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The Effects of the Physical and Chemical Properties of Soils on the Spectral Reflectance of Soils

by

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ABSTRACT

Many attempts have been made to use multispectral data to map soils on the basis of soil color, texture, organic matter content, moisture content, and free iron oxides. Researchers have endeavored to differentiate soil series and soil types, using those parameters individually. Reflective properties have been attributed primarily to one or two of these parameters. Little has been revealed as to the nature of the natural interactions occuring between those parameters. Scientists have suggested that a more complete understanding of the radiation properties of specific soil constituents and their interactions is needed before one can optimize the use of multispectral separability in differentiating soil series and soil orders.

The objectives of this study are twofold: (1) To evaluate quantitatively the effects of organic matter, free iron oxides, texture, moisture content, and cation exchange capacity on the spectral reflectance of soils, and (2) to develop and test techniques for differentiating soil orders by computer analysis of multispectral data.

By collecting 71 soil samples of benchmark soils from the different climatic regions within the United States (having different vegetative cover types, parent materials, and geological history) and using the extended wavelength field spectroradiometer (Exotech Model 20B) to obtain reflectance values and curves for each sample, average curves were constructed for each soil order (excluding Oxisols and Histosols).

Multiple regression analyses were performed, using the spectral data as the dependent variables and physical - chemical properties as independent variables. The independent variables showing the highest correlation with the multispectral measurements were CEC and silt content. These results suggest that multispectral analysis may be a valuable tool for delineating and quantifying differences between soils.

INTRODUCTION

Man has strived for many years to classify the world about him in a logical manner. Soils, being a necessary part of man's existence on this planet, have been of prime importance in classification schemes. Methods have been developed to arrange and sort soils into various meaningful categories, primarily using soil color, texture, organic matter, climatic conditions and parent material. Ground mapping of soils is the most widely used method of categorizing soils for use by man. Over 20 million hectares in the United States are mapped annually. Ground mapping of soils is a tedious and time consuming task and leaves much to be desired in terms of proficency and accuracy.

In recent years we have witnessed dramatic advances in the measurement of radiant energy to identify and characterize earth surface features. A wide variety of instruments have been employed to measure reflected and emitted energy from targets or subjects of interest (4, 10, 12, 20). Soil surveyors have never had a reliable field instrument with which they could make quantitative measurements related to soil color as well as the radiation characteristics of soils beyond the visible region of the electromagnetic spectrum. However, laboratory studies have shown relationships between certain chemical and physical soil properties and the radiation characteristics of the soil (3, 4, 6, 19), which indicate that a field instrument capable of measuring simultaneous radiation characteristics over a wide range of wavelengths will provide a valuable tool for soil research. It has also been shown that spectral classes of soils, as mapped using computer-implemented pattern recognition techniques, correlate with Soil Survey mapping units to some degree. However, it is also known that surface conditions can affect spectral properties of soils as measured by an airborne multispectral scanner. The strong effects on soil reflectance of certain soil constituents may mask the effects of other constituents. It is known that if there were a 1:1 correspondence between soil classes as mapped by the soil survey and spectral classes as mapping using remote sensing that this would be extremely valuable information.

The objectives of this study are twofold: (1) To evaluate quantitatively the effects of organic matter, free iron oxides, texture, moisture content, and cation exchange capacity on the spectral reflectance of soils, and (2) to develop and test techniques for differentiating soil orders defined by the **Soil Taxonomy** , by computer analysis of multispectral data.

Spectral reflectance curves in the wavelength region 0.5 to 2.32μm were generated for 71 soil samples from different climatic regions in the United States. Multiple regression analyses were performed, using the spectral data as the dependent variables and physical - chemical properties as independent variables. The independent variables showing the highest correlation with the multispectral measurements were CEC and silt content. These results suggest that multispectral analysis may be a valuable tool for delineating the quantifying differences between soils.

CHAPTER I

REVIEW OF LITERATURE

Gates (8) reported that the quality and intensity of reflectance and emittance from soils and plants depend upon the soil, the climate, and the geometry, morphology, chemistry, and physiology of the green plant. As any of these soils and plant variables change, the quality and quantity of radiation from a scene will be affected. The total radiation flux within a given site is highly variable, changing with time of day, season, weather and other factors. The variation of the total radiation flux from one site to another on the earth's surface is enormous. Accurate measurement of the incident radiant flux on a surface is extremely difficult because of problems of instrument calibration and in stability. The difficulty is partially absolved, however, when one recognizes the variability of solar and thermal radiation incident on a neutral surface and realizes that an absolute accuracy better than 90% is probably not necessary. The variability of solar and thermal radiation incident at the ground is the result of atmospheric changes, such as cloud, wind, air temperature, and precipitation.

The interaction of radiant energy with plants and soils can be measured under field conditions in different ways and with different spectral instruments. Krinov (12) worked in the field with spectrographs mounted on tripods and with spectrographs mounted in an aircraft. Olson (11) made field spectral measurements with a trailer-mounted Beckman DK-2A spectroreflectometer. Cipra et al (5) recorded spectral measurements of different soils with an Exotech Model 20 spectroradiometer. Holmes (10), describing techniques of spectroscopy, suggested a field spectroscope with a relatively small field of view capable of scanning subjects of interest with a rotating mirror in a rectangular, television-like roster. The input in various spectral bands are detected simultaneously and recorded in parallel on magnetic tape. An airborne multispectral scanning system has been used by the Laboratory for Applications of Remote Sensing (LARS), Purdue University, to obtain electromagnetic radiation data from many field experiments (16, 17).

Many researchers have addressed themselves to the task of evaluating various techniques being used and the inherent problems in this highly complex mechanized approach to mapping and classifying earth surface features. The fruits of their efforts have been great and are steadily increasing as they have gained a better understanding of energy-matter interactions. This literature does not represent an exhausted treatise in the area of remote sensing. Rather, it reflects only that portion of research, known to the author and considered pertinent to his research problem.

Zachary et al (24), in a study of Indiana soils using multispectral remote sensing techniques, concluded that there was a definite relationship between multispectral imagery and soil types. Large areas of bare soil could be mapped rapidly by computer techniques and these maps provide the soil scientist with a useful supplement to aerial photography when making soil surveys.

Kristof (13) and Kristof and Zachary (14) reported partial success in mapping soil types with multispectral scanner data and computer implemented pattern recognition techniques. Six categories of soil surface conditions can be mapped with reasonable accuracy by computer techniques. Soil series are conventionally differentiated by surface and subsurface properties, so surface differences may not be observable in all cases. Kristof's study was confirmed by Cipra et al (4) when they used a field spectroradiometer to measure the reflectance of samples representing seven Indiana soil series under field conditions. They attributed the percentage of visible incident energy reflected to soil color, texture, organic matter content, moisture content and surface conditions. Descriptions of the soil series studied - three Alficols, two Mollisols, one Entisol, and one Histosol - are listed in Table 1. These soils have a wide range of internal drainage characteristics under their normal field conditions.

Table 1. Description of seven soil series studied

Soil	Texture	Order	Drainage	Dry Munsell Color	Organic matter, %
Fincastle	Silt loam	Alfisol	Somewhat poor	10YR6/2	2.9
Chelsea	Sand	Entisol	Well	10YR5/2	2.1
Chalmers	Silty clay loam	Mollisol	Very poor	10YR4/1	5.9
Fox	Sandy loam	Alfisol	Well	10YR6/2	0.6
Crider					
A horizon	Silt loam	Alfisol	Well	10YR6/3	2.5
B horizon	Silty clay			7.5YR6/4	0.3
Maumee	Sandy loam	Mollisol	Very poor	N4	2.7
Carlisle	---	Hiltosol	Very poor	5YR4/1	---

Spectral curves for two Alfisols, Fox sandy loam and Fincastle silt loam, in both wet and dry conditions were plotted (Figure 1). The curve for the dry Fox sandy loam was distinctly different from any of the other curves. Following an initial steep rise, it had a steeper rise at .5μm and increased to greater than 55% reflectance at .73μm - the highest reflectance of any soil studied. A distinguishing feature of the two curves for the Fox sandy loam was the great spacing between the wet and dry curves. In an air-dry condition, Fox contained less than 1% moisture; in the wet condition it contained 11% moisture (Table 2). Fincastle had a moisture content of 3% when dry and 23% when wet.

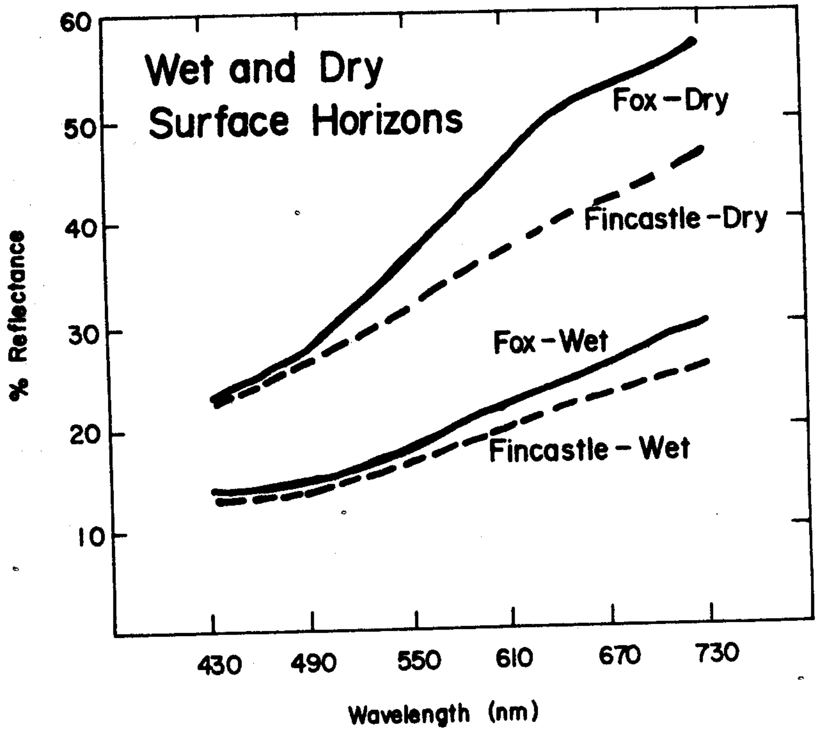

Figure 1. Percent reflectance at visible wavelengths from two Alfisols in wetted and air-dry noncrusted conditions.

Table 2. Moisture content of wetted and air-dry samples when spectra were obtained

Soil	% moisture Air-dry sample	% moisture Wetted sample
Fincastle	3.45	23.35
Chelsea	0.80	14.06
Chalmers	5.65	31.10
Fox	0.02	10.61
Crider		
A horizon	2.84	28.44
B horizon	5.02	32.55
Maumee	0.88	15.82
Carlisle	33.37	74.90

Similarities between the reflectance curves of two Mollisols and a Histosol were observed (Figure 2). Maumee, a black sandy loam, had a slightly higher reflectance than did Chalmers or Carlisle, but exhibited the same gently sloping curve which seem to be characteristic of very dark colored soils. The similarity between the reflectance curves for Carlisle muck and Chalmers silty clay loam presented difficulty in distinguishing these two soils spectrally when only the visible portion of the spectrum was used. The reflectance curve for the Crider A horizon contrasted sharply with the curves for Maumee, Carlisle, and Chalmers soils.

As anticipated, Mollisols (Chalmers and Maumee) could be distinguished easily from Alfisols (Crider, Fox, and Fincastle), by their reflectance curves. However, a light-colored, very sandy Entisol (Chelsea sand) had a curve similar to those of Alfisols. A very dark-colored, sandy

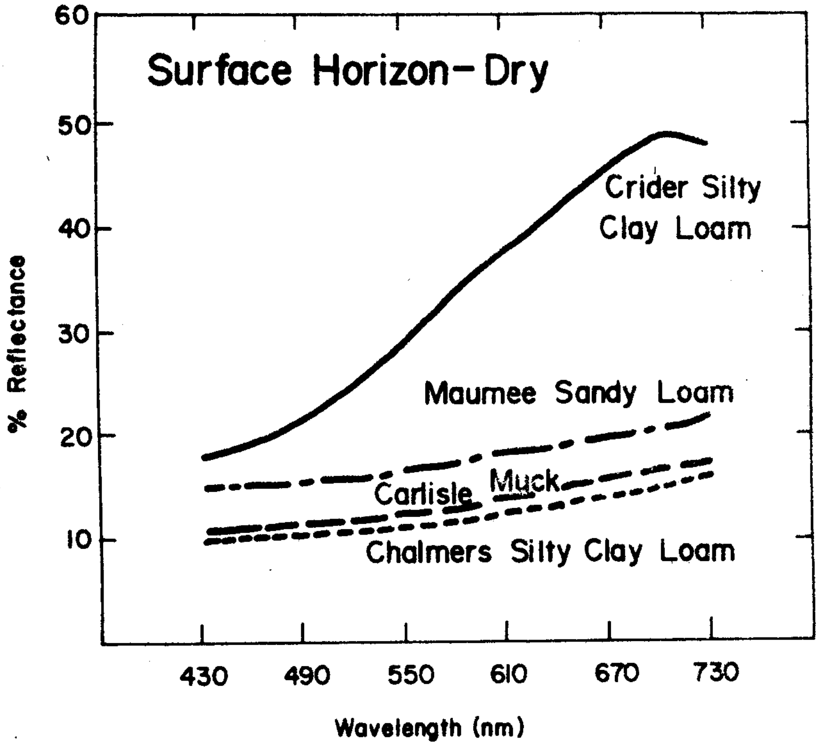

Figure 2. Percent reflectance at visible wavelengths for three dark colored soils and a light colored soil.

Mollisol (Maumee sandy loam) had a curve similar to that of Chalmers silty clay loam (a Mollisol), but had a higher reflectance throughout the visible spectrum. A Histosol (Carlisle) was almost indistinguishable from Chalmers silty clay loam, a Mollisol, at the wavelenghts studied.

In the laboratory, Bowers and Flanks (3), measured reflectance in the spectral range .400 to 2.500μm of four Kansas soils. They concluded that the surface moisture and organic matter strongly influence the reflectance and absorbance of solar radiant energy by soils. Baumgardner et al (2) demonstrated that multispectral data obtained with an airborne optical-mechanical scanner can be used with computer implemented pattern recognition techniques to produce maps which deliniate soils containing different amounts of organic matter. In this study the desired task was to obtain a computer printout (or map) of the test site showing the location of soils having five levels of organic matter. The organic matter content and corresponding spectral responses of twelve wavelength bands for each soil sample location were used to train the computer. The samples were divided into five levels of organic matter content (Table 3). The computer classified each resolution element of each scan line in the test site using a pattern recognition technique which utilized the data provided by the training samples.

Table 3. Number of samples in each of five levels of soil organic matter used for training the computer

Percent Organic Matter	Number of Samples
3.5	46
2.5 - 3.5	37
2.0 - 2.5	18
1.5 - 2.0	63
0 - 1.5	46

To provide a laboratory model of the soil patterns on the test site area a soil mosaic was constructed with the use of portions of each of the 197 surface soil samples (Figure 3a). This mosaic provides a good general representation of the soils patterns of the field. A photograph of a computer printout (Figure b) showing five different levels of organic matter in the field is shown for comparison with the soil mosaic. This organic matter map compares very well with the color patterns observed in the soil mosaic. The depressional soils which have the greatest amount of organic matter lie near the broad drainage ditch. The lower righthand area of the illustration having a high organic matter content is also indicated.

Average radiance levels of the twelve wavelength channels were plotted against soil organic matter content of each sample location. When relative response for the spectral range 0.62 to 0.66μm was plotted against organic matter content, an r value of 0.74 was obtained (Figure 4). However, the plotted data seem to indicate that perhaps a linear relationship may not be valid over the observed range of organic matter. It appears that above 2.0 percent organic matter, there may be a linear correlation with a much higher r value. Below 2.0 percent organic matter, the curve becomes much steeper. It appears that organic matter plays a dominant role in bestowing spectral properties upon the soil when the organic matter content exceeds 2.0 percent. As the organic matter drops below 2.0 percent it becomes less effective in masking out the effects of other soil constituents such as iron or manganese on spectral response of soils.

Condit (6) examined the spectral properties of 160 surface soil samples collected at various locations across the United States. Measuring percent reflectance in the .320 to 1.000 m wavelength region under laboratory conditions, he concluded that the general shapes of the spectral curves could be classified into three types. These three types of curves could be represented by the chernozem type soils, the pedalfer type silts, and the laterite type soils.

All soil samples were thoroughly dried before they were prepared for measurement. In some instances the soil dried in the form of clumps or aggregates which were reduced in size by placing them in a mortar and pressing the pestle against them with sufficient pressure to separate the aggregates into individual and small groups of particles.

Figure 3. General soil patterns of test site D.

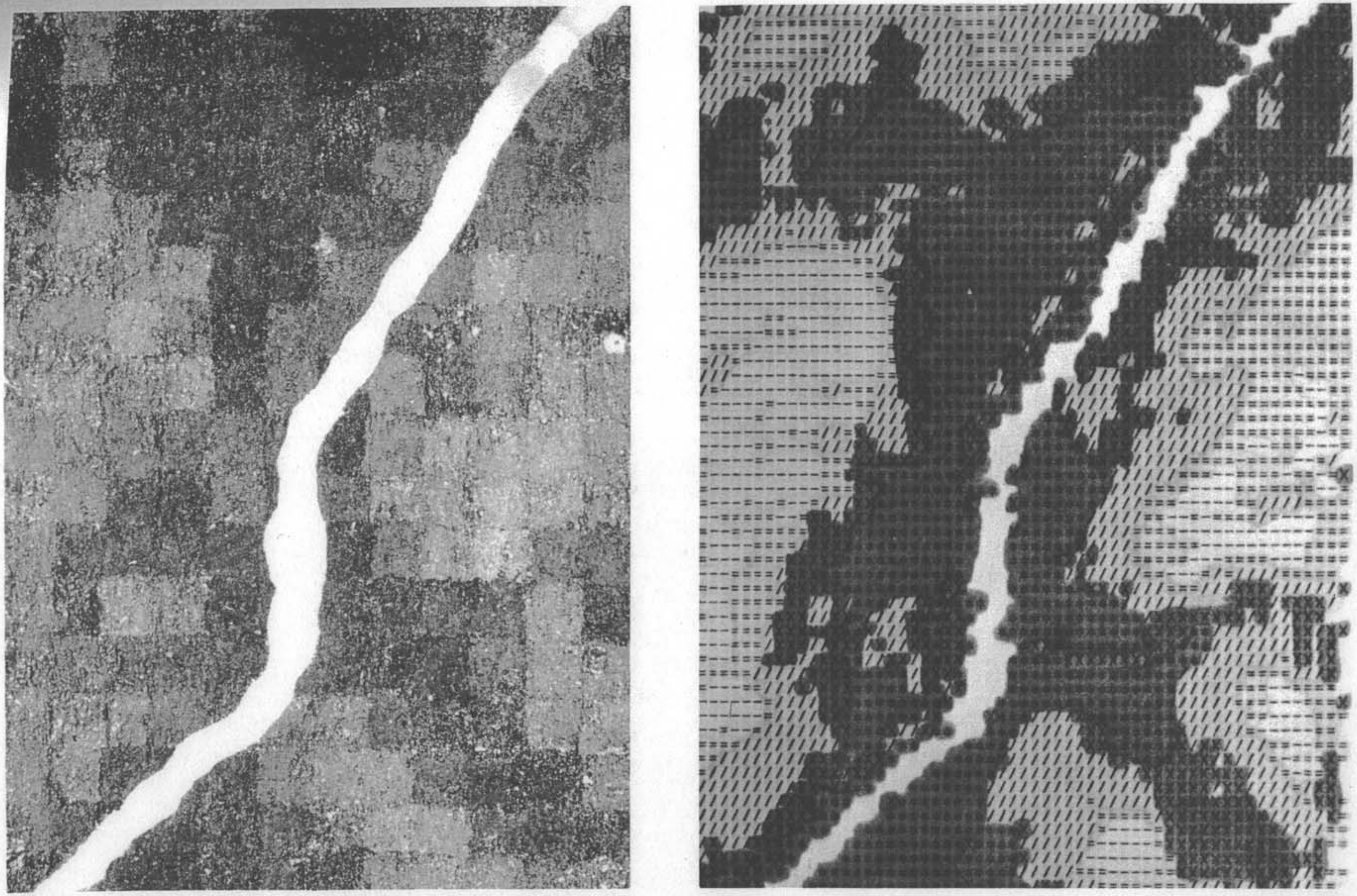

Figure 3.

Figure 4. Correlation between average radiance level (relative response) and organic matter content for 197 samples from Test Site D.

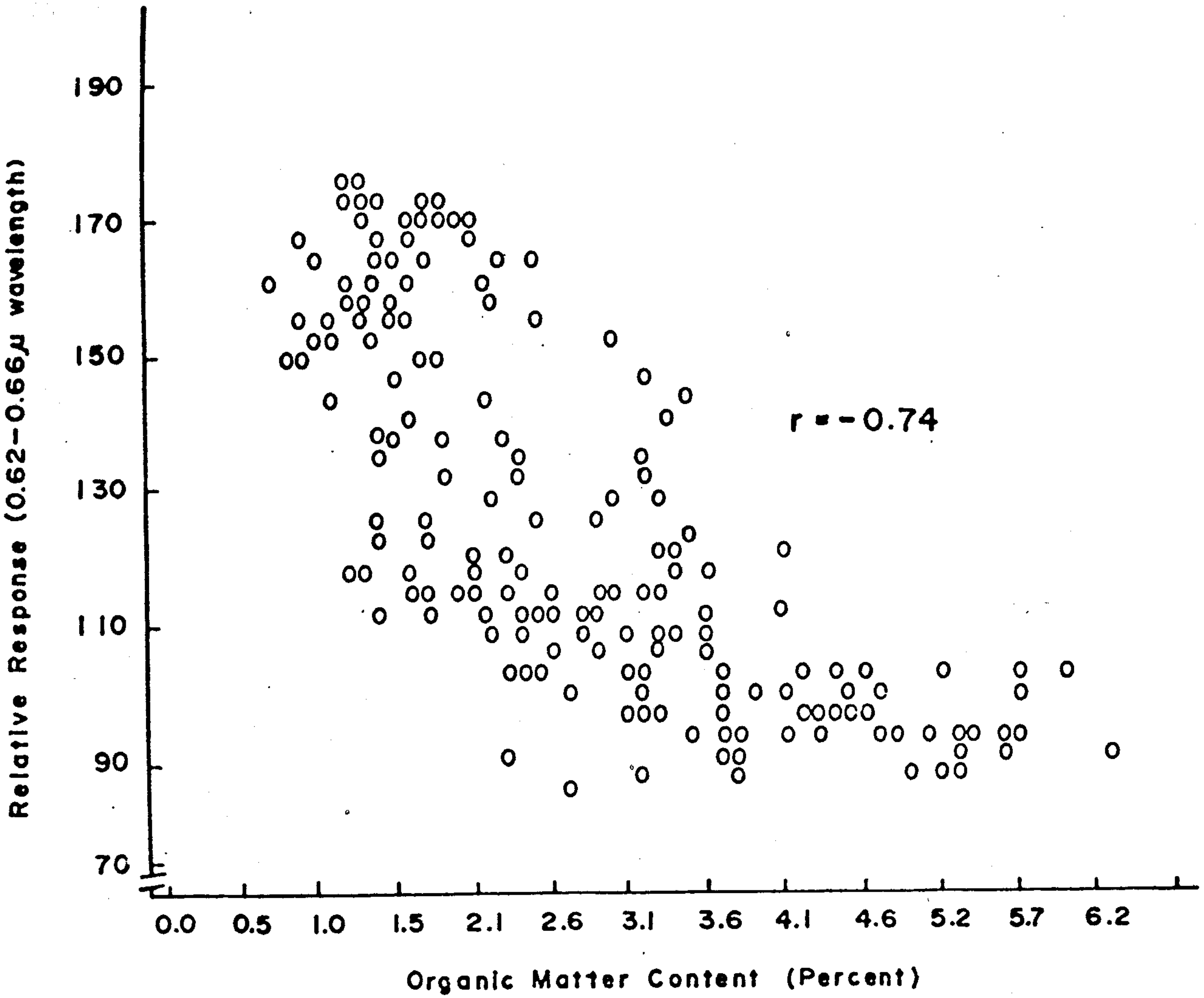
r = -0.74
Relative Response (0.62–0.66μ wavelength)
190
170
150
130
110
90
70
0.0
0.5
1.0
1.5
2.1
2.6
3.1
3.6
4.1
4.6
5.2
5.7
6.2
Organic Matter Content (Percent)

Figure 4.

An examination of the 160 sets of curves obtained indicated that the general shape of the curves can be classified into three types. The distinguishing features of Type 1 soils, presented by chernozem type soils, is that over any range of wavelengths the slope, with minor exceptions, either increases or is nearly constant. Most samples having Type 1 general shape are those with rather low reflectance.

The reflectance curves of Type 2 soils, pedalfer type silts increase fairly rapidly, especially for the dry curve, from .320 to about .450μm where a slight or even moderate dip in the slope occurs (Figure 6). Then follows an increase in the slope at about .48μm. At about .58μm another decrease in the slope is seen. From .600 to about .700μm a slight - to - moderate dip in the slope is generally present. At about .750μm the slope decreases again. Beyond .780μm the slope usually changes very little with increasing wavelength.

Type 3 curves (Figure 7), represented by red quartz and calcite sand, increase at a moderate rate from the ultraviolet region to about .530μm, then rises sharply to about .580μm, where a definite decrease in the slope appear. From about .620 to .740μm a slight - to - moderate dip in the slope is usually present. At .740μm another definite decrease in the slope occurs, often dropping to or near zero.

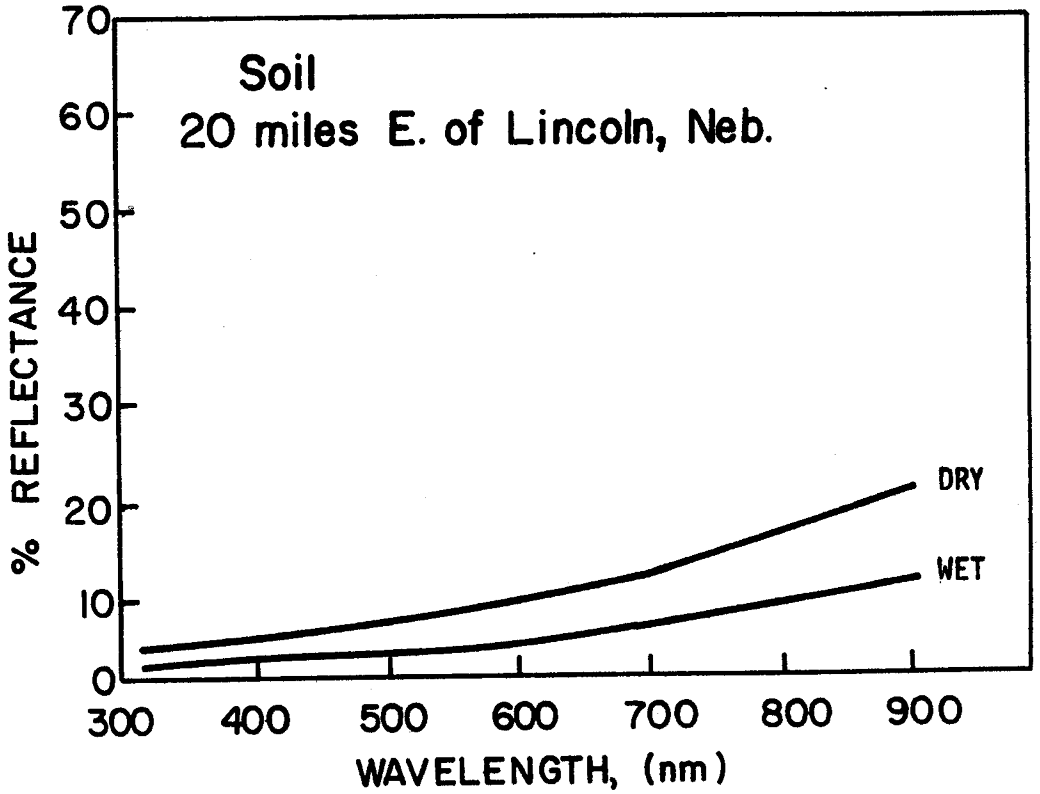

Figure 5. Type 1 curves for a sample of chernozem-type soil

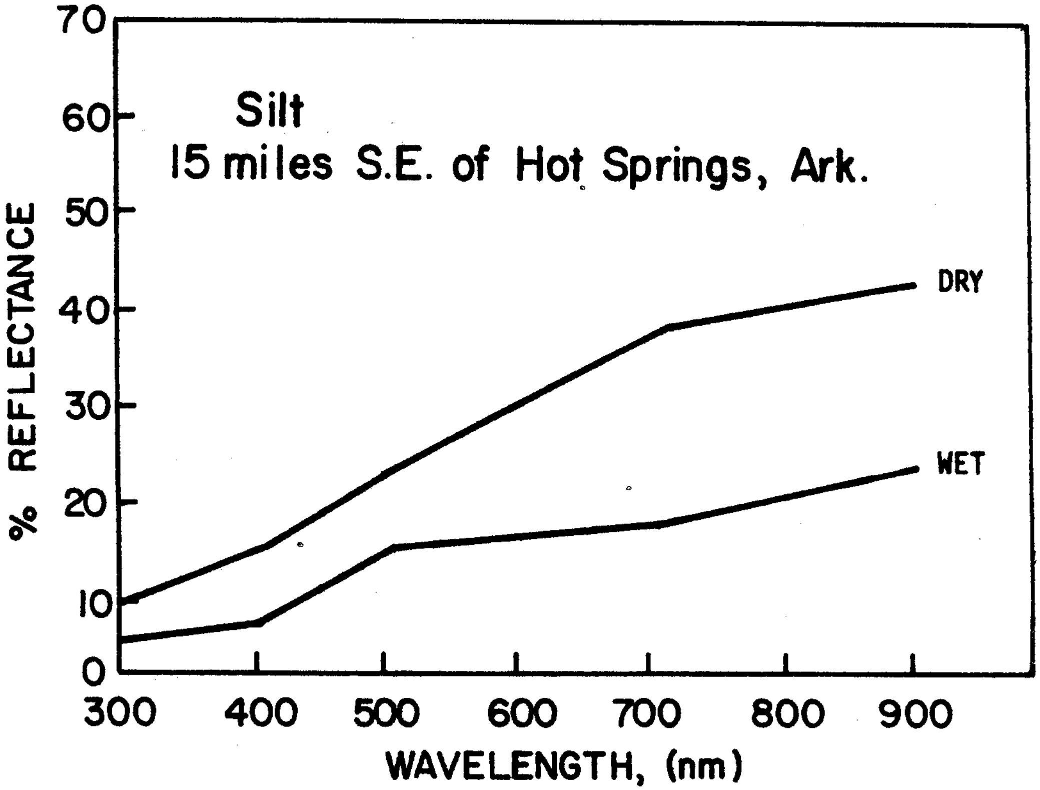

Figure 6. Type 2 curves for a sample of pedalfer-type silt.

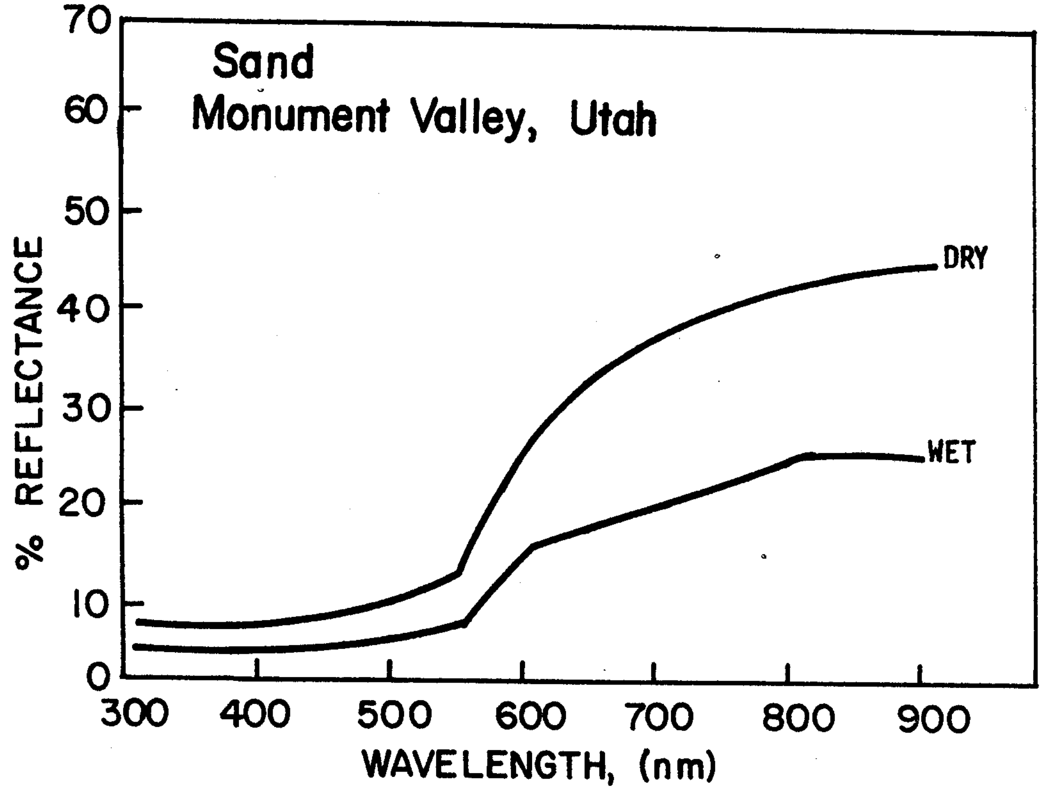

Figure 7. Type 3 curves for a sample of red quartz and calcite sand.

The necessity for extending the spectral reflectance measurements to 1.000μm and beyond can be seen from the fact that while two samples are quite similar through the ultraviolet and visible regions of the spectrum, they may by quite different in the infrared.

Mathews (19), working with data collected on a Hagerstown silt loam using a Beckman DK-2A spectrometer, reported that clay type and the amount of organic matter, Fe_2O_3, and silt influence the intensity of the energy reflected by soils in the 0.5 to 2.6μm range. He indicated that organic matter and Fe_2O_3 influenced the reflectance in the 0.5 to 1.2μm range; while clay type influenced curve shape and intensity over the entire range studied. For the Hagerstown silt loam, silt was highly correlated with percent reflectance at a number of infrared wavelengths ranging from 0.8 to 2.50μm.

Samples high in organic matter or iron content show a marked response in the 0.5 to 1.15μm region when organic matter or iron is removed, (Figure 8). However, not all soils studied show these well-defined changes. The reflectance of Hagerstown surface soils with two to three precent organic matter changed only slightly when organic matter was removed. Surface soils with 3% free iron oxide showed only slight absorption in the iron absorption band (0.9μm).

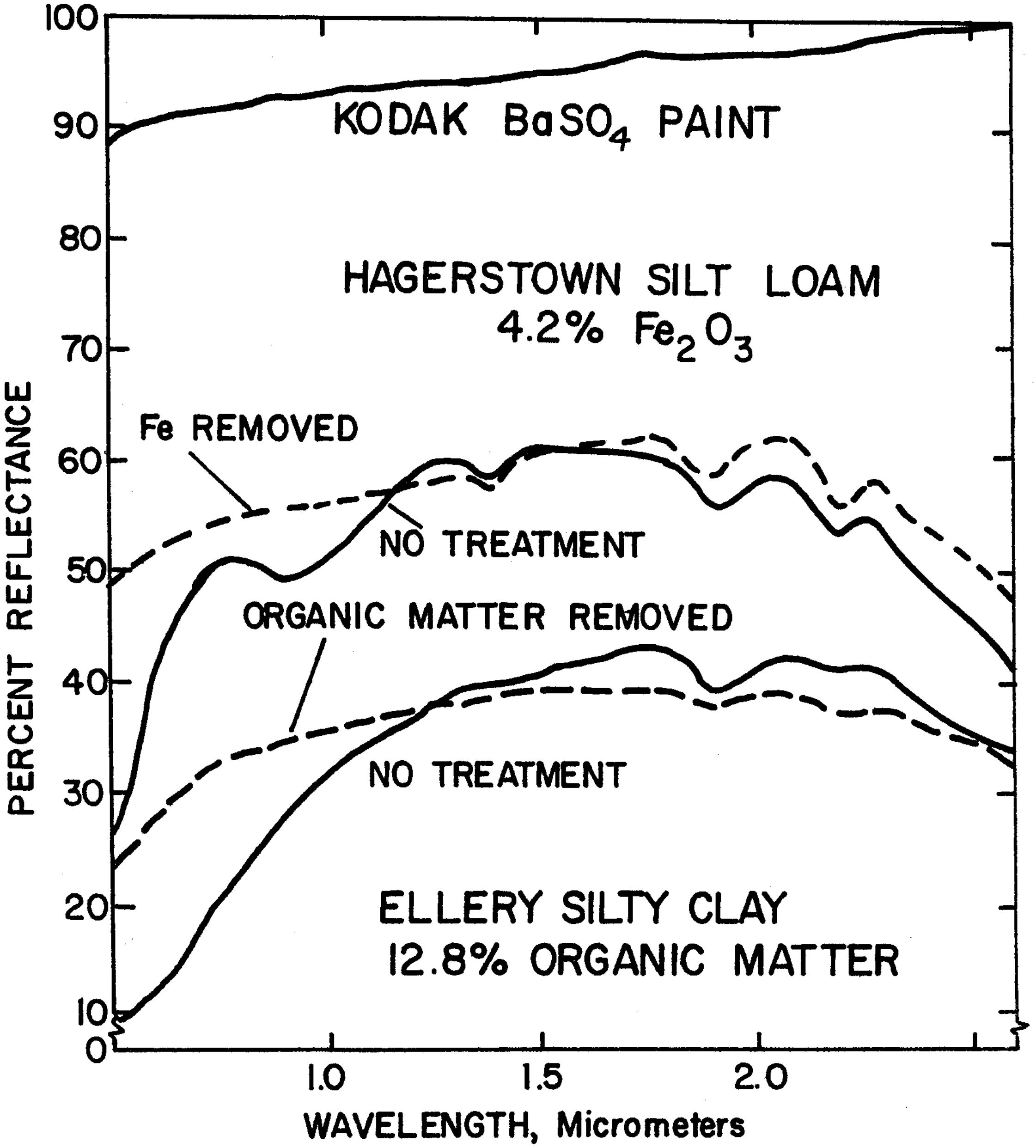

Figure 8. Spectral reflectance curves illustrating the effect of free iron oxide and organic matter on reflectance intensity (Hagerstown curve from the B21t horizon).

Samples of Ap horizons for profiles developed from contrasting parent materials (limestone, shale, and sandstone) exhibit contrasting spectral curves (Figure 9). The weak response of these samples to the water absorption bands is probably due to their low clay content (Table 4). Hagerstown, developed from limestone, contained more than twice the amount of clay as the Berks or Penn and showed a stronger response in the hydroxyl absorption bands than either of the other samples. Berks, developed from shale and low in both Fe_2O_3 and clay, showed no response in the 0.9, 1.4 and 1.9μm bands. Penn, developed from red Triassic aged sandstone, showed a weak response in the 0.9 and 2.2μm bands but no response in the 1.4 and 1.9μm bands. Not the differences in the shape of the three curves.

Table 4. Clay, Fe_2O_3, and organic matter content of the Ap horizons of three Pennsylvania soils

Soil	Clay	Fe_2O_3*	Organic Matter
	%		
Hagerstown	24	3.2	2.75
Berks	6	1.4	4.77
Penn	12	2.1	2.54

*Iron determined by the sodium dithionite-citrate-bicarbonate procedure.

Digitization of points along the spectral curves allowed correlation of the percent reflectance at several selected wavelengths with the morphological, chemical, and physical properties of the Hagerstown silt loam. Initial

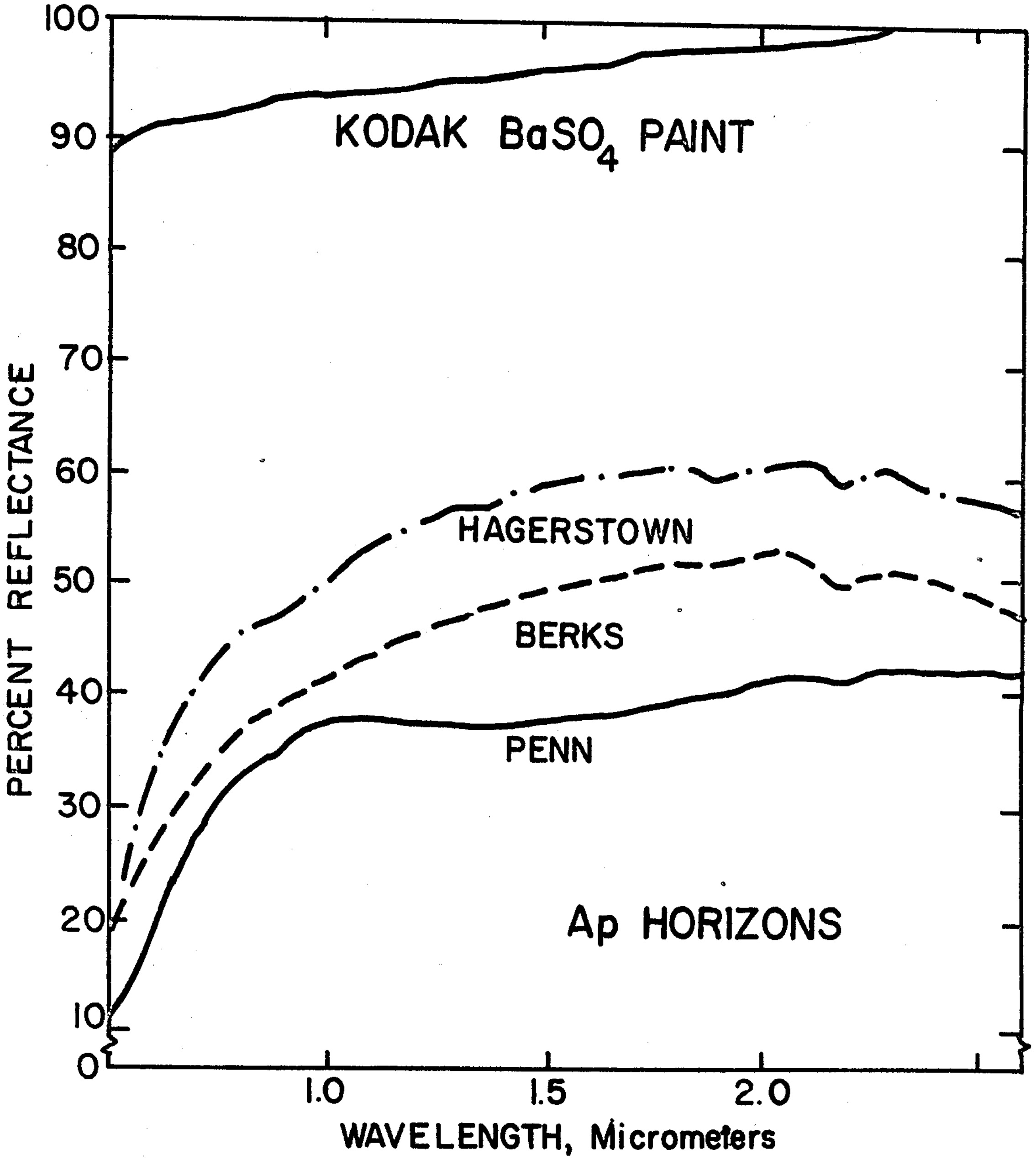

Figure 9. Spectral reflectance curves of the Ap horizons of Hagerstown, Berks, and Penn silt loams; soils developed from limestone, shale, and sandstone respectively.

simple correlations indicated that silt, clay, and iron oxide content were highly correlated with reflectance at a number of wavelengths. These three variables along with sand, carbon, hue, value and chroma were entered into multiple correlation analysis (Table 5). The results presented (Table 6) indicate that silt is the most important variable of those studied in explaining the variability of reflectance intensity at different monochromatic wavelengths. Silt, sand, Fe_2O_3, value, and organic carbon were the variables which explained significant amounts of variability for wavelengths shorter than 0.8μm; silt and chroma were the significant variables for wavelengths between 0.8 and 2.6μm.

Table 5. Summary of data used in multiple correlation analysis (data from three Hagerstown profiles, 19 horizons)

Soil Characteristic	Expressed In	Mean	Standard Deviation
Sand	%	12.2	9.3
Silt	%	42.4	19.2
Clay	%	45.5	24.1
Carbon	%	0.4	0.5
Fe_2O_3	%	4.6	1.2
Hue	Munsell Notation	3.2*	0.9
Value	Munsell Notation	4.3	0.5
Chroma	Munsell Notation	5.2	1.8

*Hue: 2.0 = 2.5YR, 3.0 = 5YR, 4.0 = 7.5YR.

John Shields of the University of Saskatchewan, conducted an investigation into the application of trichromatic analysis and organic matter fractionation to the

Table 6. Statistical relationships between soil properties from three Hagerstown profiles and the reflectance intensity of selected monochromatic wavelength bands

Dependent Variable	Independent Variables	Standard Regression Coefficient	Multiple Correlation Coefficient
Wavelength in Microns	Soil Property		
0.5	Fe_2O_3*	-.51	.81**
	Sand*	-.49	
	Value*	.31	
	Silt	.30	
0.6	Silt*	.90	.72**
	Carbon*	-.61	
	Sand	-.40	
0.7	Fe_2O_3	-.40	.40
0.8	Silt**	.88	.79**
	Chroma*	.41	
	Sand	-.24	
0.875	Silt**	.85	.81**
	Chroma	.31	
1.0	Silt**	.86	.88**
	Chroma*	.37	
	Hue	.17	
1.375	Silt**	.86	.81**
	Chroma	.31	
1.60	Silt**	.80	.76**
	Chroma	.28	
1.90	Silt**	.90	.86**
	Chroma	.20	
2.05	Silt**	.87	.87**
	Chroma	.23	
2.18	Silt**	.82	.87**
	Hue	.16	
2.50	Silt**	.88	.92**
	Hue	.12	

*Significant at 5% level. **Significant at 1% level.

study of soil colors (21). Shields reported that the decrease in value observed among the samples taken from the Brown, Dark Brown and Black Soil Zones was accompanied by a general trend of increasing carbon content. A similar but less apparent trend at a higher value level appeared for the transitional grassland - forest and forest soils indicating that these soils have a higher value per unit organic carbon. This suggested that the organic carbon of these soils is of a different nature than that of the samples taken from the Brown, Dark Brown and Black Soil Zones. The latter observations became more evident when the organic matter of the selected samples was characterized according to the humus composition, the nature of the humic acids, and the amount of the humic acids which were free or banded to nonsilicate sesquioxides. On this basis, it was found that samples representative of the transition grassland - forest and Gray Wooded Zone segregated themselves from the samples representative of the Brown, Dark Brown and Black Soil Zones. The results further indicate that the nature and composition of the organic matter in surface soils representative of the Brown and Dark Brown Soil Zones were similar, but differed from the organic matter representative of the Black Soil Zones.

Spectra of Indiana soils examined by Hoffer and Johannsen (9) showed strong absorption bands at approximately 1.4 and 1.9μm. They noted differences in the spectral characteristics in sandy and clayey soils and a difference in intensity of reflectance for samples with high and low moisture contents. Adams and Filice (1) demonstrated with spectral reflectance curves between 0.4 and 2.0μm that the reflectance of silicate rock powders increased with reduction of particle size. They concluded that mineralogy and particle size were the most important variables affecting the spectral reflectance of basic - ultrabasic rock, crystalline acidic rock, and rock glass. Shape and packing also contributed to differences in spectral characteristics.

Iron absorption is attributed to three features: (1) a band at 0.9 to 1.1μm attributed to the electronic structure of ferrous iron, (2) a band at 0.7 to 0.8μm corresponding to the maximum valence state of ferrous-ferric iron, and (3) a band at 1.9 to 2.4μm attributed to ferrous iron associated with pyroxenes. Condit (6) examined the 0.3 to /μm range of reflectance of 160 soils of the United States and concluded that measurements at only 5 wavelengths can predict the spectral reflectance of a wide variety of soils. Bowers and Hanks (3) secured data which indicated that surface moisture content, organic matter, and particle size strongly influenced soil reflectance.

CHAPTER II

METHODS AND MATERIALS

Any attempt at analyzing enough soil samples to obtain a group representative of the Continental United States and have members of all soil orders present involves the awesome task of collecting and assimilating the samples at one laboratory or convienent local. Researchers have always been confronted with the question, "How much of a sample do we need?" Soils present an economic problem when large amounts have to be sent long distances through any of the available transportative agencies. Storage of the unwanted portions of the samples is an even greater problem. Researchers are constantly wrestling with these and many other problems as they extend their research beyond the "localized experiment." Knowing the minimum sample size would remove and drastically reduce many of the problems encountered.

The author has conducted a preliminary study which deals with the problem of minimum sample size for his particular research problem. The objective of this study was to ascertain the minimum soil sample thickness required to provide adequate spectral measurements free of background effects. The cylindrical Kubulka-Monk sample-holders

(Appendix 1), designed to determine the minimum depth of samples, consist of solid aluminum cylinders, one painted with Krylon gloss white and the other gloss black spray paint and a brass ring which fits tightly around each cylinder and is free to move up and down along the wall of the cylinders. Screws which protrude through the wall of the ring, when tightened, hold the ring at a desired height above the Krylon gloss painted surface of the cylinder.

Data were collected on a soil sample taken from the Chalmers soil series (Typic Argiaquoll). The sample was analyzed at depths of 2mm, 4mm, 8mm, 15mm and 31mm. Examination of the spectral curves generated indicated that at a depth of 15mm the differences in reflectances between the sample over the black surface and the sample over the white surface were negligible. There were no detectable background interferences at a depth of 15mm.

The results of the preliminary study were used to determine the minimum amount of soil that can be analyzed using the extended wavelength field spectroradiometer (Exotech Model 20B). A safety factor of 5mm was added to the 15mm minimum required thickness as determined in the preliminary study to give a sample thickness of 20mm (2cm) for this study. The sample holder, cylindrical in shape, has a diameter of 10.16cm. By entering these values into the formula for the volume of a cylinder ($V = \pi R^2 h$) the value (V) obtained was 162.08cc.

To obtain the weight of a soil sample at volume $\underline{V}$, 162.08cc, it was necessary to use the relationship between the volume of a soil and the weight of a soil as related to bulk density (Bulk Density = $\frac{\text{weight of soil}}{\text{volume of soil}}$). In deriving a value for W, weight of soil, from this relationship it was assumed that the soils to be studied would have a bulk density of 1.33gm/cc, the average B.D. of mineral soils. Based on this a minimum weight value of 215.60gm was obtained. (Appendix 2).

Samples, representative of different climatic regions of the United States and encompassing eight of the soil orders defined in the **Soil Taxonomy** were selected from the library of Bench Mark soils of the United States. Benchmark soils are key soils selected to represent an important part of a state or resource area. They are selected because of their large geographic extent, because they represent a number of similar soils that have a large combined extent, or because they cover a range of soil characteristics that represent an important part of a state or resource area. They are important soils to study because the data are so widely applicable. Samples were crushed to provide a relative smooth surface. Many researchers report that grinding tends to enhance or destroy the spectral properties of natural soils. The samples were placed in petri dishes lined with black paper to prevent reflectance from the dishes or sample holder.

Soil spectral reflectance was measured over the wavelength interval of 0.37 to 2.37μm using an Exotech Model 20B field spectroradiometer. Eastman white reflectance standard, $BaSO_4$ especially prepared for use in spectrographic analysis, was used as a reference standard. All samples were analyzed at air-dry moisture content. The complete analysis was conducted as an in-lab experiment using an artificial light source. The configurations and operations (15) of the field spectroradiometer (Exotech Model 20B) that measures the intensity of incident and reflected radiation from 0.37 to 2.52μm and emitted radiation from 2.76 to 13.88μm have been developed. This study was confined to reflectance measurements. The instrument was built by Exotech Inc. from specifications and plans developed by the U.S.D.A. The instrument consists of two systems, each made up of an optical unit and a control unit.

A. Instrument Description

A schematic diagram of the basic mechanical-optional configuration of the instrument is shown in Figure 10. The instrument is basically divided into two heads, namely, a short wavelength head and a long wavelength head. An external view of the spectroradiometer is shown in Figure 11. Each head may be used independently of the other or they may be used in tandum in a bore-sighted mode of operation. The short wavelength head covers the wavelength range from 0.37 m to 2.5μm while the long wavelength head covers the wavelength range from 2.8μm to 14μm. Each head contains two detectors, and except for differences in detectors and circular variable filter materials, the heads are essentially identical.

The chopper wheel in the instrument is made of polished aluminum and then coated with silicon monoxide. The radiation from the scene passes through the foreoptics of the spectroradiometer and is chopped by the filter wheel. The arrangement of the detectors is such that each detector looks alternately at the scene radiation and at an internal blackbody reference. A circular variable filter (C.V.F.) in conjunction with a slit and relay optics performs the dispersion and focusing functions in the instrument. The detectors and the associated C.V.F. are arranged as follows:

Short Wavelength Head

Section (1) C.V.F. #1
One Segment 0.35μm to 0.7μm
Photovoltaic Silicon Detector 295°K
Section (2) C.V.F. #2
One Segment 0.65μm to 1.3μm
One Segment 1.25μm to 2.5μm
Photoconductive Lead Sulfide Detector 77°K

Long Wavelength Head

Section (3) C.V.F. #3
One Segment 2.8μm to 5.6μm
One Segment 2.8μm to 5.8μm
Indium Antimonide Photoconductive Detector 77°K
Section (4) C.V.F. #4
One Segment 7μm to 14μm
Mercury Cadmium Teluride Photoconductive 77°K

Joule-Thompson cooling devices are used to cool three of the detectors to 77°K. This permits the instrument to be operated at a variety of angles and enhances its use as a laboratory instrument as well as a field instrument. Although it is not necessary to operate the lead sulfide detector at 77°K, such operation does tend to remove the effects of environmental temperature variations upon the detectivity of the lead sulfide detector. A chopping frequency of approximately 1000 Hertz is used as a compromise value to satisfy the time response requirements of each detector.

The short wavelength head uses a V-groove blackbody as a reference. The blackbody operates at ambient temperature and no attempt is made to regulate its temperature. The ambient temperature of approximately 300°K is sufficiently below solar effective temperatures so as to be considered a zero reference. The reference in the long wavelength head is to temperature controlled V-groove blackbody of the same mechanical configuration as that in the short wavelength head. The temperature of the blackbody may be chosen by the operator, using a control on the instrument operating panel. The short wavelength head is equipped with a mirror that can be inserted into the optical path so as to permit the detector to view a diffuser plate located in the top of the instrument. The diffuser plate is so oriented and constructed so as to approximate a Lambertain receiver in the short wavelength range. This arrangement allows incident solar information to be included as a part of the observed data.

The radiation from the target scene is folded into the radiation processing system by the folding mirror either directly (15°FOV) or from the primary mirror of the Newtonian telescope (3/4°FOV) Figure 11. The folding mirror is rotated by a motor actuated by the FOV switch on the electronic processing circuitry front panel (Figure 13). A circular variable filter (CVF) design has been adopted because it is the best way to achieve a simple, rugged, field instrument with high radiometric efficiency.

A circular variable filter consists of a multilayer dielectric coating deposited on a circular substrate (circular substrate of short wavelength head and long wavelength head are germanium, and a composite material of glass and quartz respectively) in such a manner that coating thickness varies linearly with angle of rotation while remaining constant along a radius. The spectral characteristics of such a filter at any particular angle are equivalent to a narrow bandpass filter having about 60 per cent transmission with a bandwidth of 1 per cent to 2 per cent of the center wavelength. As the filter is rotated past a point illuminated by incident radiation, the center frequency changes so that an effective spectral scan is obtained. These characteristics are illustrated in Figure 10, which shows the transmission of the filter vs. angular rotation, with incident radiation from several sources.

When the folding mirror is in the 3/4°FOV position, the mirror on the back face of the folding mirror directs radiation from the target scene into the boresighting telescope for sighting and photography. Since the boresight uses radiation which would normally be lost due to the occulting of the folding mirror, this feature does not affect the efficiency of the radiometer.

The folded radiation enters the radiation processing system and is directed by the chopper wheel alternately to the two CVF wheels. Simultaneously, radiation from the heated reference blackbody whose temperature can be selected, is being directed alternately to the two CVF wheels (Figure 10).

KRS-5 (thallium bromide-iodide) optics image the scene on the CVF wheels and refocus the stopped image onto the detector. KRS-5 is valuable because it transmits to very long wavelength-- about 50μm. The transmittance characteristics* of KRS-5, for a thickness of 2 mm, are given in Figure 14.

The amplifiers for the various detectors are located in the instrument head in close proximity to each detector. The preamplifier output signals are fed through shielded armored cable to the control panel where ultimately they are amplified to a maximum voltage output of approximately 5 volts. The position of the circular variable filters are detected by an optical encoder and converted to a series of 1000 pulses per revolution. The pulse train is integrated

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* R. D. Hudson, Jr., John Wiley & Sons, New York, p218, 1969

so as to develop a ramp whose instantaneous amplitude is proportional to the C.V.F. position. The four radiometric signals and the two C.V.F. position (i.e., wavelength) signals constitute the data output of the instrument. In addition, several other d-c voltage levels which constitute instrument status such as control position, mirror position, etc., are available as ancillary data for recording on a suitable data track. In order to minimize electrical interference, d-c brushless Hall-effect motors are used to drive the C.V.F. units and the chopper blades.

During field use, the instrument is normally mounted on a special platform that is affixed to the bucket of an aerial lift. Armored cables are used to feed the electrical signals to an instrument van that is located in front of the aerial lift truck. Figure 15 illustrates a typical field setup of the system. The control electronics, recording equipment, and other data recording instruments are located in the instrument van. A power unit towed behind the instrument van provides power for both the instrument van and the spectroradiometer. Normally, a technician operates the equipment while the natural scientist directs the experiment.

The short wavelength unit is functionally identical to the long wavelength unit except for the following:

1) The silicon detector is not cooled.
2) The reference blackbody is not heated.

3) A solar reference port is positioned so that radiation from this diffusely translucent (Coors alumina) plate may be directed into the detectors by a mirror whose position is controlled by a knob on the front panel of the electronic processing and control module. This knob allows selection of the target scene, the solar port or an automatic mode which causes the instrument to alternate between every two scans. Fused silica relay optics are used in place of the KRS-5.

The following procedures are used to calibrate the spectrometer's short wavelength unit for laboratory studies. A perfect diffuser, pressed Barium Sulfate, is used to determine the spectral reflectance factor. The unit views the target and the radiation from the target is recorded. Secondly, a standard of known spectral reflectance is viewed and its radiation recorded. The values obtained from these observations are used to determine a ratio at each wavelength (response). The computer enters a correction factor into the ratio equation to correct for the known properties of the standard ($R = \frac{V_t}{V_s}$ x correction factor). The spectrum scan of the instrument is adjustable from two scans per second to one scan every thirty seconds. When the slow scan speed is used, the amplifier bandpass may be restricted so as to eliminate high frequency noise components from the radiometric signal. Under slow scan conditions in

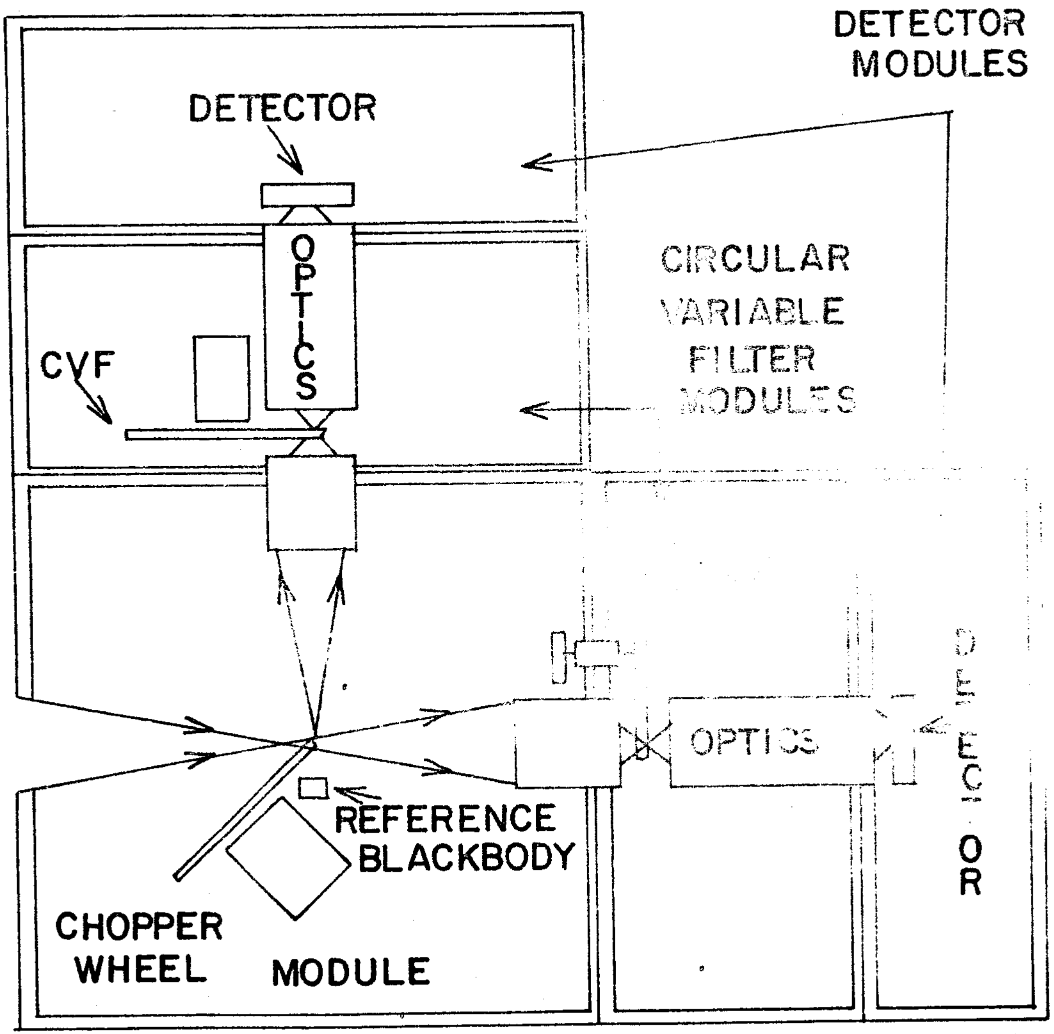

Figure 10. Radiation Sensing System for the Longwavelength Unit

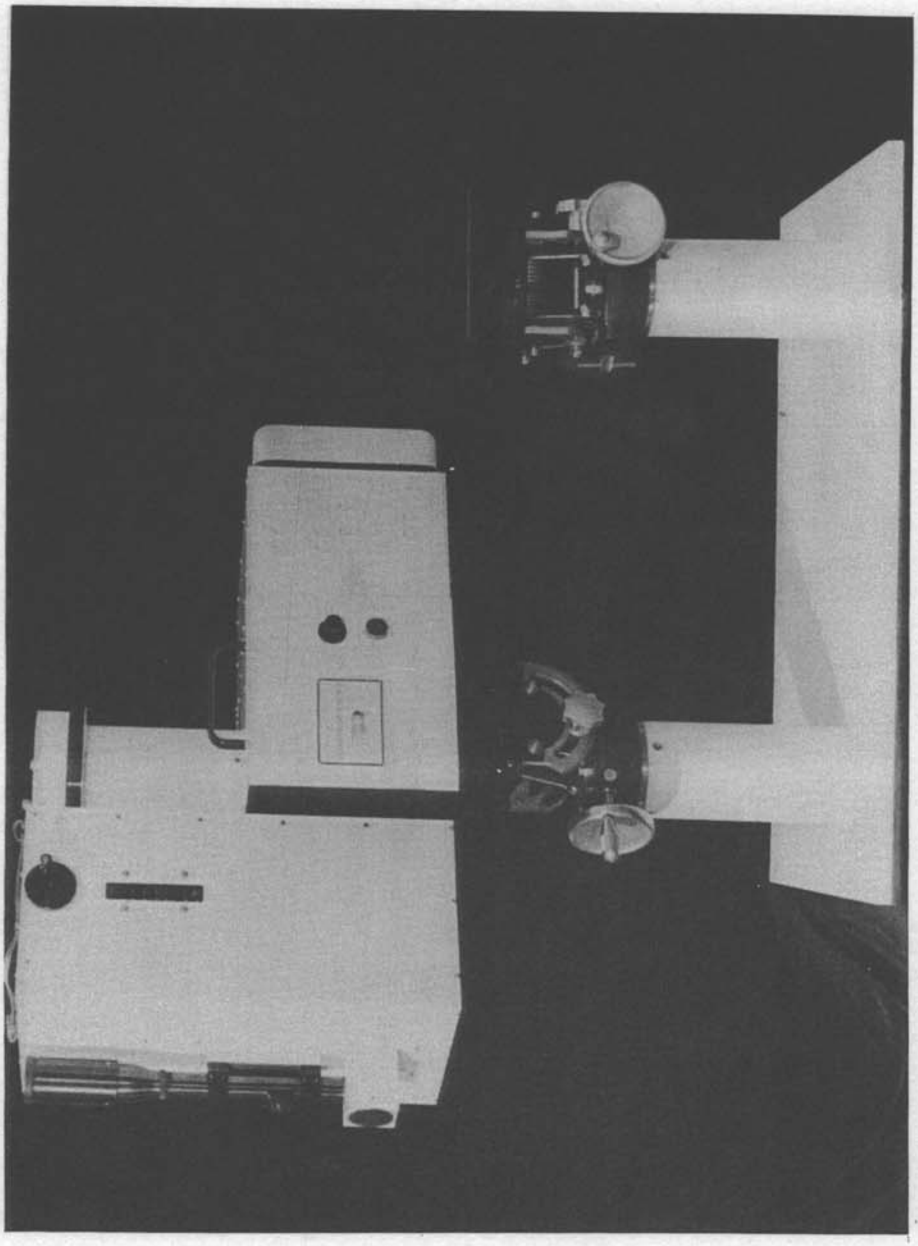

Figure 11. Short Wavelength Optical Head

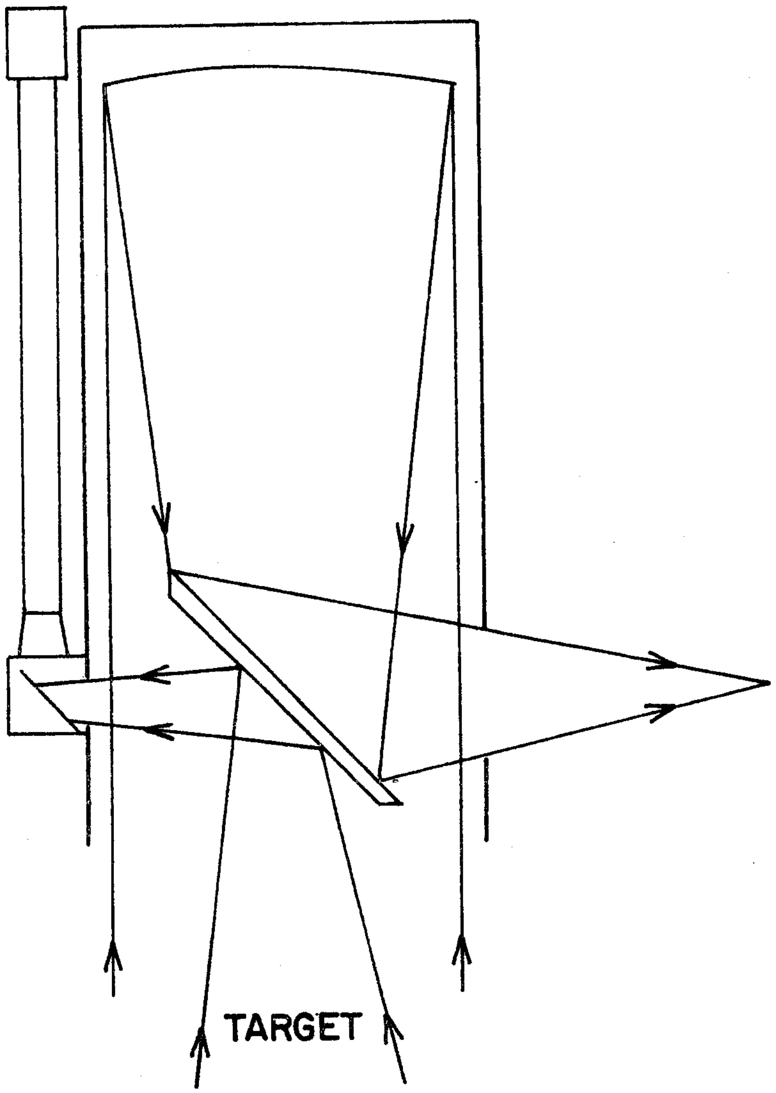

Figure 12. Schematic of Telescope showing viewing arrangement in 3/4° F.O.V.

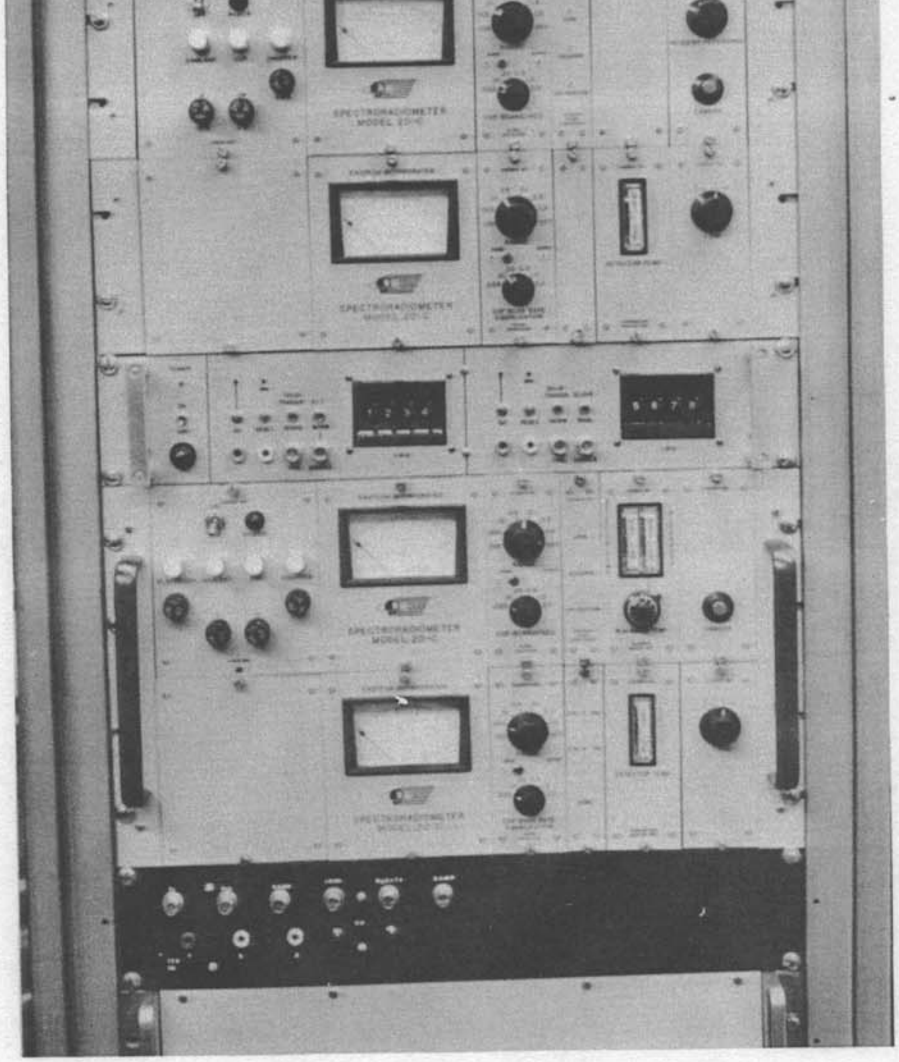

Figure 13. Panels for Electronic Processing and Control Circuitry.

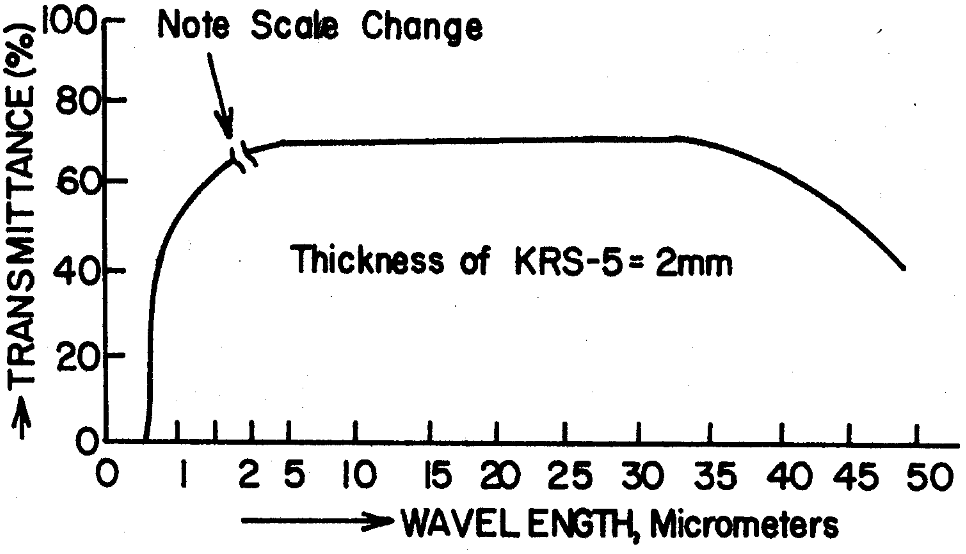

Figure 14. Transmittance of KRS-5 (Thallium Bromide-Iodide)*

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*Taken from R. D. Hudson Jr., Infrared System Engineering, John Wiley & Sons, New York, p. 218, 1969.

Figure 15. Typical Setup of the Field Spectroradiometer System

bright sunlight, signal to noise ratios in the short wavelength unit in excess of 10,000 to 1 were obtained. The scan speed chosen depends upon the lighting conditions prevalent during the experiment. The use of the fast scan results in a deterioration of the signal to noise ratio to approximately 1000:1 under high ambient lighting conditions.

In the last decade, machine processing of imagery obtained from airborne optical mechanical scanners has become increasingly important in man's effort to assess rapidly his environmental resourses. The field spectroradiometer has proved to be an invaluable instrument in the overall data collecting system. It has shown great promise for laboratory studies. Here-to-fore the Beckman DK-2 has been used extensively as the best laboratory instrument for collecting spectral data from an object.

The development of an artificial light source (Figure 16) for use with the field spectroradiometer by Robinson et al., has placed the value and importance of the Beckman DK-2 in jeopardy. Here is an instrument capable of collecting spectral data from a sample in its undistributed state, a feat yet to be performed by other inlab instruments. With the artificial light source it has become dual purpose, in that it can be brought into the lab (Figure 17) during adverse weather conditions, and mounted in the ceiling (Figure 18) and used in various experiments that cannot be performed outside and yet apply the results to the natural

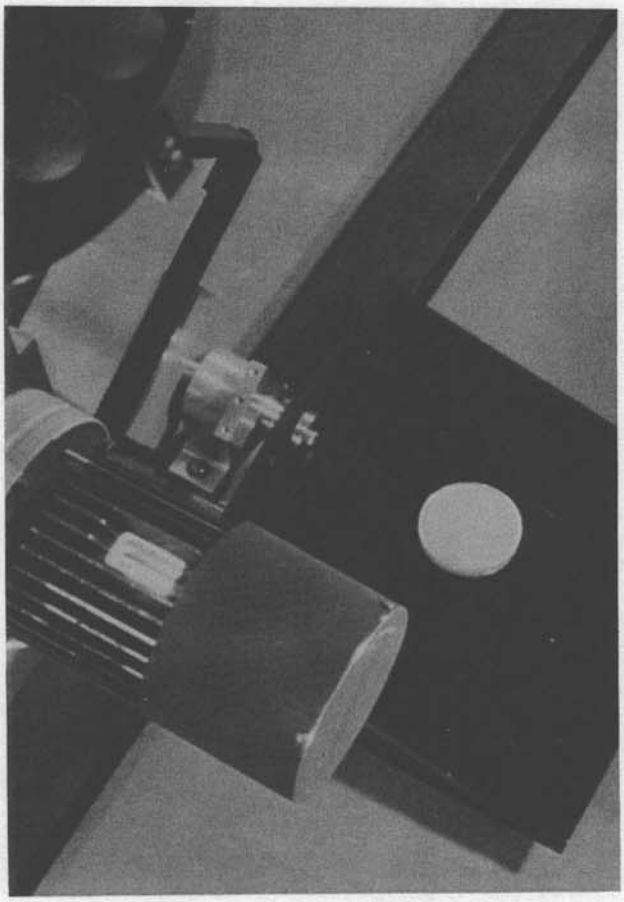

Figure 16. Artificial light source for the field spectroradiometer.

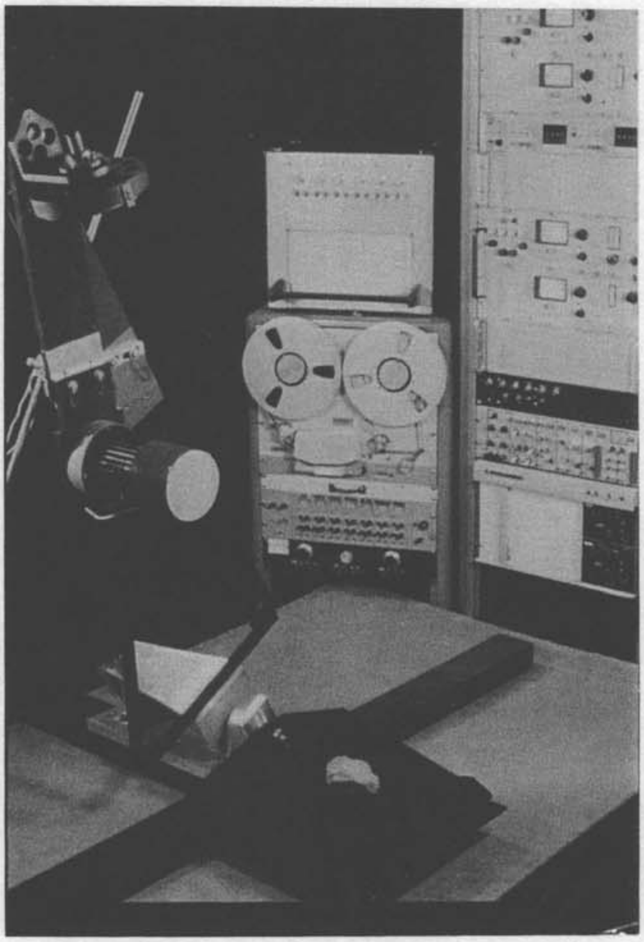

Figure 17. Inlab setup.

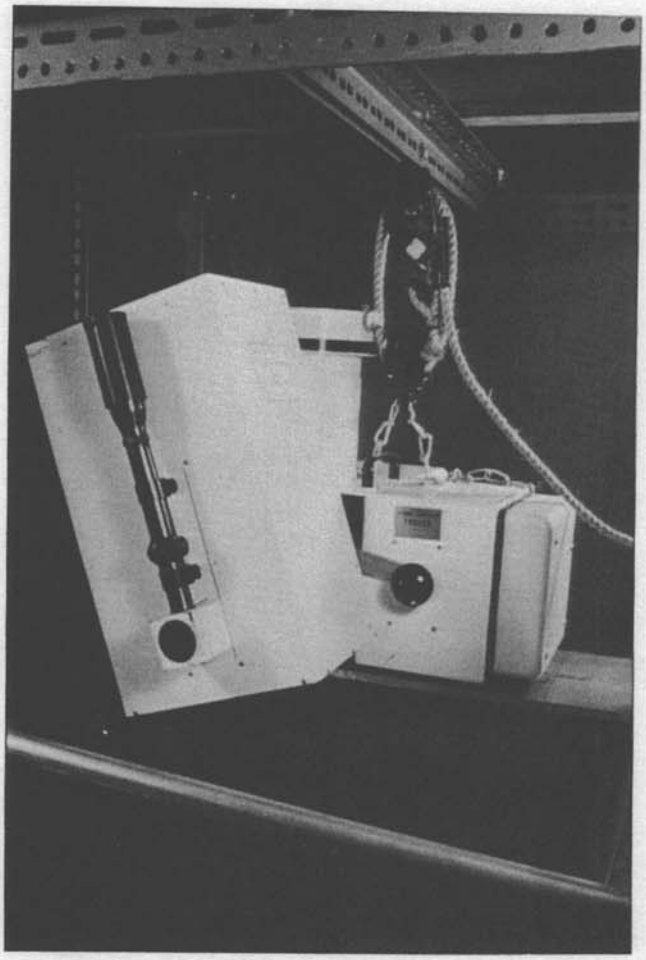

Figure 18. Position of Exotech in ceiling.

situation, and with data collected by airborne scanners.

The radiometric data were recorded in two forms. For on-the-spot observation, the spectra were presented on a multichannel strip chart recorder. At the same time the same data were recorded on magnetic tape for subsequent digitization and computer processing.

B. Description of Soil Orders

The description of soil orders found in this report were taken from the handbook on the **Soil Taxonomy**, A Comprehensive System of Soil Classification produced by the Soil Conservation Service, under the auspices of the United States Department of Agriculture (22). All existing orders are described but only eight of them will be given any attention in the latter part of the study. Those excluded are Oxisols and Histosols.

1. Ultisol

The Ultisols include most soils that have been called Red-Yellow Podzolic soils, Reddish-Brown Lateritic soils, and Rubrozems in the United States. Also included are some very acid soils that have been called Humic Gley and Low-Humic Gley soils, and some called Ground-Water Laterite soils.

The Ultisols have no oxic or natric horizon, but they have an argillic horizon. The argillic horizon is not permitted to have tongues of an albic horizon penetrating from the top. The argillic horizon has less than 35 percent base saturation (measured by sum of cations), or base saturation decreases with depth either in the argillic horizon or in the C. In addition, the Ultisols may have a mollic, umbric, ochric, or histic epipedon or a fragipan. Plinthite is often present. These horizons and the plinthite are used to define the classes of Ultisols.

The Ultisols are restricted to humid climates ranging from the temperate zones to the tropics. Land surfaces are commonly old, or if they are of late Pleistocene age, the parent materials were highly weathered before they were deposited. The native vegetation may have been forest, savannah, or even marsh or swamp flora.

Perhaps it should be pointed out that the exclusion of oxic horizons from the Ultisols requires that the Ultisols have some weatherable minerals. There may be very small amounts of micas or feldspars in the silt or sand fraction. Or, there may be allophane or 2:1 lattice clays in the clay fraction. The amount of weatherable minerals need not be large, but there must be enough to identify. This concept is presented for testing.

It is normal in the Ultisols that the amount of weatherable minerals is small in the silt and sand fractions. The definition of the order might have been on this basis, had it not been for the enormous difficulty of determining percentages of the various minerals in the silt-fraction. There is, however, no requirement that the amount of weatherable minerals be small. Some Ultisols have a large amount of 2:1 lattice clay. Others have a very appreciable content of feldspar or mica in the silt fraction.

2. Entisols

The central concept of Entisols is that of soils that have little or no evidence of development of pedogenic horizons. Many have ochric epipedons. A few sands have albic horizons. Some soils in coastal marshes have histic epipedons consisting of organic materials (peat or muck). Most have no horizons. The reasons for the lack of horizons vary. In many, time has been too short for horizons to be formed. These soils may be on steep, actively eroding slopes, or on floodplains or glacial outwash plains that receive new deposits of alluvium at frequent intervals. But some Entisols are very old and consist mostly of quartz or other minerals that do not alter to form horizons. Buried horizons are permitted if they are buried to depths of more than 50 cm or to depths between 30 and 50 cm as defined later.

Entisols may have any moisture or temperature regime, but not a combination of pergelic and aquic or peraquic and gray colors, and any parent material, vegetation, or age. As an order, the only common features are the virtual absence of horizons and the mineral nature of the soil. The only evidence of pedogenic alteration are a small accumulation of organic matter in the upper 25 cm and a slight loss of carbonates and concentration of clay in the upper 12 cm.

Entisols are minerals soils that:

1. have sulfidic material within 50 cm of the mineral surface or above a layer that is frozen about 2 months after the summer solstice or have an n-value of more than 0.7 in all subhorizons between 20 and 50 cm below the mineral surface and have no permafrost; or
2. have no diagnostic horizon, unless it is a buried horizon, other than an ochric epipedon, or a histic epipedon consisting of organic materials, or an albic horizon, or a spodic horizon with an upper boundary deeper than 2 m, with or without any of the following:
    a. a salic horizon, except that if the soil is saturated with water within 1 m of the surface for 1 month or more, and has not been irrigated, the upper boundary of the salic horizon must be 75 cm or more below the surface;
    b. if textures are finer than loamy fine sand, sodium saturation may exceed 15 percent in more than half of the upper 50 cm only of sodium saturation increases or remains constant with depth below 50 cm and the soil is saturated with water within 1 m of the surface for 1 month or more when not frozen in any part;
    c. a calcic or gypsic horizon or duripan if its upper boundary is more than 1 m below the surface

(these are presumed to be buried soil horizons or of geologic origin);

d. if textures are loamy fine sand or coarser to a depth of 1 m, plinthite may be present in the form of discrete nodules or disconnected soft red mottles if it constitutes less than half of the volume in all subhorizons;

e. buried diagnostic horizons may be present if the surface of the buried soil either is at depths between 3o and 5o cm and the thickness of the buried soil is less than twice the thickness of the overlying deposits or the surface of the buried soil is deeper than 5o cm;

f. ironstone at any depth; and

3. if soil temperature regimes are frigid, mesic, isomesic or warmer, and if there are cracks in most years as wide as 1 cm at 5o cm depth when not irrigated, Entisols, after the upper 18 cm are mixed, have less than 3o percent clay in some subhorizon within a depth of 5o cm, or lack all of the following:

a. gilgai;

b. at some depth between 25 cm and 1 m, wedge-shaped natural structural aggregates with their long axes tilted 10 to 60 degrees from the horizontal;

Weathering that has destroyed the weatherable minerals in an oxic horizon need not have occurred in the place where the soil is now found. It may have occured in another place prior to the movement of the weathered materials to their present position. Chemically and mineralogically, the materials in an oxic horizon may be indistinguishable from materials at comparable depths in Entisols. When first deposited, strongly weathered earth could be classified with the Entisols. Only when the soil has been in place long enough to have lost the original fine stratification of the sediment, and to develop visible pores and possibly weak structure, can it be classified with the Oxisols.

3. Mollisols

The Mollisols include most soils that have been called Chernozem, Brunizem (Prairie), Chestnut, and Reddish Prairie, and associated Humic Gley soils and Planosols. They also include those Rendzinas, Brown soils, Reddish Chestnut soils, and Brown Forest soils that have a mollic epipedon.

The Mollisols must have a mollic epipedon, but not all soils that have this epipedon are Mollisols. Those soils with a mollic epipedon that has a clay fraction dominated by volcanic ash are excluded. So are the soils with an argillic horizon that has a base saturation of less than 35 percent, or a base saturation that decreases with depth from the argillic horizon to the C. And, the Mollisols may not have an oxic or spodic horizon, nor may they have the diagnostic properties of Vertisols. These are the exclusions.

In addition to the mollic epipedon, the Mollisols may have an albic horizon, cambic horizon, argillic horizon, natric horizon, duripan, <u>ca</u>, <u>cs</u>, or <u>sa</u> horizon.

The vast majority of the Mollisols have developed under a grass vegetation, either tall or short, but closely enough spaced to form a sod. A few have had mostly sedges and water-loving plants, and a few others have developed under deciduous hardwood forest. Those under hardwood forest are only known on basic and calcarious parent materials and have had a large earthworm population. The worms pull the leaves underground, where they decay and produce conditions similar to those produced by underground decomposition of grass roots.

The climatic range of Mollisols is from boreal or alpine to tropical. Rainfall may be sufficient to provide some annual leaching through the soil in most years, or it may only moisten the solum. Dry seasons are normal.

4. Vertisols

The Vertisols include swelling clays that have gone by many names. Among them are Grumusol, at least a part of the Regur and Tirs, Black Cotton, Tropical Black Clays, Gray and Brown soils of heavy texture, and Smonitza. The Vertisols also include some soils that have been called

Alluvial soils, particularly those with large amounts of expanding lattice clays in climates with pronounced hot dry seasons.

The common characteristics of the soils of the order are: high content of expanding lattice clay, more than 35 percent and usually more than 40 percent; more than 30 milliequivalents exchange capacity in all horizons below the surface 5cm. (2 inches); cracks, unless irrigated, 1 to 25cm. wide at some seasons that reach to the middle of any solum present; and with gilgai, or with slickensides close enough together to intersect in places, or at some depth between 25 and 100cm., with wedge or parallelepiped structural aggregates having a long axis tilted 10° to 60° from the horizontal. Vertisols may have a mollic umbric epipedon. If one of these is present, the lower boundary is often very irregular, but the irregularity is not diagnostic for it can be the result of frost action. There may also be a horizon meeting the requirements of an argillic horizon, if its upper boundary lies within 5cm. (2 inches) of the surface. An albic horizon as much as 5cm. thick may overlie the argillic horizon. Calcic horizons and <u>ca</u> horizons are common.

The Vertisols normally are developed in montmorilloritic parent materials derived from limestones or basic igneous rocks but they may be found in granitic areas too. Climates may be subhumid to arid, but normally there are seasonal sources of water adequate to saturate the soil, with consequent swelling and closing of cracks. The water may come as rain or in floods. At the extreme, it seems likely that some Vertisols that are not irrigated have, at some season, a moisture content low enough to produce wide cracking. Temperatures may range from tropical to temperate. Hot dry seasons are normal, and in most years air temperatures at some time exceed 38°C. (100°F.)

The vegetation on Vertisols not cultivated is normally grass or herbaceous annuals. On some of them, scattered, usually drought-tolerant, woody plants may be present. <u>Eucalyptus</u>, <u>Acacia</u>, <u>Juniperus</u>, and <u>Prosopis</u> (Mesquite) are common genera.

The Vertisols are found in a wide variety of positions, from the floodplains of rivers to steeply sloping uplands.

The central concept of Vertisols is one of soils that crack widely, and that often remoisten from water that runs into the cracks rather than from water that percolates through the soil. If the surface mulches during the dry season there may be a significant amount of A1 material that sloughs into the cracks. In these the lower boundry of the A1 is often very irregular and there is gilgai microrelief unless the area has been leveled by man. In other Vertisols, sloughing is probably minor in its influence. However, the moistening and swelling of a layer, with dry soil above and below, causes shearing within the soil and produces slickensides and wedgeshaped or parallelepiped structure.

The shrinking, cracking, and shearing in the Vertisols, and the mass movement, make them unstable and introduce severe problems in use. Fences and telephone poles are thrown out of line; Trees are tilted. Pavements may be broken and shifted laterally. Foundations of buildings may be destroyed, and pipelines broken. Terraces may crack and give rise to gullying when the rains come. These are some of the problems.

5. Aridisols

The Aridisols are primarily soils of dry places. They have an ochric epipedon and one or more additional diagnostic horizons. These are cambic, argillic, natric, calcic, gypsic, and salic horizons and duripans. The Aridisols do not have a spodic or oxic horizon, nor do they have a mollic or umbric epipedon.

Included in Aridisols are most soils that have been called Desert soils and Red Desert soils, Sierozems, and Reddish Brown soils, and Solonchak. Some of the Regosols, and Lithosols of dry climates, and some Brown soils and Solonetz are also included.

The Aridisols include soils having one of the following combinations of properties.

(1) Soils that are usually dry when not frozen and not irrigated and that have a calcic horizon that immediately underlies a calcareous ochric epipedon.

(2) Soils that are usually dry when not frozen and not irrigated and that have an ochric epipedon and an argillic horizon.

(3) Soils that are usually dry when not frozen and not irrigated, that have both an ochric epipedon and conductivity of the saturation extract greater than 1 millimho per cm. at 25°C. at some depth, and in addition, have one or more of the following: a cambic, calcic, gypsic or salic horizon, or a duripan that can be softened by a single treatment with acid followed by a single treatment with concentrated alkali.

(4) Soils that are usually moist, and have no argillic or spodic horizon, but that have a calcic, gypsic, or salic horizon and, in addition, have conductivity of the saturation extract greater than 1 millimho per cm. at 25°C. at some depth.

The first three of the above combinations of properties are found in positions where there is normally no ground water. The fourth combination is normally found in positions that receive runoff or seepage. No hydromorphic suborder has been defined, because those Aridisols that show mottling with low chromas, or that have blue hues, also show, as a rule, a salic horizon, duripan, or other distinctive horizon.

6. Inceptisols

The Inceptisols are soils with one or more of the diagnositc horizons that are thought to form rather quickly and that do not represent significant illuviation or eluviation or extreme weathering. They are most often found on young but not recent lend surfaces; hence, the name Inceptisol, derived from the Latin <u>inceptum</u>, for beginning.

The order includes many of the soils that have been called Brown Forest soils, Subarctic Brown Forest soils, Tundra, Ando soils, Sols Bruns Acides, Lithosols and Regosols, and a number of the strongly gleyed associated soils that have been called Humic Gley and Low-Humic Gley soils.

The order includes soils that are usually moist and that have no spodic, argillic, natric, calcic, gypsic, salic, or oxic horizon, or plaggen epipedon, but that have conductivity of the saturation extract of less than 1 millimho per cm. at 25°C. and that have one or more of the following: A histic, umbric, or ochric epipedon, a cambic horizon, a fragipan, or a duripan. If the clay fraction is dominated by allophane, and the silt end sand by ash and pumice, a mollic epipedon may be present. The histic epipedon is diagonstic for horizon between 20 and 50cm. (8 and 20 inches). An ochric epipedon is permitted if there are other diagnostic horizons, but is not itself diagnostic. The soils of the order may therefore have either a dark or light colored surface horizon. So far as is known, all Inceptisols have either an umbric or mollic epipedon, or a cambic horizon.

There must therefore be an appreciable accumulation of organic matter or there must be some evidence that the parent material has been altered by weathering. The weathering cannot be so intensive that all weatherable minerals are lost from the sand or silt fraction, or that all allophane and 2:1 lattice clays are absent. This follows from the definitions of the cambic and oxic horizons.

Since argillic and spodic horizons are absent, there cannot be evidences of significant illuviation. Textural differences may be present between horizons, if parent materials are stratified, or if clay has been differentially formed in place. But soils are excluded if they have evidences of illuviation in the finer textured horizons sufficient to make an argillic horizon. Typically, textures are uniform or nearly so. To depths of at least 50cm. (20 inches), textures must be as fine or finer than loamy very fine sand if the only diagnostic horizons are an ochric epipedon and a cambic horizon. Sand and loamy sand textures may be found throughout the upper 50cm. if the epipedon is umbric or mollic.

The Inceptisols are normally found in humid climates but range from the Arctic to the Tropics. They are also common in alpine areas. A few may occur in arid climates in positions where there is some natural irrigation.

The native vegetation is most often a forest, but it may be a boreal or even a tropical rain forest. Some soils in the tundra may be included. A few of the Inceptisols have developed under grass. Some have had a grass cover under an open forest canopy or have had mixtures of coarse grasses and sedges.

7. Spodosols

The Spodosols include primarily the soils that have been called Podzols, Brown Podzolic soils, and Ground-Water Podzols. Not all soils called Podzols, however, are in this order.

All mineral soils are included that have a spodic horizon thick enough to be demonstrable after plowing and cultivation for a few years. Those with a very thin spodic horizon that lies entirely within the surface 15cm. (6 inches) are apt to be excluded. Repeated plowing can mix a thin spodic horizon with an albic horizon so thoroughly that it is impossible to demonstrate that a spodic horizons are not diagnostic for this classification, because it is desired to keep virgin soils with their cultivated counterparts until marked changed have occurred. Spodosols are recognized by the spodic horizon, and not by the albic horizon. Soils with thick, white albic (A2) horizons may be placed in several places in this system.

Spodosols are found only in humic regions, but their range is from the boreal forests to the tropics. Most have had a coniferous forest, but those of the warmer regions may be under savannah or under rain forest.

The parent materials are usually siliceous. So far as is known, Spodosols do not form in clayey parent materials. If the crystalline clay content is high, even as high as 30 percent, Spodosols do not seem to form until there has been significant eluviation. In the tropics, the only parent materials of the Spodosols seem to be nearly pure quartz sand. In addition to the spodic horizon, a number of other diagnostic horizons may be present. These include histic, umbric, ochric, and possibly anthropic epipedons. Argillic horizons, duripans, and fragipans may also be found.

For Spodosols, the categoric level at which these horizons are used as differentiae is not the same as the level used for many other orders. This is particularly true of the umbric epipedons, and of the fragipans. Among the Spodosols, these two are considered as family differentiae.

The fragipans are considered family differentiae for Spodosols because the soils that lack a fragipan normally seem to have a horizon that is comparable to it but that is of too coarse a texture to become impermeable to roots and water. The brittle consistence of the fragipan is evident in most of the soils of the great groups in which fragipans occur. The fragipans therefore seem to have no covarying properties but texture. In other orders where fragipans occur the soils with fragipans differ from those without fragipans in a number of important properties.

8. Alfisols

The Alfisols are the mineral soils that are usually moist and **may** have **a** mollic epipedon, or spodic horizon. They do have an argillic or natric horizon that has base saturation of more than 35 percent, as measured by the sum of cations. The base saturation, if it is very high, remains constant with depth below the argillic horizon. Base saturation, if not high in the argillic horizon, increases with depth below the argillic.horizon. The Alfisols also include soils with argillic horizons that have base saturations of less then 35 percent if there are tongues of an albic horizon in the argillic horizon, and if base saturation increases with depth in or below the argillic horizon but within the soil.

The Alfisols include most soils that have been called Noncalcic Brown soils, Gray-Brown Podzolic soils, and Gray-Wooded soils, many that have been called Planosols, some that have been called Half-Bog soils, and a few that have been called solodized Solonetz.

They may be found under boreal forests or deciduous broadleaf forests. Some are found in relatively dry climates where there is marked seasonal variation in rainfall and a cover of grass and scattered zerophytic trees, including <u>Eucalyptus</u> and some <u>Quercus</u>. A very few others, in humid climates, have had a tall grass vegetation; these have been called Planosols.

The relatively high base saturation of the argillic horizon limits the occurrence of these soils to places where there has been little movement of water through the soil, or to places where the parent materials are young, unweathered, and basic. So, in humid climates, the parent materials usually contain carbonates and the land surfaces are no older than late Pleistocene.

In cold or cool humid regions the Alfisols are almost entirely restricted to young calcareous parent materials. Here, the argillic horizon seems unstable and is usually at the base of the solum, adjacent to the calcareous parent material.

In subhumid regions the land surfaces may be older. Some Alfisols are possibly older than Pleistocene and have formed in old, very strongly weathered materials that contain plinthite. The present base saturation may reflect addtions of bases from cyclic salts in rain or from dust from adjacent deserts.

9. Oxisols

Oxisols are the reddish, yellowish or grayish soils of tropical and subtropical regions with mostly gentle slopes on surfaces of great age. They are primarily mixtures of quartz, kaolin, free oxides, and organic matter. They are nearly featureless soils for the most part without clearly marked horizons. Changes in properties with depth are so gradual that horizon boundaries are mostly arbitrary.

Because Oxisols are on stable surfaces, weathering has commonly proceeded to great depths, producing a thick regolith. Because changes with depth are gradual, an arbitrary limit of 2 meters is considered the lower boundary of most Oxisols. They have a relatively high permeability that, combined with gentle slopes, makes them; as a group, highly resistant to erosion when cultivated.

Without amendments most Oxisols have low productivity for cultivated plants. There are large areas that have such sparse vegetation that a high percentage of the soil surface lies bare, even though moisture is ample during a long rainy season. These lie idle. Other areas support or can support a dense rain forest, and are commonly farmed under shifting cultivation.

With modern fertilizers, pesticides, and machinery, many Oxisols are highly productive. These are commonly farmed in plantations. A few of the drier Oxisols require irrigation but these are not extensive. Oxisols occupy small areas in Hawaii and Puerto Rico, huge areas in South America and Africa, and important areas in Southeast Asia.

The classification of Oxisols that follows seems to produce satisfactory groupings of the limited numbers of the soils in Hawaii and Puerto Rico. It needs to be tested more widely, however, for it is cartain to have many shortcomings, and is far from completion.

<u>OXISOLS</u> are mineral soils that

1. have an oxic horizon at some depth within 2 m of the surface, or
2. have plinthite within 30 cm of the surface and are saturated with water within this depth at some time during the year in most years, and
3. have no spodic horizon or argillic horizon that overlies the oxic horizon.

10. Histosols

Histosols are soils that are dominantly organic. They are mostly soils that are commonly called bogs, or moors, or peats and mucks. A very few consist of shallow organic material that have 20 percent or more organic carbon and rest on rock or rubble. The organic materials that constitute Histosols are either more than 12 to 18 percent organic carbon by weight depending on the clay content of the mineral fraction and kind of materials, and well over half organic matter by volume. More than half of the upper 80 cm (about 32 inches) of Histosols consists of organic materials unless rock or fragmental materials are shallower than this depth, a rare condition, or the bulk density is very low.

Most Histosols by far are saturated or nearly saturated with water most of the year unless they have been drained.

At the extreme, thay may be only a mat, floating on water. It is common in cool very humid climates that the soil consists primarily of Sphagnum (spp) fed by rain water. In this situation the Histosols may blanket a dissected landscape. Water does not stand on the surface, but free water is only a few cm below. These have been called blanket bogs, high moors, or raised peats.

Histosols can form in virtually any climate, even in arid regions, so long as water is available. They occur with permafrost and on the equator. They may be in closed depressions, coastal marshes, on steep slopes where there is seepage, or they may blanket a dissected landscape. The common denominator is water, which may come from any source. The blanket bogs are restricked to cool any very humid climates but there is no other necessary climate relation with the presence or absence of Histosols. Vegetation consists of a very wide variety of water loving or water tolerant plants.

The classification of Histosols that follows must be considered provisional. The taxa of most other orders have been tested insofar as the soils of the U.S. permit. The classification of Histosols, however, has had relatively little testing. It differs significantly from the 1938 classification, and most series definitions of Histosols, as recognized prior to 1968, require revisions. It is believed that most of the subgroups exist, but only a little is known about the significance of some differentiae used to distinguish subgroups and taxa in lower categories. In addition, laboratory methods for the study of Histosols have received little attention and either do not exist of have not been generally tested and accepted.

In general, the suborders of Histosols are defined by moisture regimes and by the degree of decomposition of the organic materials. The degree of decomposition is closely related to bulk density and to the intial subsidence that follows within two or three years after drainage. The great groups are defined in part by the soil temperature regimes. Soil temperature is emphasized because it is important to the rate of decomposition and disappearance of the organic materials (and the Histosol) if the soils are drained and used. The warmer the soil, the shorter its existence under use, even with careful management. The Histosols were called Bog soils and Lithosols in the 1938 classification.

Hostosols are soils with:

1. organic woil materials that, except frr thin mineral layers as defined later, extend from the surface to one of the following depths:
   a. 60 cm or more if three fourths or more of the volume is fibric sphagnum or moss or the bulk density is less than 0.1 gm/cc;
   b. 40 cm or more if(1) the organic soil material is saturated with water for pro-

longed periods (6 months) or is artificially drained, and (2) the organic material consists of sapric or hemic materials, or consists of fibric materials that have less than three fourths by volume of moss fibers and have a bulk density of 0.1 or more;

c. a depth within 10 cm or less of a lithic or paralithic contact, provided that the thickness or the organic soil materials is more than twice that of the mineral materials above the contact;

d. any depth if the organic material rests on fragmental material (gravel, stones, cobbles) with interstices filled or partially filled with organic materials, or rests on a lithic or paralithic contact; and

2. a. no mineral layer 40 cm or more thick either at the surface or with an upper boundary within a depth of 40 cm from the surface; and

   b. no mineral layers, taken cumulatively, as thick as 40 cm within the upprr 80 cm.

Note that the general rule is that unless the surface tier has a bulk density < 0.1 a soil is classed as a Histosol if half or more of the upper 80 cm is organic, and it is classed as a Histosol without regard to thickness of organic materials if these rest on rock or on fragmental material with interstices filled or partially filled with organic materials. If the bulk density is very low, < 0.1, three-fourths or more of the upper 80 cm is organic.

The second suborder, without a "mollic" or "umbric" epipedon, would have several great groups.

Table 7. Present Soil Orders and Approximate Equivalents In Revised Classification of Baldwin et al.

Present order	Approximate equivalents
1. Entisols	Azonal soils, and some Low Humic Gley soils.
2. Vertisols	Grummsols.
3. Inceptisols	Ando, Sol Brun Acide, some Brown Forest, Low-Humic Gley, and Humic Gley soils.
4. Aridisols	Desert, Reddish Desert, Sierozem, Solonchak, some Brown and Reddish Brown soils, and associated Solonetz.
5. Mollisols	Chestnut, Chernozem, Brunizem (Prairie), Rendzinas, some Brown, Brown Forest, and associated Solonetz and Humic Gley soils.
6. Spodosol	Podzols, Brown Podzolic soils and Ground-Water Podzols.
7. Alfisols	Gray-Brown Podzolic, Gray Wooded soils, Noncalcic Brown soils, Degraded Chernozem, and associated Planosols and some Half-Bog soils.
8. Ultisols	Red-Yellow Podzolic soils, Reddish-Brown Lateritic soils of the U.S., and associated Planosols and Half-Bog soils.
9. Oxisols	Laterite soils, Latosols.
10. Histosols	Bog soils.

CHAPTER III

RESULTS AND DISCUSSION

A. Analysis of Spectral Curves for Soils

Spectral data were collected on the entire set of samples with the field spectrometer. The reflectance characteristics were studied in the portion of the spectrum from 0.52 to 2.32μm. The barium sulfate reference sample was viewed intermittently throughout the data collection period. The ratio of the radiated energy from the reference standard to the radiated energy of the sample defines the percent of reflectance for the sample ($\%R = \frac{R_{sample}}{R_{standard}} \times 100$). Since Rho-Prime ($\rho'$) has been accepted by the National Bureau of Standards as the best unit for defining the type of radiation being observed, it becomes necessary to relate percent reflectance to ρ'. The highest theoretically attainable value for ρ' is 31.8, which is equal to 100% reflectance ($R = \pi\rho' = 100$). Responses reported in this study will be expressed in terms of ρ'.

Data were collected on three dates, March 21, April 16 and April 26. Several samples were analyzed on two dates to determine the reproducibility of a set of results using the spectroradiometer. Other samples were introduced to three artificially created environments of 19.9, 79.3 and

and 98% relative humidities to test the effect of relative humidity on the spectral response of the soil. The methods for creating these environments are described in the Handbook of Physics and Chemistry (26).

The following phenomena were observed as the soils were compared first for inter-order similarities and secondly for intra-order similarities.

1. Entisols

These soils were observed throughout the spectrum and the results indicate the soils belonging to this order are very similar throughout the entire spectrum. The only significant spectral difference appears to be the magnitude of the response in the 0.54 to 2.37μm (Figure 19) range. This difference is indicative of their color variations. The Anthony, a light brown (7.5YR6/4) is much darker than the light gray (2.5YR6/1) Vandu. Soil texture aids in explaining these differences, a sandy loam versus a silty clay. Strong absorption bands at 1.4μm, 1.9μm, and 2.2μm indicate the presence of structural water. Hunt and Salisbury (20) state that the presence of both the 1.4μm and the 1.9μm band is diagnostic of water of hydration while the appearance of the 1.4μm band without the 1.9μm band indicates that hydroxyls other than those in water are present in the material. Mathews (19) working with data collected on a Hagerstown silt loam, using the Beckman DK-2A spectroreflectometer, observed these bands in his data.

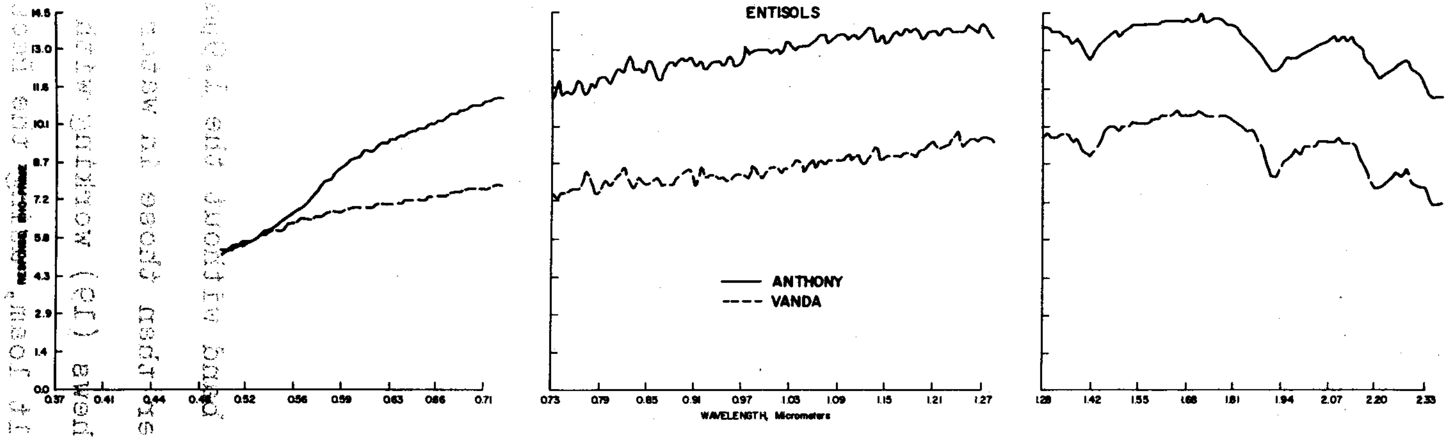

Figure 19. Spectral curves for Entisols.

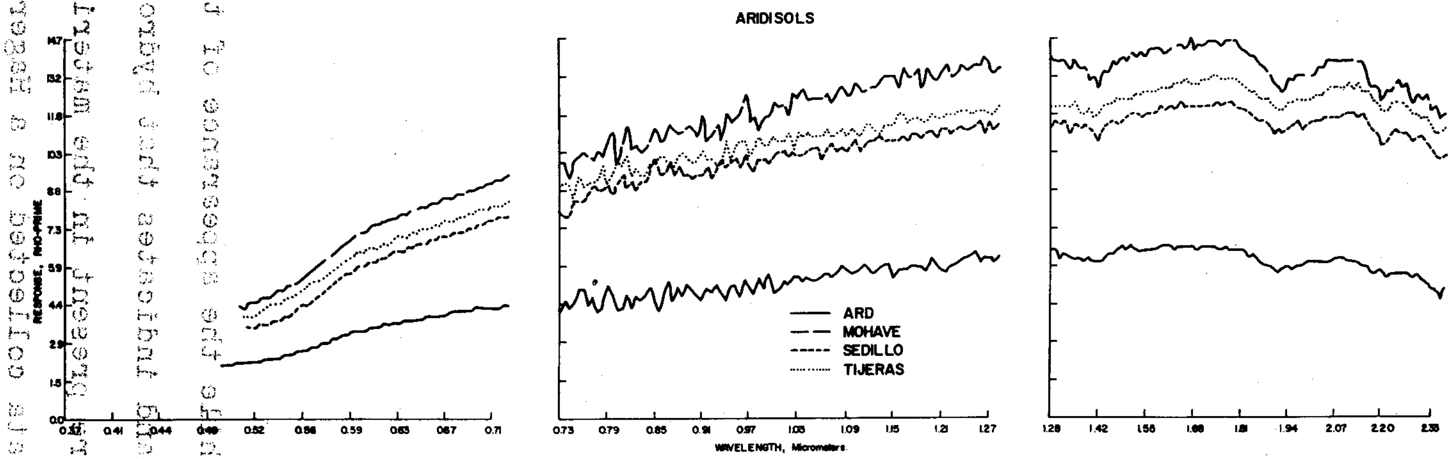

Figure 20. Spectral curves for Aridisols.

2. Aridisols

The curves for thses solis covered a slightly higher response range than the soils observed for the entisols. They, too, are very similar throughout the range of 0.52 to 2.32μm. Soil color and texture are probably responsible for their spectral differences. Table 8 contains the Munsell Color Notations for each of the graphed samples in Figure 20 along with their textral class.

Table 8. Aridisols

Soil Series	Color	Texture	Location
Mohave	7.5YR5/4	fine sandy loam	Arizona
Sedillo	10YR5/3	loam	New Mexico
Tijeras	7.5YR5/3	sandy loam	New Mexico
Arp	5YR4/2	gravelly clay loam	Arizona

The increase in response of one series over another is partially due to texture, surface condition and the varying amounts of structural hydroxyls. Kristof (13), and Kristof and Zachary (14) reported that actual surface moisture, organic matter content and surface conditions were credited with the differences which they observed while studying soil series.

3. Inceptisols

Soils belonging to this order (Table 9) exhibit the same general trend with frequent overlapping such as those at 0.63 to 0.65μm and 1.8 to 2.32μm.

Table 9. Inceptisols

Soil Series	Color	Texture	Location
Vista	10YR4/2	sandy loam	California
Sharkey	10YR3/2	silty clay	Kentucky
Pachappa	10YR5/3	sandy loam	California
Bluffdale	10YR6/2	silty clay loam	Utah
Nevine	10YR6/2	silt loam	Washington

Although the trend is the same, the light textured soils have stronger absorption bands at 1.4µm, 1.9µm and 2.2µm which account for most of the overlapping (Figure 21). The low intensities of the 1.4 and 1.9µm band are probably due to smaller amounts of absorbed water present.

4. Alfisols

The Alfisols (Figure 22) are mineral soils that have been called noncalcic Brown soils, Gray-Brown Podzolic soils, and Gray-Wooded soils, and some that have been called planosols. The spectral response of these relatively young soils is very similar and is contained within a response range of 4.6 to 19.1ρ'. The McGary I a grayish brown silt loam and McGary 2 are samples taken from the same soil series (Table 10). Their differences are attributed to, or possibly, are due to their vegetative cover and topographic locations.

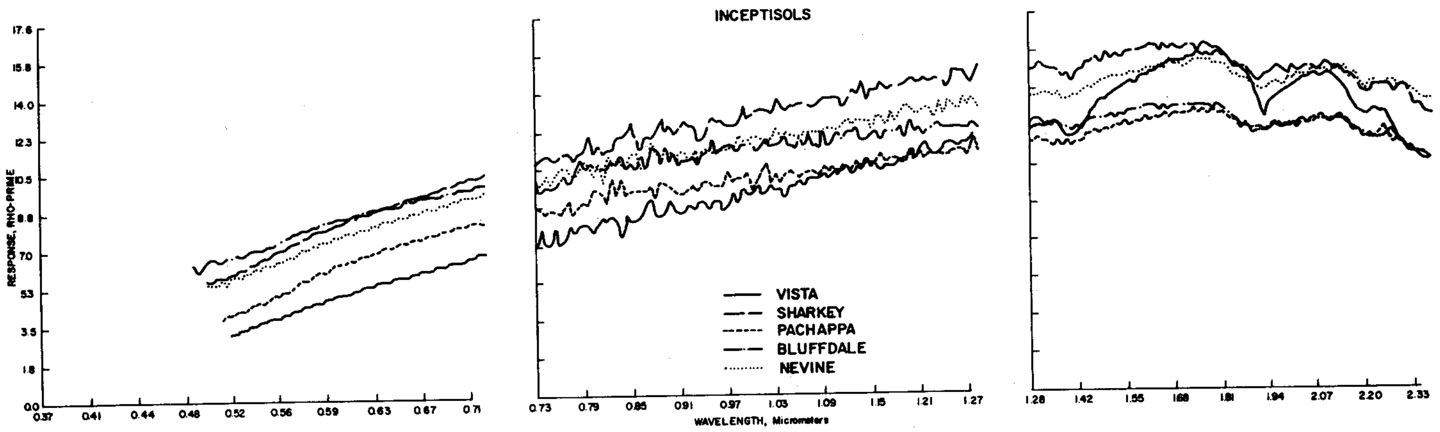

Figure 21. Spectral curves for Inceptisols.

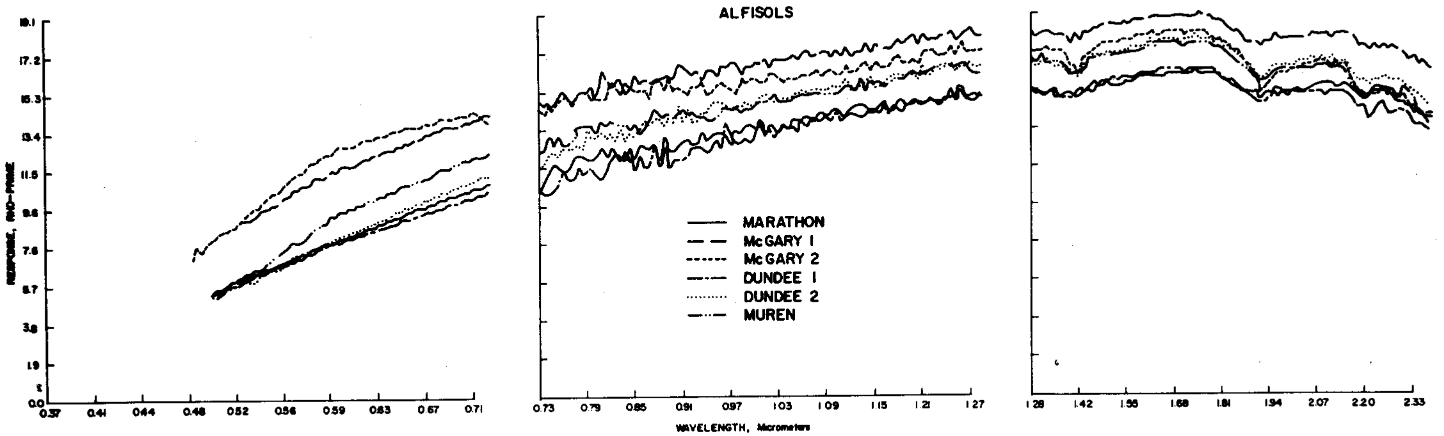

Figure 22. Spectral curves for Alfisols.

Table 10. Alfisols

Soil Series	Color	Texture	Location
Marathon	10YR4/2	silt loam	Wisconsin
McGary 1	10YR5/2	silt loam	Indiana
McGary 2	10YR5/2	silt loam	Indiana
Dundee 1	10YR3/2	silty clay loam	Kentucky
Dundee 2	10YR4/3	very sandy loam	Louisiana
Muren	10YR5/4	silty clay loam	Illinois

McGary 2 has stronger absorption bands which seem to indicate the presence of large amounts of water which leads one to believe that there may be possible minute textural differences. The Marathon, a dark grayish brown, silt loam and Dundee 1, a very dark grayish brown silty clay loam, respond almost identically throughout the entire range. The relative closeness in color and the high silt contents are credited with production of these very similar responses. All of the soils of this order are very close together and cover a response range of 1.2 to 13.3ρ'. The silt contents are very high in all but one of the soils and is believed to cause the likenesses in spectral response.

5. Ultisols

The spectra for the soil series belonging to the order ultisols exhibit a wide range of response (Figure 23). Although the spectral response covers a wide range from 2.2 to 22.8ρ', the general shape of the curves is the same. There are a gradual increase in response out to 1.26μm and small absorption bands at 1.4, 1.9 and 2.2μm. The differences in the magnitude of response is attributed to differences in soil color ranging from 5YR4/3 to 10YR4/3 (Table 11).

Table 11. Ultisols

Soil Series	Color	Texture	Location
Josephine	7.5YR3/2	gravelly loam	Oregon
Sites	5YR4/3	loam	California
Savanah	10YR4/3	silt loam	Mississippi
Olympic	7.5YR3/2	silt loam	Washington
Worsham	5YR3/2	silt loam	North Carolina
Alamance	5YR4/2	silt loam	North Carolina

Shields (22) reports that soil color measured spectrophotometrically, using a Bauch and Lomb model Spectronic 20 spectrophotometer, provides a quantitative method for measurement of soil color whose accuracy and reproducibility is superior to the visual method. The overlapping of other graphs by the Sites series is probably due to its color and texture. The depth of the A-horizon is the only requirement which prevents it from being classed as a Mollisol. This type of soil falls in a group of transition soils between Alfisols and Mollisol. It has some of the physical and chemical properties of both orders. This slightly darker soil has a higher organic matter content (5.85%) which explains the strong absorption bands at 1.4 and 2.2µm. The smaller bands at 1.9µm, for all samples considered, indicate the possible presence of hydroxyls other than those of water. Baumgardner et al (2), reported that organic matter plays a dominant role in bestowing spectral properties upon the soil when the organic matter content exceeds 2.0 percent.

6. Mollisols

The graphs for six Mollisols are strikingly similar throughout the entire range studied, (Figure 24). These soils were obtained from six different states (Table 12). The Tetonia, Marshall, Harney, Dakota, Ortello and Montgonery series occupy a very narrow color range from 10YR5/2 to 10YR2/1, from a grayish brown to a black. Very small amounts of hygroscopic water is present as indicated by the very broad and weak absorption bands. Differences observed in the 1.0 to 2.3μm range are probably due to the silt and clay content. Mathews (19) has previously reported that silt is highly correlated with percent reflectance at a number of infrared wavelengths from 0.8 to 2.5μm and that clay content affects response throughout the spectrum. The range of response for this order extends from 0.0 to $16.2\rho'$.

<u>Table 12.</u> <u>Mollisols</u>

Soil Series	Color	Texture	Location
Tetonia	10YR4/3	silt loam	Wyoming
Marshall	10YR2/1	silty clay loam	Iowa
Harney	10YR5/2	silt loam	Kansas
Dakota	10YR2/1	loam	Minnesota
Ortello	10YR4/2	sandy loam	Nebraska
Montgomery	10YR3/1	silty clay loam	Indiana

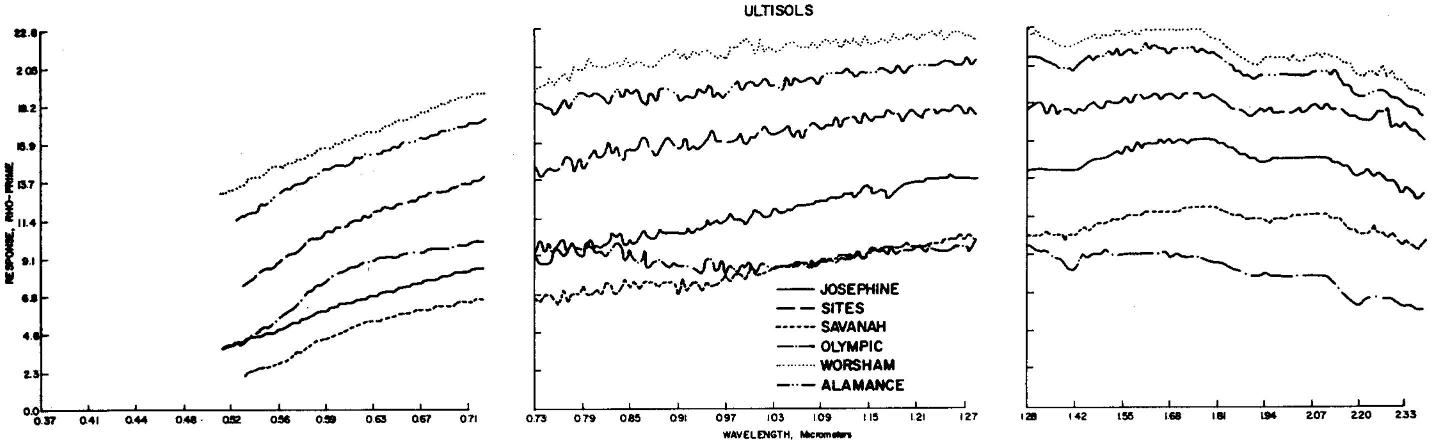

Figure 23. Spectral curves for Ultisols.

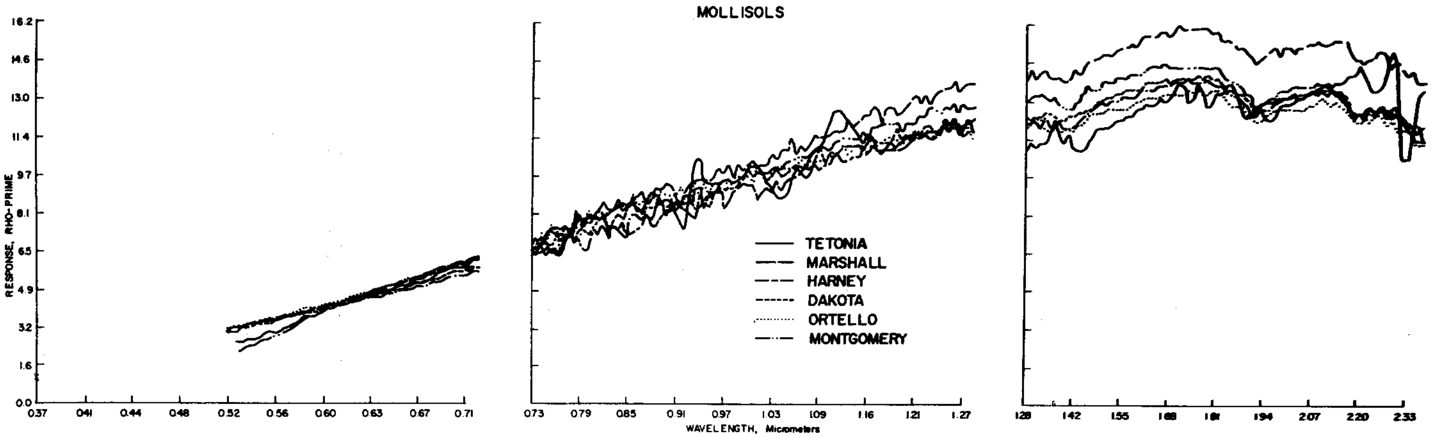

Figure 24. Spectral curves for Mollisols.

7. Vertisols

An insufficient number of samples for this order prohibits any quantitative interpretation of the spectral characteristics of this order. The only Vertisol studied, the Burlesen series, provides a means for comparing the shrinking, cracking and shearing soils with orders which do not exhibit these characteristics and are very low in the type of expanding lattice clays found in this order (Figure 25).

8. Spodosols

The soils in this series exhibit the same type of interorder similarities as previously discussed orders (Figure 26). The water absorption bands are of particular interest in that there is very little evidence of absorption in either of the bands. The phenomena illustrate the effect of texture in bestowing spectral character to soils (Table 13). The soils in this order are found only in humid regions and do not form in clayey parent materials. In the tropics, the only parent materials of the Spodosol seem to be nearly pure quartz sand. Color is another factor which contributes to the explanation of the spacing of the responses.

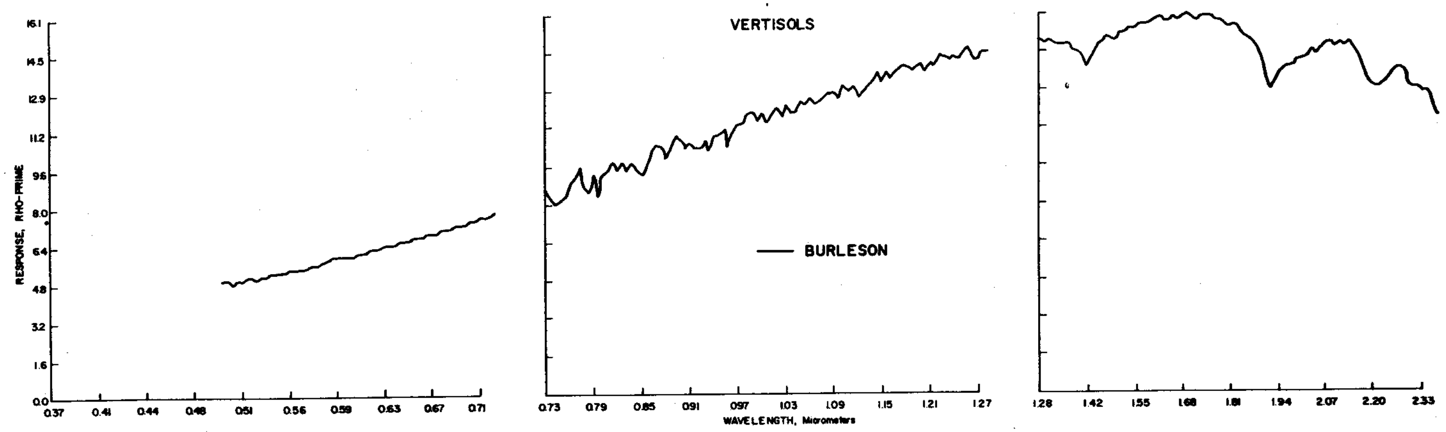

Figure 25. Spectral curves for Vertisols.

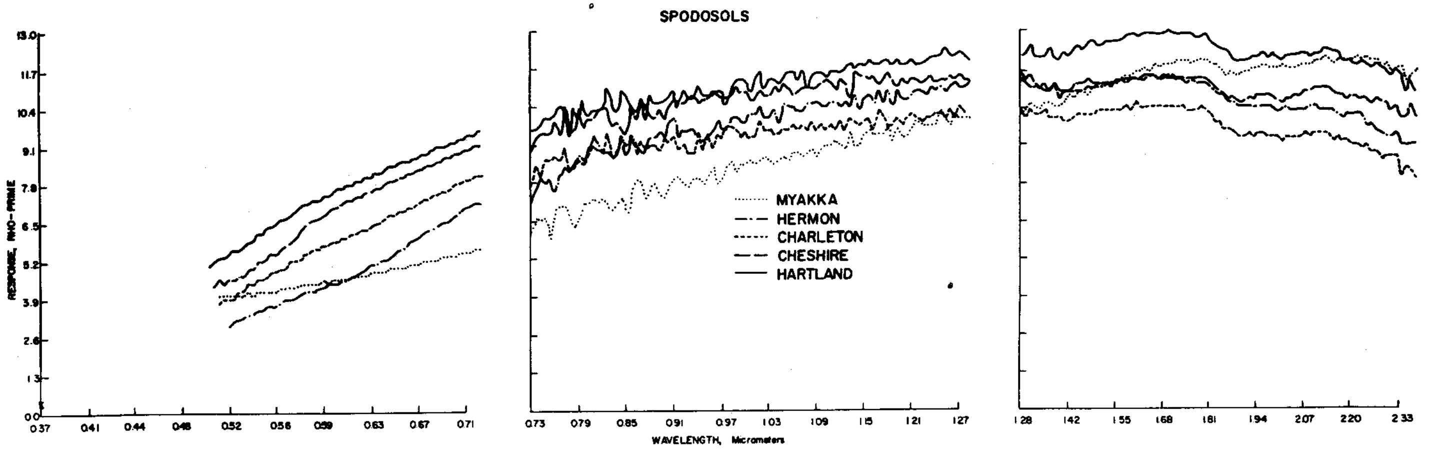

Figure 26. Spectral curves for Spodosols.

Table 13. Spodosols

Soil Series	Color	Texture	Location
Myakka	10YR4/1	sand	Florida
Hermon	10YR3/4	sandy loam	New Hampshire
Charleton	10YR3/3	loam with coarse skeleton	New Hampshire
Cheshire	7.5YR3/2	sandy loam	Connecticut
Hartland	10YR4/3	silt loam	New York

B. Relative Humidity Tests

Several samples were selected to test the effect of relative humidity on the spectral response of soils. These soils were introduced to three artificially created environments of 19.9, 79.3 and 98 percent relative humidities. These humidities were created by dissolving salts of different concentrations in water and placing them in the bottom of dessicators. The atmosphere of 19.9R.H. was produced by dissolving 253g of Potassium Acetate (KOAc) in 100ml of water. By dissolving 29.7g of Ammonium Chloride (NH_4Cl) in 100ml of water we were able to produce an atmosphere of 79.3 percent relative humidity. Water was used to establish the 98 percent relative humidity environment. The samples were placed in the dessicators and given 98 hours to equilibrate. At the end of the equilibration period, the samples were removed from the dessicators.

The Harney series (Mollisol) and the Olympic series (Ultisol) were used to observe the differences in spectral response of the same series at 19 and 79%R.H. (Figure 27).

It was observed that those samples which were introduced to the 19%R.H. showed a higher response throughout the entire spectrum. This difference, indicating a reduction in reflectivity, establishes itself in the visible portion of the spectrum from 0.50 to 0.70μm and is maintained through the spectrum studied. There seems to be no significant peaks which may be due to differences in relative humidity. The water absorption bands indicate that the amount of absorbed water is negligible.

A comparison was made between the spectral response for the Wahpeton series, a Mollisol, and the Sites series, an Ultisol, at 19 and 98% relative humidities. The reduction of response due to relative humidity is manifested in the visible range and continues throughout the spectrum. Differences due to relative humidity are also expressed in the intensity of the water absorption bands. The soils from the environment of 98 percent relative humidity show stronger absorption bands than those from the 19 percent humidity environment.

It is assumed that the relative humidity serves to reduce the reflectance from a sample. The higher the relative humidity, the lower the response; but the significance of this observed phenomena is dependent on soil texture. The lighter textured soils are not influenced as much as those of heavier textures. The greatest effects due to relative humidity are found with the silty clay, Wahpeton.

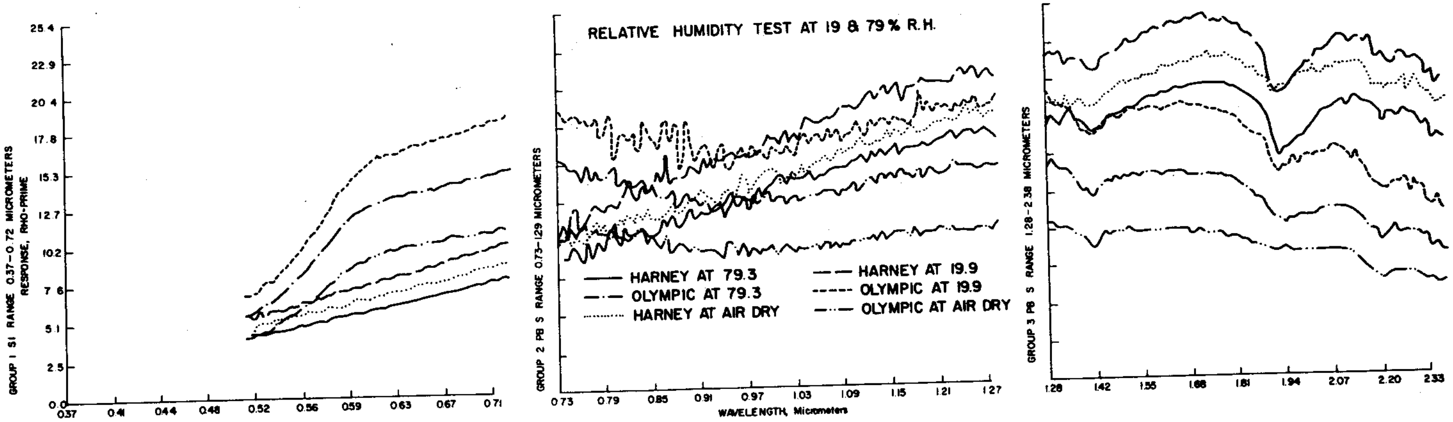

Figure 27. Relative humidity tests at 19 and 79% RH.

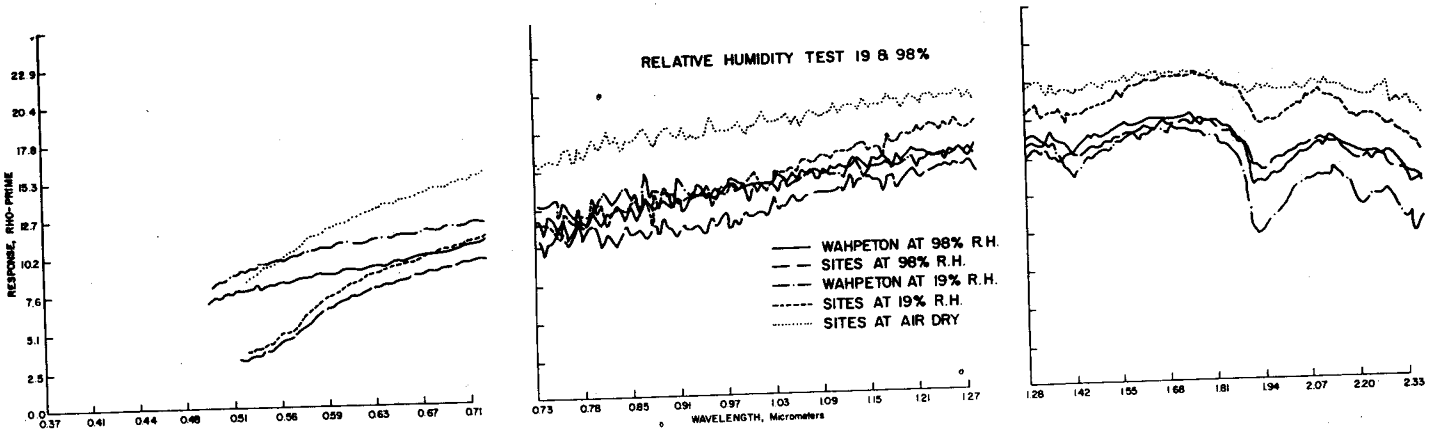

Figure 28. Relative humidity tests at 19 and 98% RH.

Table 14. Relative Humidity

Soil Series	Color	Texture
Harney	10YR5/2	silt loam
Olympic	7.5YR3/2	silt loam
Wahpeton	10YR4/1	silty clay
Sites	5YR4/3	loam

C. Check Samples

The samples from the Anthony, Pachappa and Bladock series were analyzed on two occasions to check the reproducibility of results obtained using the field spectrometer.

A comparison of the spectral graphs from the two dates (Figure 29) indicates that the reproducibility of a set of data is very good. They show that the same trends are recorded on both dates. The degree of precision is as high as one can reasonably expect. Differences can be explained by the inability to reproduce the same degree of surface roughness and the same relative humidity. It has been shown by Cipra et al (5) that surface roughness can reduce or enhance the degree of reflection as indicated in the previous discussion on the effect of relative humidity.

D. Analysis of Averaged Spectral Curves for Seven Soil Orders

A comparison of the averaged spectral curves for soil orders reveal distinct spectral differences in soil orders. These curves represent the average spectral response of all samples belonging to a particular order (Appendix 3). The

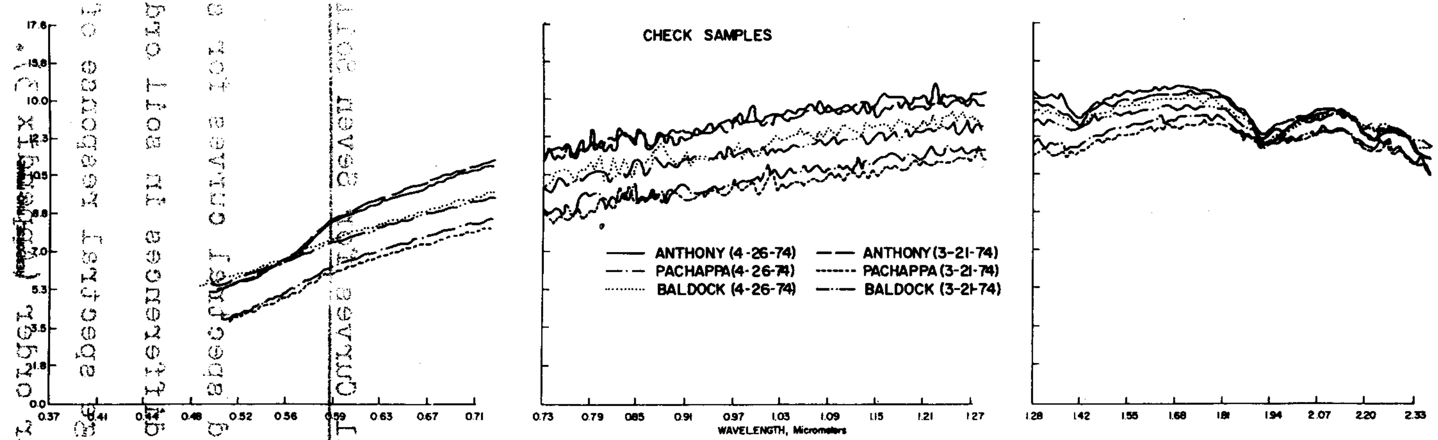

Figure 29. Spectral curves of check samples.

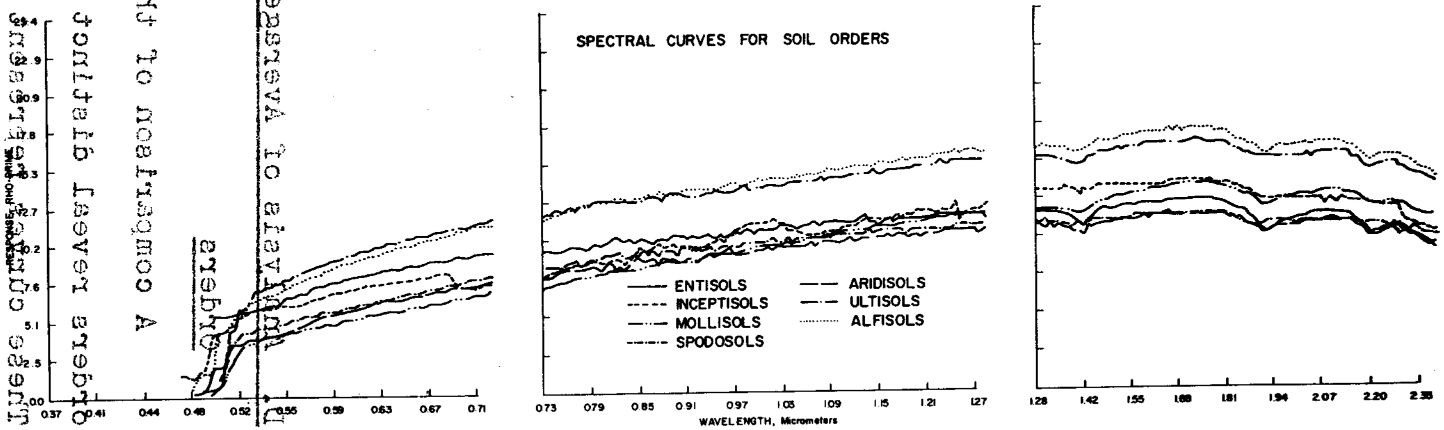

Figure 30. Averaged spectral curves for soil orders.

differences observed are real for each order in that the peaks observed appear in each of the samples of the respective order.

Reflectance curves for seven of the soil orders (Ultisols, Alfisols, Entisols, Inceptisols, Spodosols, Aridisols and Mollisols) were compared (Figure 30). The curves for the Entisols, Inceptisols, Spodosols, and Aridisols are similar to the Type 1 curves described by Condit (6) in that the slope increased throughout the spectral range and had an overall low reflectance. The reflectance of these soil orders ranged from 3 to 7%ρ'. The Type 2 curves which increased fairly rapidly from .32 to about .45μm where a slight or even moderate dip in the slope occurs, followed by an increase in the slope at about .48μm. At about 0.58μm there is another decrease in the slope. The Mollisols went from slightly above 10% to 40% reflectance. The Ultisols have a curve similar to that of the Type 3 curves observed by Condit (6). The slope of the curve increases at a sharp rate from the ultraviolet to about 0.53μm. The Alfisols have a curve resembling that of the Ultisols, a sharp increase throughout the entire range.

Alfisols and Ultisols are very similar, but there are significant differences in their response in several regions if the spectrum. At 0.89μm the Ultisols tend to absorb energy where as, the Alfisols reflect energy. Both orders have the water absorption bands at 1.4 and 2.2μm. The absorption band at 1.9 is undiscernible for the Ultisols. The Aridisols and the Spodosols are separable in the 0.96 to 0.98µm region and in each of the regions of water absorption. The Aridisols have a moderate drop in these regions indicating the presence of absorbed water, where as the Spodosols show little or no evidence of water absorption in these regions. The Inceptisols show distinct differences in the 0.67 to 0.70µm, 0.92 to 1.06µm and the 1.2 to 2.7µm regions. A sharp drop is observed in the 0.67 to 0.70µm indicating energy absorption. A broad band in the 0.92 to 1.06µm region and an intense peak at 1.25µm which distinguishes Inceptisols from other orders. The Mollisols have an overall low reflectance throughout the range studied. They reflect lower than the Spodosols and Aridisols in the visible region and slightly higher in the infrared region. The Entisols, very young soils having very little horizon development, show an overall low reflectance, increasing from 16% to 40%.

E. Multiple Regression Analysis of the Physical - Chemical and Spectral Properties of Soils.

The effect of the physical - chemical properties on the spectral reflectance of soils was studied over the wavelength interval 0.52 to 2.32. Regression analysis indicates that cation exchange capacity (CEC) and silt content influence the intensity of energy reflected by soils in the 0.52 to 2.32µm range. Clay influenced the curve shape from 0.52 to 0.59µm; while CEC and silt influenced the curve shape and intensity throughout the entire range studied. An increase in CEC causes a decrease in the reflectance of soils for all wavelength intervals studied. The influence of CEC on reflectance may be attributed to its combined relationship to the organic matter content and clay content of soils. An increase in clay or organic matter content increases the CEC of soils. Reflectance was found to increase with increased silt content. T-values for CEC and silt content at each wavelength band were computed (Table 15). Regression equations for the spectral response of soils and their computed F-values for regression are presented in Table 16. Although insignificant at $\alpha = 0.05$, the influence of Fe_2O_3 was found to be fairly constant throughout the 0.60 to 2.32µm range.

The main regression analysis indicate that CEC and silt are the only parameters which excite a significant influence on the spectra of soils; while clay, organic matter and pH does not significantly effect the spectral reflectance of soils when observed as single variables. CEC is not viewed by researchers as a visible soil parameter, but as an indicator for other parameters and their interactions. A second regression analysis was performed using the CEC as the dependent variable and organic matter, clay content, pH and their interactions as the independent variables (Table 17). Results indicate that CEC is an indicator of organic matter and clay content and the organic-clay and pH-clay interactions. The individual parameters, organic matter and clay content, explained a significant amount of the variations in CEC. The effect of pH on CEC appeared non-significant, but this phenomena is explained by noting that pH is expressed as the negative log of the hydrogen ion concentration (-log H+), thus their relationship would not be linear. It should also be pointed out that while these parameters explain significant amounts of the CEC, they in no way explain the total variation of CEC. This suggests that there are other parameters and their natural interactions which affect CEC and the total amount of energy reflected from the surface of soils.

Table 15. Significance of Regression Coefficients

Spectral Response in Band	T-values for CEC	T-values for Silt
0.56 - 0.59	-2.268	2.229
0.60 - 0.63	-2.324	2.351
0.64 - 0.67	-2.459	2.495
0.68 - 0.71	-2.946	2.701
0.73 - 0.78	-2.712	2.829
0.79 - 0.84	-2.711	2.878
0.85 - 0.90	-2.645	2.885
0.91 - 0.96	-2.690	2.906
0.97 - 1.02	-2.575	2.476
1.03 - 1.08	-2.882	2.602
1.09 - 1.14	-2.908	2.731
1.15 - 1.20	-2.706	2.780
1.21 - 1.26	-2.678	2.761
1.29 - 1.40	-2.071	2.536
1.41 - 1.53	-2.260	2.533
1.54 - 1.66	-2.441	2.477
1.67 - 1.79	-2.544	2.376
1.80 - 1.92	-2.360	2.513
1.94 - 2.06	-2.581	2.537
2.07 - 2.19	-2.816	2.489
2.20 - 2.32	-2.855	2.591

Table 16. Regression Equations for Response

Equations	Computed F-value for Regression
$Y_{(0.52-0.55)} = 7.53953 - 0.07446_{x6} - 0.02967_{x1}$	6.045
$Y_{(0.56-0.59)} = 5.74989 + 0.03583_{x2} - 0.05861_{x6}$	5.225
$Y_{(0.60-0.63)} = 6.56313 + 0.04076_{x2} - 0.06475_{x6}$	5.665
$Y_{(0.64-0.67)} = 7.20989 + 0.04529_{x2} - 0.07143_{x6}$	6.394
$Y_{(0.68-0.71)} = 7.83934 + 0.05152_{x2} - 0.08777_{x6}$	8.444
$Y_{(0.73-0.78)} = 12.21275 + 0.07015_{x2} - 0.13148_{x6}$	8.102
$Y_{(0.79-0.84)} = 9.52766 + 0.05339_{x2} - 0.09398_{x6}$	8.081
$Y_{(0.85-0.90)} = 9.94260 + 0.05218_{x2} - 0.09398_{x6}$	8.254
$Y_{(0.91-0.96)} = 10.28716 + 0.05219_{x2} - 0.09491_{x6}$	8.282
$Y_{(0.97-1.02)} = 10.73528 + 0.04929_{x2} - 0.08143_{x6}$	6.662
$Y_{(1.03-1.08)} = 11.09339 + 0.05201_{x2} - 0.09014_{x6}$	7.942
$Y_{(1.09-1.14)} = 11.46729 + 0.05417_{x2} - 0.09034_{x6}$	7.461
$Y_{(1.15-1.20)} = 11.76632 + 0.05435_{x2} - 0.08394_{x6}$	7.925
$Y_{(1.21-1.26)} = 12.13116 + 0.05418_{x2} - 0.08347_{x6}$	7.785
$Y_{(1.29-1.40)} = 12.47923 + 0.04897_{x2} - 0.06542_{x6}$	5.553
$Y_{(1.41-1.53)} = 12.86200 + 0.04904_{x2} - 0.07083_{x6}$	5.979
$Y_{(1.54-1.66)} = 13.55750 + 0.04909_{x2} - 0.07745_{x6}$	6.296
$Y_{(1.67-1.79)} = 13.92733 + 0.04783_{x2} - 0.08129_{x6}$	6.311
$Y_{(1.80-1.92)} = 13.34857 + 0.04380_{x2} - 0.04380_{x6}$	6.185
$Y_{(1.94-2.06)} = 13.17658 + 0.04417_{x2} - 0.08662_{x6}$	6.848
$Y_{(2.07-2.19)} = 13.41510 + 0.04403_{x2} - 0.09533_{x6}$	7.399
$Y_{(2.20-2.32)} = 12.60595 + 0.04409_{x2} - 0.09047_{x6}$	7.815

x2 = Silt content

x6 = CEC

Table 17. Significance of Regression Coefficients for CEC

Parameter	T-value	F-value
Organic Matter	6.253	39.096
Clay	5.070	25.710
pH	1.755	3.080
Organic Matter and Clay	5.857	34.310
pH and Clay	5.051	25.509

Regression Equation for CEC

$$Y_{CEC} = 1.14378 + 4.86076_{x3} + 0.08383_{x6} - 0.06182_{x5}$$

x3 = Organic Matter

x6 = pH and Clay interaction

x5 = Organic Matter and Clay interaction

SUMMARY AND CONCLUSIONS

The results obtained in this study indicate that the use of a field spectroradiometer in multispectral analysis is a very promising approach to mapping and delineating soils. Results also indicate that CEC and silt content influence soil spectra throughout the 0.52 to 2.32µm range.

Spectral curves for soils within orders indicate that soils belonging to the same order have very strong similarities and are often inseparable in the visible portion of the spectrum. Differences observed are attributed to soil color, moisture content, surface roughness, and relative humidity. Results of relative humidity tests reveal a decreasing spectral response from soils with increased relative humidity. The general trend of spectral curves are not affected by fluctuations in relative humidity.

Regression analysis indicates that CEC and silt content were the only variables which explained significant variation in the spectral response of soils. An increase in CEC causes a decrease in the reflectance of soils for all wavelength intervals studied. The influence of CEC on reflectance may be explained by its relationship to the organic matter content and clay content of soils. An increase in clay or organic matter content increases the

CEC of soils. The observed non-significant correlation between reflectance and organic matter and clay content may be attributed to the uneven distribution of organic matter and clay content among the data sets. Reflectance was found to increase with increasing silt content. Although insignificant at $\alpha = 0.05$, the influence of Fe_2O_3 was found to be fairly constant throughout the 0.60 to 2.32μm range. These results suggest that multispectral analysis may be a valuable tool for delineation and quantifying differences between soils.

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APPENDICES

APPENDIX 1

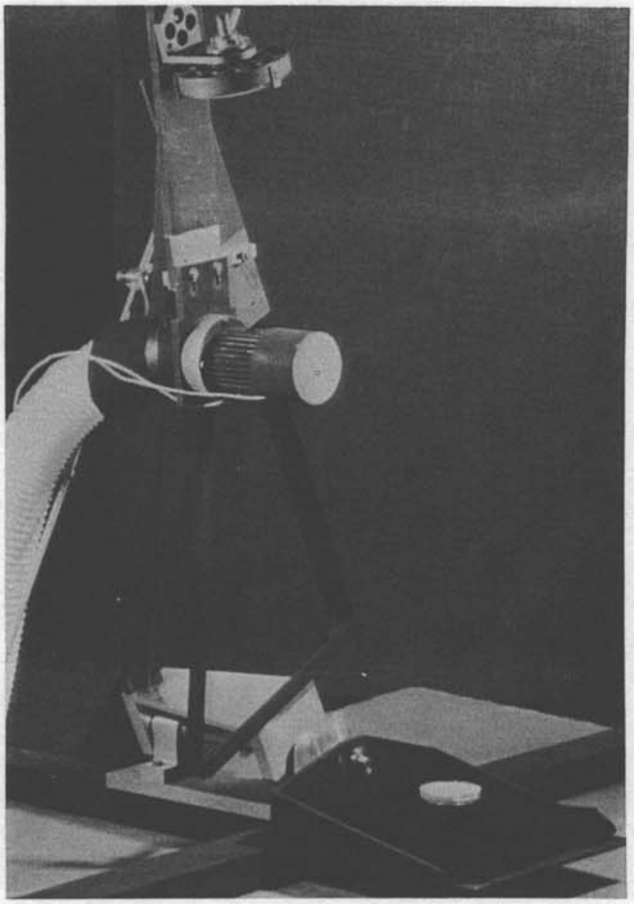

Figure 31a. Position of Samples with Respect to the Field Spectroradiometer.

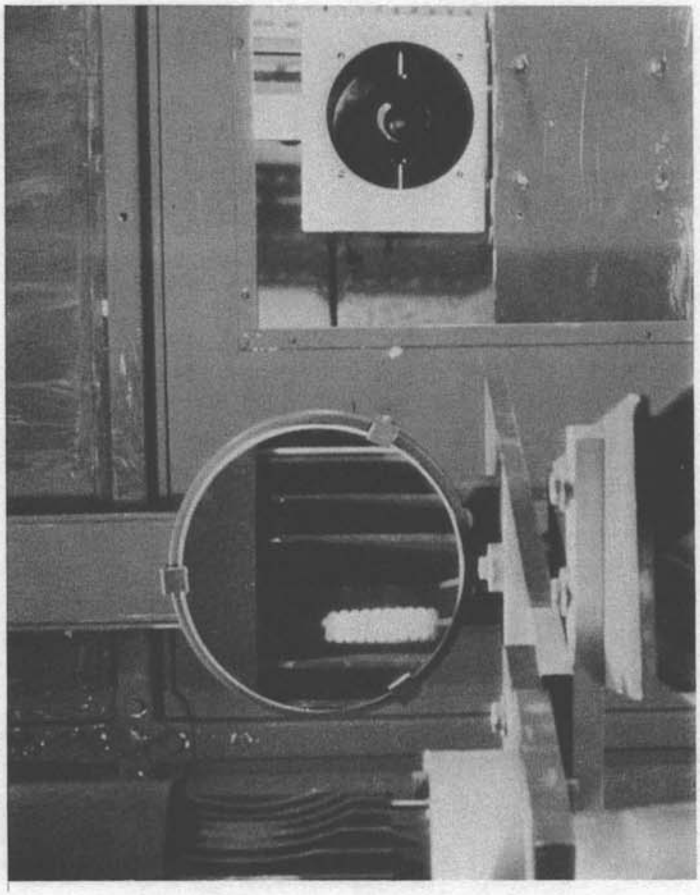

Figure 31b. Position of Samples with Respect to the Field Spectroradiometer.

APPENDIX 2

Determination of Minimum Sample Size

CALCULATIONS

I. Volume of Soil Required

$V = \pi R^2 h$

$\pi = 3.14$

$R^2 = 25.81\text{cm}^2$

$h = 2\text{cm}$ - final depth obtained from preliminary study.

$V = 3.14\ (25.81\text{cm}^2)\ (2\text{cm}) = 162.08\text{cc}$

II. Weight of Soil Required

$W = B.D \times V$

$B.D. = 1.33\text{gm/cc}$

$V = 162.08\text{cc}$

$W = (1.33\text{gm/cc})\ (162.08) = 215.60\text{gm}$

APPENDIX 3

Table 18. Description of Soil Selected for this Study

Sample Number	Soil Series	Soil Order	Soil ID	Soil Location
1	Anthony	Estisol	691079	Arizona
2	Arp	Aridisol	65183	Arizona
3	Arp	Aridisol	65184	Arizona
4	Vista	Inceptisol	641	California
5	Josephine	Ultisol	691036	Oregon
6	Tetonia	Mollisol	69607	Wyoming
7	Marshall	Mollisol	18356	Iowa
8	Harney	Mollisol	68L365	Kansas
9	Dakota	Mollisol	70L1100	Minnesota
10	Ortello	Mollisol	69L808	Nebraska
11	Marathon	Alfisol	70L883	Wisconsin
12	McGary	Alfisol	13492	Indiana
13	McGary	Alfisol	13493	Indiana
14	Dundee	Alfisol	14394	Kentucky
15	Dundee	Alfisol	19170	Louisiana
16	Muren	Alfisol	16935	Illinois
17	Henshaw	Alfisol	13484	Indiana
18	Weller	Alfisol	69L1052	Iowa
19	Alford	Alfisol	16926	Illinois
20	Alford	Alfisol	16928	Illinois
21	Dubbs	Alfisol	14387	Kentucky
22	Lindy	Alfisol	18217	Texas
23	Montgomery	Mollisol	13507	Indiana
24	Patton	Mollisol	14375	Kentucky
25	Amsterdam	Millisol	71L1044	Montana
26	Moreay	Mollisol	20149	North Dakota
27	Ulen	Mollisol	67L610	Minnesota
28	Wahpeton	Mollisol	67L682	North Dakota
29	Marshall	Mollisol	18359	Iowa
30	Keg	Mollisol	70L1135	Iowa
31	Verdigris	Mollisol	13427	Oklahoma
32	Harney	Mollisol	68L368	Kansas
33	Wakeen	Mollisol	68L408	Kansas
34	Austin	Mollisol	17717	Texas
35	Tripp	Mollisol	15683	Nebraska
36	Vanda	Entisols	71L938	Montana
37	Sharkey	Inceptisol	14400	Kentucky

Table 18. (Continued)

Sample Number	Soil Series	Soil Order	Soil ID	Soil Location
38	Tunica	Inceptisol	16437	Tennessee
39	Savanna	Ultisol	15172	Mississippi
40	Burleson	Vertisol	17753	Texas
41	Pachappa	Alfisol	6344	California
42	Sheridan	Mollisol	65580	California
43	Tournquist	Mollisol	66327	California
44	Bluffdale	Inceptisol	67211	Utah
45	Bradshaw	Mollisol	67236	Utah
46	Secca	Alfisol	68832	California
47	Hoda	Alfisol	68844	California
48	Sites	Ultisol	68883	California
49	Casto	Alfisol	68995	Arizona
50	Nevine	Inceptisol	69253	Washington
51	Baldock	Inceptisol	69720	Idaho
52	Mohave	Aridisol	691071	Arizona
53	Sedillo	Aridisol	71355	New Mexico
54	Tijeras	Aridisol	71368	New Mexico
55	Lint	Inceptisol	72330	Oregon
56	Olympic	Ultisol	72440	Washington
57	Myakka	Spodosol	71-175	Florida
58	Hermon	Spodosol	60559	New Hampshire
59	Charleton	Spodosol	60583	New Hampshire
60	Cheshire	Spodosol	69105	Connecticut
61	Hartland	Spodosol	69220	New York
62	Worsham	Ultisol	66145	North Carolina
63	Alamance	Ultisol	66119	North Carolina
64	Cecil	Ultisol	6074	North Carolina
65	Hayesville	Ultisol	6064	North Carolina
66	Benndale	Ultisol	67427	Mississippi
67	Norfolk	Ultisol	7170	Alabama
68	Ruston	Ultisol	7198	Alabama
69	Americus	Ultisol	62215	Georgia
70	Red Bay	Ultisol	62287	Georgia
71	Marna	Alfisol	698766	Minnesota

Table 19. Physical and Chemical Properties of Soils Studied

Sample Number	Soil Order	Texture Class	pH	% O.M	C/N	% Fe_2O_3	% H_2O	CEC	Bulk Density	Base Sat.
1	Entisol	10	7.7	0.09	12	0.5	4.5	6.9	1.65	39
2	Aridisol	3	6.7	0.82	13	3.1	11.3	29.5	1.30	92
3	Aridison	3	6.7	0.82	13	3.1	11.3	29.5	1.30	92
4	Inceptisol	10	6.9	0.96	12	1.0	5.4	16.9	1.55	42
5	Ultisol	9	6.0	7.68	23	3.6	21.0	33.2	0.97	67
6	Mollisol	7	6.7	1.76	10	0.8	7.9	17.5	1.30	100
7	Mollisol	5	6.2	2.61	13	1.0	13.2	22.6	1.27	99
8	Mollisol	7	6.6	1.41	11	0.6	10.8	21.0	1.20	97
9	Mollisol	9	5.4	1.62	11	1.1	8.7	16.6	1.48	91
10	Mollisol	10	5.4	1.46	12	0.3	5.5	10.9	1.40	74
11	Alfisol	7	4.4	2.25	14	0.6	6.6	11.4	1.31	46
12	Alfisol	7	6.5	0.89	10	2.2	8.5	13.6	1.56	91
13	Alfisol	7	6.5	0.89	10	2.2	8.5	13.6	1.56	91
14	Alfisol	5	6.3	1.82	11	2.1	19.4	25.5	1.68	100
15	Alfisol	10	6.1	0.59	12	0.5	4.9	12.1	1.37	95
16	Alfisol	5	4.8	1.02	10	0.6	9.5	14.7	1.44	67
17	Alfisol	7	6.2	0.83	10	1.2	14.1	7.4	1.54	85
18	Alfisol	7	5.0	1.16	9	0.7	7.9	13.3	1.41	60
19	Alfisol	7	6.5	1.00	9	0.8	5.6	8.1	1.45	100
20	Alfisol	7	6.5	1.00	9	0.8	5.6	8.1	1.45	100
21	Alfisol	5	5.7	1.56	11	1.6	11.9	20.2	1.67	89
22	Alfisol	9	6.5	1.09	12	3.1	8.1	12.9	1.59	39
23	Mollisol	5	6.7	2.33	12	2.2	9.6	24.6	1.54	100
24	Mollisol	7	5.9	1.28	11	1.0	7.9	15.0	1.56	94

Table 19. (Continued)

Sample Number	Soil Order	Texture Class	pH	% O.M	C/N	% Fe_2O_3	% H_2O	CEC	Bulk Density	Base Sat.
25	Mollisol	7	6.6	1.47	12	0.6	13.2	23.6	1.40	99
26	Mollisol	2	7.8	1.93	11	1.1	16.1	27.8	1.43	50
27	Mollisol	10	8.0	1.55	11	1.0	4.3	9.4	1.56	100
28	Mollisol	2	7.5	3.11	11	1.0	24.4	43.8	1.28	100
29	Mollisol	5	6.2	2.61	13	1.0	13.2	22.6	1.27	99
30	Mollisol	7	5.2	1.81	11	0.6	9.6	20.2	1.31	86
31	Mollisol	5	6.3	2.63	12	1.9	15.6	26.8	1.38	106
32	Mollisol	7	6.6	1.41	11	0.6	10.8	21.0	1.20	97
33	Mollisol	5	7.6	1.76	10	0.5	10.5	19.3	1.20	96
34	Mollisol	2	7.5	1.86	11	1.0	16.4	37.9	1.34	100
35	Mollisol	10	7.7	0.54	9	0.6	6.2	12.5	1.34	88
36	Entisol	2	8.4	1.02	10	0.7	21.9	36.2	1.20	100
37	Inceptisol	2	6.5	1.54	11	2.2	16.5	25.5	1.76	100
38	Inceptisol	2	6.5	2.57	14	1.8	23.9	34.9	1.34	100
39	Ultisol	7	4.5	0.65	12	1.6	15.3	4.2	1.58	60
40	Vertisol	1	5.4	1.03	14	1.8	16.9	30.6	1.54	100
41	Alfisol	10	6.6	0.82	13	3.0	3.0	7.9	1.65	80
42	Mollisol	9	6.4	1.68	13	1.7	5.0	12.7	1.54	91
43	Mollisol	9	5.6	3.86	26	5.0	17.7	35.4	1.04	55
44	Inceptisol	3	8.7	1.06	10	0.6	11.8	18.3	1.47	98
45	Mollisol	9	7.5	3.06	13	1.7	12.4	24.1	0.97	77
46	Alfisol	7	6.2	1.50	11	4.9	11.0	20.8	0.99	84
47	Alfisol	9	5.8	2.03	13	2.4	7.3	11.1	1.24	43
48	Ultisol	9	5.9	6.00	30	9.2	23.5	31.8	0.94	43
49	Alfisol	10	7.8	1.50	12	0.5	17.7	47.4	0.61	100
50	Inceptisol	7	6.0	18.91	23	0.6	8.8	32.4	0.95	75
51	Inceptisol	9	8.8	1.14	9	0.8	19.8	20.5	1.48	100
52	Aridisol	10	7.7	0.84	10	0.7	9.5	19.8	1.47	98
53	Aridisol	9	7.7	0.53	10	0.7	4.4	8.9	1.47	100
54	Aridisol	10	7.3	0.23	10	0.8	4.4	8.7	1.60	100

Table 19. (Continued)

Sample Number	Soil Order	Texture Class	pH	% O.M	C/N	% Fe_2O_3	% H_2O	CEC	Bulk Density	Base Sat.
55	Inceptisol	7	5.2	21.36	13	1.3	61.3	66.2	0.89	37
56	Ultisol	7	5.6	5.35	12	1.7	18.3	32.0	0.94	43
57	Spodosol	13	4.0	2.23	11	1.4	4.4	4.4	1.53	34
58	Spodosol	10	4.3	5.10	15	0.2	3.9	26.8	1.33	14
59	Spodosol	9	4.3	2.77	12	1.2	13.2	20.6	1.33	14
60	Spodosol	10	6.4	1.52	10	0.1	5.2	6.8	1.46	90
61	Spodosol	7	5.4	4.25	12	1.4	8.4	17.9	1.42	57
62	Ultisol	7	4.8	1.65	20	0.5	6.8	16.8	1.64	42
63	Ultisol	7	4.3	1.13	11	1.6	4.3	13.5	1.55	20
64	Ultisol	9	4.3	1.63	15	1.0	6.0	10.3	1.39	43
65	Ultisol	9	4.3	2.69	14	1.0	9.0	16.0	1.28	7
66	Ultisol	10	5.4	1.16	16	0.4	4.7	5.9	1.53	39
67	Ultisol	10	6.0	1.16	16	0.11	4.0	5.7	1.43	81
68	Ultisol	10	4.7	3.05	16	0.11	5.6	9.8	1.33	23
69	Ultisol	11	4.5	0.58	20	0.80	2.6	3.7	1.56	14
70	Ultisol	10	5.9	0.40	24	0.30	1.8	3.6	1.64	58
71	Alfisol	5	5.8	3.33	12	0.6	19.4	41.7	1.33	100