that sun angle can have on image classification results, the presence of clouds may lead to diffuse rather than collimated irradiation of the target of interest. Also, many early studies of soil reflectance properties utilized a laboratory integrating sphere reflectometer whose directional characteristics differ from bidirectional reflectance factor measurements. The technical basis for bidirectional reflectance factor measurements allows for direct comparison of field-collected data with laboratory-collected data when a standard calibration procedure is closely followed (DeWitt and Robinson, 1976; Leamer, et al., 1973).

The fundamental property describing the geometrical reflectance distribution characteristics of a surface is the bidirectional reflectance distribution function. Immeasurable amounts of radiant flux through infinitesimal elements of solid angle render this function useful only as an underlying concept, with a more practical measure being bidirectional reflectance factor (BRF). Bidirectional reflectance factor (BRF) can be described as the ratio of the flux reflected by an object under specified conditions of irradiation and viewing to that reflected by the ideal, completely reflecting, perfectly diffusing surface, identically irradiated and viewed with the restriction that measurements are made through negligibly small solid angles of illumination and viewing (Nicodemus, et al., 1977).

A BRF reflectometer developed as an accessory to a field spectroradiometer permits conditions of variable incident irradiance of a horizontally placed 3.2cm diameter soil area (DeWitt and Robinson, 1976). In this manner, specially prepared soil samples can be irradiated and viewed from above, thus simulating the remote sensing situation as closely as possible. Quantitative measurements of soil reflectance using this instrument setup have been helpful in relating BRF to important soil properties (Beck, et al., 1976; Montgomery and Baumgardner, 1974; Montgomery, 1976).

Most commercially available spectroradiometers were designed for absorption or transmission measurements with accessories available for measurement of hemispherical reflectance, often with an integrating sphere (Hunt and Ross, 1967). Aside from the differing conditions of directional-hemispherical reflectance, these reflectance accessories often required that the sample be mounted vertically (Mathews, et al., 1973) or even horizontally with the beam impinging on the sample from below (Lindberg and Snyder, 1972). This required awkward soil sample preparation techniques involving high pressure compaction of finely sieved soil into bottle caps or the use of glass microscope slides to hold the soil in place (Bowers and Hanks, 1965; Condit, 1972; Lindberg and Snyder, 1972; Mathews, et al., 1973b; Obukhov and Orlov, 1964; Schreier, 1977). As a result, the remote sensing data gathering situation was not reproduced and soil sample preparation for control of important moisture variables and soil surface conditions was made difficult.

Spectral Reflectance of Surface Soils

Green Vegetative Cover

The spectral composition of the reflected radiation from soil is strikingly different from that of plants (Gates, 1963; Gates, 1965). Single leaves exhibit absorption maxima in the blue and red at 0.47 and 0.68μm, respectively, while the familiar green reflectance peak occurs at 0.55μm.

Total lack of pigment absorption and lack of appreciable absorption by liquid water results in strong near infrared reflectance in healthy leaves from 0.7 to 1.3μm. Major water absorption bands appear at 1.45 and 1.95μm in leaves as they do in moist soils (Myers and Allen, 1968). Density, morphology, and condition of the geometrical arrangement of leaves in a plant canopy determine the extent to which green vegetative cover affects the reflectance from surface soils (Hoffer and Johannsen, 1969). Girard-Ganneau (1975) reported that up to a vegetative cover of 15% a surface appears as soil whereas in excess of 40% cover, the spectral behavior resembles that of vegetation.

Near infrared wavelength data from digitized photographs were used to estimate percent ground cover in a maize canopy on both a Mollisol and an Alfisol (Stoner, et al., 1976). Using aircraft multispectral scanner data, Kristof and Baumgardner (1975) found that the ratio between relative reflectance in the infrared spectrum could be used to characterize the seasonal variation which is intimately connected with changes in green vegetative cover. Importantly, soil patterns remained visible in spite of dense maize cover well into the growing season.

Although dense vegetative canopies of crops or naturally occurring plant communities may mask the soils themselves, it is important to realize that inherent fertility, drainage, and moisture holding capacity differences among soils tend to influence the vegetative growth on these soils. Thus, although the soil itself eventually is masked by plant canopies, the canopy varies in phenological and morphological characteristics with different soils (Westin and Lemme, 1978). In this way, green vegetative cover is especially important in soil mapping of wild areas of native vegetation cover (Ranzani, 1969).

Non-Soil Residues

Common seasonal components of remotely sensed ground scenes are non-soil, non-green vegetation residues of senesced vegetation or even snow and ice in temperate zones. Although topographic information may be obtained from snow-covered areas (Lewis, et al., 1975), generally the presence of snow cover only obscures the soil patterns of interest in soil mapping, and winter-collected data are usually avoided. It is not uncommon, however, in cultivated regions to have a cover of crop residue on the soil surface at times of the year that would otherwise be ideal for obtaining remotely sensed data from soils (Stoner and Horvath, 1971).

Senesced leaves behave differently in the near infrared wavelength region than do live, healthy leaves (Gausman, et al., 1976). Whereas multiple leaf layers of healthy green leaves exhibit enhanced reflectance up to a stack of eight leaves, senesced leaves do not show increased infrared reflectance beyond two or three leaf layers. Aircraft and spacecraft reflectance measurements would not be expected to distinguish between different densities of senesced vegetation.

Field spectroradiometric investigations showed that sugarcane crop residue littered on the soil surface had higher reflectance than bare soil, but that standing sugarcane crop residue had lower reflectance than bare soil (Gausman, et al., 1975). Residue-covered soils for a variety of crops and grasses were best discriminated from bare soils with Landsat reflectance measurements from 0.5 to 0.6μm in the visible region of the spectrum. Further work by Gausman, et al. (1977) with wheat straw suggested that the near infrared region from 0.75 to 1.3μm seemed better than the visible region or water absorption bands for distinguishing among reflectances of soil-tillage-straw treatments.

Again, as in the case of green vegetation cover, indications are that the presence of non-soil residue does not fully obscure detectable soil patterns when areas of similar residue cover are isolated and classified separately using airborne scanner data (Stoner and Horvath, 1971). Field spectroradiometric studies of maize residue cover on an Alfisol and Mollisol provide evidence that the characteristic trends of spectral curves for these soils are not altered by residue cover or moisture differences (Stoner, et al., 1979).

Surface Roughness and Crusting

Early remote sensing research in soils recognized the fact that soils often formed a surface crust that could make a soil appear dry when it was actually wet (Hoffer and Johannsen, 1969). Cipra, et al (1971) found that crusted surfaces gave higher reflectance values in the 0.43 to 0.73μm wavelength region than did soils with the crust broken. The lower reflectance of the disturbed soil was attributed to the rough surface which presumably caused scattering of light as well as a shadowing effect. Surface roughness of a sandy Alfisol appeared to override the effects of moisture on reflectance (Johannsen, 1969).

Sensor view angle of most reflectance-type measuring devices is normal to the surface being viewed, but important illumination angle effects commonly result from differences in solar elevation angle with time of day and season of the year. Recently cultivated soils, aside from their generally higher surface moisture content than undisturbed soils, often exhibit a random geometry of reflecting surfaces whose overall reflectance may vary with illumination angle (Crown and Pawluck, 1974; Coulson and Reynolds, 1971). Tilled clay soil broken into aggregates several centimeters in size demonstrated marked differences in reflectance as a function of sun elevation (Coulson and Reynolds, 1971). A strong decrease in reflectance occurred with increasing sun elevation, possibly caused by trapping of radiation among the coarse particles as the fraction of incident radiation entering the spaces increased with increasing sun elevation. Soils with well-defined structure in the plow layer were found to reflect 15 to 20% less light energy than structureless soils (Obukhov and Orlov, 1964).

Difficulties in fully characterizing the moisture content and surface roughness of soils under various tillage treatments make this area one of the least understood areas of surface soil reflectance.

Soil Parameters Influencing Soil Reflectance

Soil Moisture

It is a common observation that most soils appear darker when wet than when dry. This results from decreased reflectance of incident radiation in the visible region of the spectrum. Angstrom (1925) attributed this darkening effect of moisture in soils to internal total reflections within the thin water film covering soil particles. It was felt that a portion of the energy would not be reflected to space but would be re-reflected between the surface of the particle and the surface of the water film. Planet (1970) indicated that the reflectance difference of a soil between its dry and wet states could be determined if the following factors were taken into account: 1) variations in index of refraction of the water due to dissolved soil constituents, 2) changes in the physical nature of soil particles by the presence of water, and 3) similarities in the indices of refraction of the soil and water leading to the Christiansen effect.

Hoffer and Johannsen (1969) showed that moist soils had an overall lower reflectance than their dry counterpart in the 0.4 to 2.6μm wavelength region. Bowers and Hanks (1965) noted a lowering in reflectance for Newtonia silt loam at six increasing soil moisture contents over the wavelength range of 0.5 to 2.5μm. Obukhov and Orlov (1964) observed that the spectral curve does not change in appearance upon wetting of soil and that the ratio of the reflectance of moist soil to that of dry soil remained practically constant in the visible portion of the spectrum. It was also noted that the decrease in reflectance was greater upon wetting of forest soils containing little organic matter than upon wetting of prairie soils high in organic matter. Condit (1970, 1972), in his well-known study of 160 soils from 36 states in the United States was able to identify three characteristic shapes of reflectance curves in the 0.32 to 1.0μm wavelength range. Although the curve shape was not noted to change between dry and wet soil reflectance readings, the soil moisture content was not reported for any of the soil samples. The need for carefully controlled moisture tension equilibria and soil moisture content determination in soil reflectance studies was recognized by Beck, et al. (1976).

The shape of soil reflectance curves is affected by the presence of strong water absorption bands at 1.45 and 1.95μm, and occasionally weaker water absorption bands at 0.97, 1.2 and 1.77μm. Specifically, these bands are overtones and combinations of the three fundamental vibrational frequencies of the water molecule which occur beyond 2.5μm (Bowers and Smith, 1972). The band at 1.94μm, a combination of the $\upsilon_2 + \upsilon_3$ fundamental frequencies is the most sensitive to water, and has been found best for relating reflectance measurements to soil moisture content (Bowers and Hanks, 1965). An absorption band at 2.2μm was not identified in early studies (Bowers and Hanks, 1965) but was later identified as a vibrational mode of the hydroxyl ion (Hunt and Salisbury, 1970). Absorption due to the hydroxyl ion also gives rise to a band at 1.45μm, the same as that of liquid water. The appearance of the 1.45μm band without the 1.95μm band indicates that hydroxyl groups and not free water are present in the material. Sharp bands at 1.45 and 1.95μm indicate that the water molecules are located in well defined ordered sites while broad bands at these wavelengths indicate that they are relatively unordered, as is often the case in naturally occurring soils. Weak absorption bands at 0.97, 1.2 and 1.77μm correspond to the absorption bands observed in transmission spectra of water of a few millimeters in thickness (Lindberg and Snyder, 1972). These weak water absorption bands can be assigned in terms of water vibrations, with the additional combination of librations of the water molecule in the 1.77μm (Hunt and Salisbury, 1971b).

Beck, et al. (1976) found that of several factors studied, soil moisture had the greatest influence on soil reflectance at the one-third bar moisture tension level. Because of the impracticality of measuring soil reflectance in the field in the 1.95μm water absorption band (also a region of strong atmospheric water absorption), reflectance in the 1.50 to 1.73μm wavelength region was suggested as the best possibility for mapping water content in surface soils. Although the importance of soil moisture to reflectance was recognized by Montgomery (1974, 1976) the contribution of this parameter to soil reflectance was not evaluated quantitatively because of the air dry state in which all of the soil samples were measured.

Bowers and Smith (1972) showed that a linear relation between absorbance and percent soil water was adequate for moisture determination from air dry to the moisture equivalent. The practicality of an absorbance measurement at 1.94μm, however, is limited to laboratory applications. Peterson, et al. (1979) demonstrated that the loss of reflectance from the oven dry state to field capacity for 15 surface Mollisols and Alfisols from central Indiana is definitely related to the oven dry reflectances of these soils. This relationship held true for visible as well as near and middle infrared reflective bands. These results point to the existence of orderly relationships among soil moisture tensions and soil reflectance values.

Organic Matter

Soil organic matter content and composition of organic constituents are known to have a strong influence on soil reflectance. A general observation has been that as organic matter content increases, soil reflectance decreases throughout the 0.4 to 2.5μm wavelength range (Hoffer and Johannsen, 1969). Baumgardner, et al. (1970) found that organic matter plays a dominant role in bestowing spectral properties to soils when the organic matter content exceeds 2.0 percent. As the organic matter drops below two percent it becomes less effective in masking out the effects of other soil constituents. Although it was not recognized by Condit (1970, 1972), his Type 1 and Type 2 curves corresponded respectively to the reflectance curves of high surface organic content Mollisols and low surface organic content Alfisols (Cipra, et al., 1971).

Organic constituents including humic and fulvic acid and nonspecific compounds including decomposing plant residues are known to influence soil reflectance to differing degrees (Obukhov and Orlov, 1964), although the contribution of each has been difficult to quantify. Montgomery (1976) found that soil reflectance in the 0.60 to 1.10μm region had the highest correlation with certain organic constituents. Better techniques for determining specific organic constituents are needed to help clarify their contribution to soil reflectance.

Oxidation of organic matter in a soil sample with H_2O_2 resulted in increased reflectance from 0.4 to 2.4μm, although the difference in reflectance beyond 1.3μm became very small (Bowers and Hanks, 1965). Mathews, et al. (1973) destroyed the organic matter in a 12.8% organic matter silty clay soil with the resulting reflectance being increased greatly from 0.4 to 1.3μm, while the reflectance actually decreased slightly from 1.5 to 2.4μm.

Regression studies indicated that organic matter content could be related to soil reflectance by a curvilinear exponential function (Schreier, 1977). Mathews, et al. (1973) found that organic matter correlated most highly with reflectance in the 0.5 to 1.2μm range, while Beck, et al. (1976) suggested that the 0.90 to 1.22μm range was best for mapping organic carbon in soils. Montgomery (1976) indicated that organic matter contents as high as 9.0% did not appear to mask out the contributions of other soil parameters to soil reflectance. Montgomery differed from Beck in recommending the visible wavelength region as the best for spectral measurement of organic matter content in soils.

Particle Size Distribution

Aside from the reflectance differences cited earlier which can be accounted for by differences in surface roughness and soil structure, soil particle size and shape as well as the size and shape of soil aggregates resulting from mild crushing appear to influence soil reflectance in varying manners. Bowers and Hanks (1965) measured the reflectance of pure kaolinite in size fractions from 0.022 to 2.68mm dia (coarse silt to very coarse sand particle size classes) and found a rapid exponential increase in reflectance at all wavelengths between 0.4 and 1.0μm with decreasing particle size. The most notable increases in reflectance occurred at sizes less than 0.4mm dia (approximately medium sand particle size class and finer). It was felt that particles or aggregates larger than 2-3mm dia would have little influence on additional absorption of solar energy.

Orlov (1966) found the reflectance of aggregates from 0.25 to 10mm in diameter to vary little for Mollisol-type soils. However, for the fraction less than 0.25mm dia (fine sand particle size class and finer) reflectance increased, a fact that Orlov attributed to sharp changes in chemical composition of aggregates less than 0.25mm dia compared with coarser aggregates.

Surface roughness on a micro scale may be the determining factor in explaining changes in reflectance as a function of particle or aggregate diameter. Bowers and Hanks (1965) observed that as particle size decreased, the surface of kaolinite became smoother. Similarly, Orlov (1966) found that fine particles filled a volume more completely and gave a more even surface. Coarse aggregates, having an irregular shape, formed a complex surface with a large number of interaggregate spaces. As light falls on large, irregularly shaped aggregates, most of the incident flux penetrates into light traps and is completely extinguished there.

Hunt, et al. (1970, 1971a, 1971b, 1971c, 1973a, 1973b, 1973c, 1974, 1976a, 1976b) measured the reflectance of a large number of minerals and rocks in four size fractions: 0-0.005 mm, 0-0.074 mm, 0.074-0.25 mm, and 0.25-1.2 mm. For silicate and carbonate minerals it was noted that the general effect of decreasing the particle size of the samples was to increase the reflectance at all wavelengths and to decrease the contrast of any well-resolved spectral features. Conversely to previously mentioned studies, in the case of oxides and sulphides the reflectance as a function of wavelength sometimes actually decreased with decreasing particle size. This phenomenon appeared to occur in materials of very low reflectance. As in other studies, however, it was found that only integral reflection varied with particle diameter, whereas the shape of the spectral curve remained the same.

Regression studies by Montgomery (1974, 1976) found silt content to be the single most significant parameter in explaining the spectral variations in soils. It was felt that the significance of silt content may have been attributable to the size of the silt particles relative to the reflective wavelengths. Beck, et al. (1976), studying predominantly silty soils, concluded that the wavelength region from 1.50 to 1.73μm was best for mapping clay content in surface soils.

Iron Oxides

The type and relative amount of constituent iron oxides are known to influence the colors of red and yellow soils high in sesquioxide clays (Bigham, et al., 1978). Predominantly yellow soils high in goethite were found to absorb more phosphate per unit weight than did otherwise similar red soils high in hematite. Soil spectral reflectances may be meaningful criteria for both taxonomic and management separations in highly weathered soils.

Obukhov and Orlov (1964) reported that soils with an elevated content of iron could be easily distinguished by the inflection characteristic for pure Fe_2O_3. They found the intensity of the reflection in the region from 0.5 to 0.64μm inversely proportional to the iron content. Karmanov (1970) noted that the reflection intensity of iron hydroxides containing little water and having a dark brown-red color increased most strongly in the wave interval from 0.554 to 0.596μm while that of hydrous iron oxides increased most strongly in the wave range from 0.50 to 0.54μm. Neither of these studies investigated iron oxide reflectance beyond the visible wavelengths.

Most of the well-resolved electronic features of iron oxides in minerals and rocks can be attributed to transitions in the iron cations (Hunt, et al., 1971b). Typically, the ferrous ion produces the band near 1.0μm due to the spin allowed transition between the E_g and T_{2g} quintet levels into which the D ground state splits in an octahedral crystal field. For the ferric ion, the major bands produced in the spectrum are a result of transition from the $^GA_{1g}$ ground state to $^4T_{1g}$ at about 0.87μm; and to $^4T_{2g}$ at 0.7 m. Whereas only 1% by weight of finely powdered hematite was found to alter a clayey, yellow Oxisol from 10YR to 5YR in color (Resende, 1976), as little as 0.0005% of iron by weight was capable of producing a perceptible iron band at 0.87μm in a highly transparent calcite mineral (Hunt and Salisbury, 1971a). In addition to the ferrous iron band at 1.0μm, another absorption band near 1.0μm has been identified in a sample of gibbsite as a second overtone and combination of stretching modes of the hydroxyl radical (Hunt, et al., 1971b).

Montgomery (1976) found the free iron oxide content of soil to be significant in both visible and infrared regions of the spectrum, but observed that the significance of iron increased with increasing wavelength. The presence of organic matter did not diminish the contribution of iron to soil reflectance. Percent iron in iron-organic complexes, along with percent carbon and exchangeable Mg and K were most significantly correlated with spectral measurements in a study by Schreier (1977). The narrowness of infrared iron absorption bands is incompatible with the broad infrared wavelength bands of the present Landsat satellites, and may render quantitative comparisons of reflectance with iron oxide levels in soils impractical.

Clay Mineralogy

Examination of the reflectance spectra of montmorillonite and kaolinite group clay minerals indicates that they owe the major features of their absorption spectra to the presence of water (Lindberg and Snyder, 1972). Very strong molecular water bands at 1.4 and 1.9μm are due to the bound water typical of montmorillonites (Hunt and Salisbury, 1970). Strong hydroxyl bands centered at 1.4 and 2.2μm are typical of kaolinite reflectance, with the lack of appreciable bound water resulting in only a weak band at 1.9μm. The presence of a small amount of the ferrous ion results in a slight band near 1.0μm in kaolinite, while ferrous iron in a six fold site in montmorillonite results in a strong band at 1.0μm. Mathews, et al. (1973) measured a consistently low reflectance response for wavelengths less than 1.7μm in a sample of illite and showed low absorption intensities for the water and hydroxyl bands when compared to kaolinite and nontronite (montmorillonite group) samples. For most kaolinite and montmorillonite group minerals, a general decrease in reflectance occurs with decreasing wavelength beginning at about 0.7μm (Lindberg and Snyder, 1972).

Aside from the silicate clay minerals, sesquioxides typical of highly weathered soil regions present reflectance spectra dominated by ferric iron and occasionally by hydroxides. Samples of hematite, limonite, and goethite exhibit well-defined ferric iron absorption bands near 0.9μm (Hunt, et al., 1971b). Gibbsite, whose chemical formula is $Al(OH)_3$, shows a weak but relatively sharp band at 1.0μm attributed to overtones of Al-O-H bending modes and combinations of stretching modes. Magnetite samples display overall low reflectance, changing very little throughout the visible and infrared. This opaque, spectrally featureless spectral behavior is due to iron oxide and titanium conduction bands extending throughout the spectral range.

Soil clays occur in intimate combination with other soil constituents. Mixed clay mineralogies are more common than clay mineralogies predominated by single clay types. Montgomery (1976) analyzed separately a group of montmorillonitic mineralogy soils and noted little difference between statistical correlations of reflectance and soil properties for this group and for soils as a whole. The contribution of the mineralogy of size fractions other than clay to soil reflectance has not been reported but is probably important.

Parent Material

Mathews, et al. (1973) first demonstrated the influence of soil parent material on soil reflectance. Reflectance curves for soils developed from limestone, shale, and sandstone exhibited contrasting, characteristic shapes and were separable at all wavelengths. Schreier (1977) also noted that soil parent material seemed to affect the overall spectral reflectance of soils developed from deltaic, organic, marine alluvial, and outwash materials. Hunt, et al. (1973b, 1973c, 1974) observed that the overall reflectance intensities of igneous rocks decreased from acid to intermediate to basic, with ultrabasic forms always displaying a well-defined ferrous iron band near 1.0μm. These findings suggest that local geographic areas of similar parent material may best be studied separately when trying to relate soil reflectance to other soil parameters. Just such an approach was used successfully to separate drainage classes within parent material groups in Jasper County, Indiana (Weismiller, et al., 1979).

Applicability of Laboratory-Measured Soil Reflectance to Airborne Sensor Data

Differences in laboratory instrument and airborne sensor configurations complicate comparisons of soil reflectance measured by these methods. Whereas most laboratory instruments utilize calibration standards viewed and irradiated identically to the target, airborne sensors must often rely on internal calibration sources. Solar radiation and atmospheric attenuation may vary from one airborne sensor flight to another.

Laboratory and field spectra of moist Alfisol and Mollisol surface soils measured with the same spectroradiometer and calibrated to a pressed barium sulphate standard exhibited characteristically-shaped spectral curves for both soils (Stoner, et al., 1979). Spectral response for either soil measured in the field was about 1.5 times greater than the spectral response of laboratory-measured moist soils at any given wavelength from 0.52 to 1.75μm. Lower moisture levels and formation of a drier surface crust could easily account for the observed spectral differences, but importantly the ability to extend laboratory-measured soil spectra to field conditions was demonstrated.

May and Petersen (1975) attempted to correct for solar radiation and atmospheric attenuation in comparing airborne multispectral scanner data to laboratory reflectance spectra of soil. By using supervised and unsupervised classification routines, computer-generated maps using the laboratory and multispectral scanner derived reflectances resulted in maps that compared well with field survey maps. An agreement of 90% was obtained between classification maps produced using multispectral scanner derived reflectance and laboratory derived reflectance could be substituted for multispectral scanner response data with only a slight decrease in soil mapping accuracy.

Relationships of Soil Reflectance to Site Characteristics

Soil reflectance, expressed in terms of soil color, has been found to be a good indicator of soil characteristics of use in the study of soil genesis and in arriving at conclusions concerning their best management and use (Kohnke, 1968). Soil in humid temperate and cold zones are predominantly grayish. Red and yellow soils are found mostly in the subtropics and tropics, although limestone-derived soils can be red even in warm temperate regions. Local topography influences soil color because of the higher organic matter content in depressional areas. Eroded and depositional areas exhibit altered soil colors as a result of relief differences. Poorly drained soils exhibit darker colors because of a micro-climate of reducing conditions.

Kohnke, et al. (1968) expressed climate by the use of a precipitation and temperature index called the "biofactor" and found this factor highly correlated with pH, exchangeable hydrogen, cation exchange capacity, nitrogen content and organic carbon for the surface 25 cm of soils from many countries. Similar correlations were obtained using the Thornthwaite (1948) moisture index, but the biofactor was preferred because of its simplicity. Buntley and Westin (1965) studied color development across a climosequence of grassland soils, concluding that quantitative numerical color-development equivalents yielded results that were characteristically similar within great soil groups and dissimilar among great soil groups. Montgomery (1976) obtained higher correlations between soil reflectance and physicochemical properties of soils when soils from similar climatic zones were grouped together.

Free iron is known to decrease in soils of increasingly poor natural drainage, thus making drainage class an important soil site characteristic in understanding soil reflectance (Buol, et al., 1973). In soils with weatherable iron-bearing minerals, the age of formation of soils is closely related to their reflectance properties because of the observed increase in the percentage of free iron with increasing weathering.

MATERIALS AND METHODS

Soil Sample Selection

Approximately 240 soils, representing a statistical sampling of the more than 10,000 soil series in the United States were selected for this study. Selections were made from a list of the more than 1300 benchmark soil series in the United States and Caribbean Area (Soil Survey Staff, 1972). Benchmark soil series represent these soils with a large geographic extent and whose broad range of characteristics renders these soils so widely applicable for study. Information about these benchmark soils can be extended to many of those closely related in classification and geograpny. The type location of each benchmark soil series was marked on a map of United States counties to show the representative geographic location where the described soil profile meets the central concept for that series.

Soil sample selection was based on a stratification of the 48 contiguous states in the U.S. into climatic zones based on soil temperature regime and moisture zone delineation (Figure 1). An adequate number of soil samples was desired to represent each climatic region approximately in proportion to the geographic extent of the seventeen regions.

Each individual soil has a characteristic temperature regime that can be measured and described. For practical reasons, the soil temperature regime can be described by the mean annual soil temperature and the average

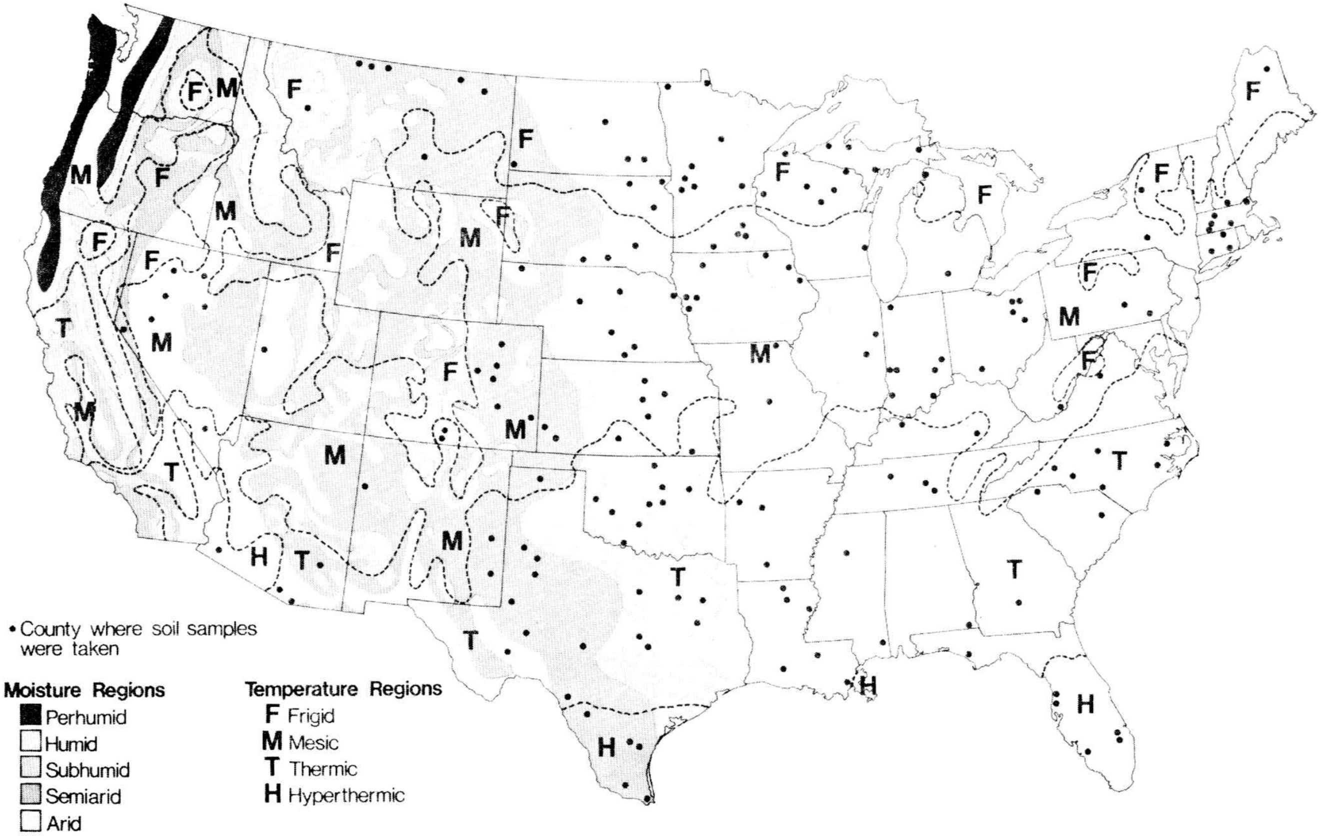


Figure 1. Climatic zones in the continental United States as identified by soil temperature regime (Soil Survey Staff, 1975; FAO-UNESCO, 1975) and the Thornthwaite (1948) moisture index.

seasonal fluctuations from that mean at a depth of 50 cm (Soil Survey Staff, 1975). The mean annual soil temperature is related most closely to the mean annual air temperature and can be estimated for much of the United States by adding 1°C to the mean annual air temperature (Smith, et al., 1964). This makes it possible for maps of soil temperature regimes to be drawn in the absence of necessarily large numbers of soil temperature measurements (FAO-UNESCO, 1975). The four classes of soil temperature regime most widely occurring in the 48 contiguous states are defined in the U.S. Soil Taxonomy as shown in Table 1.

Moisture zone classification is not as straightforward as soil temperature classification, but many systems have been proposed and modified to describe adequately the water balance at the earth's surface. Thornthwaite (1948) modified an earlier "precipitation effectiveness" classification by calculating the potential evapotranspiration and comparing it with precipitation to develop measures of water surplus and water deficiency. Thornthwaite's basis for climatic classification consists of a moisture stress index dependent only on potential evapotranspiration and precipitation. Five main moisture zones are defined on this basis in the 48 contiguous states (Table 2).

Only those soils whose type locations were at least one county away from a climatic zone boundary were considered for this study. Some climatic zones had very few benchmark soils, and in these cases all benchmark soils within these zones were chosen for study. To facilitate field sampling by Soil Conservation Service personnel it was necessary to choose approximately twenty percent of the benchmark soils based on the presence of field mapping parties in counties that were type locations for potential soils of interest. Aside from these restrictions, a random sampling procedure was used within each stratified climatic zone to select the desired number of soils for each climatic region. The resulting distribution of soil samples covers a well-scattered pattern encompassing seventeen continental climatic zones in 39 of the lower 48 states of the United States (Figure 1, Table 3, Appendix Table 10). In addition, the distribution of benchmark soils selected for this study is very similar to the proportional areal extent of the nine soil orders found in the continental United States (Table 4).

Field Sampling

The Soil Survey Investigations Division of the Soil Conservation Service (USDA) cooperated with the Laboratory for Applications of Remote Sensing (LARS)/Purdue University by taking responsibility for field collection of the requested soil samples. Soil Conservation Service field survey personnel were responsible for sample collection of benchmark soils in their locality. Over 95% of the requested benchmark soil series were sampled, properly identified, and forwarded to LARS for analysis.

Sampling guidelines specified that all soils should be sampled at sites that represent the dominant use of the benchmark soil in question. Samples were collected in cultivated sites if this was the dominant use. The first site for each soil was near the type location for the current official series to assure conformity to the central concept of the benchmark soil series. Care was taken to avoid areas next to gravel roads, fence rows,

Table 1. U.S. taxonomic soil temperature regimes (Soil Survey Staff, 1975).

temperature class*	mean annual soil temperature
frigid	MAST < 8°C
mesic	8°C ≤ MAST < 15°C
thermic	15°C ≤ MAST < 22°C
hyperthermic	22°C ≤ MAST

*Difference between mean summer and winter temperatures for all classes is more than 5°C at a depth of 50 cm.

Table 2. Moisture zones according to Thornthwaite (1948).

moisture zone	moisture index
perhumid	100 and above
humid	20 to 100
subhumid	-20 to 20
semiarid	-40 to -20
arid	-60 to -40

Table 3. Distribution of soil series by climatic zone.

temperature regime	moisture zone arid	 semiarid	 subhumid	 humid	 perhumid	subtotals
frigid	2	9	21	19		51
mesic	16	23	23	37	6	105
thermic	12	10	18	30		70
hyperthermic	1	5	2	6		14
subtotals	31	47	64	92	6	240 (total)

Table 4. Distribution of soils by soil order.

	benchmark soil series		United States extent
soil order	number	percent	percent
Mollisol	73	30.4	24.6
Alfisol	40	16.7	13.4
Entisol	39	16.2	7.9
Aridisol	25	10.4	11.5
Ultisol	22	9.2	12.9
Inceptisol	18	7.5	18.2
Spodosol	15	6.2	5.1
Vertisol	4	1.7	1.0
Histosol	4	1.7	0.5
	240 total		

old farmsteads, and any other areas of undesirable chemical or physical alteration of the soil profile.

A second profile was located at a site about two to thirty kilometers from the first site and in a different mapping delineation. Sampling sites were investigated to verify the similarity of profile characteristics at the two locations before duplicate samples were taken. Specifically, obviously different surface texture phases were not desired.

Samples represented the surface soil only and contained material from 0 to 15 cm, if depth to a B horizon permitted. About two kilograms of soil were sampled at each site. Sample bags were identified as to soil series name, county, and soil survey sample number. Additional information regarding exact sampling location, physiographic position, topography, drainage, vegetation, and parent material was requested for each soil sample.

The duplicate samples of 240 benchmark soil series form a collection of 480 surface soil samples for detailed measurement of physicochemical characteristics and reflectance properties as they would be viewed by airborne sensors. All samples conform to the central concept of each individual soil series as each soil would be identified and mapped by an experienced soil surveyor in the field.

Soil Sample Preparation

After receipt of the soil samples and initial data logging, samples were dried, mildly crushed with a wooden rolling pin to break up clods, and passed through a 10 mesh sieve to remove all particles and aggregates larger than 2 mm diameter. Use of the soil size fraction less than 2 mm diameter for soil reflectance measurements was an attempt to standardize this procedure in line with the use of this same size fraction for most laboratory determinations of soil properties (SCS-USDA, 1972; Franzmeier, et al., 1977).

Sieved soil samples were carefully divided and placed in cardboard containers which were identified as to soil series name, sampling number, and county where sampled. For each soil sample, one quart container was placed in storage at LARS for possible future study, while subsamples for soil characterization and spectral analysis were stored in pint containers at their respective work sites.

Establishment of Uniform Moisture Tension

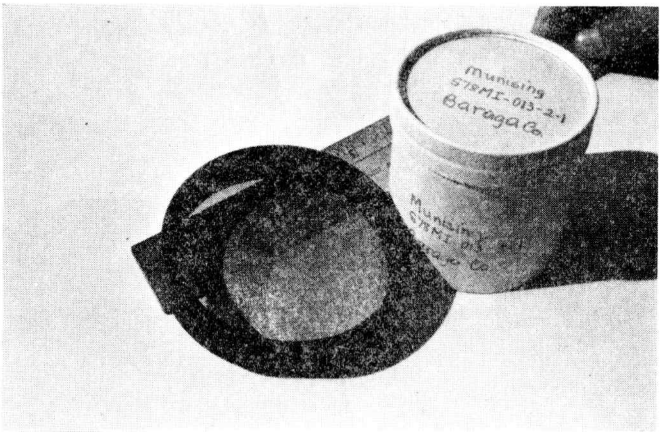
Several factors led to establishment of a standard procedure for preparing large numbers of soil samples for reflectance measurements. Firstly, the nature of the spectroradiometer/reflectometer setup permitted a view of a 3.2 cm diameter sample of whole soil in a horizontal position without the hindrance of glass slide covers or the artificial nature of very fine soil compacted under extreme pressure. Secondly, realizing that soil moisture plays a critical role in soil reflectance, and realizing that the extraneous contribution of soil moisture deriving from environmental factors should be controlled as much as possible, a system capable of maintaining uniform moisture tension in soil samples was desired. Thirdly, the large number of soil samples measured in this study (more than 500 total), and the ideal operating load of 40 to 60 samples per spectroradiometer session, required the use of a large volume soil moisture tension equilibration apparatus.

An asbestos tension table setup was chosen to equilibrate soil samples at approximately one-tenth bar moisture tension. A one-tenth bar tension is obtained by exposing the upper side of a membrane (in this case asbestos) to atmospheric pressure while a column of water 100 cm in height provides the tension to the lower side (Kohnke, 1968). This moisture tension is somewhat drier than the aeration-porosity limit (approximately one-twentieth bar), but would be moister than the one-third bar wet limit of the range of plant-available water under general field conditions. Direct comparison to field soil moisture tension is difficult, however, because the moisture retention of sieved samples is known to increase over core samples at tensions less than 0.4 bar (Elrick and Tanner, 1955).

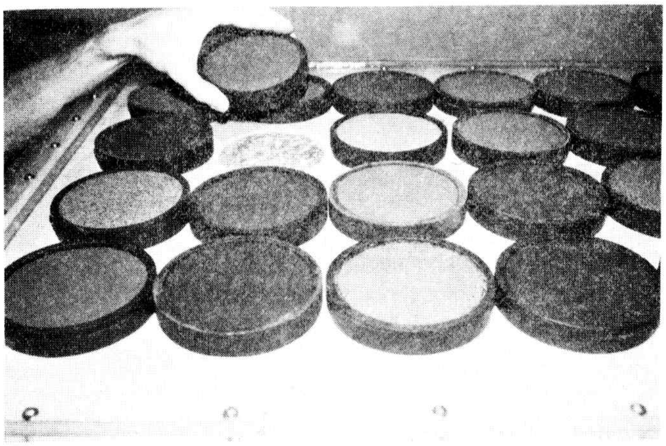
Two 61 x 91 cm plexiglass-framed tension table units each with a 28 sample capacity were constructed following the method of Jamison and Reed (1949) in which a more durable asbestos membrane is used in place of the blotter paper apparatus described by Leamer and Shaw (1941). An additional feature added to the units was a plexiglass top which covered the equilibrating soil samples and prevented exposure to room air currents while not sealing off the upper membrane to atmospheric pressure. Crusting of the soil surface was avoided in this manner.

Sample holders were designed to fit the specifications of the spectroradiometer field of view and the tension table operating principle. A 10 cm inside diameter sample holder was selected to allow ample leeway in positioning the sample with the 3.2 cm diameter field of view of the instrument. The depth of 2 cm provided sufficient soil bulk to obscure the bottom of the sample holder, assuring that only soil was being viewed. The necessity for direct contact of the soil sample with the asbestos membrane was met by stretching 60 mesh brass strainer cloth taut and fastening it in a countersunk groove in one end of the 2 x 10 cm plastic ring. While very little soil fell through this fine screen, filter paper protected the asbestos from staining, and adequate contact with the asbestos membrane could be maintained. The plastic sample rings were painted with non-reflecting black paint to reduce unwanted reflectance.

Soil samples were transferred to the sample holders with special care taken to avoid segregation of aggregate sizes. A level surface was obtained by striking off the excess soil with a straight edge (Figure 2). Samples were placed in large trays and deionized water was added to a depth of about 1 cm. After saturating the soil samples for about four hours, the samples were placed on the tension tables for 24 hours in order to reach equilibration (Figure 2). An equilibration time of 24 hours has been found to be more than adequate for most soils at the 100 cm water tension (Jamison and Reed, 1949). Samples were removed from the tension tables one at a time for spectral measurement, and were replaced for subsequent sampling of the approximate soil area viewed to a depth of 1 cm for gravimetric moisture determination.

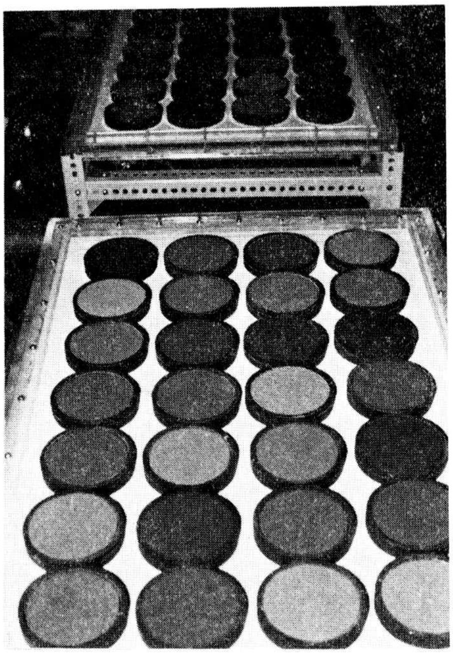


a. Soil sample and 10 cm diameter sample holder.

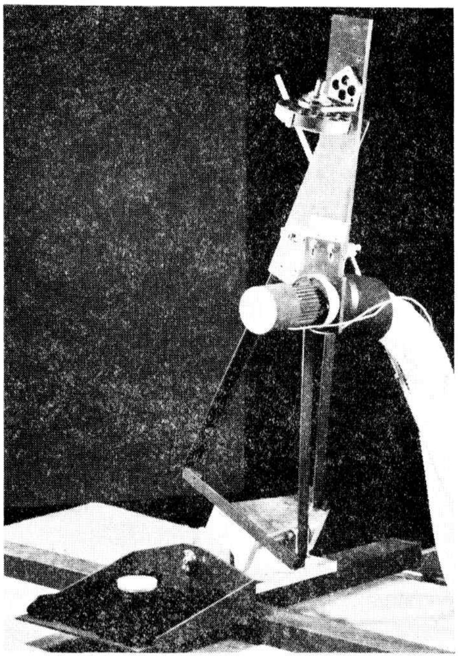


b. Saturated sample being placed on asbestos tension table.

Figure 2. Setup for laboratory spectral measurements of soils.



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



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

Figure 2. (Cont.)

Reflectance measurements were made on batches of 56 soil samples per spectroradiometer session. Soil samples within each batch were selected at random from among the 480 benchmark soil samples plus some other soils that were studied at the same time. Each batch contained two subsamples of a sample of Fincastle silt loam soil (Aeric Ochraqualf, fine-silty, mixed, mesic) as check samples. The run order within each batch was also randomized for the 54 soil samples plus two check samples. Ten spectroradiometer sessions were necessary to complete all the spectral measurements.

Bidirectional Reflectance Factor Measurement

An Exotech Model 20C spectroradiometer was used in an indoor configuration with a bidirectional reflectance factor reflectometer in order to obtain spectral readings in 0.01μm increments in the 0.52-2.32μm wavelength range. The short wavelength head of the spectroradiometer contains a silicon detector for measuring radiation in the 0.37 to 0.74μm wavelength range and a lead sulfide detector to cover two wavelength ranges, 0.65 to 1.3μm, and 1.25 to 2.5μm (Silva, et al., 1971). Each of these wavelength ranges corresponds to one segment of a circular variable filter (CVF), through which spectral scans are made by rotation through the optical path in front of the detectors. Circular variable filters provide the instrument with the capability to operate under natural conditions because of the rapid spectrum scan time of 2 complete scans/sec (Leamer, et al., 1973). Data recording is done on both a multichannel strip chart recorder and on magnetic tape for subsequent digitization and computer processing.

The sensing head of the spectroradiometer is mounted in a vertical fixed position approximately 2.4 m above the sample stage. The illumination source is a 1000 watt tungsten iodine coiled filament lamp which transfers a highly collimated beam by means of a paraboloidal mirror to the sample-viewing plane. Incident irradiation is about 6° off vertical. The 3/4° field of view mode of the spectroradiometer is used to detect a sample area of about 3.2 cm diameter (DeWitt and Robinson, 1976).

Pressed barium sulfate is used as a standard to calibrate the instrument. After every fifth soil sample the pressed barium sulfate is measured to account for changes in intensity of the illumination source. The bidirectional reflectance factor data are corrected for dark-level instrument offset and less than unity reflectance of the barium sulfate standard. Six complete scans covering the entire wavelength range are made and later averaged when the magnetic tapes are digitized and processed.

Measurement of Physicochemical Properties

All laboratory measurements of soil properties were carried out in the Purdue University Agronomy Department. Particle size distribution of organic matter-free soil was determined in the Soil Characterization Laboratory of this department. Eight particle size separates were measured on a percentage basis by weight: very coarse sand (2-1 mm), coarse sand (1-0.5 mm), medium sand (0.5-0.25 mm), fine sand (0.25-0.10 mm), very fine sand (0.10-0.05 mm), coarse silt (0.05-0.02 mm), fine silt (0.02-0.002 mm), and clay (< 0.002 mm).

The procedure followed for particle size analysis involved initial removal of organic matter with hydrogen peroxide and heat (SCS-USDA, 1972; Franzmeier, et al., 1977). This is followed by filtering and washing through a Buchner funnel to obtain the organic matter-free soil portion Sodium metaphosphate is used as a dispersing agent. Sands are separated from silt and clay by washing the dispersed sample on a 300 mesh sieve. Clay and silt contents are determined by sedimentation-pipetting while sand size fractions are separated by passing through a nest of sieves.

Cation exchange capacity (CEC) was measured for each soil as the sum of extractable cations of Ca, Mg, K, Na plus extractable acidity (H), all expressed in terms of milliequivalents per 100g of soil. Ammonium acetate extraction is used and extracts are analyzed by atomic absorption for calcium and magnesium and by emission spectroscopy for sodium and potassium (SCS-USDA, 1972). Extractable acidity is determined with a barium chloride and triethanolamine buffer solution by titration with hydrochloric acid. Base saturation is calculated as CEC minus extractable acidity, the difference divided by CEC, and multiplied by 100 to express as a percentage.

Organic carbon was determined by the modified Walkley-Black procedure of acid dichromate digestion with ferrous ammonium sulfate titration (Franzmeier, et al., 1977). Beck, et al. (1976) found no significant difference among three methods of determining organic carbon content in soils in explaining the variation in spectral response, and adequate results were obtained with the modified Walkley-Black procedure.

Free (extractable) iron was measured by the so-called CBD procedure which involves reducing the iron with sodium dithionite, chelating it with sodium citrate in a sodium bicarbonate buffer, followed by colorimetric measurement at 510 nm (Franzmeier, et al., 1977)

Data Logging Procedure

An identification record containing complete soil taxonomic information along with site characteristics and laboratory analysis results was prepared and implemented for storage and rapid retrieval of all soils information as part of the LARSPEC software package (Simmons, et al., 1975). The soils record consists of seven computer cards of information for each spectroradiometer observation. Information from these cards is placed together with the spectroradiometer measurement for each respective soil when the digital computer tape is reformatted.

Summary descriptive information as desired can be obtained by using the data identification list processor of LARSPEC. Data graphical display of soil spectral curves or of any other stored soil parameter is possible using another LARSPEC processor. Wavelength bands can be specified for extraction of average response values from the soil reflectance curves for subsequent use in statistical analysis.

Catalog of Soil Spectra

A format was developed for presentation of a selected number of physicochemical and site characteristics together with the reflectance curves for each pair of duplicate benchmark soils studied (Figure 3). The large quantity of data stored in the soil data base for each soil sample was reduced to include essential soil parameters that may be helpful in understanding the reflectance properties of that soil. Information included for each soil sample are: soil series name and state abbreviation, taxonomic subgroup and family, climatic moisture zone, parent material, county where sampled, horizon, slope class, drainage, texture class, percent sand, silt, and clay, moist and dry Munsell colors, percent organic matter, cation exchange capacity, iron oxide content, and moisture percentage by weight. The corresponding spectral curves are displayed as a plot of bidirectional reflectance factor (%) versus wavelength from 0.52 to 2.32μm (Stoner, 1979).

RESULTS AND DISCUSSION

Repeatability of Spectral Measurements

On each of the ten days in which soil spectral measurements were taken, two check samples were randomly assigned to each block of 56 soil samples as a verification of repeatability of the tension table apparatus as well as the instrument setup. Check samples consisted of subsamples of a larger surface soil sample of Fincastle silt loam, a fine-silty mixed mesic Aeric Ochraqualf. Resulting spectral curves for these 20 check samples were divided into two time blocks for sake of illustration (Figure 4). Reflectance of the check samples varied very little between the two check samples measured on the same day or among different days of measurement. In addition, the moisture percentage by weight as measured gravimetrically following spectral reading differed by only 5% relative to an average content of 31.3% moisture for any single soil sample. This served as a verification of the repeatability of the tension table apparatus for equilibrating soil moisture tension as well as for the sample preparation techniques. For the soil chosen as a check sample, the experimental procedure used to measure soil reflectance at equipotential moisture tension provided quantitative reliable spectral measurements in the 0.52 to 2.32μm wavelength range.

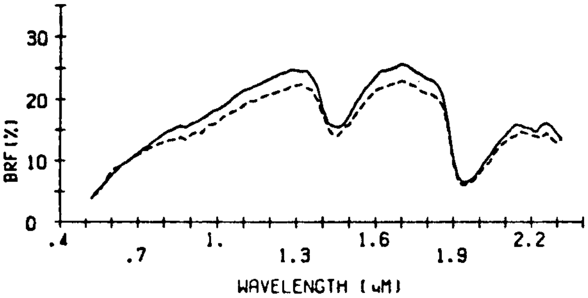
In addition to the Alfisol check samples, several other reflectance measurements were made on subsamples of individual soil samples representing the Mollisol and Oxisol soil orders. Reflectance measurements of two subsamples of Chalmers silty clay loam, fine-silty mixed mesic Typic Haplaquoll, were made on separate days. Resultant spectral curves reveal almost identical reflectances for the two subsamples of this Mollisol (Figure 5). The high organic matter content (4.7%) Chalmers soil exhibits a characteristic concave shape contrasting with the convex shape of the lower organic matter content (1.4%) Fincastle soil.

Reflectance measurements of two subsamples of a high iron content (23%) Oxisol from Paraná State, Brazil contrast sharply with the previous soil reflectance curves (Figure 6). Again, spectral curves for subsamples of the same individual soil sample show very close correspondence at all wavelengths from 0.52 to 2.32μm. This soil from a prime soybean growing region of Brazil has been classified as a very-fine oxidic thermic Haplic Acrorthox (Fasolo, 1978).

RED BAY(AL)

Rhodic Paleudult
fine-loamy, siliceous, thermic
humid zone
marine sediments
Houston Co.

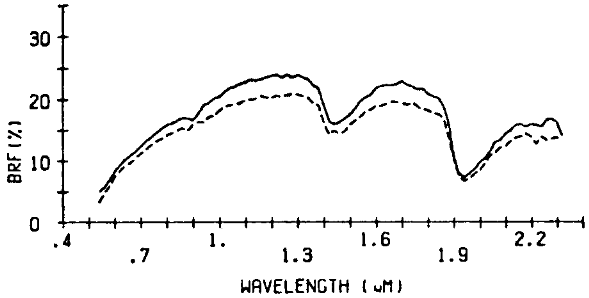
——	----
Ap horizon	Ap horizon
B slope	B slope
well drained	well drained
loamy sand	sandy loam
83%S 7%Si 10%C	76%S 11%Si 13%C
5YR 3/4 (moist)	5YR 3/4 (moist)
7.5YR 5/6 (dry)	7.5YR 5/6 (dry)
0.58% O.M.	0.91% O.M.
10.8 meq/100g CEC	7.1meq/100g CEC
0.80% Fe_2O_3	1.32% Fe_2O_3
12.8 MW%• ——	15.2 MW%• ----



CONTINENTAL(AZ)

Typic Haplargid
fine, mixed, thermic
arid zone
acid rock alluvium
Santa Cruz Co.

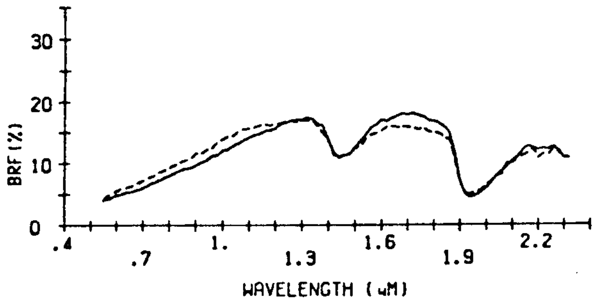
——	----
All horizon	All horizon
A slope	A slope
well drained	well drained
coarse sandy loam	fine sandy loam
70%S 20%Si 9%C	53%S 35%Si 11%C
5YR 3/4 (moist)	5YR 3/3 (moist)
7.5YR 4/6 (dry)	7.5YR 4/6 (dry)
0.48% O.M.	0.71% O.M.
6.0 meq/100g CEC	15.7 meq/100g CEC
0.74% Fe_2O_3	1.55% Fe_2O_3
12.6 MW%• ——	17.2 MW%• ----



PIMA(AZ)

Cumulic Haplustoll
fine-silty, mixed, thermic
arid zone
mixed alluvium
Santa Cruz Co.

——	----
Ap horizon	Ap horizon
A slope	A slope
well drained	well drained
silty clay	silty clay loam
8%S 48%Si 44%C	9%S 52%Si 39%C
7.5YR 3/2 (moist)	7.5YR 3/2 (moist)
10YR 4/2 (dry)	10YR 5/2 (dry)
3.66% O.M.	1.86% O.M.
52.6 meq/100g CEC	44.8 meq/100g CEC
0.94% Fe_2O_3	1.25% Fe_2O_3
50.9 MW%• ——	55.9 MW%• ----



WHITE HOUSE(AZ)

Ustollic Haplargid
fine, mixed, thermic
arid zone
mixed alluvium
Santa Cruz Co.

——	----
A1 horizon	A1 horizon
A slope	B slope
well drained	well drained
fine sandy loam	sandy loam
52%S 34%Si 14%C	62%S 26%Si 12%C
5YR 3/3 (moist)	5YR 3/3 (moist)
7.5YR 4/4 (dry)	7.5YR 4/4 (dry)
1.68% O.M.	1.70% O.M.
15.7 meq/100g CEC	10.6 meq/100g CEC
1.84% Fe_2O_3	1.85% Fe_2O_3
21.8 MW%• ——	18.8 MW%• ----

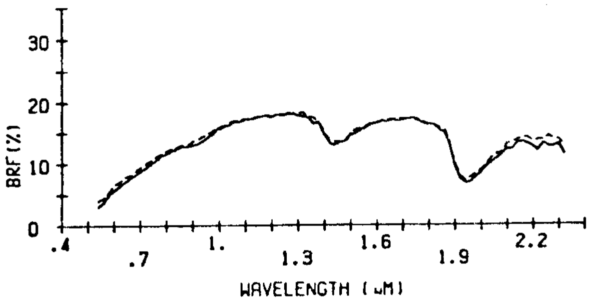


Figure 3. Example of soil information in catalog of soil spectra.

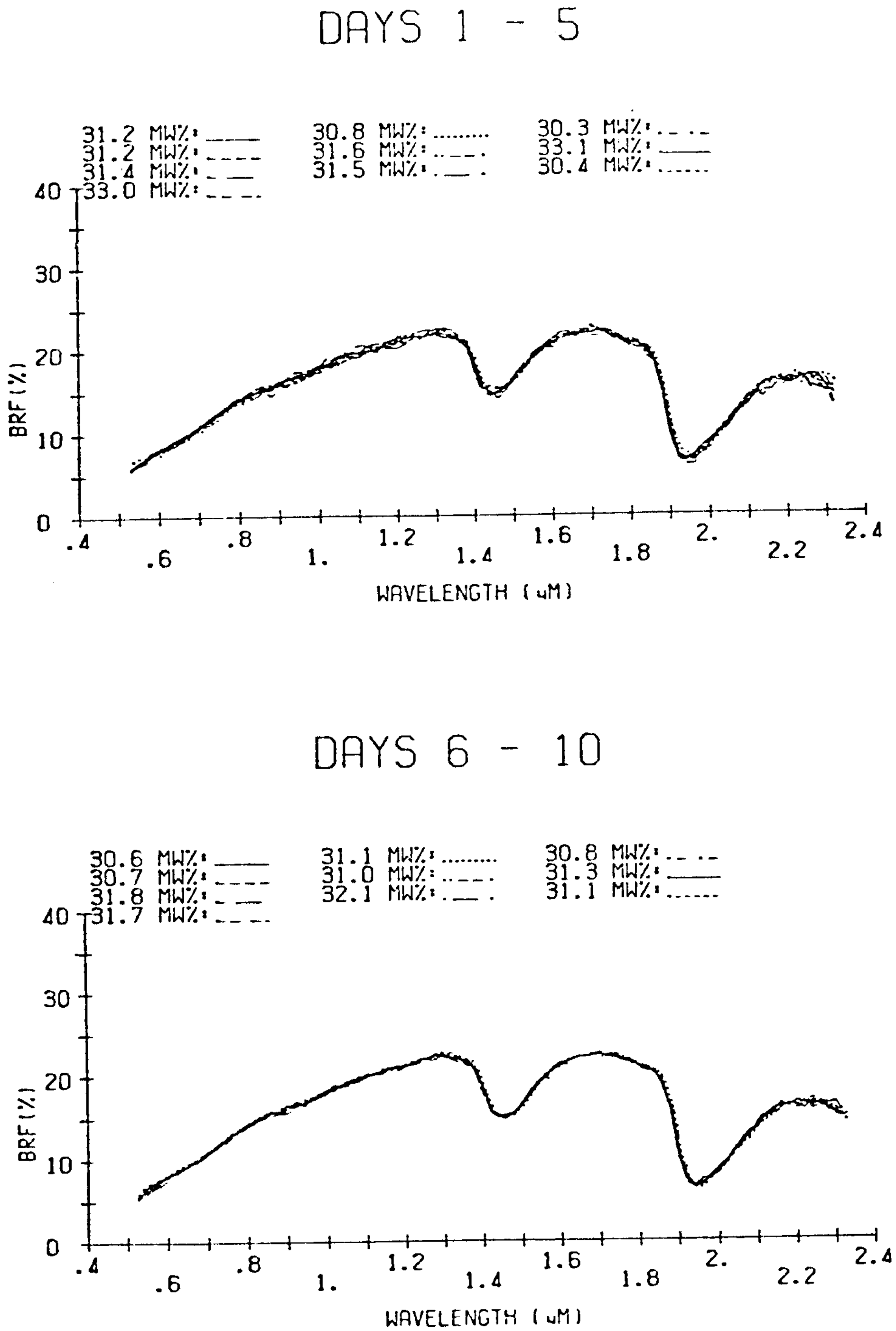


Figure 4. Soil reflectance curves and moisture percentages by weight (MW%) for 20 check samples of Fincastle sil, a fine-silty mixed mesic Aeric Ochraqualf, from ten different setups of the tension table apparatus.

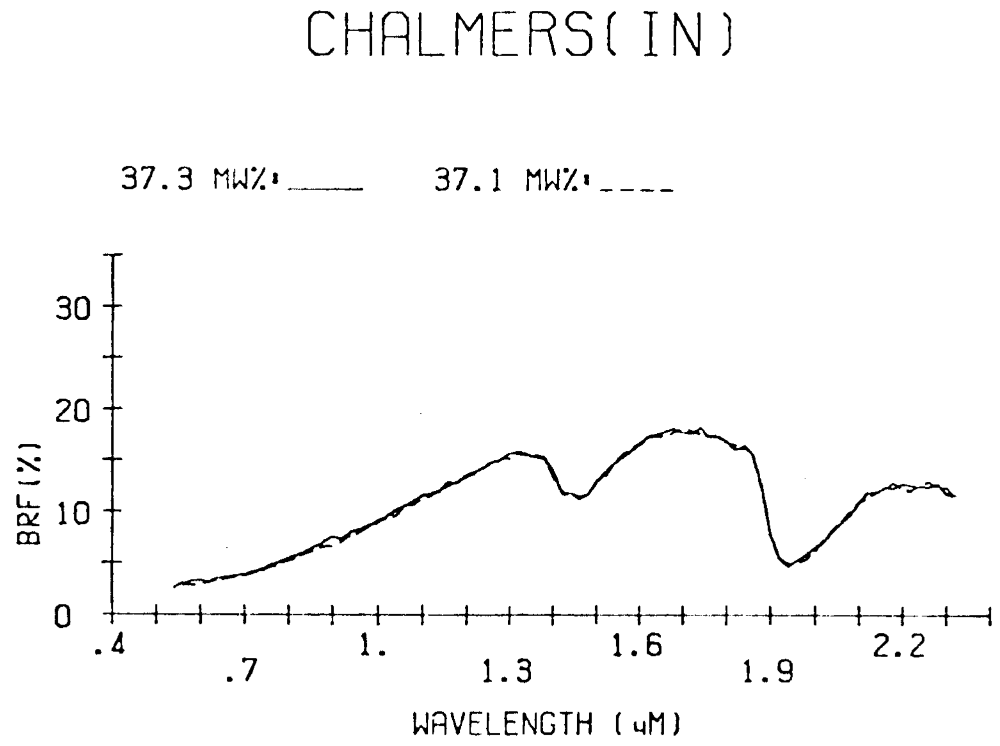


Figure 5. Soil reflectance curves for two subsamples of Chalmers sicl, a fine-silty mixed mesic Typic Haplaquoll.

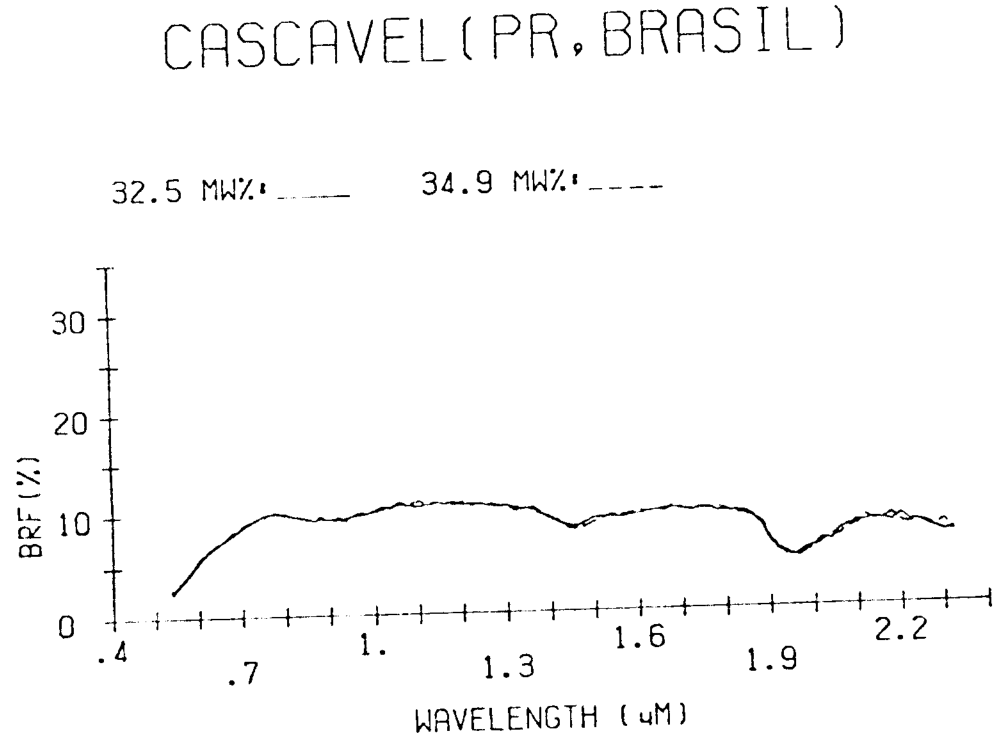


Figure 6. Soil reflectance curves for two subsamples of a high iron, clay surface soil, a very-fine oxidic thermic Haplic Acrorthox.

Using these highly contrasting curves for representative soils from the Alfisol, Mollisol, and Oxisol soil orders as examples, the repeatability of soil reflectance measurements using the described preparatory and instrumental procedures can be demonstrated.

Soil Reflectance/Absorption Characteristics

Curve Types

Condit (1970, 1972) first characterized soil reflectance curves by three types of curve shape. Type 1 curves exhibit rather low reflectance with a slightly increasing slope which gives them their characteristic concave form from 0.32 to about 1.0μm. Soil reflectance curves for certain Mollisols (Figures 5 and 7) and Vertisols (Figure 8) are seen to follow this general curve type. However, from about 1.0 to 1.3μm the slope is seen to be nearly constant for these soils, a characteristic overlooked by Condit because of the limited spectral range (0.32 to 1.0μm) of the instruments used.

Type 2 curves are characterized by a generally decreasing slope to about 0.6μm, followed by a slight dip from 0.6 to 0.7μm, with continued decreasing slope beyond 0.75μm. The result is a typical convex shaped curve from the visible to 1.3μm. Some soils from the Alfisol soil order (Figure 4) and certain Ultisols (Figure 9) can be seen to exhibit this Type 2 curve shape. It has been observed that Type 2 soils tend to be better drained and lower in organic matter content than Type 1 soils.

The third type of soil reflectance curve observed by Condit shows a slightly decreasing steep slope to about 0.6μm, followed by a slight dip from 0.62 to 0.74μm with the slope decreasing to near zero or even becoming negative from 0.76 to 0.88μm. Beyond 0.88μm (to 1.0μm) the slope increases with increasing wavelength. The Talbott soil, a humid thermic region Alfisol, can be seen to demonstrate this Type 3 curve shape (Figure 10). Moderately high free iron contents are observed in most Type 3 soils.

Because of the limited scope of the Condit studies other curve types were not observed or described. Although similar in some respects to the Type 3 curve, a fourth curve type is seen to exhibit decreasing slope from 0.88 to 1.0μm with the slope decreasing to zero and becoming negative from 1.0 to 1.3μm (Figures 6 and 11). This fourth curve type has been observed in soils high in iron content and also high in organic matter.

Yet another modification of the Type 3 curve shape which could be considered a fifth characteristic curve type is that in which the slope drops to zero and becomes negative from 0.75μm to 1.3μm (Figure 12). In this curve type, the reflectance at 1.3μm is actually lower than the reflectance in the red portion of the spectrum. Only this fifth curve type has been observed not to show the strong water absorption band at 1.45μm, while every soil in this study shows the strong water absorption band at 1.95μm. Soils showing this fifth curve type are very high in iron content with low organic matter contents.

DRUMMER(IL)

Typic Haplaquoll
fine-silty, mixed, mesic
humid zone
thick loess over outwash and drift
Champaign Co.

———	- - - -
Ap horizon	Ap horizon
A slope	A slope
poorly drained	poorly drained
silty clay loam	silty clay loam
13%S 56%Si 32%C	8%S 60%Si 32%C
10YR 2/1 (moist)	10YR 2/1 (moist)
10YR 3/2 (dry)	10YR 3/2 (dry)
5.61% O.M.	6.09% O.M.
40.3 meq/100g CEC	41.7 meq/100g CEC
0.76% Fe_2O_3	0.92% Fe_2O_3

41.1 MW%: ——— 40.2 MW%: - - - -

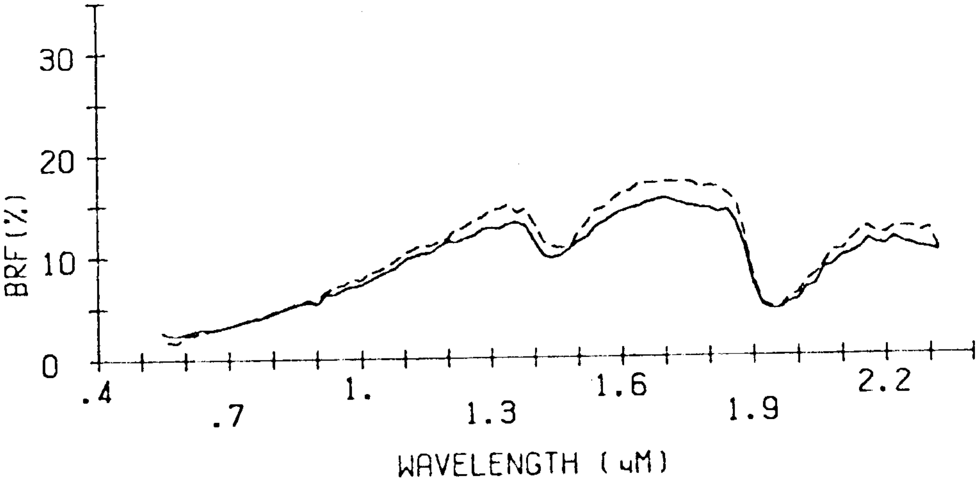


Figure 7. Reflectance curves, soil analyses and site characteristics of duplicate samples of the Drummer soil series.

TRINITY(TX)

Typic Pelludert
very-fine, montmorillonitic, thermic
subhumid zone
calcareous clayey alluvium
Kaufman Co.

———	----
Ap horizon	Ap horizon
A slope	A slope
s. poorly drained	s. poorly drained
silty clay loam	clay
18%S 46%Si 35%C	1%S 29%Si 70%C
7.5YR 3/0 (moist)	10YR 3/1 (moist)
10YR 4/1 (dry)	10YR 4/1 (dry)
3.53% O.M.	3.17% O.M.
38.9 meq/100g CEC	92.8 meq/100g CEC
0.47% Fe_2O_3	0.77% Fe_2O_3

43.1 MW%: ____ 62.9 MW%: ----

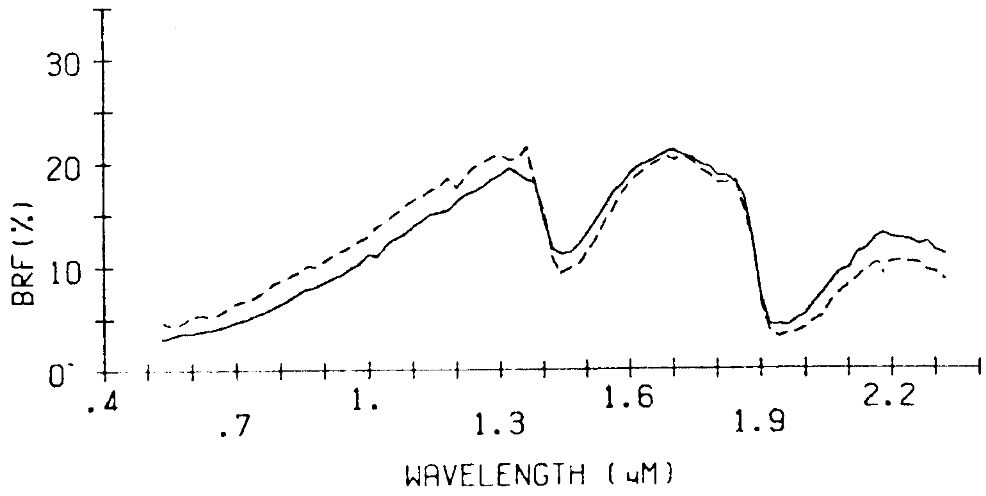


Figure 8. Reflectance curves, soil analyses and site characteristics of duplicate samples of the Trinity soil series.

FREDERICK(VA)

Typic Paleudult
clayey, mixed, mesic
humid zone
clayey residuum from dolomitic
limestone
Rockingham Co.

———	----
Ap horizon	Ap horizon
C slope	C slope
well drained	well drained
silt loam	silt loam
21%S 62%Si 17%C	20%S 65%Si 15%C
10YR 4/4 (moist)	10YR 5/4 (moist)
10YR 7/4 (dry)	10YR 7/4 (dry)
1.16% O.M.	2.47% O.M.
7.2 meq/100g CEC	10.1 meq/100g CEC
1.30% Fe_2O_3	1.23% Fe_2O_3

27.1 MW%: ———   33.6 MW%: ----

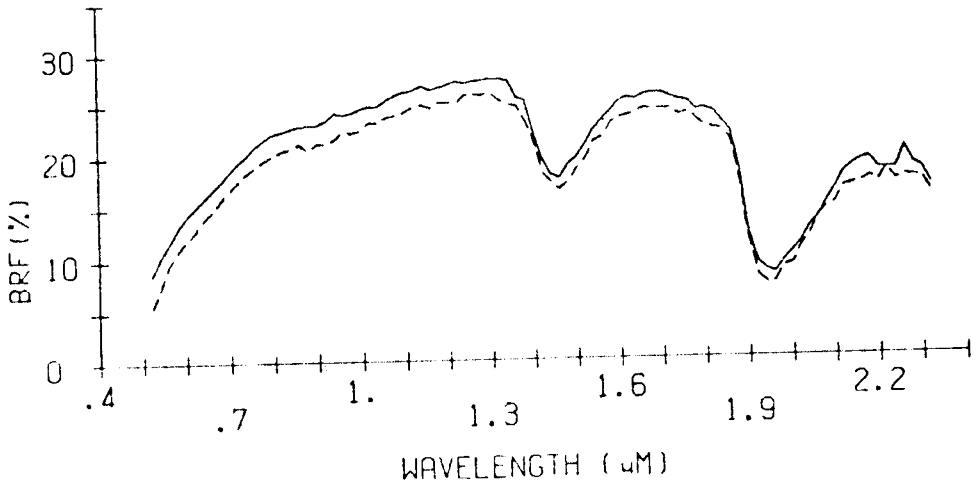


Figure 9. Reflectance curves, soil analyses and site characteristics of duplicate samples of the Frederick soil series.

TALBOTT(TN)

Typic Hapludalf
fine, mixed, thermic
humid zone
clayey limestone residuum
Rutherford Co.

———	----
Ap horizon	Ap horizon
B slope	B slope
well drained	well drained
silty clay loam	silt loam
14%S 58%Si 28%C	11%S 67%Si 23%C
7.5YR 4/6 (moist)	7.5YR 4/6 (moist)
10YR 6/6 (dry)	10YR 6/6 (dry)
1.84% O.M.	2.50% O.M.
15.6 meq/100g CEC	13.8 meq/100g CEC
3.68% Fe_2O_3	3.34% Fe_2O_3

28.2 MW%: ____ 30.2 MW%: ----

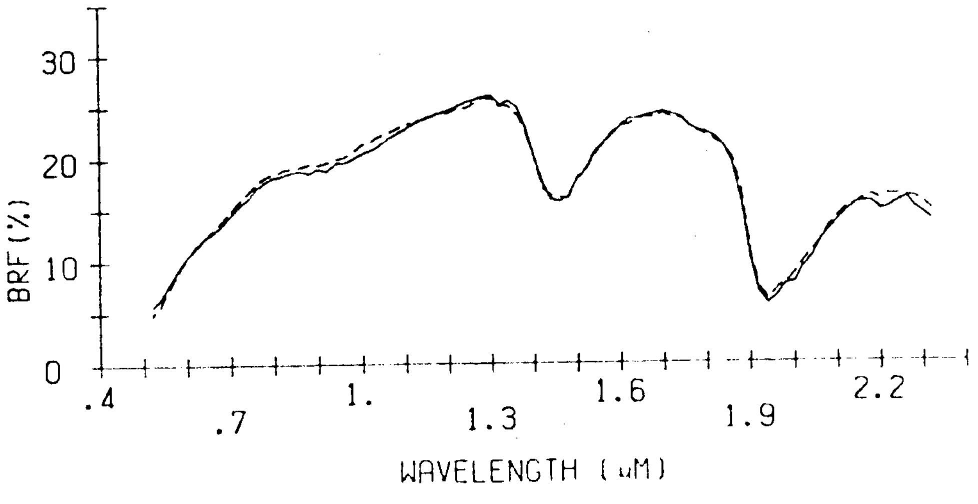


Figure 10. Reflectance curves, soil analyses and site characteristics of duplicate samples of the Talbott soil series.

ONTONAGON(MI)

Glossic Eutroboralf
very fine, mixed
humid zone
glacial lake plain sediments
Ontonagon Co.

——	----
Ap horizon	Ap horizon
B slope	B slope
mod. well drained	mod. well drained
clay	clay
7%S 22%Si 70%C	6%S 29%Si 66%C
2.5YR 3/6 (moist)	2.5YR 4/4 (moist)
5YR 6/4 (dry)	5YR 6/4 (dry)
4.88% O.M.	3.95% O.M.
38.0 meq/100g CEC	31.6 meq/100g CEC
1.73% Fe_2O_3	2.76% Fe_2O_3

47.5 MW%: ——   43.2 MW%: ----

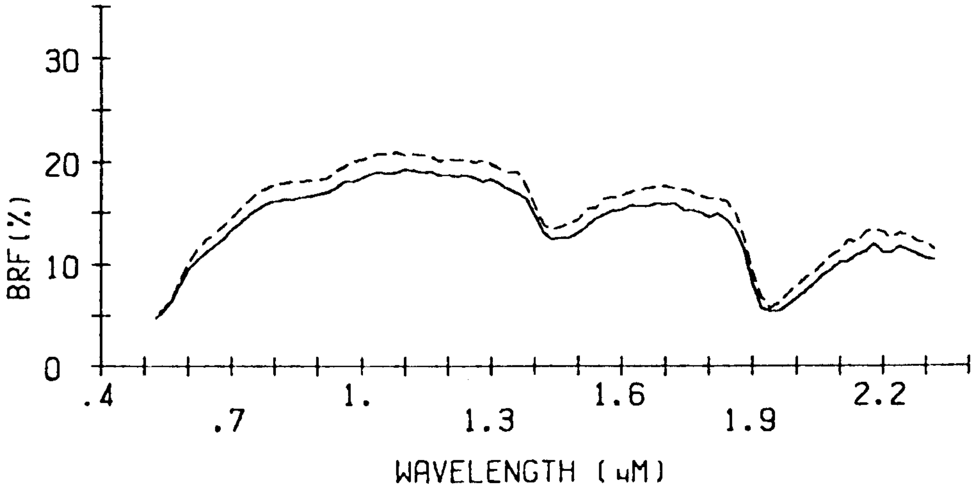


Figure 11. Reflectance curves, soil analyses and site characteristics of duplicate samples of the Ontonagon soil series.

LONDRINA(PR, BRASIL)

Typic Haplorthox
very-fine, kaolinitic, hyperthermic
humid zone
basalt
Municipio of Londrina

Allp horizon
C slope
excess. drained
clay
9%S 14%Si 77%C
2.5YR 3/6 (moist)
2.5YR 4/6 (dry)
2.28% O.M.
22.1 meq/100g CEC
25.6% Fe_2O_3

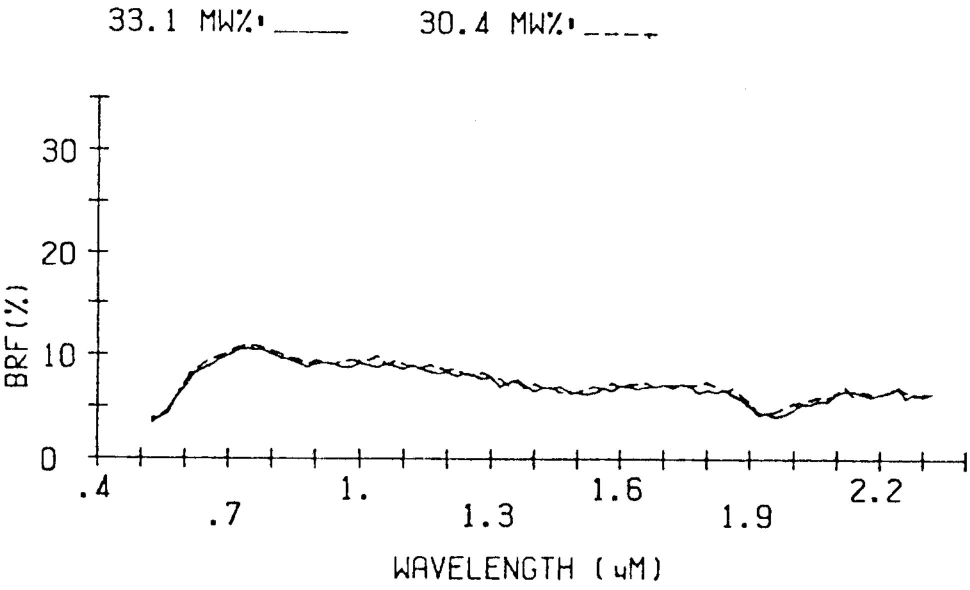


Figure 12. Reflectance curves, soil analyses and site characteristics of subsamples of a soil from Londrina, Paraná State, Brazil.

Absorption Bands

As mentioned previously, strong water absorption bands are present at 1.45 and 1.95µm for almost all the soils studied (Figures 4 to 16). The broadness of these bands indicates the presence of water molecules in relatively unordered sites, probably as water films on soil particle surfaces (Hunt and Salisbury, 1970; Angstrom, 1925). Weak water absorption bands at 1.2 and 1.77µm can be seen in low organic matter content fine sands (Figure 13). These weak absorption bands correspond to the absorption bands observed in transmission spectra of relatively thick water films of the type that may be expected to fill the voids between fine sand grains (Lindberg and Snyder, 1972).

The 2.2µm hydroxyl absorption band is difficult to identify in moist soil spectra but can be seen in samples of Talbott and Ontonagon soils (Figures 10 and 11). Absorption due to the hydroxyl ion also occurs at 1.45µm, but is not observed in any of the soils in this study because of the predominance of liquid water absorption in this same region.

Iron absorption bands occur either as well resolved dips in the reflectance curve or as broad features centered on specific wavelengths but extending their influence over a wide range of wavelengths. The ferric iron absorption band at about 0.87µm is the most common seen in soils of this study. A sharp, well-defined ferric absorption band at 0.87µm can be seen in samples of a fine sand with iron oxide coatings (Figure 13) while another sharp ferric band closer to 0.9µm is seen in a silty clay loam Mollisol (Figure 7). This same ferric absorption band can be quite broad, extending its influence over a 0.2µm-wide band centered on 0.9µm (Figures 10 and 11) or even forming a conduction band whose influence extends into the middle infrared region (Figure 12). In most but not all of those soils that exhibit the 0.9µm region ferric band, a slight dip attributable to the ferric ion occurs at 0.7µm (Figures 10, 11, 12, and 13). The slight ferric iron absorption band at 0.7µm together with the stronger 0.9µm ferric iron absorption band produces the characteristic Type 3 curve shape or modifications thereof.

The quantity of iron present in a soil appears to affect the strength of the ferric iron absorption when comparing soils similar in most characteristics except for their iron content. An example is the Cecil soil series, in which the duplicate samples differ markedly in their free iron oxide content while possessing similar texture and organic matter contents (Figure 14). The second sample, with over four times the iron oxide content of the first sample, shows pronounced ferric iron absorption bands at 0.7 and 0.9µm while the first sample exhibits only slight absorption in these bands.

As was observed in reflectance studies of minerals (Hunt and Salisbury, 1971a), very small amounts of iron may impart characteristic iron absorption bands to soils. Soil samples of Leon sand show a sharp ferric iron absorption band at 0.9µm even though only a trace of free iron oxides was measurable (Figure 15).

Ferrous iron absorption is more difficult to identify in the soil samples in this study. Typically, the ferrous ion produces a band near 1.0µm. Close observation reveals evidence of the 1.0µm ferrous band in

TOQUOP(NV)

Typic Torripsamment
mixed, thermic
arid zone
deep sandy alluvium
Clark Co.

———	- - - -
A1 horizon	A1 horizon
A slope	A slope
excessively drained	excessively drained
fine sand	fine sand
92%S 5%Si 3%C	94%S 3%Si 3%C
5YR 6/6 (moist)	7.5YR 5/6 (moist)
7.5YR 7/6 (dry)	7.5YR 7/6 (dry)
0.0% O.M.	0.23% O.M.
9.0 meq/100g CEC	4.9 meq/100g CEC
0.20% Fe_2O_3	0.30% Fe_2O_3

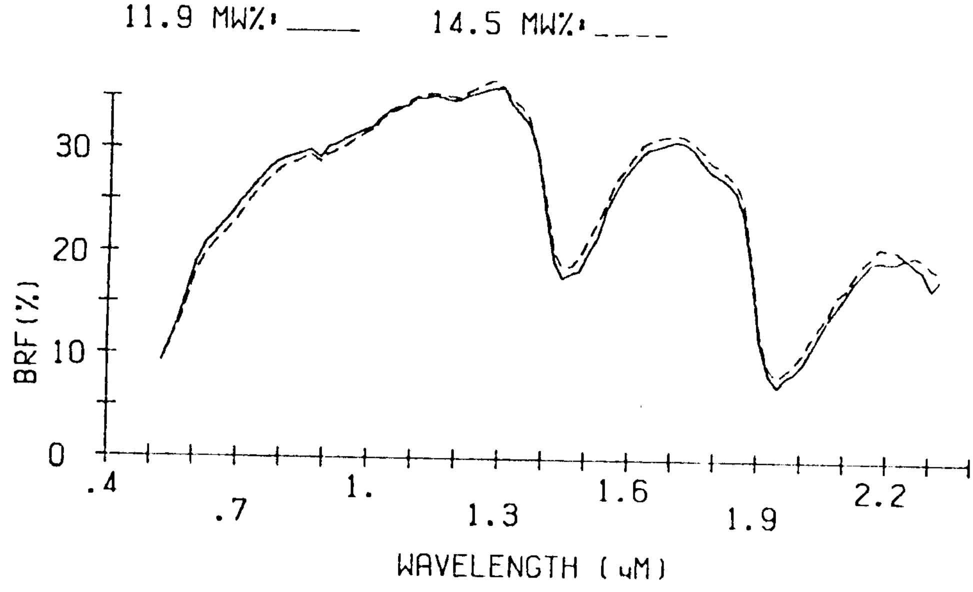


Figure 13. Reflectance curves, soil analyses and site characteristics of duplicate samples of the Toquop soil series.

CECIL(NC)

Typic Hapludult
clayey, kaolinitic, thermic
humid zone
acid igneous and metamorphic rocks
Catawba Co.

———	----
Ap horizon	Ap horizon
B slope	B slope
well drained	well drained
sandy loam	loam
70%S 23%Si 7%C	51%S 28%Si 21%C
10YR 5/4 (moist)	10YR 4/6 (moist)
10YR 6/4 (dry)	7.5YR 6/6 (dry)
2.12% O.M.	2.24% O.M.
8.8 meq/100g CEC	10.0 meq/100g CEC
0.64% Fe_2O_3	2.64% Fe_2O_3

15.9 MW%: ——— 11.2 MW%: ----

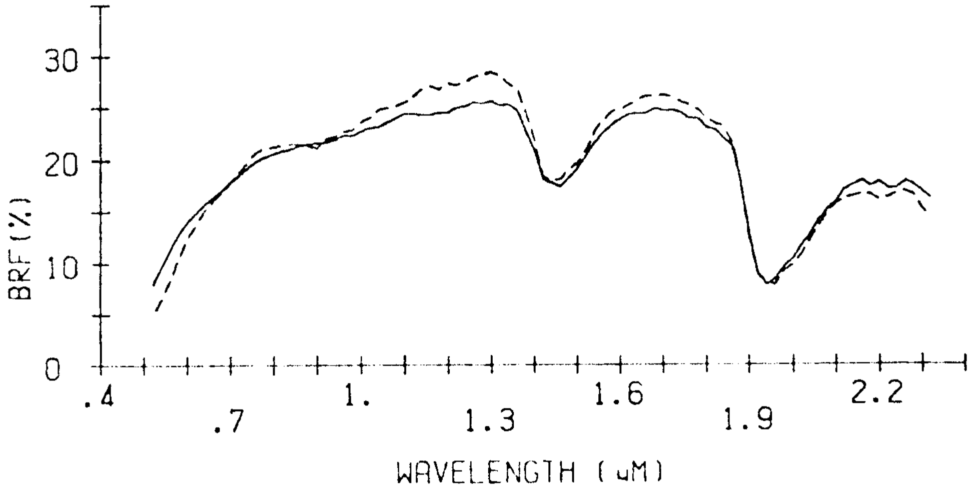


Figure 14. Reflectance curves, soil analyses and site characteristics of duplicate samples of the Cecil soil series.

LEON(FL)

Aeric Haplaquod
sandy, siliceous, thermic
humid zone
acid marine sands
Bay Co.

———	----
A1-A21 horizon	A1-A21 horizon
A slope	A slope
poorly drained	poorly drained
sand	sand
97%S 2%Si 1%C	99%S 0%Si 1%C
7.5YR 4/1 (moist)	10YR 5/1 (moist)
10YR 7/1 (dry)	10YR 6/1 (dry)
0.85% O.M.	1.07% O.M.
2.1 meq/100g CEC	3.4 meq/100g CEC
trace Fe_2O_3	trace Fe_2O_3

12.1 MW%: ——— 16.8 MW%: ----

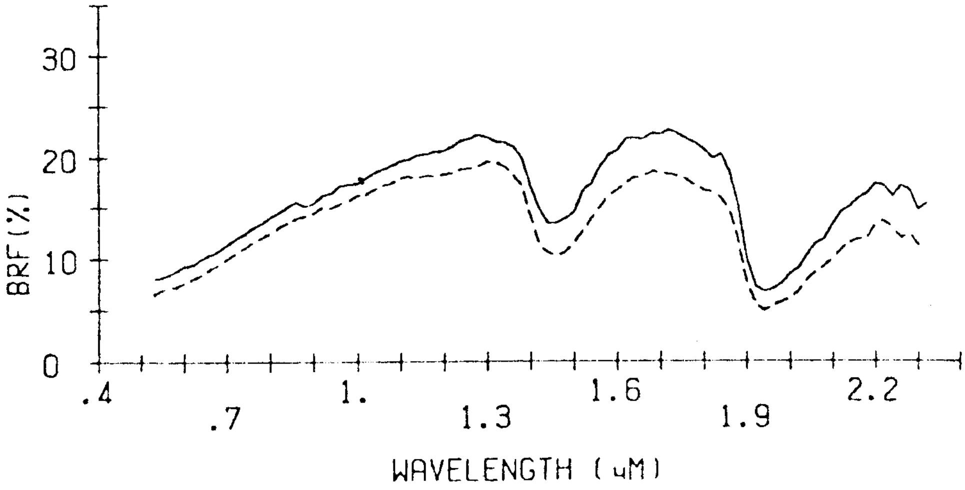


Figure 15. Reflectance curves, soil analyses and site characteristics of duplicate samples of the Leon soil series.

several samples of poorly drained soils. One of the samples of the somewhat poorly drained Trinity series shows a sharp ferrous absorption band at 1.0μm while the other sample shows a slight ferric band at 0.9μm (Figure 8). The sample of poorly drained Leon sand with only a trace of free iron also exhibits a slight ferrous absorption band at 1.0μm in addition to the 0.9μm ferric band (Figure 15). Even in a high organic matter soil such as the poorly drained Pickford series, obvious ferrous and ferric bands, respectively at 1.0 and 0.9μm are evident (Figure 16).

Comparison with Munsell Designations

Soils with the same Munsell color designation do not necessarily have the same reflectance characteristics. It can be said that a given visible wavelength reflectance curve produces one and only one visual sensation of color, whereas for any color there exist many spectral distributions which can generate that color. Of course, soils with similar colors may differ greatly in their infrared reflectance characteristics.

Three soils that have the same dark red Munsell color designation of 2.5YR 3/6 are quite different in their infrared reflectance characteristics (Figure 17). The Dill soil from Oklahoma is a loamy fine sand with 0.6% organic matter and 0.8% iron oxide. The Arroyo soil from Spain is a clay with 1.28% organic matter and 2.00% iron oxide. The soil from Londrina, Paraná State, Brazil is a highly aggregated clay with 2.28% organic matter and 25.6% iron oxide. All three soil reflectance curves show varying degrees of evidence of ferric iron absorption at 0.7 and 0.9μm. Visible reflectance is very similar for the Dill and Arroyo soils while the Londrina soil has a generally lower reflectance in the visible than the other two.

Both visible and infrared reflectance can be markedly different for soils with the same Munsell color designation. Two yellowish brown soils with the Munsell color designation of 7.5YR 5/6 serve as examples (Figure 18). Talbott silt loam from Tennessee has 2.5% organic matter and 3.3% iron oxide. The clayey Oxisol from the moist cocoa region of Southern Bahia State, Brazil contains only 0.3% organic matter but has 21.6% iron oxide. X-ray diffractograms of the clay fraction of this soil from Bahia indicate the presence of gibbsite as well as kaolinite and goethite (Resende, 1976). The broad absorption band centered on 1.0μm in the Bahia soil corresponds to the band described as a hydroxyl absorption band of gibbsite by Hunt, et al. (1971b). This same soil shows an extremely strong ferric iron absorption band at 0.7μm. Talbott exhibits the ferric iron absorption bands at 0.7 and 0.9μm to a much lesser extent. Absorption characteristics related to the mineralogy of these two soils can only be determined from visible and infrared reflectance properties. Munsell color evaluation gives the erroneous notion that the reflectance properties of these two soils are similar.

Aside from mineral soil differences between Munsell color designations and soil reflectance properties, organic soils having a black color can differ in their infrared reflectance depending on the decomposition state of the organic material. Highly decomposed sapric material reflects much less than the moderately decomposed hemic or slightly decomposed fibric material (Figure 19). Fibric material has a very high reflectance in the

PICKFORD(MI)

Aeric Haplaquept
fine, mixed, nonacid, frigid
humid zone
clayey glacial till or
lacustrine material
Chippewa Co.

———	----
A11-A12 horizon	Ap horizon
A slope	A slope
poorly drained	poorly drained
silty clay	clay
5%S 48%Si 47%C	7%S 29%Si 64%C
5YR 2.5/2 (moist)	10YR 3/2 (moist)
10YR 4/2 (dry)	10YR 5/2 (dry)
14.57% O.M.	15.16% O.M.
51.6 meq/100g CEC	50.8 meq/100g CEC
3.71% Fe_2O_3	0.64% Fe_2O_3

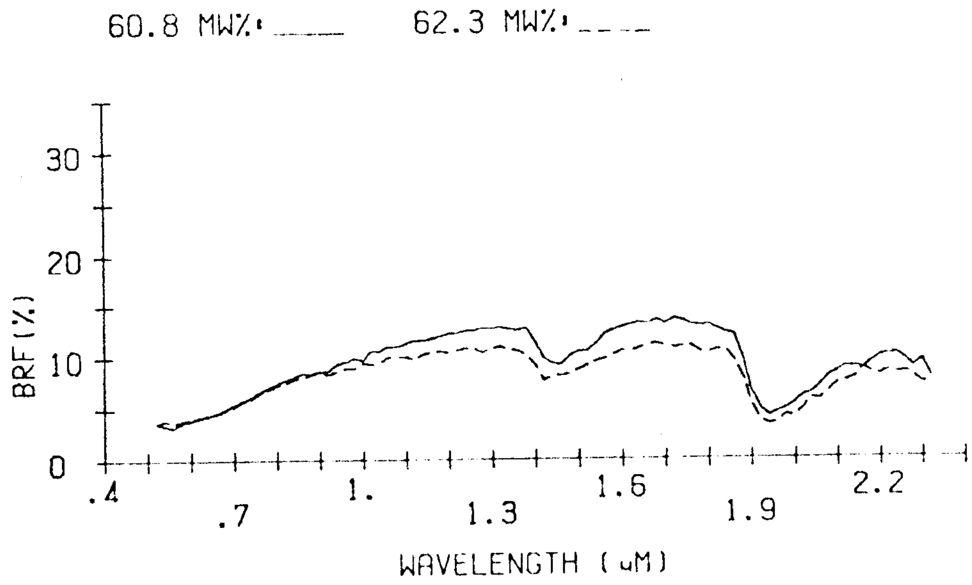


Figure 16. Reflectance curves, soil analyses and site characteristics of duplicate samples of the Pickford soil series.

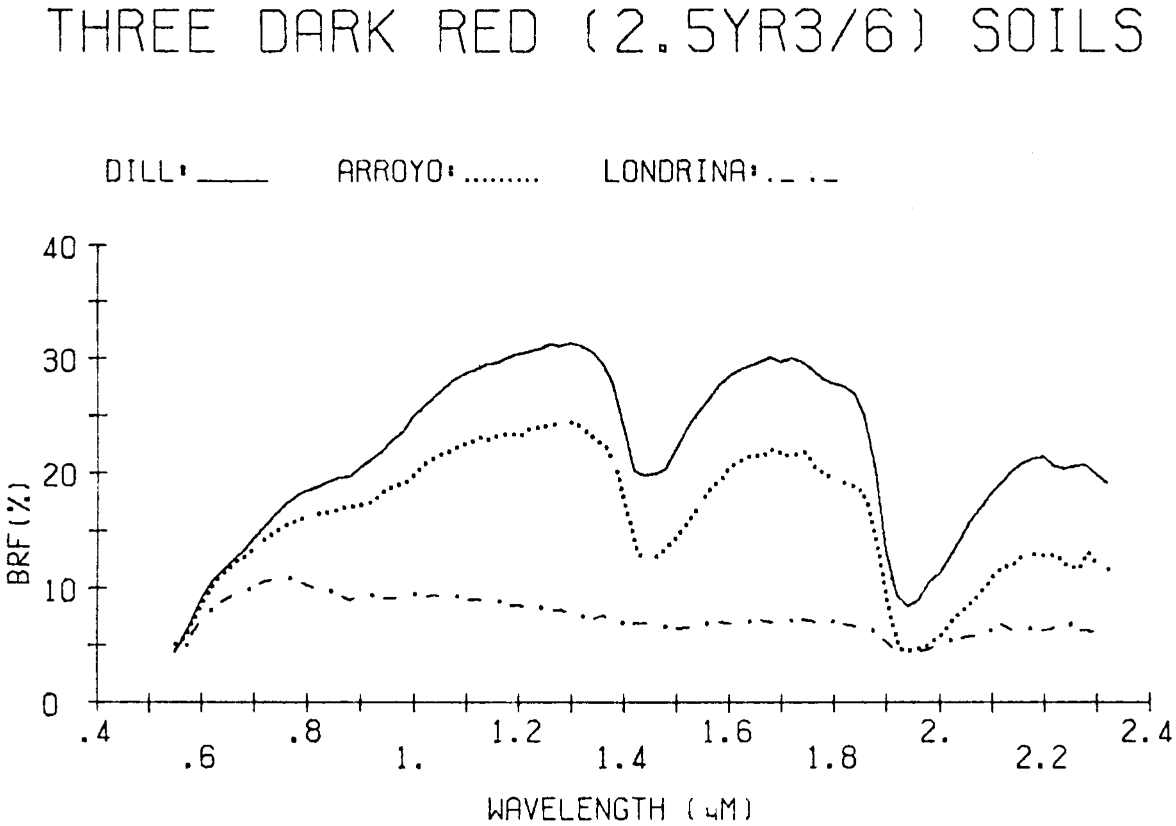


Figure 17. Reflectance curves for three soils with the same Munsell color designation of 2.5YR 3/6.

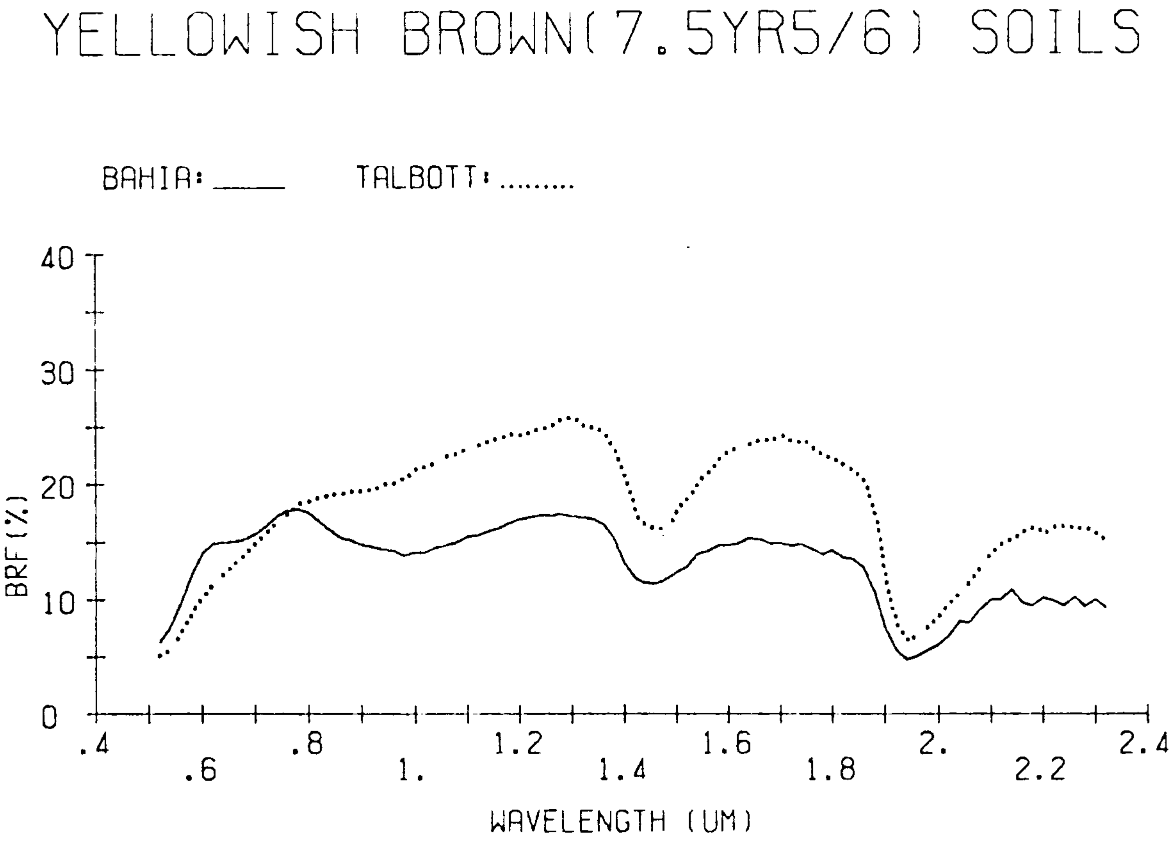


Figure 18. Reflectance curves for two soils with the same Munsell color designation of 7.5YR 5/6.

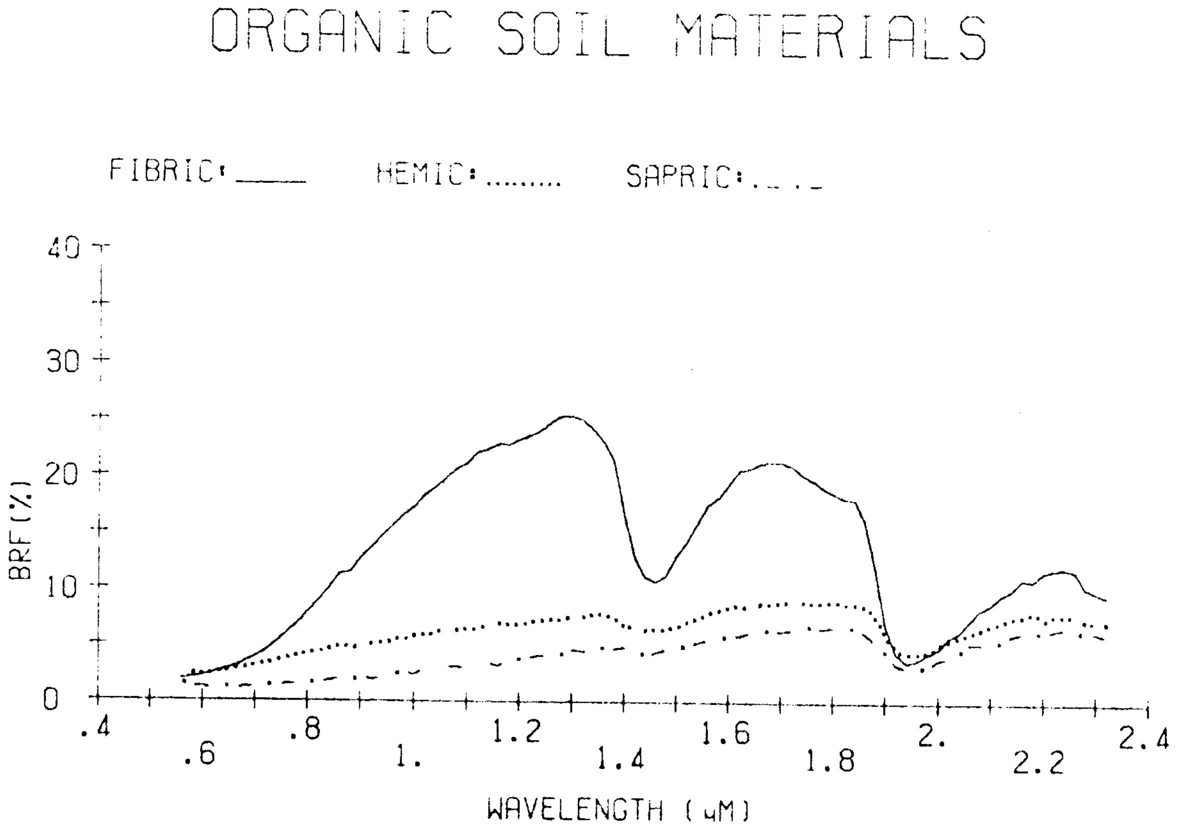


Figure 19. Reflectance curves for three black organic soils representing three decomposition states of organic material.

infrared region resembling the infrared reflectance of senesced leaves (Gausman, et al., 1976). This increased infrared reflectance has been attributed to tissue morphology in which an increased number of air voids provide more air-cell interfaces for enhanced reflection. It is probable then that remnant cell structure of well preserved fibers contributes to the higher infrared reflectance of slightly decomposed organic material.

Munsell color designation for all of the soils in this study were computer coded together with the reflectance of each corresponding soil, permitting the display of averaged reflectance values for soils with specified Munsell color designations. For the Munsell hue 10YR, five levels of chromas were distinguished for moist soils (Figure 20). It is interesting to notice that the averaged reflectance for the 10YR /1 chroma resembles the Type 1 curve, while those of the 10YR /2, 10YR /3, and 10YR /4 chromas resemble the Type 2 curve. The averaged reflectance for the increased purity or saturation of the 10YR /6 chroma resembles the Type 3 curve. In general, reflectance increases throughout the visible and infrared wavelengths with increasing Munsell chroma.

A similar technique was used to display the averaged reflectance values for soils with specified Munsell color values for the hue 10YR (Figure 21). Munsell value refers to the relative lightness of color and is a function of the total amount of light. As such, it was not unexpected that averaged reflectance for soils with specified Munsell values increased throughout most of the visible and near infrared spectrum with increasing Munsell chroma. Middle infrared reflectance was similar for soils with Munsell values of 10YR 5/ and 10YR 6/. When the reflectance limits of the 95% confidence intervals for soils having specified Munsell values are displayed, overlapping is seen to occur for soils evaluated as having different Munsell values (Figure 22). Munsell values 10YR 2/ and 10YR 3/ are still seen to have separate reflectances in the visible although their reflectances overlap quite a bit in the near and middle infrared. Munsell values 10YR 3/, 10YR 4/, 10YR 5/, and 10YR 6/ overlap with adjacent values even in the visible wavelengths.

Comparison between averaged reflectance spectra and soils evaluated as having specified Munsell notations reveals the difficulty of using Munsell color designations to describe in a precise and quantitative manner the actual reflectance properties of soils. Important reflectance/absorption characteristics of both mineral and organic soils can be described adequately only with the use of spectroradiometric reflectance data.

Averaged Spectra of Soil Component and Site Classes

Organic Matter

Organic matter content is one of the soil parameters most important in understanding soil reflectance. State of decomposition of organic soil materials has been seen to influence the character of organic soil reflectance curves (Figure 19). When mineral soils are grouped into three levels of organic matter content: 0 to 3%, 3 to 5%, and 5 to 10%, the resulting averaged reflectance curves exhibit decreased reflectance with increasing organic matter content throughout the 0.52 to 2.32μm wavelength region (Figure 23). The soils in the 5 to 10% organic matter range show some

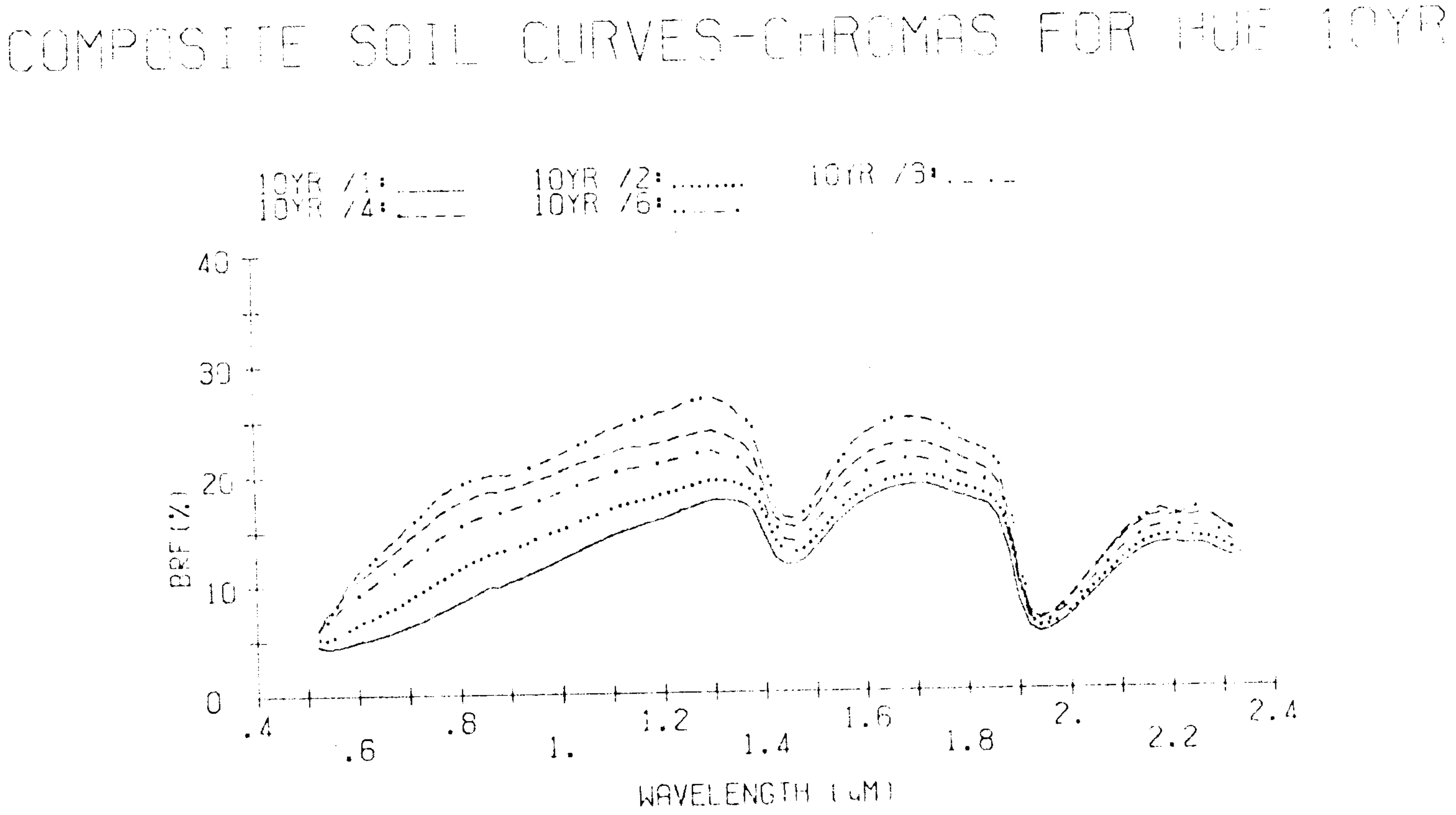


Figure 20. Averaged reflectance spectra for soils evaluated as having specified chromas for the Munsell hue 10YR.

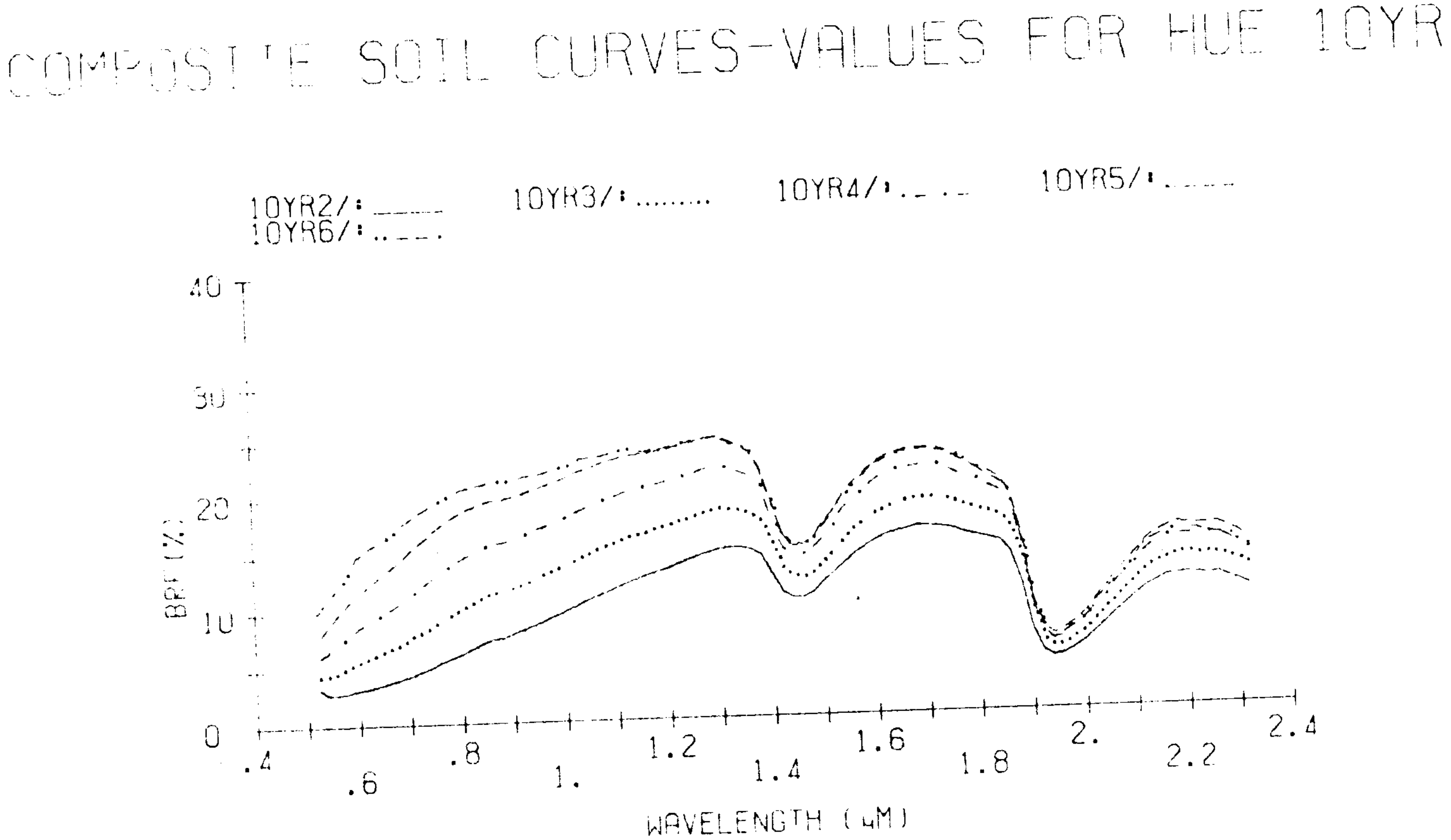


Figure 21. Averaged reflectance spectra for soils evaluated as having specified values for the Munsell hue 10YR.

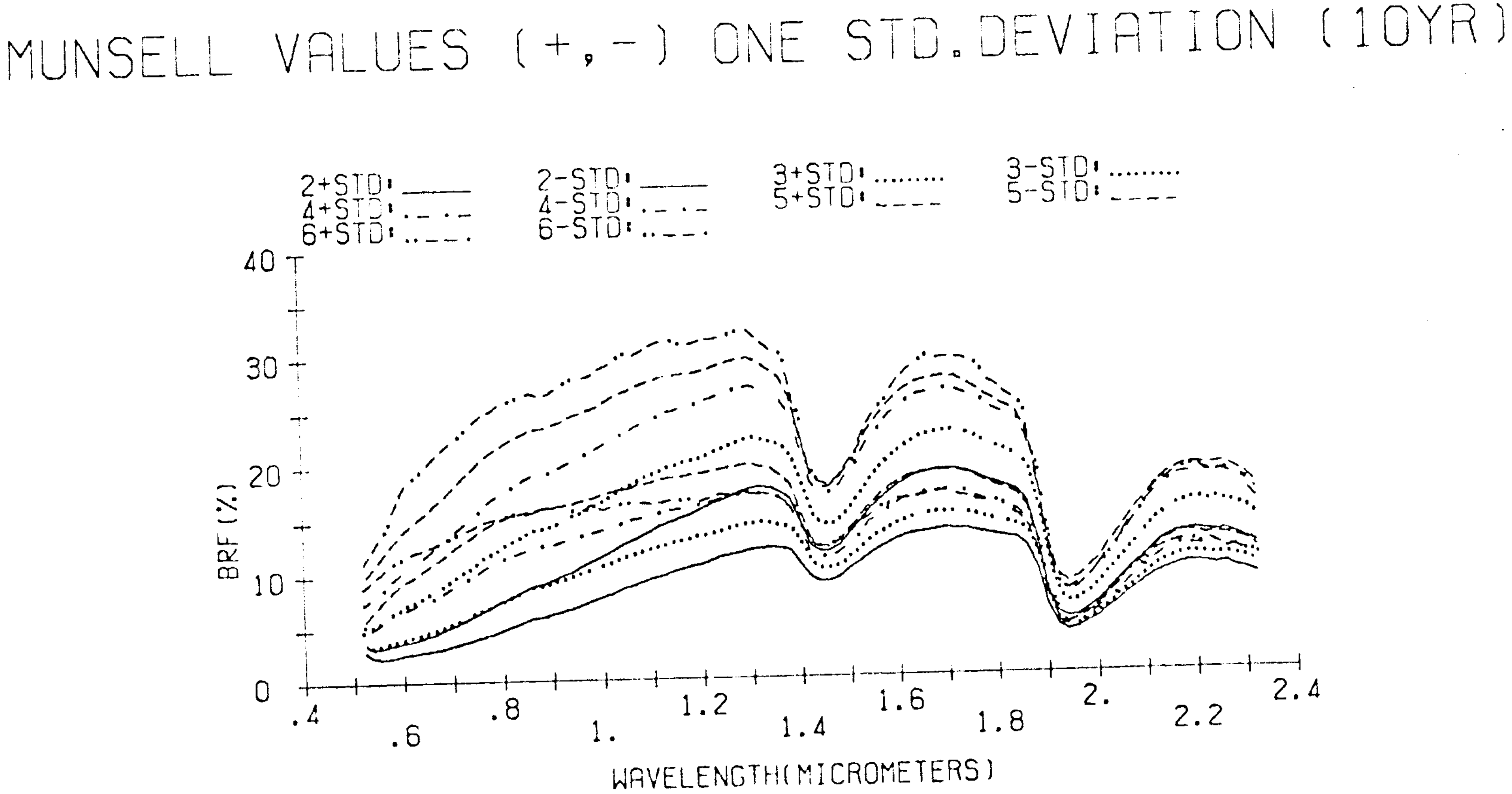


Figure 22. Bracketed reflectance spectra representing the 95% confidence intervals for soils evaluated as having specified values for the Munsell hue 10YR.

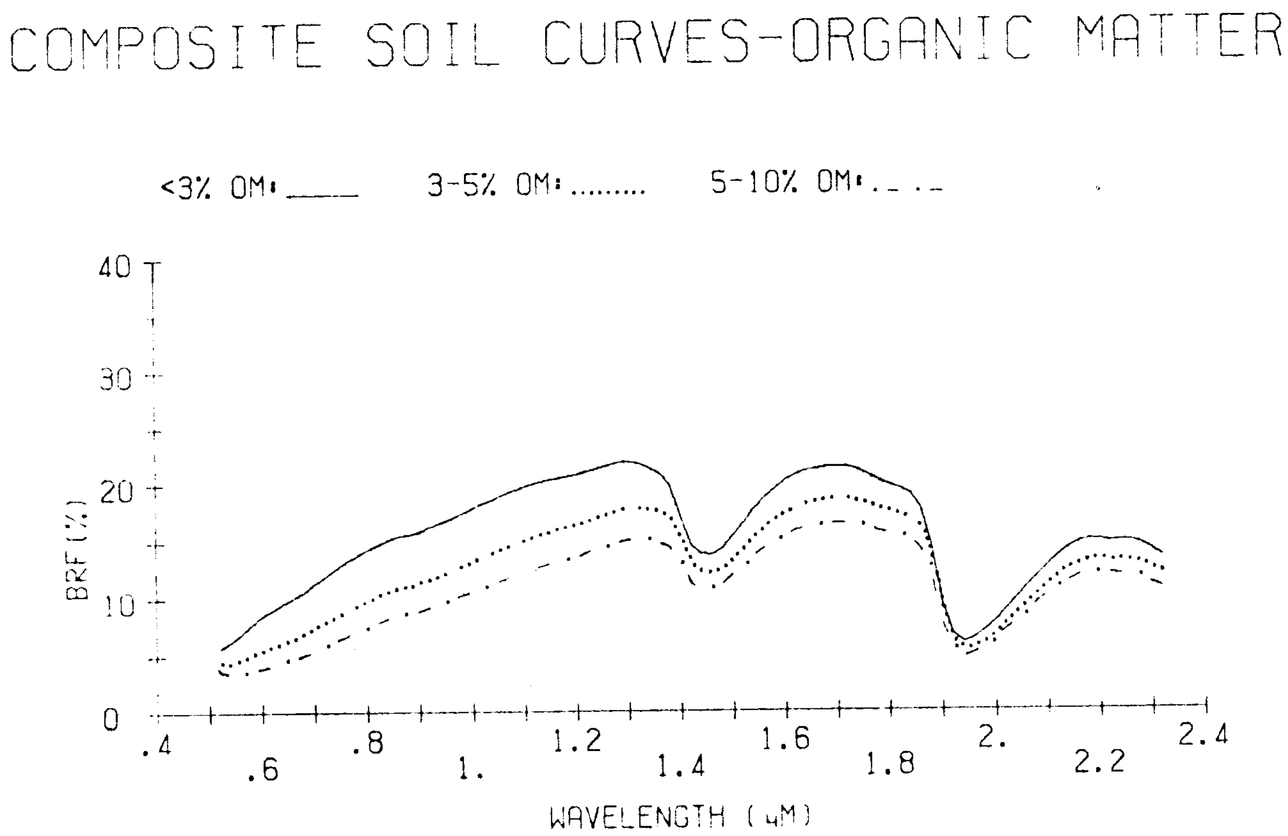


Figure 23. Averaged reflectance spectra for mineral soils with three levels of organic matter.

characteristics of the concave-shaped Type 1 curve, whereas soils in the 0 to 3% and 3 to 5% ranges follow the Type 2 curve pattern. The magnitude of differences in reflectance between the curves of these three organic matter ranges seems to be greater in the visible and near infrared regions than in the middle infrared wavelengths. This qualitative observation supports the findings of Mathews, et al. (1973), Beck, et al. (1976), and Montgomery (1976) that reflectance in wavelengths up to 1.2μm are best for separating organic matter levels in soils.

Particle Size Distribution

Reflectance of pure kaolinite in size fractions from coarse silt to very coarse sand was found to increase exponentially with decreasing particle size (Bowers and Hanks, 1965). Reflectance differences among specific textural classes of naturally occurring soils have not been reported. By grouping all of the soils in this study that fall into specific textural classes and averaging their reflectance curves, some generalizations can be made about the reflectance properties of different soil particle size classes.

Sandy loam soils are seen to increase in reflectance as the proportion of fine and very fine sand becomes larger (Figure 24). This increase is especially prominent in the near infrared wavelengths. This is in agreement with the findings of Bowers and Hanks (1965) and Orlov (1966) that finer and finer sand size particles tend to fill voids and result in smoother surfaces which reflect more light. Very fine sandy loam soils reflect more than fine sandy loams which in turn reflect more than sandy loams because there are fewer light traps to extinguish the incident flux as sand particles become smaller.

A similar relationship is seen in the reflectance curves of sand and loamy sand textured soils (Figure 25). Fine sandy soils reflect more than loamy fine sands at all wavelengths. Possible lower organic matter contents associated with the fine sand texture result in higher reflectance values than for loamy fine sands. Loamy fine sand, in turn, reflects more than loamy sand in the visible and near infrared because of the tendency for the finer sand particles to fill voids and form a smoother reflecting surface. Loamy coarse sand reflects less than any of these three textures because of the predominance of light-trapping voids between coarse sand grains.

The situation is reversed, however, for medium to fine textured soils (Figure 26). When considered as a group, the often slight reflectance differences are best viewed in the 2.08 to 2.32μm middle infrared region. Contrary to previous observations in sand textured soils, the reflectance in this middle infrared region can be seen to decrease with finer and finer textures. Here the formation of water stable aggregates in fine textured soils creates a different viewing surface than is the case with the often single grain structure of sandy soils. Reflectance differences cannot be explained in terms of individual particles filling voids to varying degrees.

Reflectance of soils in the middle infrared region has been most closely related to soil moisture content (Bowers and Smith, 1972). A reasonable explanation for the decreased reflectance in the 2.08 to 2.32μm

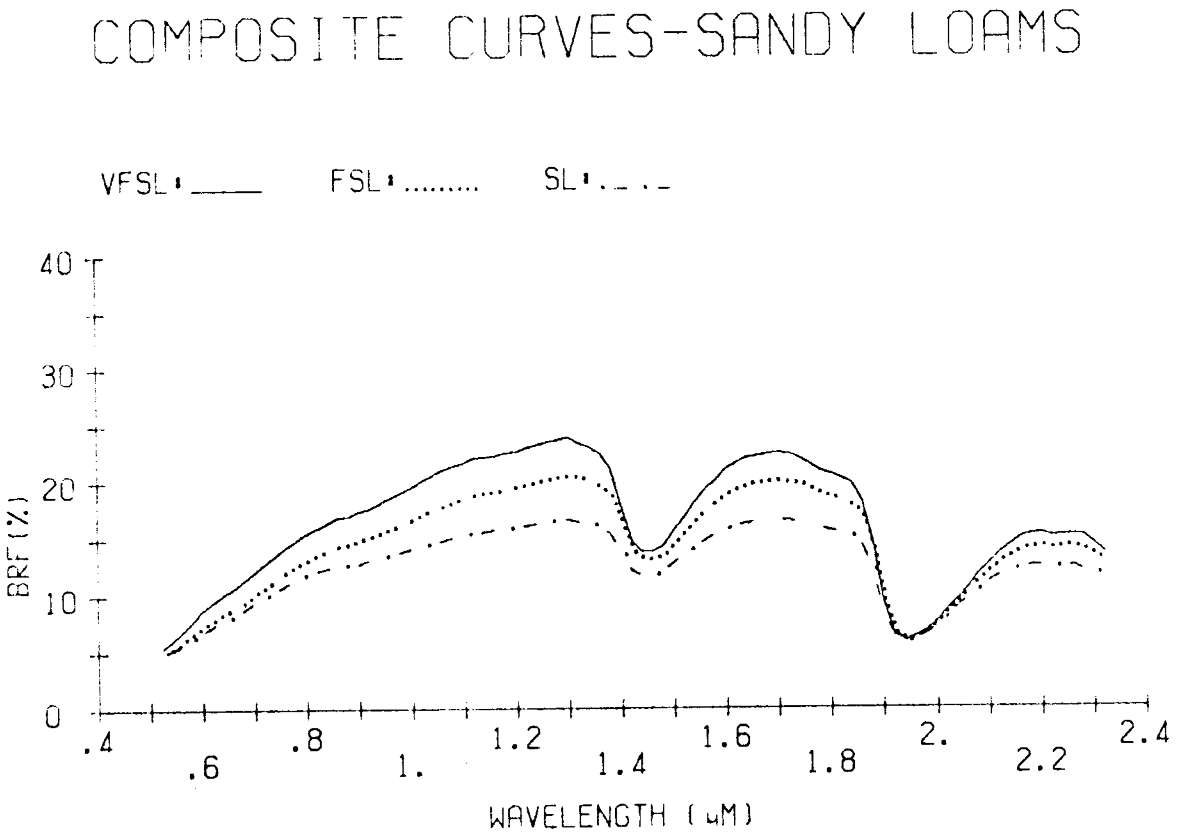


Figure 24. Averaged reflectance spectra for soils of sandy loam texture.

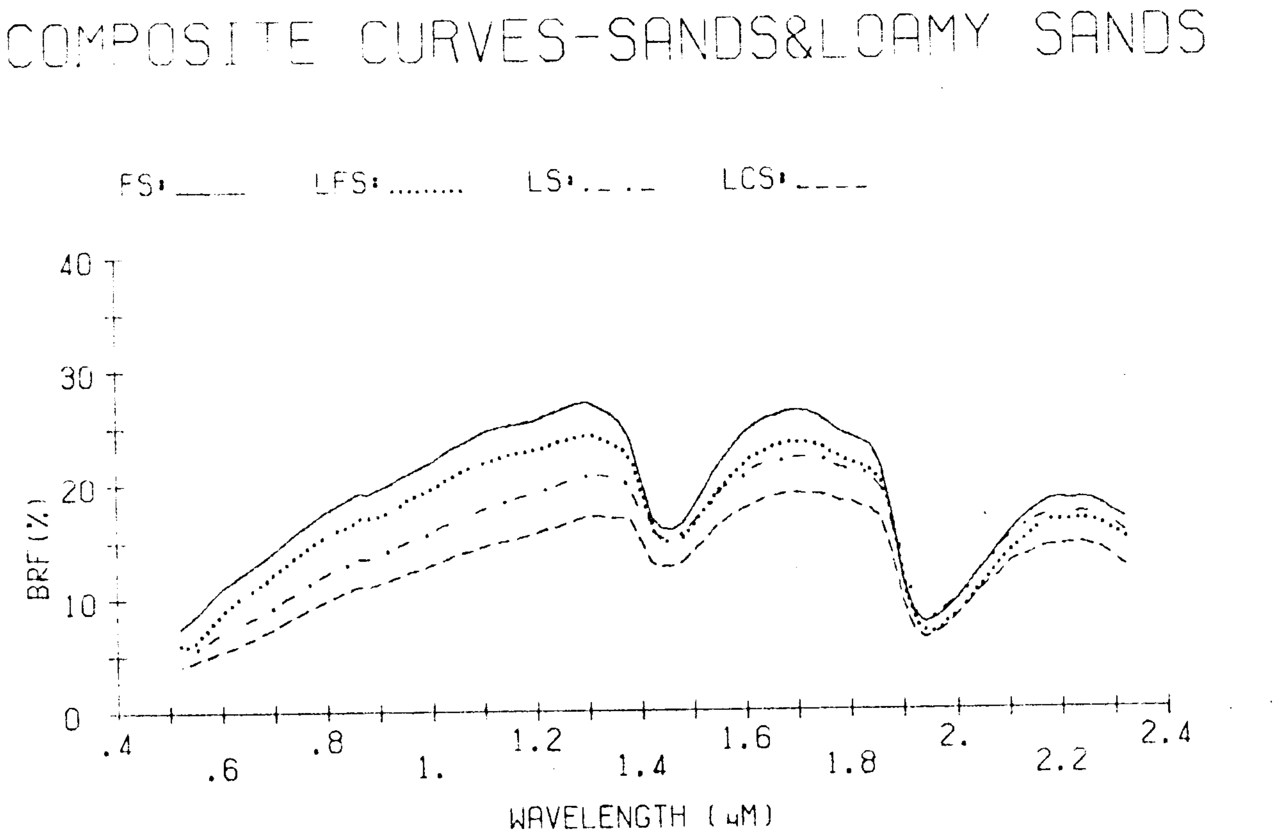


Figure 25. Averaged reflectance spectra for soils of sand and loamy sand textures.

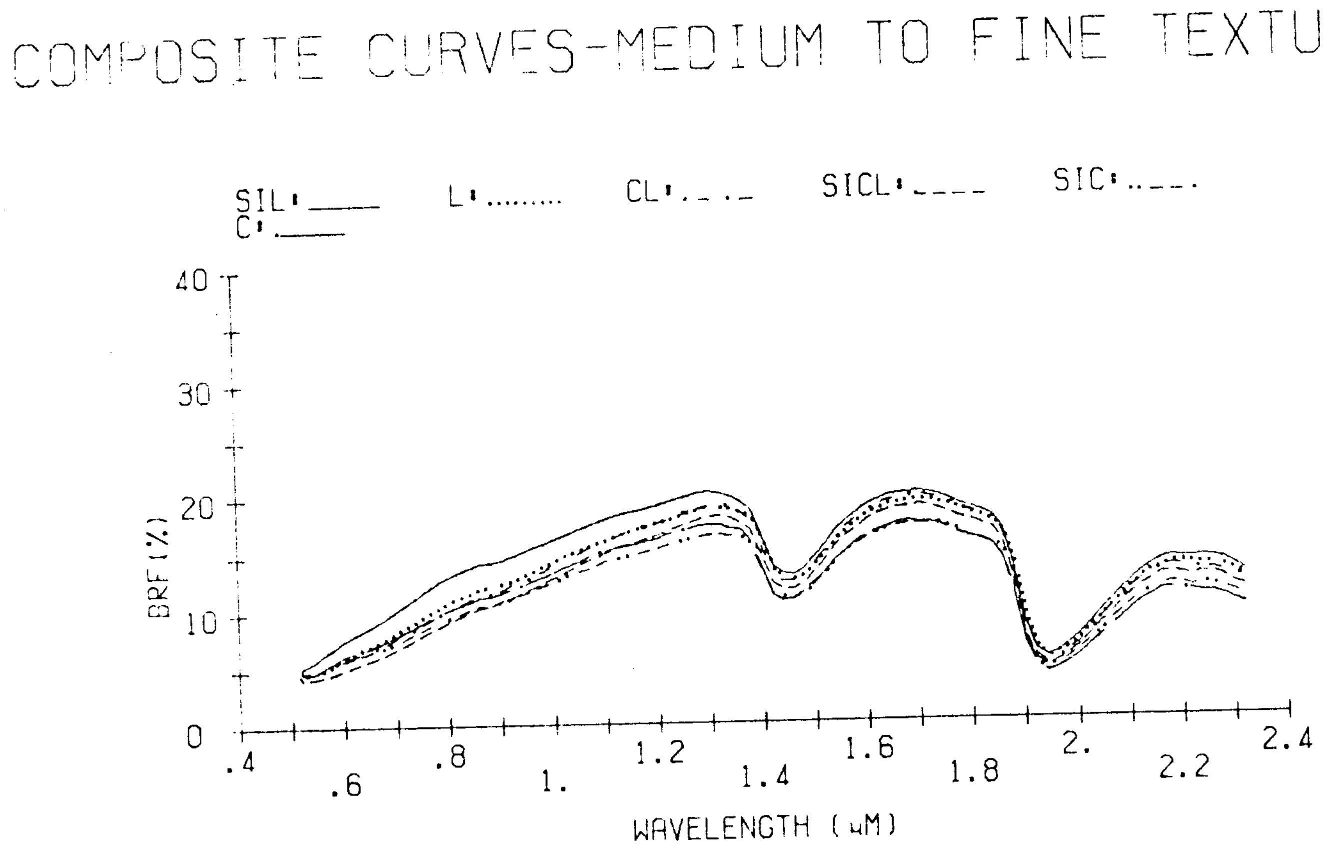


Figure 26. Averaged reflectance spectra for soils with medium to fine textures.

wavelength region with finer and finer textures is the associated increase in moisture content with increasing clay content in the soils. High clay content soils tend to hold more water at one-tenth bar moisture tension than do silty soils. As will be seen later, both moisture percentage by weight and clay content are negatively correlated with reflectance in band 2.08 to 2.32µm. This would explain decreased reflectance in this band with finer textured soils.

Soil Taxonomic Order

Averaged reflectance spectra for soils representing the ten soil orders of the U.S. soil taxonomy (Soil Survey Staff, 1975) are helpful in understanding the interrelationships among soils that may occur together in a landscape as well as among soils of very contrasting origin (Figure 27). Histosols and Mollisols are seen to have very low overall reflectance as can be expected due to their elevated organic matter contents. Only Oxisols exhibit lower reflectance than Histosols in the middle infrared region. The high organic content surface horizons diagnostic for Mollisols are responsible for their low reflectance. Both Mollisols and Histosols exhibit the characteristic concave Type 1 curve. Vertisols also have this Type 1 curve shape but show a much higher middle infrared reflectance than Mollisols.

Ultisols reflect more than Alfisols at all wavelengths. Although the defining characteristics of these two soil orders are based on differences in base saturation of subsurface horizons, the generally stronger leaching and oxidation conditions under which it forms result in overall higher soil reflectance of the Ultisol compared to the Alfisol. Ultisols, because of a higher iron oxide content resulting in prominent ferric iron absorption bands at 0.7 and 0.9µm display the Type 3 curve. Alfisols as well as Aridisols, Entisols, Inceptisols, and Spodosols have Type 2 curves. The limited sample of five Oxisols exhibits the previously described fifth curve shape characteristic of very highly weathered soils high in free iron oxides.

Parent Material

As one of the soil forming factors, parent material can be expected to demonstrate an eventual influence on soil reflectance. Certain soils referred to as lithochromic are even known to owe their spectral colors to inheritance from the parent material rather than from soil-forming processes.

Most of the soils in this study were grouped into six broad parent material categories. Averaged reflectance curves for soils falling into these categories show different magnitudes of reflectance which are especially prominent in the 1.55 to 1.75µm middle infrared region (Figure 28). Igneous parent material soils show the effect of ferric iron absorption at 0.9µm and even display a definite hydroxyl absorption band at 2.2µm. Soils of glacial origin reflect the least of all the parent material groupings, an observation that can be explained by a combination of factors including finer silt and clay size particles ground by the glaciers as well as higher organic contents resulting from prairie grass vegetation adapted to glacier-flattened plains.

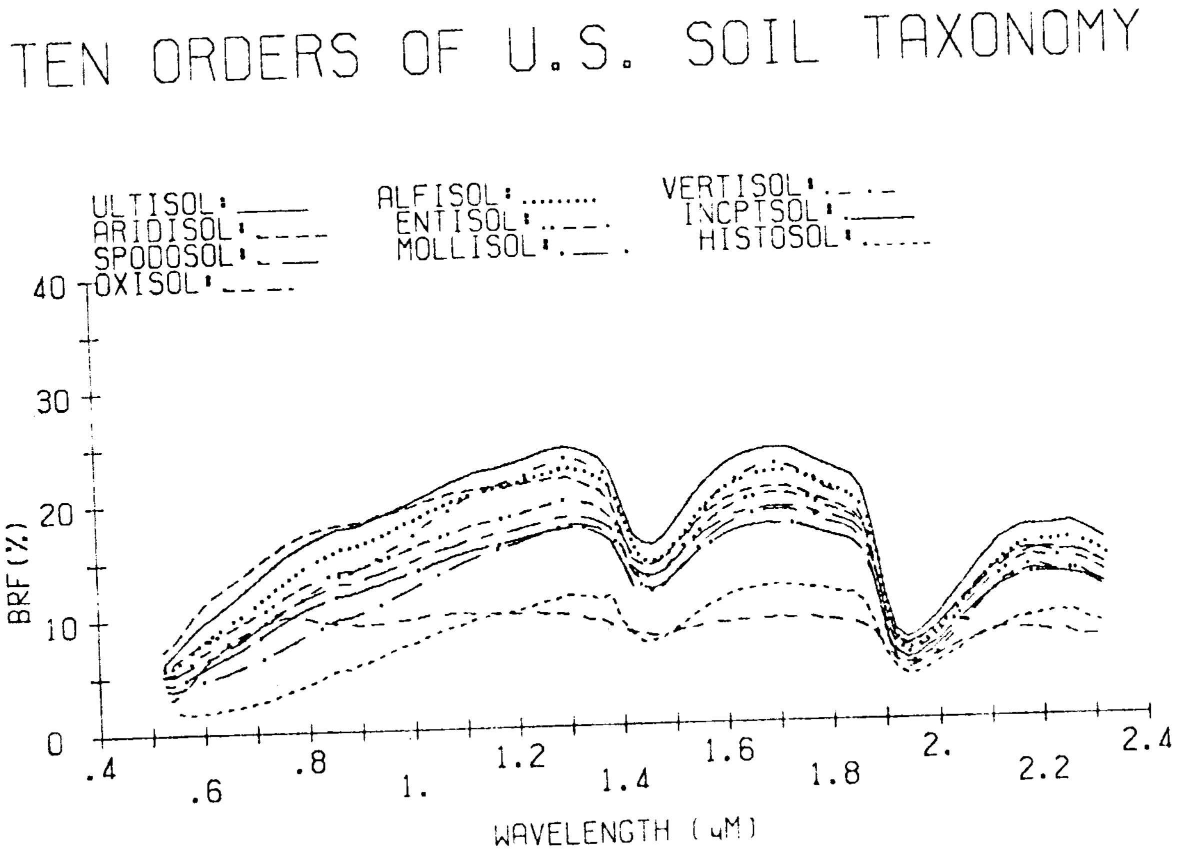


Figure 27. Averaged reflectance spectra for soils representing ten orders of soil taxonomy (Soil Survey Staff, 1975).

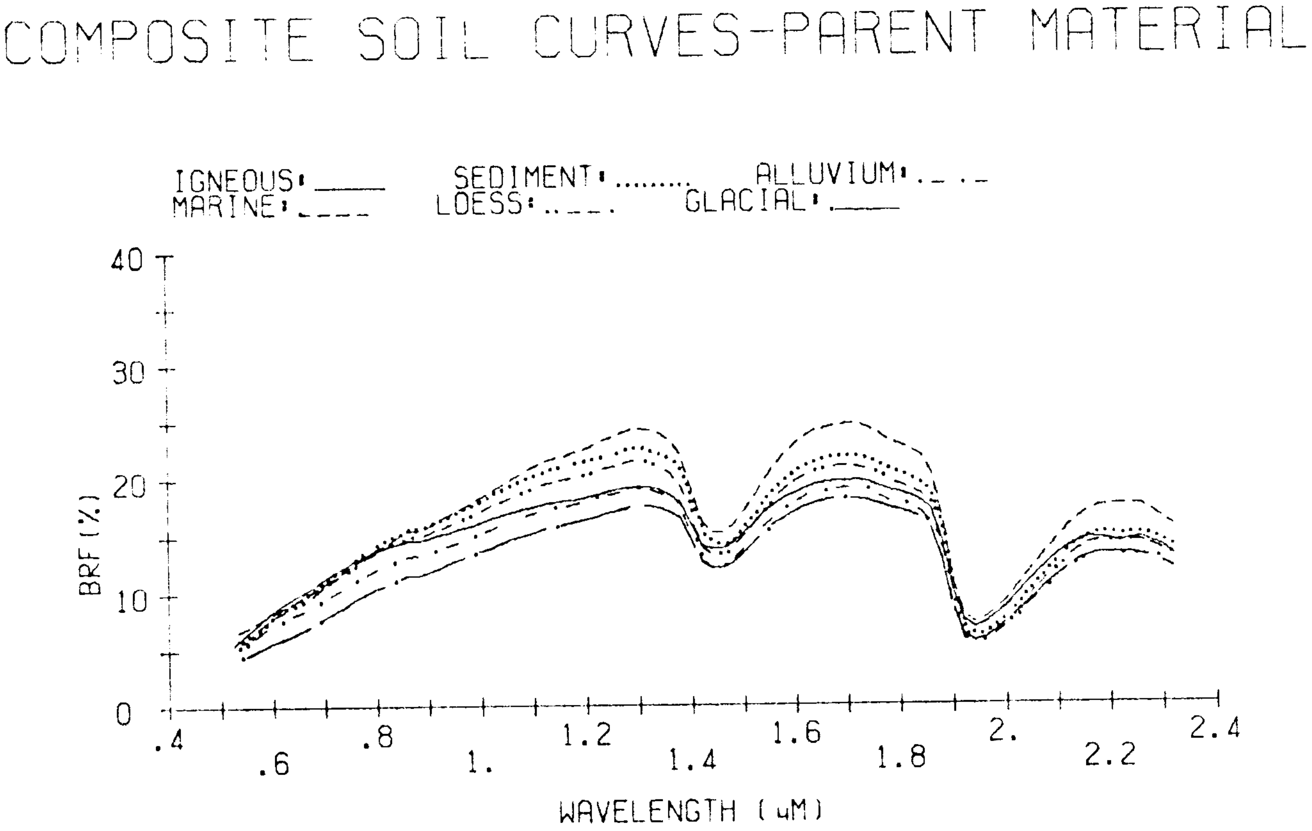


Figure 28. Averaged reflectance spectra for soils having specified parent materials.

Mineralogy

Mineral soils grouped according to mineralogy classes of the U.S. soil taxonomy have in common similar sets of soil-forming processes which favor the formation of certain minerals as weathering products of the parent material. Soil mineralogy can be thought to reflect the overall environment and initial conditions under which soil-forming processes proceed over the time of soil formation.

Averaged soil spectra for soils belonging to seven mineralogy classes show a wide range of reflectances (Figure 29). Soils with gypsic mineralogy reflect more at all wavelengths than any other class, whereas montmorillonitic soils reflect the least from the visible to 1.0μm. Micaceous mineralogy soils display a very flat reflectance curve beyond 0.8μm and reflect the least of all classes in the middle infrared. The lower visible reflectance of montmorillonitic soils may be associated with higher organic matter contents in these soils while the higher reflecting gypsic mineralogy soils may derive their reflectance properties directly from the highly reflecting gypsum (Hunt, et al., 1971c). Kaolinitic mineralogy soils have a broad ferric iron absorption band at 0.9μm, indicative of higher free iron contents associated with these soils. Most soils in this study are of mixed mineralogy, exhibiting the Type 2 curve of soils that as a group are neither high in organic matter content nor high in iron.

Temperature Regime

Temperature as a component of climate is considered to be an independent soil-forming factor (Jenny, 1941). Temperature exerts an influence over many of the reactions involved in the process of forming soil. The type and quantity of vegetation and thus the amount and kind of organic matter produced are markedly influenced by temperature. The rate of organic matter decomposition is almost directly controlled by temperature (Buol, et al., 1973). Organic matter contents tend to decrease as the temperature increases.

Soils grouped according to temperature regimes as defined by the U.S. soil taxonomy demonstrate the effects of temperature on soil reflectance properties (Figure 30). Frigid region soils reflect less than mesic region soils from the visible portion of the spectrum to about 1.2μm, but have a slightly greater reflectance in the 2.08 to 2.32μm wavelength region than mesic region soils. Higher organic matter contents associated with cooler region soils may explain the lower reflectance in the 0.52 to 1.2μm range which has been seen to be the wavelength region of strong organic matter influence. Clay contents are also known to increase with increases in temperature. Higher moisture contents related to increased clay contents in mesic temperature regions may lead to lower reflectance in the moisture sensitive 2.08 to 2.32μm range.

Thermic temperature regime soils reflect more than any other soil temperature class from 0.52 to 1.32μm. Again, lower organic matter contents in warmer region soils are probably responsible for this high level of reflectance. Hyperthermic region soils are seen to reflect less than thermic region soils in this wavelength interval, a seeming contradiction to what has previously been observed. Here the relatively small number of

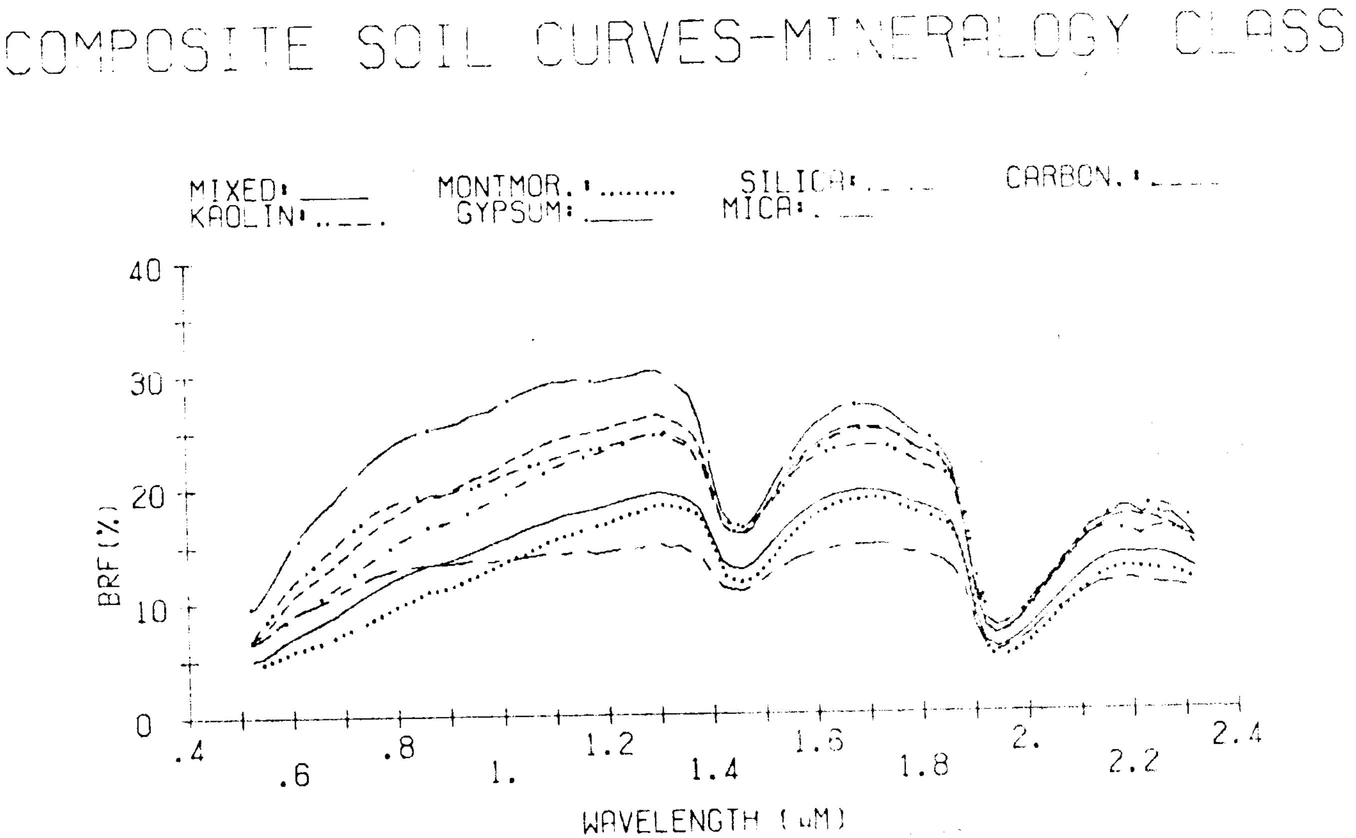


Figure 29. Averaged reflectance spectra for soils having specified mineralogies.

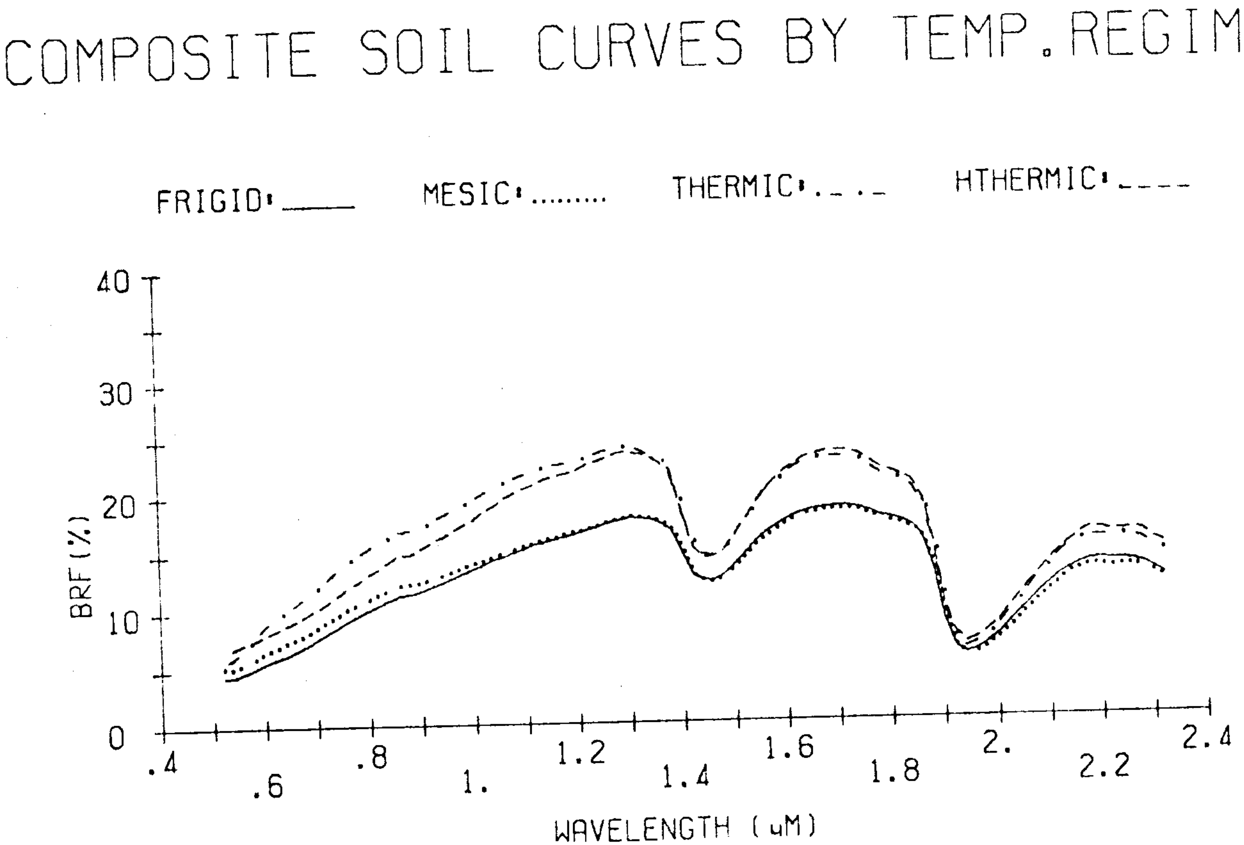


Figure 30. Averaged reflectance spectra for soils formed in specified temperature regimes.

soils involved (fourteen soil series) may not form an adequate representative sample of hyperthermic region soils.

With increasing soil temperature, soil colors tend to become less gray and more reddish. Although these reflectance curves have not been assigned color designations, it can be observed that warmer region soils display a broad 0.9μm iron absorption band that is usually seen in red-hued soils. This band is not as prominent in cooler region soils.

Moisture Zone

Water is a vital agent in the formation of soil. Water acts to dissolve soluble material, promote the growth of plants and other organisms that contribute organic material to the soil, transport material from one part of the soil to another, and physically alter soil material upon freezing. The important functions of water depend on the amount of water in the soil profile (Buol, et al., 1973).

Composite reflectance curves averaged for soils grouped by moisture zone reveal the greatest differences in the visible and near infrared portions of the spectrum (Figure 31). Arid soils which could be expected to have the lowest organic matter contents reflect the most in this organic matter sensitive wavelength interval. Perhumid zone soils high in organic matter reflect the least at all wavelengths, probably in part because of increased clay content associated with higher rainfall. Subhumid zone soils in the United States include a large number of soils formed under prairie grass vegetation and, as such, can be expected to exhibit lower visible and near infrared reflectance than the predominantly forested humid zone soils.

Drainage

All soil series have a specific internal drainage which is indicative of the local landscape position and broader climatic conditions under which they formed. Even for soils in which the marks of seasonal soil saturation may by definition extend upward no higher than to horizons untouched by tillage equipment, the soil-forming processes involved exert their influence on the whole soil profile and often are evident in the surface soil.

Soils grouped by internal drainage class display ever decreasing soil reflectance with increasingly poorer drainage (Figure 32). Well drained and moderately-well drained soils show very little difference in reflectance as could be expected. Very poorly drained soils reflect considerably less than any of the other drainage classes at all wavelengths. Whereas the well drained and moderately-well drained soils show evidence of ferric iron absorption at 0.9μm, all three poorly drained soil classes lack the ferric iron absorption band. As a site characteristic integrating the effects of climate, local relief, and accumulated organic matter, soil drainage characteristics can be expected to be closely associated with reflectance properties of surface soils.

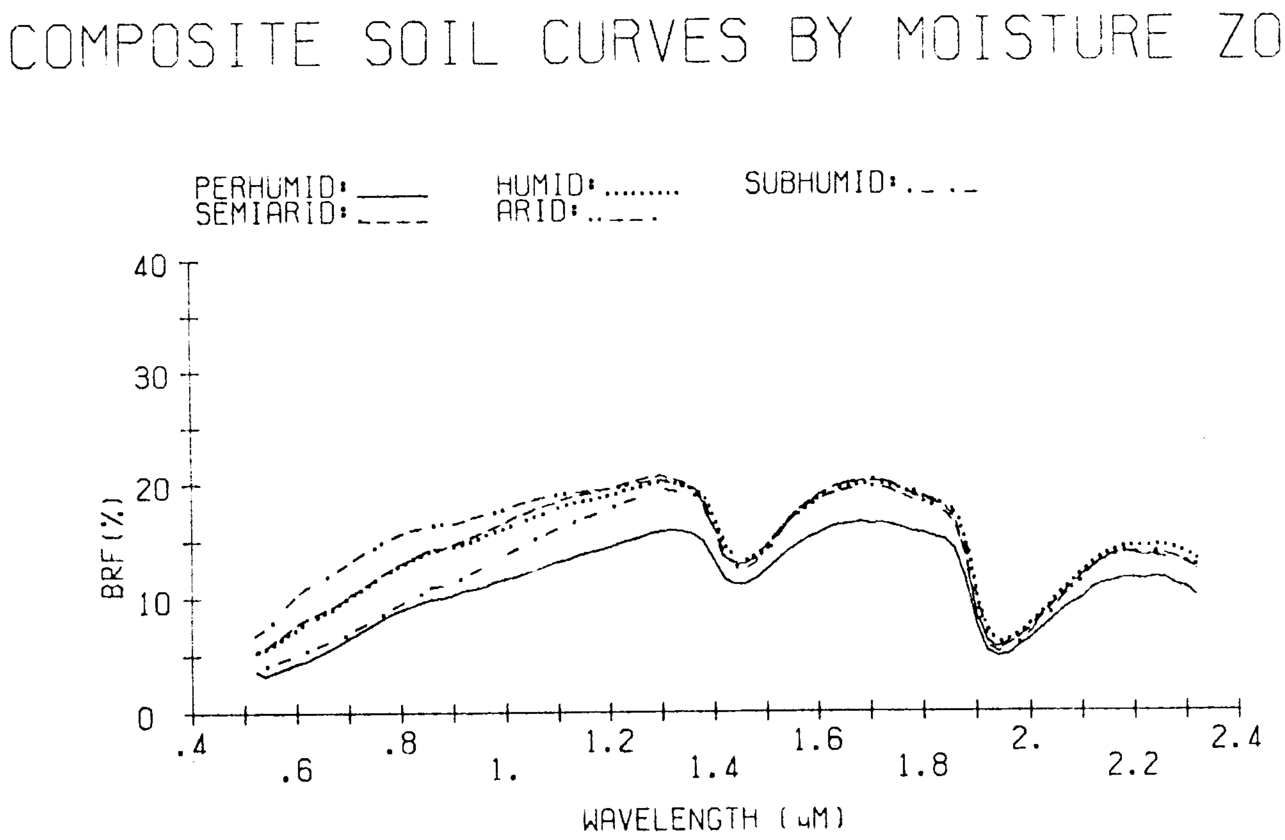


Figure 31. Averaged reflectance spectra for soils formed in specified moisture zones.

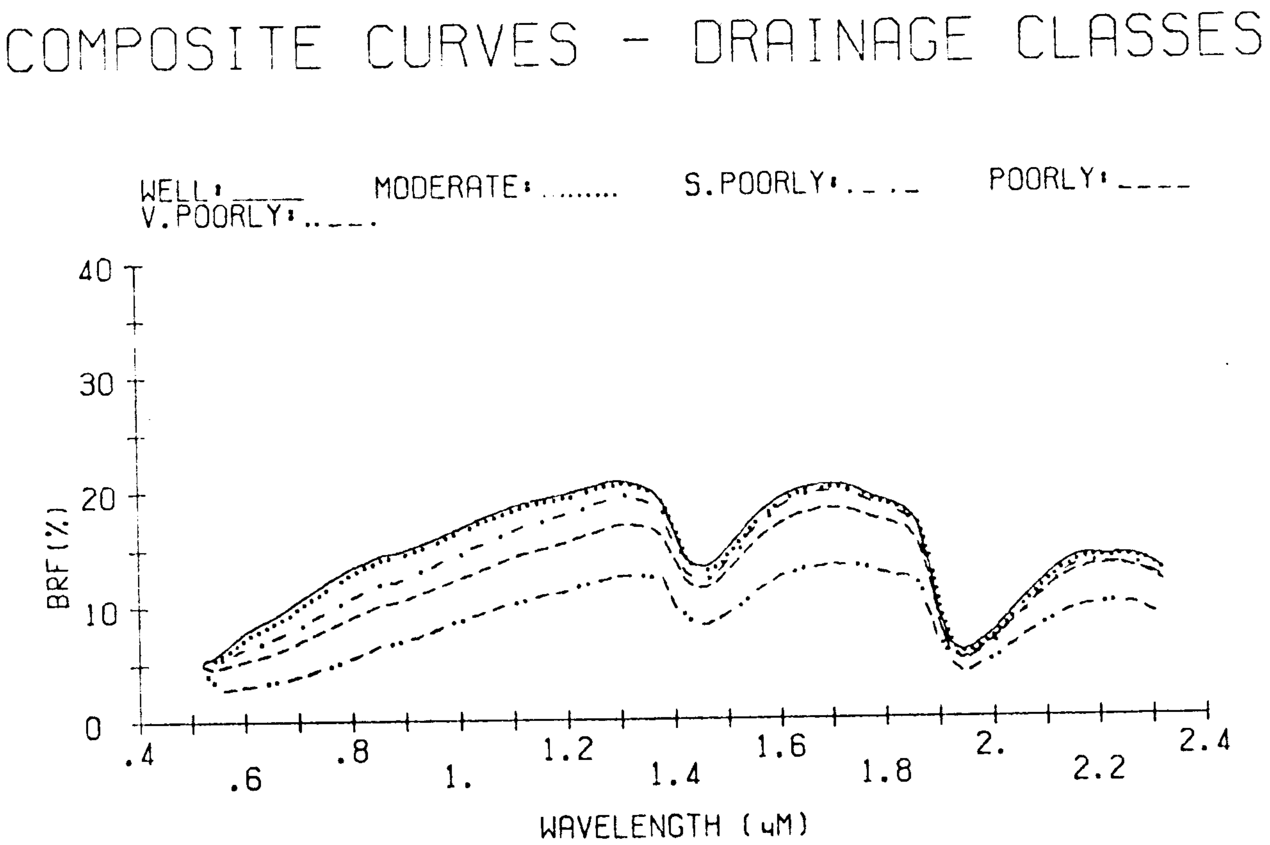


Figure 32. Averaged reflectance spectra for soils formed under specified conditions of internal drainage.

Relationships of Soil Reflectance to Physicochemical and Site Characteristics

Correlations

For the purpose of statistical analyses, all of the 481 soil samples from the continental United States were considered as single observations. Three soil series without duplicate samples account for the odd numbered total. None of the non-United States soil samples were included in statistical analyses.

The decision was made to treat each soil sample as a separate observation for several reasons. Firstly, it was not the purpose of the study to test for significant differences between reflectances of a given soil series. Each pair of duplicate samples for a given soil series was assumed to represent an allowable range of soil physical, chemical, and reflectance properties as nearly as that soil could be identified and would be mapped by an experienced soil surveyor in the field. Secondly, of greater interest than the reflectance differences between samples of a given soil series were the physicochemical and site characteristics which imparted reflectance properties unique to each soil sample. This provided many situations in which a difference in just one property among the many others that were similar for duplicate soil samples revealed the influence of that specific property on the reflectance curve. Thirdly, by considering each soil sample as a separate observation it was possible to double the number of observations for statistical purposes. The use of duplicate samples as separate observations represents another restriction on randomization of soil sample selection but still allows for inference of statistical results over the large geographic areas covered by each climatic zone.

It was necessary to divide the reflectance data into spectral bands for statistical study. Ten wavelength bands were selected covering the 0.52 to 2.32μm wavelength range (Table 5). Bands 1 to 8 all have 0.1μm band-widths. Bands 1 and 2 are visible wavelengths bands. Bands 2 and 4 cover the spectral regions of known ferric iron absorption. Most of bands 1 to 8 resemble, but may not coincide precisely with existing bands of the Landsat multispectral scanner or bands used on the Skylab S192 multispectral scanner. Bands 9 and 10 are proposed Thematic Mapper bands with band 10 being slightly altered by the cutoff of spectroradiometric data at 2.32μm.

Table 5. Spectral reflectance bands for statistical analysis.

band	wavelength (μm)	spectral region	band	wavelength (μm)	spectral region
1	0.52-0.62	visible	6	1.02-1.12	near IR
2	0.62-0.72	visible	7	1.12-1.22	near IR
3	0.72-0.82	near IR	8	1.22-1.32	near ir
4	0.82-0.92	near IR	9	1.55-1.75	middle IR
5	0.92-1.02	near IR	10	2.08-2.32	middle IR

Scatter diagrams of reflectance in specific bands plotted against important laboratory-measured soil parameters reveal the nature of the statistical relationships involved. A definite negative curvilinear relationship can be seen between organic matter content and reflectance in visible band 1 (Figure 33). A natural logarithmic transformation of organic matter content was found to be best for relating organic matter content to reflectance data. The wide scatter of points at the lower organic matter levels indicates that grouping of all soils from all climatic zones may not result in very high correlations between organic matter and reflectance.

Reflectance in the 2.08 to 2.32μm wavelength band is also seen to be negatively correlated with moisture percentage by weight of all 481 soils (Figure 34). Again, improvements are to be expected when soils from similar climatic zones are plotted alone. Reflectance in band 10 is also negatively correlated with clay content, cation exchange capacity, and even iron oxide content while it is positively correlated with fine and medium sand contents.

Simple correlation coefficients were calculated between five important soil parameters and reflectance in ten individual bands. Reflectance band ratios were considered, but were rejected because they showed almost no improvement over correlations with individual bands. Soil parameters studied were the natural logarithm of organic matter content, moisture percentage by weight, cation exchange capacity, iron oxide content, and particle size distribution by content of eight particle size classes. In each case, correlation coefficients for the single most highly correlated band were recorded. For particle size distribution, the particle size class having the highest simple correlation with a given band was recorded. Because different sample sizes were being considered as climatic groupings of soils, the 95% confidence intervals on the correlation coefficients were calculated from Z values (Waugh, 1944). As sample sizes become smaller, the 95% confidence intervals on the correlation coefficients become broader.

For all 481 soils grouped together a negative correlation of .68 is seen between the natural log of organic matter and reflectance in the visible band 2 (Table 6). A correlation of -.53 between moisture percentage by weight and band 10 reflectance confirms the relationship displayed in the scatter diagram (Figure 34). Correlations with clay content, cation exchange capacity, and iron oxide content are not as strong when all soils are considered as a group.

Soils grouped according to moisture zone or temperature regime show improved correlations in most cases between soil parameters and reflectance data over correlations for all 481 soils (Table 6). Correlations as high as -.78 are seen between the natural log of organic matter and band 6 reflectance for subhumid region soils. Within the same climatic region a similar -.78 correlation is evident between moisture percentage and band 10 reflectance. Correlations between cation exchange capacity and reflectance are often higher than correlations between particle size distribution and reflectance, while most correlations between iron oxide content and reflectance remain low. Certain moisture zones like the humid and semiarid as well as the frigid and mesic temperature regimes appear to be too heterogeneous in their soil makeup for good correlations between reflectance data and physicochemical characteristics.

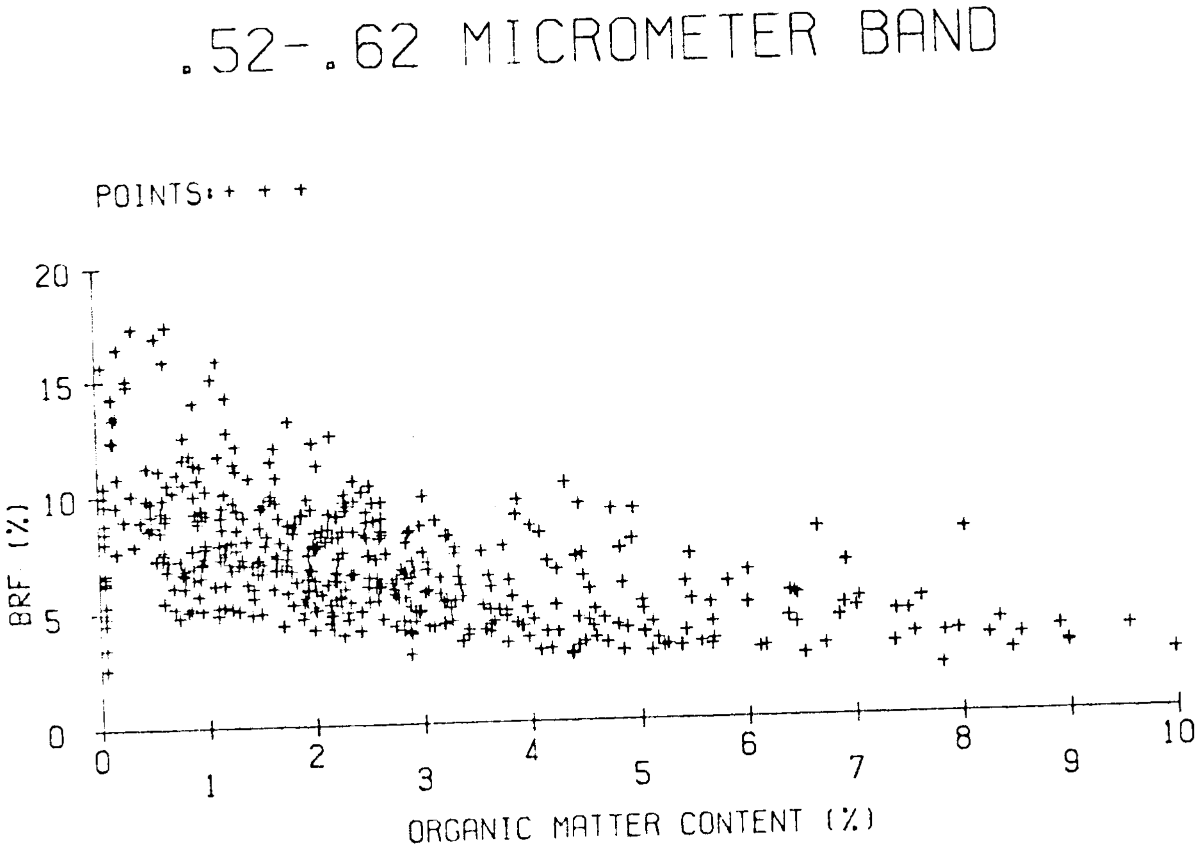


Figure 33. Reflectance in the 0.52-0.62 μm wavelength band plotted against organic matter content for all continental U.S. soil samples within the 0-10% organic matter range.

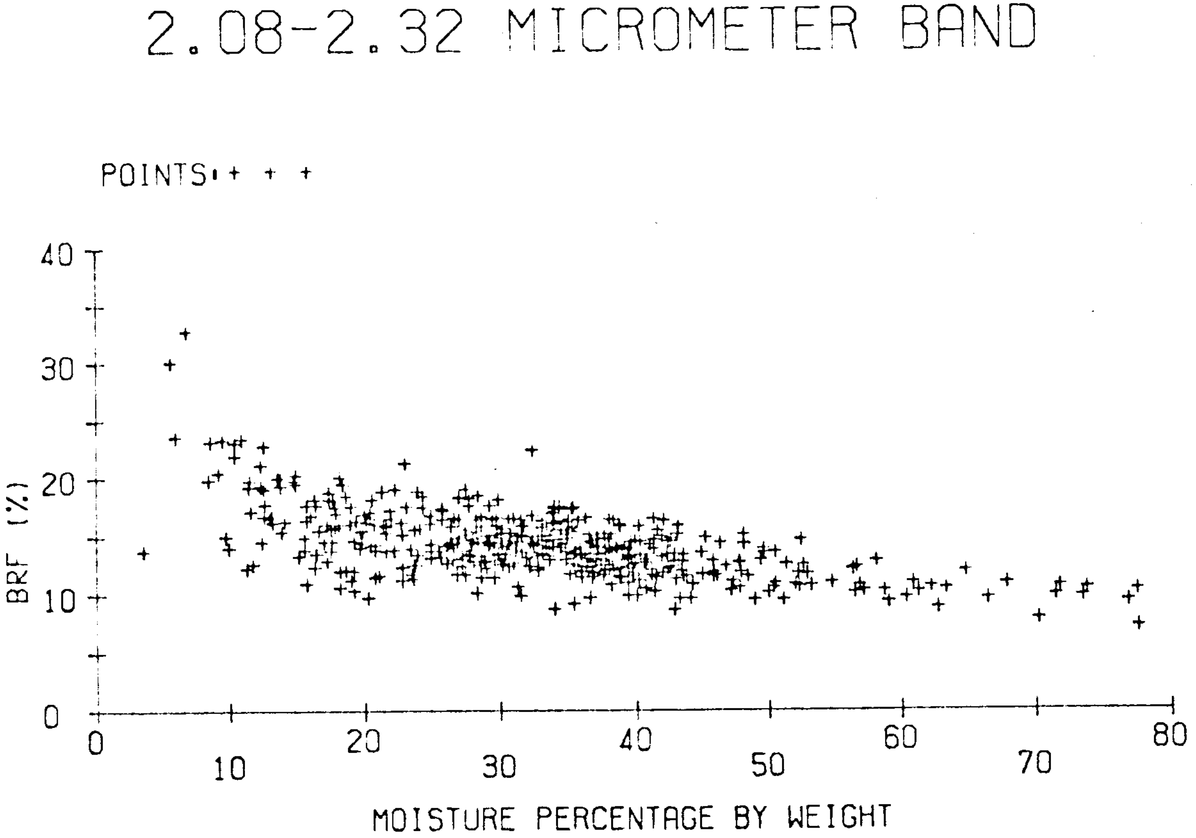


Figure 34. Reflectance in the 2.08-2.32 μm wavelength band plotted against moisture percentage by weight for 481 continental U.S. soil samples.

Table 6. Simple correlation coefficients between five soil parameters and reflectance in individual bands for all soils and for soils grouped by moisture zone and by temperature regime.

r values for most highly correlated band (parentheses) with 95% confidence intervals on r

	soil parameter				
climatic grouping no. of soils in class	$\log_e$(O.M.)	moisture percentage by weight	particle size distribution	cation exchange capacity	iron oxide content
all soils 481	-.68(2) -.73<r<-.63	-.53(10) -.59<r<-.46	clay -.41(10) -.48<r<-.33	-.48(10) -.55<r<-.41	-.16(10) -.25<r<-.07
moisture zone					
humid 185	-.68(1) -.72<r<-.64	-.47(10) -.53<r<-.41	clay -.25(10) -.32<r<-.18	-.50(1) -.55<r<-.44	.18(2) .11<r<.25
subhumid 128	-.78(6) -.81<r<-.74	-.78(10) -.81<r<-.74	clay -.61(10) -.66<r<-.55	-.71(10) -.75<r<-.66	-.16(10) -.25<r<-.07
semiarid 94	-.53(3) -.60<r<-.45	-.39(10) -.48<r<-.30	fine sand .47(10) .38<r<.55	-.22(10) -.31<r<-.11	-.55(8) -.62<r<-.47
arid 62	-.73(2) -78<r<-.66	-.71(2) -.77<r<-.64	fine sand .69(2) .60<r<.74	-.37(10) -.47<r<-.25	-.28(1) -.40<r<-.16
temperature regime					
frigid 102	-.43(1) -.54<r<-.34	-.41(10) -.49<r<-.32	clay -.40(10) -.47<r<-.31	-.47(10) -.54<r<-.38	.40(3) .31<r<.48
mesic 211	-.68(1) -.71<r<-.64	-.48(10) -.53<r<-.42	clay -.27(10) -.33<r<-.20	-.52(10) -.57<r<-.47	.08(4) .01<r<.15
thermic 140	-.64(6) -.69<r<-.59	-.68(10) -.72<r<-.63	clay -.57(10) -.61<r<-.51	-.48(10) -.54<r<-.41	-.19(10) -.27<r<-.10
hyperthermic 28	-.75(3) -.82<r<-.65	-.75(8) -.82<r<-.65	fine silt -.68(8) -.77<r<-.56	-.65(8) -.75<r<-.52	-.23(10) -.40<r<-.03

For eleven specific climatic subgroups of at least eighteen soils each the correlations between soil parameters and reflectance data are seen to improve in most cases over more generalized climatic groupings (Table 7). Correlations as high as .90 between fine sand content and band 4 reflectance for arid thermic zone soils show considerable improvement over correlations for either the arid or thermic regions analyzed separately. Correlations between iron oxide content and reflectance data are much improved for specific climatic zones. Iron oxide content shows positive correlations with bands 2 and 4 in the ferric iron absorption regions and negative correlations with bands 9 and 10 in the middle infrared. Again, cation exchange capacity frequently reveals higher correlations with reflectance data than does particle size. As was surmised by Montgomery (1976), cation exchange capacity may be acting as a natural integrating factor for numerous soil parameters that influence soil reflectance.

Prediction Models

Soil reflectance has been seen to be a cumulative property which derives from inherent spectral behavior of the mineral, organic, and fluid matter that comprise most soils. Thorough statistical modeling of the factors involved in soil reflectance would require much more detailed mineralogical and biochemical analysis than the scope of this study allowed. However, there is value in attempting to explain some of the variation in soil reflectance in given wavelength regions in terms of familiar physicochemical and site characteristics. This approach recognizes the important contributions already identified as being important to reflectance of such soil properties as organic matter content, moisture content, iron oxide content, and texture, while introducing the possibility that such site characteristics as climate, parent material, and drainage may be important factors in explaining soil reflectance.

A forward stepwise inclusion procedure was used to develop regression equations for prediction of reflectance in each of ten wavelength bands from data on physicochemical characteristics and from site characteristics coded as dummy variables (Nie, et al., 1975; Draper and Smith, 1966). Independent variables included the natural log of organic matter content, moisture percentage by weight, percentage contents of eight particle size classes, cation exchange capacity, iron oxide content, six classes of parent material, six drainage classes, and sixteen climatic categories. Each regression equation was limited to inclusion of ten independent variables.

The order of inclusion of the first ten independent variables into regression equations for each spectral band reveals the importance of these variables in explaining soil reflectance (Table 8). Only those variables that were included in at least one regression equation are shown. The natural log of organic matter is seen to be the first variable to enter the regression equation for every band except for the middle infrared band 10 which has moisture percentage by weight as the first variable to enter. Moisture content is included in only one other regression equation, that for band 6. Fine sand and fine silt contents are frequently included in regression equations while clay content is included only in equations for bands 3 and 10. Iron oxide content is included in regression equations for bands 2, 3, and 10.

Table 7. Simple correlation coefficients between five soil parameters and reflectance in individual bands by climatic zone.

r values for most highly correlated bands (parentheses) with 95% confidence intervals on r

	soil parameter				
climatic subgroup no. of soils in class	$\log_e$(O.M.)	moisture percentage by weight	particle size distribution	cation exchange capacity	iron oxide content
humid frigid 38	-.66(10) -.74<r<-.55	-.43(1) -.55<r<-.28	fine sand .37(10) .22<r<.51	-.45(1) -.57<r<-.31	.56(2) .43<r<.66
humid mesic 75	-.66(1) -.72<r<-.59	-.29(10) -.39<r<-.18	fine silt .58(9) .50<r<.65	-.73(1) -.78<r<-.67	.30(2) .19<r<.40
humid thermic 60	-.71(8) -.77<r<-.64	-.65(10) -.72<r<-.56	clay -.53(10) -.62<r<-.43	-.73(9) -.79<r<-.66	-.18(10) -.30<r<-.05
subhumid frigid 42	-.77(4) -.83<r<-.70	-.75(10) -.81<r<-.67	clay -.67(9) -.75<r<-.57	-.86(9) -.90<r<-.81	-.20(10) -.35<r<-.04
subhumid mesic 46	-.81(6) -.89<r<-.75	-.64(10) -.72<r<-.54	clay -.63(10) -.71<r<-.53	-.71(10) -.78<r<-.63	.52(2) .40<r<.62
subhumid thermic 36	-.62(2) -.72<r<-.50	-.82(10) -.87<r<-.75	sand .76(2) .68<r<.82	-.63(10) -.72<r<-.51	-.44(6) -.57<r<-.29
semiarid frigid 18	-.28(1) -.50<r<-.03	-.48(10) -.65<r<-.26	clay -.67(10) -.79<r<-.50	-.60(10) -.74<r<-.41	.26(2) 0<r<.48
semiarid mesic 46	-.32(2) -.45<r<-.18	-.34(10) -.47<r<-.20	very fine sand .43(2) .30<r<.55	-.44(1) -.56<r<-.31	-.42(9) -.54<r<-.29
semiarid thermic 20	-.58(3) -.72<r<-.40	-.55 (10) -.70<r<-.36	medium sand .66(10) .50<r<.78	-.40 (3) -.58<r<-.18	-.67(9) -.78<r<-.51
arid mesic 32	-.79(3) -.85<r<-.71	-.79(3) -.85<r<-.71	clay -.62(3) -.72<r<-.49	-.73(4) -.80<r<-.63	.39(4) .22<r<.54
arid thermic 24	-.67(2) -.77<r<-.53	-.75(10) -.83<r<-.63	fine sand .90(4) .85<r<.93	-.47(10) -.62<r<-.28	-.73(9) -.82<r<-.61

Table 8. Physicochemical and site characteristics as predictors of reflectance in individual spectral bands.

band (μm) (R^2)	order of inclusion of first ten variables into stepwise regression equations																							
	physicochemical characteristics						site characteristics (dummy variables)																	
							climate												drainage		parent material			
	$\log_e$(O.M.)	moisture percentage by weight	fine sand content	fine silt content	clay content	iron oxide content	humid frigid	humid mesic	humid thermic	subhumid frigid	subhumid mesic	subhumid thermic	semiarid frigid	semiarid mesic	semiarid hyperthermic	arid frigid	arid mesic	arid thermic	somewhat poorly	poorly	sedimentary	marine	alluvial	igneous
1 (.52-.62) (.59)	1			2				8	7	4	3	5					10	6	9					
2 (.62-.72) (.63)	1		8	5		10			2	6	4							3	7	9				
3 (.72-.82) (.61)	1		10	8	9	4			2	6	5							3	7					
4 (.82-.92) (.58)	1		9	6					2	5	4						7	3	8	10				
5 (.92-1.02) (.56)	1		8	7			10		2	5	4						6	3			9			
6 (1.02-1.12) (.55)	1	8						10	2	5	4		9	6			3				7			
7 (1.12-1.22) (.53)	1		8	7			9		3			4			6		2	5			10			
8 (1.22-1.32) (.51)	1		10	9					3			4			5		2	6					8	7
9 (1.55-1.75) (.45)	1		7	6					3			4			8	10	2				9	5		
10 (2.08-2.32) (.48)	3	1	8	7	6	10			5			9					4					2		

The remarkable feature of these prediction equations is the frequent inclusion of dummy variables for specific climatic zones, drainage classes, and parent material groupings. Although the low R^2 values indicate that the reflectance in individual bands has not been fully accounted for, it is significant to know that site characteristics play a prominent part in explaining soil reflectance when all the currently known soil parameters influencing reflectance are considered. Of all of these physicochemical and site characteristics, the only one about which we normally have prior knowledge in the case of soil survey in unmapped areas, is climate. Knowing the climate, we may get a better idea of expected information that may be obtained from soil reflectance data.

The ultimate objective of prediction modeling of soil reflectance properties is to be able to predict the level of certain soil parameters within areas of known climatic type from reflectance data. The same forward stepwise inclusion procedure was used this time to develop regression equations for prediction of soil parameters from reflectance data in ten wavelength bands. Independent variables were the ten spectral bands which in this case were not limited in number for inclusion in regression equations. The dependent variables, or the variables being estimated from reflectance data were the natural log of organic matter, moisture content, cation exchange capacity, iron oxide content, and percentage content of certain particle size classes.

Spectral bands entered into regression equations and R^2 values are indicated for soils from eleven climatic zones (Table 9). R^2 values as high as .78 for prediction of organic matter, .95 for prediction of moisture content, .84 for prediction of cation exchange capacity, .90 for prediction of clay content, and .70 for prediction of iron oxide content were obtained for soils within specific climatic zones. The inclusion of reflectance data from numerous bands in the visible, near infrared, and middle infrared is essential for development of these prediction models. Not all soil parameters are highly predictable from reflectance data for all climatic zones, but those situations in which strong relationships exist can be seen here. Indications are that further subdivision of climatic subgroups by soil drainage and parent material classes could improve upon these simple prediction models, although the limited number of soils in this study did not permit statistical evaluation of these more specific soil groupings.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary and Conclusions

Measurement of bidirectional reflectance factor of soils in the 0.52 to 2.32μm wavelength interval at the uniform moisture tension of one-tenth bar using an asbestos tension table apparatus and a spectroradiometer adapted for indoor use provides repeatable quantitative reflectance data from soil samples viewed and illuminated in much the same way as airborne sensing devices. Soil reflectance curves of subsamples of highly different Alfisol, Mollisol, and Oxisol soils demonstrate the reliability of the experimental procedures developed for this study. Importantly, the equilibration of soil moisture at one tension for all soils studied permits the evaluation

Table 9. Soil reflectances in individual bands as predictors of soil parameters within certain climatic zones.

R^2 values and spectral bands entered into regression equations

	soil parameter				
climatic subgroup no. of soils in class	$\log_e$(O.M.)	moisture percentage by weight	particle size distribution	cation exchange capacity	iron oxide content
humid frigid 38	.78 10,9,2,8,4,1	.95 1,6,10,3,8	clay .54 10,2,1,3,4,8	.84 1,8,10,4	.67 2,10,5,9,8,4,1
humid mesic 75	.61 1,10,3,5,9	.32 10,8,9,5,2,1	fine silt .48 9,1,4,10	.65 1,10,9,8,4	.21 2,1,4,8,5,10
humid thermic 60	.53 8,10,2,4	.54 10,2,3,7,1	clay .30 10,9	.65 9,2,3,6,10,1	.49 10,2,1,4,8,5,9
subhumid frigid 42	.66 4,9,6,1,10	.60 10,9,8	clay .51 9,6,4,2,10	.75 9,7	.23 10,2,1,3,7,6,9
subhumid mesic 46	.70 6,10,1,3,	.52 10,5	clay .73 10,9,7,3	.72 10,1,6,9,4	.51 2,1,4,8,3,9,5,10
subhumid thermic 36	.73 2,3,5,9,10,1	.87 10,2,9,8,4,1	clay .69 5,1,7,10,9	.77 10,9,8,3	.51 6,2,7,1,3,8,10,9
semiarid frigid 18	.67 1,5,10,4,8	.77 10,8,3,9,2,1	clay .90 10,9,4,2,6,1	.74 10,8,4,2,9,1	.37 2,1,3,9,5,4,10,8
semiarid mesic 46	.40 2,8,4,9	.64 10,9,1,4	clay .49 10,9,1,3	.57 1,3,6,10,9	.38 9,1,6,8,5,2,3,10
semiarid thermic 20	.59 3,1,9	.68 10,3,1,8	clay .65 3,1,10,9	.74 3,1,10,9	.68 9,10,7,5,1,2
arid mesic 32	.68 3,1,10,5	.75 3,1,10,9	clay .80 3,1,8,10	.73 4,1,8,10	.40 4,1,9,7,3,10
arid thermic 24	.60 2,4,1	.76 10,9,3,8	fine sand .83 4,10,9,8	.60 10,9,1,8,4	.70 9,10,7,1,6,4,3

of differences in moisture content among soils as a factor influencing soil reflectance. Standard procedures for laboratory study of soil reflectance allow for comparison of soils from widely scattered sites with extraneous variables controlled to a greater extent than possible in the field.

Soil reflectance curves can be grouped according to curve shape into at least five general types, two more than had previously been recognized. High iron content Oxisols were observed that actually decrease in reflectance with increasing wavelength, contrary to all published accounts of soil reflectance behavior. Absorption bands at 0.7 and 0.9μm, tentatively attributed to ferric iron, impart characteristic curve forms to soils with moderate to high amounts of free iron oxides. Ferrous iron absorption as well as hydroxyl absorption of gibbsite, both centered at 1.0μm, can also be seen to influence the shape of soil reflectance curves. Low organic matter, low iron, better drained soils exhibit a convex curve shape from 0.52 to 1.3μm. High organic matter, low iron, poorer drained soils show a concave curve shape from 0.52 to 1.3μm.

Soils with similar Munsell color designations have been seen to possess very contrasting reflectance properties, especially in the infrared wavelengths. The difficulty of using Munsell color designations to describe in a precise and quantitative manner the actual reflectance properties of soils is apparent. Spectroradiometric measurement of soil reflectance is not only a more quantitative and reliable measure of soil spectral properties than standard color charts, but also extends our knowledge beyond the visible into the reflective infrared wavelengths.

Averaged reflectance curves for soils with similar organic matter content reveal the dominant role of organic matter in determining both curve form and reflectance magnitude in the visible and near infrared wavelengths. Decreasing particle size is seen to increase soil reflectance among sand textured soils, but the inverse is true for medium to fine textured soils. Higher moisture contents associated with increasing clay content cause a decrease in reflectance in the 2.08 to 2.32μm band as textures vary from silt loam to clay.

Soils grouped according to temperature regime demonstrate the effects of temperature on soil reflectance properties. Soils generally exhibit higher reflectances with increased temperature primarily as a result of decreased organic matter levels. Soils grouped by moisture zone also tend to increase in reflectance with decreasing rainfall associated with reduced organic matter levels. An exception is the subhumid zone in which organic rich soils formed under prairie grass vegetation reflect less than the predominantly forested humid zone soils. Soil drainage class, as a site characteristic integrating the effects of climate, local relief, and accumulated organic matter, is also found to be closely associated with reflectance properties of surface soils.

Statistical correlation studies for 481 benchmark soil samples show the nature of the relationships between soil reflectance and soil parameters. Reflectance in each of ten wavelength bands is negatively correlated with the natural logarithmic transofrmation of organic matter content, indicating that reflectance decreases very little after a rather high organic matter content is reached. Reflectance in the important 2.08 to 2.32μm wavelength band is also negatively correlated with moisture content, clay content, cation exchange capacity, and iron oxide content, while it is positively correlated with fine and medium sand contents.

Soils grouped according to moisture zone or temperature regime show improved correlations over correlations for all 481 samples, except for the heterogeneous humid and semiarid moisture zones and the frigid and mesic temperature regimes. Greatly varied parent material types, vegetation types, and even topographic differences within these regions may account for the lack of good correlation between reflectance and soil properties. Correlations are best for soils grouped by specific climatic zone. Cation exchange capacity frequently reveals higher correlations with reflectance than do any of the textural classes or even organic matter, an observation supported by the high correlations of CEC with soil parameters that do exhibit spectral behavior such as clay and organic matter.

Prediction models indicate that site characteristics such as climate, parent material, and drainage are important variables along with organic matter, moisture content, texture, and iron oxide content in explaining reflectance differences among 481 soil samples. Organic matter is the single most important variable in the visible and near infrared bands while moisture content is the most important variable in the 2.08 to 2.32μm band for explaining reflectance differences.

Prediction equations using reflectance data in ten wavelength bands as the independent variables show high predictive values for organic matter content, moisture content, content of specific particle size classes, iron oxide content, and cation exchange capacity when inferences are drawn among soils from specific climatic zones. Reflectance bands in the visible, near infrared, and middle infrared repeatedly are included in regression equations for soil properties indicating that all of these wavelength regions are important to an understanding of relationships between soil reflectance and physicochemical characteristics.

Extending these results to the level of airborne remote sensors, it is likely that reflectance data from carefully selected wavelength bands could be used to extract information from bare soil areas that could be related to levels of organic matter, soil moisture, iron oxide content, particle size content, or even an indicator of potential productivity such as cation exchange capacity for certain specified climatic areas. Where prior information is available about soil drainage and parent material classes, even better correlations can be expected within more homogeneous areas of soil inference.

Based on results of statistical analyses as well as on qualitative evaluation of soil reflectance/absorption characteristics, the following wavelengths are critical for identification of soil reflectance characteristics: 0.52 to 0.62μm (green wavelength region highly correlated with organic matter content), 0.7μm and 0.9μm (ferric iron absorption wavelengths), 1.0μm (ferrous iron and hydroxyl gibbsite absorption wavelengths), 1.22 to 1.32μm and 1.55 to 1.75μm (regions of highest reflectance for many soils, correlated with many soil properties), 2.08 to 2.32μm (region of highest correlations with soil moisture). Although spectral bands for the Thematic Mapper mission include 0.52 to 0.60μm, 1.55 to 1.75μm and 2.08 to 2.35μm, the 0.76 to 0.90μm near infrared wavelength band is too broad for specific iron oxide studies in soils, a fact that could limit its usefulness in erosion studies as well as soil productivity surveys.

In summary it can be stated that soils that vary widely in their physicochemical and site characteristics are no more similar in their reflectance properties than are different species of plants throughout their growth cycles. To treat soil reflectance as a constant, unchanging characteristic from location to location and from date to date is to ignore the well-ordered physical and chemical relationships that impart diverse spectral reflective character to soils.

Recommendations

Because of the demonstrated quantitative, repeatable nature of soil reflectance measurements made using the described procedure, consideration should be given to the development of a spectroradiometric measurement procedure as an aid to soil characterization in the laboratory. The purpose would not be to replace soil color standards as they exist, but to supplement them with infrared as well as visible reflectance data. To this end it may be desirable to extend the range of spectral measurements to shorter wavelengths such as 0.4μm to include most of the visible region. Low intensity of moist soil reflectance along with reduced illumination limited the range of noise-free data in this study to 0.52 to 2.32μm.

With the development of laboratory spectroradiometric standards of soil reflectance, the concept should be carried to the field in the form of a portable recording multiband radiometer. Such an instrument would have selectable wavelength bands over the 0.4 to 2.4μm wavelength range and would serve not only for the necessary controlled field study of soil conditions but would also provide the soil surveyor with a more powerful tool with which to determine soil spectral properties.

Serious consideration for future design of satellite spectral bands should be given to the inclusion of narrower wavelength bands in the near infrared more specific for iron content. With the expansion of attempts to use satellite sensor data to study crop inventory in tropical areas of highly weathered soils, spectral bands centered on 0.7, 0.9, and 1.0μm will be essential for thorough characterization of background soil reflectance.

Systematic characterization of the mineralogical and biochemical properties of naturally occurring soils should continue in an effort to help further explain observed reflectance differences in soils. From the collection of almost 250 duplicate benchmark soil samples on hand at the Laboratory for Applications of Remote Sensing it should be possible to identify soils for more detailed study by selection of soil pairs otherwise similar in physical and chemical properties to reduce the effects of extraneous variables.

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APPENDIX

Table 10. Benchmark soil series used in this study, arranged by climatic zone.

climatic zone	state	county	soil series
perhumid mesic	Oregon	Tillamook	Astoria Brenner Hebo Nehalem
		Curry	Blacklock Orford
humid frigid	Maine	Aroostook	Caribou Plaisted
	Massachusetts	Franklin	Berkshire
	Michigan	Baraga	Iron River Munising
		Chippewa	Pickford
		Delta	Angelinca Grayling Onaway Rifle
		Emmet	Emmet
		Ontonagon	Ontonagon
	New York	Lewis	Adams
	Wisconsin	Bayfield	Vilas
		Florence	Pence
		Langlade	Antigo*
		Marathon	Fenwood*
		Polk	Campia Cushing
		Price	Goodman
humid mesic	Connecticut	New Haven	Charlton
		New London	Ninigret*
		Tolland	Hollis
	Illinois	Champaign	Drummer* Flanagan*
		Iroquois	Ridgeville*
	Indiana	Clark	Haymond
		Decatur	Russell*
		Fayette	Genesee
		Knox	Alford*
		Porter	Door*
		Vigo & Clay	Iva

Table 10. (Cont.)

	Iowa	Clayton	Downs*
		Dubuque	Dubuque*
		Howard	Waukee
	Kentucky	Daviess	Newark
		Laurel	Whitley
	Massachusetts	Essex	Sudbury*
		Franklin	Winooski
		Hampden	Agawam*
			Ridgebury*
		Hampshire	Hadley*
		Worcester	Hinckley*
	Michigan	Jackson	Hillsdale
	Missouri	Moniteau	Union
		Scotland	Kilwinning
	New Hampshire	Hillsboro	Acton*
	New York	Chenango	Norwich*
	Ohio	Highland	Cincinnati
		Summit & Medina	Holly
		Tuscarawas	Keene*
		Wayne	Canfield*
	Pennsylvania	Lancaster	Duffield*
			Edgemont*
		Perry	Elliber*
	Virginia	Augusta	Frederick
	West Virginia	Monroe	Murrill
	Wisconsin	Ozaukee	Fox
humid thermic	Alabama	Houston	Red Bay
	Arkansas	Franklin	Enders
		Ouachita	Saffell
		Pope	Linker*
	Florida	Bay	Leon*
	Georgia	Irwin	Ocilla

Table 10. (Cont.)

	Kansas	Montgomery	Verdigris*
	Louisiana	Acadia	Midland
		E. Baton Rouge	Calhoun
		Jefferson	Kenner
		Ouachita	Rilla
		Tensas	Commerce
		Union	Ruston
	Mississippi	George	Susquehanna
		Grenada	Grenada
	North Carolina	Alamance	Appling
		Cabarrus	Mecklenburg*
		Catawba	Cecil
		Craven	Craven*
		Scotland	Wagram
		Washington & Hyde	Ponzer
	Oklahoma	Tulsa	Newtonia
	South Carolina	Florence	Rains
		Spartanburg	Pacolet
	Tennessee	Coffee	Dickson
			Mountview
		Humphreys	Bodine
		Rutherford	Cumberland
			Talbott
	Texas	Smith	Kirvin*
humid hyperthermic	Florida	Lee	Myakka
			Pompano
		Pasco	Basinger
		Hernando	Wabasso
		Palm Beach	Terra Ceia
		Martin	Paola
subhumid frigid	Minnesota	Cass	Warba
		Grant	Roliss
		Isanti	Anoka
		Kittson	Grygla
			Redby
		Lake of the Woods	Cormant
			Taylor

Table 10. (Cont.)

		Ottertail	Buse
		Pope	Langhei
		Stevens	Flom
	Montana	Missoula	Greenough*
			Tarkio*
	Nevada	Douglass	Toiyabe*
	North Dakota	LaMoure	Svea
		Ransom	Tonka
		Wells	Divide
	South Dakota	Brown	Beotia
			Exline
		Codington	Fordville
			Renshaw
		Roberts	Peever
subhumid mesic	Iowa	Clay	Sac
		Crawford	Ida
		Harrison	Monona
		Monana	Haynie
	Kansas	Cloud	Hedville
		Geary	Irwin
		McPherson	Goessel*
		Saline	Lancaster
	Minnesota	Martin	Nicollet
		Steele	Canisteo
			Glencoe
		Rice	Hayden
		Waseca	Cordova
	Nebraska	Buffalo	Hord
		Clay	Hastings*
		Holt	Jansen*
		Thomas	Loup
		Thurston	Crofton
		Webster	Gibbon
	South Dakota	Davison	Betts
			Stickney
			Tetonka
		Gregory	Boyd

Table 10. (Cont.)

subhumid thermic	Kansas	Pratt	Pratt
	Oklahoma	Cotton	Foard
		Grady	Port
		Lincoln & Payne	Darnell
		Kay	Renfrow
		Oklahoma	Bethany
			Canadian
			Zaneis
		Payne	Dougherty*
		Roger Mills	St. Paul
		Washita	Dill
	Texas	Bell	Brackett
		Anderson	Elrose
		Coryell	Denton*
			Frio*
		Kaufman	Trinity
		Parker	Windthorst
		Menard	Tarrant
subhumid hyperthermic	Texas	Cameron	Willacy
		Nueces	Victoria
semiarid frigid	Montana	Hill	Chinook
			Elloam
		Liberty	Ethridge
		Roosevelt	Lihen*
		Toole	Joplin
		Valley	Marias
		Yellowstone	Absarokee
	New Mexico	McKinley	Fortwingate
	North Dakota	Bowman	Ekalaka
semiarid mesic	Colorado	Crowley	Glenberg
			Apishapa
		Elbert	Kutch
		Prowers	Haverson
			Kornman
			Minnequa
			Rocky Ford
			Wiley
	Kansas	Grant	Richfield
		Hamilton	Colby

Table 10. (Cont.)

	Montana	Yellowstone	Keiser
	Nebraska	Dawes & Box Butte	Alliance
	Nevada	Humboldt	Rio King*
		Douglass	Indian Creek*
			Mottsville*
			Ophir*
			Ormsby*
			Reno*
			Turria*
	South Dakota	Todd	Tuthill
	Texas	Sherman	Sherm
	Utah	Millard	Palisade
			Pharo
semiarid thermic	Arizona	Santa Cruz	White House
			Pima
	New Mexico	Lea	Jal
			Kimbrough
		Roosevelt	Portales
	Texas	Andrews	Triomas
		Lamb	Amarillo
		Lubbock	Acuff
		Lynn	Patricia
		Upton	Reagan
semiarid hyperthermic	Texas	Hidalgo	Hidalgo
			Sarita
		Jim Wells	Clareville
		Zavala	Uvalde*
		Kinney	Montell
arid frigid	Colorado	Alamosa	Mosca
		Alamosa & Conejos	LaJara

Table 10. (Cont.)

arid mesic	Nevada	Churchill	Appian
			Carson
			Dia
			Pirouette
		Pershing	Blackhawk
			Humboldt
			Lovelock
			Placeritos
			Ryepatch
			Sonoma
		Eureka & Elko	Cortez
		Humboldt	Bloor*
			Ninch*
			Valmy*
	Utah	Millard	Abbott
			Harding
arid thermic	Arizona	Santa Cruz & Pima	Continental
		Graham	Gila*
			Glendale*
	Nevada	Clark	Bitterspring*
			Calico*
			Land*
			McCarran*
			Morman Mesa*
			Overton*
			Toquop*
			Virgin River*
	Texas	Pecos	Hodgins
arid hyperthermic	Arizona	Yuma	Superstition*

*non-randomly chosen soil series selected to facilitate sampling by SCS field parties assigned to certain counties.