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Soil Mineralogical Studies By Remote Sensing

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Abstract

THE increasing pressures on global land resources call for a re-examination of traditional soil inventory and management methods. Of the 13 billion hectares of land on planet earth, soil surveys with sufficient detail for rational soil management decisions are available for only a small fraction. Further, the lack of quantitative information about relationships among soil mineralogical, chemical, physical and biological properties, potential productivity and susceptibility to degradation under different environmental conditions severely limit the ability of decision-makers to rationalize their soil management and conservation practices.

During recent years many new advances have been made in aerospace remote sensing technology. The capability to observe the earth's surface repetitively from space adds a new dimension to the study of soils and land resources. Masses of data not previously available about land, mineral, vegetation and water resources are currently acquired routinely by earth orbiting satellities. A broad array of laboratory, field and air- and space-borne sensors now provide quantitative spectral, spatial and temporal data about earth surface features.

Emphasis in this paper is placed on soil research to explain differences among soils as measured by reflectance in the visible and infra-red regions of the electromagnetic spectrum. Special attention is given to the variations in surface soil reflectance as it is affected by mineralogy, iron oxides, organic matter, internal drainage, and severity of erosion.

Since the mineralogy of soils is so important in defining the potential productivity and susceptibility to degradation of arable lands, the paper suggests that soil mineralogists might find remote sensing technology a useful tool to improve our knowledge of the mineralogical characteristics of soils.

The future benefits to be derived from improved earth observation systems will be largely dependent upon the results of research to define quantitative relationships between the radiation characteristics and other physical, chemical, and biological properties of earth surface features. Soil scientists have a significant role to play in this research.

IT is my pleasant task to review for this assembly the state-of-the-science in using remote sensing techniques in the study of soil mineralogy. In the

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context of the general theme of this panel discussion, 'Whither Soil Research — Present and Future?', my assignment is a challenging and exciting one. The objective of this paper is threefold: (a) to describe recent developments in data acquisition and analysis technology, now commonly referred to as ' remote sensing'; (b) to review some research results and applications of this technology to the study of soil mineralogy and related areas; (c) to consider future technological trends as they may contribute to the delivery of more accurate, useful, timely soils resource information to decision-makers in the production and distribution of food and fibre.

Remote Sensing in Perspective

Observers of the landscape have been using remote sensing techniques for decades, if not centuries. Soil scientists in particular have used photographic methods for half a century to observe and record variations in soils. But it has been only recently that a broad array of data acquisition, storage and analysis technology has provided a rather new approach to the study of soils.

In 1947 Frederick Hoyle, noted British physicist, stated prophetically: 'Once a photograph of the earth, taken from the outside is available — once the sheer isolation of the earth becomes plain, a new idea as powerful as any in history will be let loose.'

Dr. Robert Frosch (1977), former administrator of the National Aeronautics and Space Administration (NASA), made this observation:

> We are the first generation to see the earth as a whole. For centuries man has observed and tried to represent by drawings tiny areas of the earth surface. He would piece these drawings together in an attempt to show what the earth would look like if he could see it as a whole. A few decades ago he made a dramatic advance by inventing the camera, then later placing the camera on an airplane. By these developments man extended his powers of observing the surface of the earth. He could see much larger areas and less piecing together was necessary. But this is the first generation to see data that went the other way.
>
> Today man can begin with a broad synoptic view of the earth through images derived from earth observation satellites. Great detail may then be extracted from these same data. So, in a sense, we have turned the whole enterprise around. Instead of starting with the details and trying to construct the big picture, we now have the capability to go the other way — to look at the big picture and then figure out how to extract the details that explain it.

All participants in this Congress were on hand at the birth of the 'new idea as powerful as any in history' described by Hoyle. We are part of that first generation suggested by Frosch to see the earth as a whole. Although it is difficult, if not impossible, to foresee the long-range implications of these new concepts, there is little doubt that significant changes lie ahead in our capabilities to acquire, store and analyse data and to extract and deliver improved information related to land, water, vegetation, and mineral resources.

For soil scientists this new technology is very timely because the ever-expanding global population places increasing demands on and causes accelerating degradation of the land resources of the world. To date we have had very limited capabilities of monitoring quantitatively changes in the quantity and quality of arable land for a given country or on a global basis. Human use and misuse of land resources have become a major factor which must be included in any model to estimate the current and future carrying capacity of the world.

Many thoughtful persons have suggested that the 1970s were a turning point in history with respect to the human capacity to improve and sustain the capability of the global land resources to feed the human population (Toffler 1980; Brandt *et al.* 1980; Laszlo *et al.* 1977). Many events and trends of the 1970s corroborate this suggestion:

> During the mid-seventies the world population reached 4 billion.
>
> Global awareness of environmental degradation expanded dramatically and was expressed in many ways, including the establishing of the United Nations Environment Programme (UNEP).
>
> The era of inexpensive energy came to an abrupt end.
>
> The Club of Rome published an astonishing series of reports related to human use and misuse of earth resources and to the search for the changes required for human survival in a quality environment.
>
> The decade gave birth to the era of orbiting earth observation satellites.
>
> "Futurism" was born with an accelerating interest by individuals, organizations, and governments in predicting from past and present trends what the human condition will be in the years 2000, 2030 and 2050.

These are but a few of the indicators of change during the past decade, but each of these indicators has implications for every scientist who is concerned with the understanding of soils and the role of soils and the soil scientist in human survival.

The results of every study on the changing status of earth resources and the carrying capacity of the world were derived from mathematical models in which many assumptions were made. When the desired quantitative data are not available, assumptions must be made. The unavailability of resource data

has resulted in the use of many questionable assumptions. During recent decades significant progress has been achieved in resource information technology which may provide quantitative resource data where assumptions were used previously. The current trend in information technology holds great promise for providing a steady and continuing improvement in the acquisition of quantitative information about soil resources and the changing status of these resources.

Recent Developments in Remote Sensing Technology

For the purposes of this paper a broad definition of 'remote sensing' is used. Remote sensing is the observation and/or measurement of a scene or target without physical contact of the target by the observer. The distance between the two may be a fraction of a metre or thousands of kilometres.

Three areas of intense technological development during the past three decades have provided significant improvement in our capability to deliver accurate, useful, timely resource information to decision-makers.

Data Acquisition

Major advances have been made since 1960 in instruments, remote sensing devices, equipment and sampling strategies for observing, characterizing and monitoring a scene or target. New data acquisition methods in the laboratory, in the field and from air and space platforms provide new views of the universe, never available before, from the sub-atomic structure to the rings of Saturn to a synoptic view of 25,000 km of the landscape surrounding New Delhi or any other area of the earth.

For the purposes of this paper, attention will be limited to remote sensing devices which record variations in the visible and infra-red regions of the electromagnetic spectrum. Although major attention during the past decade has been given to the aerospace segment in remote sensing, laboratory and field instruments are being accorded increasing importance in remote sensing research. The significance of this research has been repeatedly demonstrated as essential for the analysis and interpretation of much air- and space-acquired data.

The launch of Landsat-1 by the National Aeronautics and Space Administration (NASA) in July 1972 ushered in a new era in earth observations. Landsat-2 and -3 followed in January 1975 and March 1978, respectively. Landsat-D, which will become Landsat-4 after a successful launch, is scheduled to be placed in polar orbit during the fourth quarter of 1982. Landsat-1, -2 and -3 are in near polar, sun-synchronous orbit at an altitude of approximately 920 kilometres. The orbital and sensor designs are such that each satellite has the capability of observing the entire surface of the earth every 18 days. Each image obtained by the Landsat sensor covers an area of 185 × 185 km (34,000 km^2). After 5 years of successful data acquisition, Landsat-1 was retired from service in January 1978. Deterioration in performance of Landsat-2 sensors in late 1979 led to a shutdown of its data acquisition system after almost 4 years of service.

Each Landsat is equipped with some combination of the following sensors: return beam vidicon cameras (RBV), multispectral scanner (MSS), and thematic mapper (TM). Basic specifications of the sensors are summarized in Table 1.

Table 1. Specifications of the return beam vidicon (RBV), multispectral scanners (MSS) and thematic mapper (TM) on Landsat-1, -2, -3, and -D

Landsat	Sensor	Spectral bands (μm)	Description	Spatial Resolution (m)
1, 2	RBV	0.475-0.575	visible blue, green	80
		0.580-0.680	visible orange, red	80
		0.690-0.830	near-infra-red	80
3		0.505-0.750		30
1, 2, 3, D	MSS	0.5- 0.6	visible green	80
		0.6- 0.7	visible red	80
		0.7- 0.8	near-infra-red	80
		0.8- 1.1	near-infra-red	80
3		10.4-12.6	thermal infra-red	240
D	TM	0.45- 0.52	visible blue	30
		0.52- 0.60	visible green	30
		0.63- 0.69	visible red	30
		0.76- 0.90	near-infra-red	30
		1.55- 1.75	middle infra-red	30
		2.08- 2.35	middle infra-red	30
		10.40-12.50	thermal infra-red	120

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Landsat-D will have a nominal orbital altitude of 705 km and will maintain a 16-day cycle of repetitive coverage. The two on-board sensors (MSS and TM) will provide ground coverage of about 185 × 170 km per scene.

Data from Landsat sensors are transmitted to receiving stations in digital form. Receiving stations in operation include the following (U.S. Geological Survey 1980):

USA (3 stations)
  Greenbelt, Maryland
  Goldstone, California
  Fairbanks, Alaska
Canada (2 stations)
  Prince Albert, Saskatchewan
  Shoe Cover

Argentina — Mar Chiquita
Australia — Alice Springs
Brazil — Cuiaba
India — Hyderabad
Italy — Fucino
Japan — Ohasi

Receiving stations are under construction in Chile, China and Thailand. The common reception radius of ground receiving stations is 2780 km.

The products available from receiving stations include black and white single-band images, false colour (multiband) images and digital data on computer compatible tape (CCT). These images can be analysed and interpreted by visual methods, or the digital data can be analysed by computer-implemented pattern-recognition techniques.

Concurrent to the development of aerospace sensors has been the design and development of many laboratory and field spectroradiometers for research and ground control data acquisition in support of the earth observation programme.

Data Analysis

Traditionally, the ability of the observer to acquire data has exceeded by far his/her ability to analyse and interpret data. The computer revolution of the past 30 years has provided a giant leap forward in the human capability to cope with the masses of data accumulated.

In this presentation, emphasis will be given to the application of pattern-recognition techniques by digital analysis of multispectral data. The principle of computer-implemented pattern-recognition techniques may be illustrated by examination of the spectral properties of different features in the landscape. Typical spectral curves have been plotted for green vegetation, bare soil and water (Fig. 1). The horizontal axis represents wavelength in the visible (0.38 to 0.72 μm) and reflective infrared (0.72 to 2.50 μm) portions of the electromagnetic spectrum. The vertical axis represents the intensity of reflected energy as measured by a spectroradiometer. An examination of these curves reveals that there are certain wavelengths that are much better than others in separating green vegetation, soil and water.

The same data used for plotting these spectral curves may be plotted in

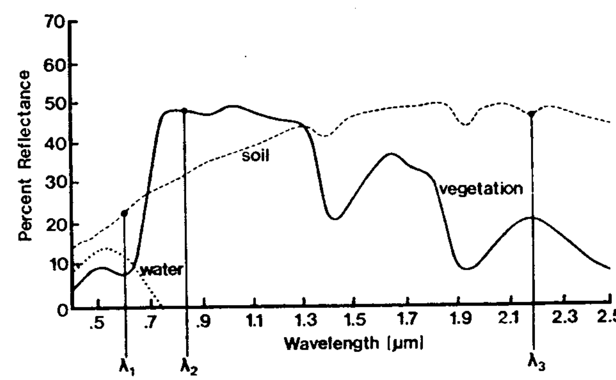

Fig. 1. Spectral curves of green vegetation, bare soil and water.

another fashion. For example, the reflectance values for each landscape feature (vegetation, soil, water) at three different wavelengths, represented by λ_1, λ_2, and λ_3, may be plotted in three-dimensional space (Fig. 2).

In the analysis of multispectral data by pattern-recognition techniques, one of two general approaches is usually followed. One approach is termed 'clustering' or 'non-supervised' classification. With this approach an algorithm is used which directs the computer to examine the spectral data for the area of interest and to assign each picture element (pixel) to a cluster of pixels having similar spectral characteristics. The number of cluster classes to be spectrally separated is generally set arbitrarily by the analyst and may or may not be determined by the analyst's prior knowledge of the area being analysed.

The other general approach is termed 'supervised' classification. In this case the analyst provides the computer with a spectral definition of the classes to be spectrally identified and mapped. This spectral definition is provided in the form of a set of training samples of known identity from specific addresses within the multispectral data. The quality of the supervised classification results is dependent upon the spectral separability of the desired classes with existing spectral data and upon the quality of the training sets, i.e., the degree to which the training samples selected by the analyst are representative of the features to be classified by spectral analysis.

The identification and delineation of green vegetation, bare soil and water by spectral analysis is quite simple and can be accomplished with a high level of accuracy with little or no knowledge of the ground scene by the analyst. However, the classification problem by spectral analysis becomes much more difficult when the objective is to classify the ground scene into many different subcategories of green vegetation, soil and water. Subcategories of interest might include many crop species, differences in plant vigour and biomass production, soils with varying contents of organic matter or different internal drainage characteristics and water containing varying amounts of suspended

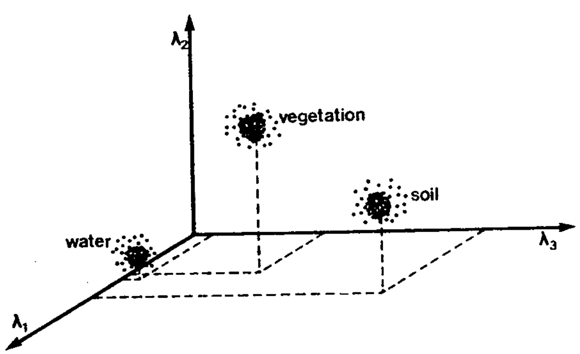

Fig. 2. Three earth surface features (vegetation, soil, water) plotted spectrally in three-dimensional space.

matter. Complexity of classification at this level requires special interpretive skills by the analyst. Such skills can best be obtained through broad experience in spectral and intimate knowledge of the area being classified.

Although human experience is limited to three-dimensional perception, the computer has no such constraints; it can operate in n-dimensional space. Thus, with appropriate algorithms the computer can examine the quantitative reflectance values for each of the four wavelength bands of a Landsat scanner and classify or assign each data point or picture element (pixel) to a specific spectral category. Many different algorithms have been developed for the computer-implemented analysis of multispectral data.

Information Dissemination

The technology of communication is another of man's activities which has undergone revolutionary changes during the past two decades. It is now possible to transmit instantaneously voices, images and masses of quantitative data from any point to any other location on the surface of the earth. This capability adds a new dimension to the delivery of useful, timely information to decision-makers and policy-makers.

New domestic and global communication systems have important implications for the future development and management of earth resources. This technology plays an essential role in several segments along the path of information flow from the moment of data acquisition by aerospace sensors to the delivery of useful information to the user.

Landsat-3 transmits through its communication channels a modest 1 million data points (quantitative reflectance measurements) per second to ground receiving stations. There will be a 10-fold increase in the amount of data transmitted from the sensors of Landsat-D. Communications technology will play an increasingly vital role in the development and management of both renewable and non-renewable resources. These developments have profound implications for the future design and use of soil information systems.

Applications of Remote Sensing to Soils Studies

Early Work

Remote sensing as black-and-white panchromatic photography has been a standard soil study and mapping tool since its introduction in 1929 in the state of Indiana, USA (Bushnell 1951). Photographs increased both the speed and accuracy of soil scientists because of the wealth of ground detail shown, the accessibility to areas of rugged terrain, and the three-dimensional view of the soil in the landscape. Soil boundary delineation was possible largely from tonal characteristics with the understanding that the same land area could vary in appearance from one date to another (Bushnell 1951).

Since those early days of aerial photographic usage in soil survey, many improvements have occurred in camera systems and film/filter combinations. High-altitude photography has been used extensively in the preparation of medium- to small-scale soil maps (Rust *et al.* 1976). Colour aerial films, black-and-white and colour infra-red emulsions, and multi-lens camera systems further expanded the possibilities for aerial photographic surveys (Carroll 1973a). Still, photo-interpretation techniques were not conducive to maximum extraction of tone information from aerial imagery, leading some to suggest the use of instruments to perform this task (Cihlar and Protz 1972).

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

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

The availability of visible and near-infra-red multispectral scanner data from 0.45 ha resolution elements within a 34,000 km^2 image frame presented new possibilities and challenges in soil mapping in the 1970s.

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

well as from topography enhanced by low-elevation solar illumination of snow-covered terrain.

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

Spectral Characterization of Soils

In all the early soil studies with multispectral scanner data, whether from air- or space-borne platforms, researchers faced the dilemma of not being able to understand or explain the causes of many of the variations in reflectance from surface soils. Digital analysis of spectral data from these new sensors could classify a landscape scene into many spectrally separable categories on the basis of very subtle differences in one or more of the spectral bands. One of the major problems for the soil scientist then in using this technology became that of defining quantitatively the spectral characteristics of soils under a wide range of environmental conditions. Now instruments are generally available to conduct research to explain reflectance variations of soils (Stoner *et al.* 1980b).

Visible soil reflectance, or colour, is an essential part of the definition of certain diagnostic horizons in modern comprehensive soil classification (USDA Soil Survey Staff 1975). Unlike other differentiating characteristics such as particle size distribution or base saturation, which are verifiable by established laboratory procedures, soil reflectance is determined by visual comparison with standard colour charts. A more quantitative approach to the spectral characterization of soils might lead to improvements in soil information systems and in prediction models related to soil management and productivity.

Soil reflectance is a cumulative property which derives from inherent spectral behaviour of the heterogeneous combination of mineral, organic and fluid matter that comprises mineral soils. Numerous studies have described the relative contributions of soil parameters such as organic matter, soil moisture, particle size distribution, soil structure, iron oxide content, soil mineralogy and parent material to reflectance of naturally occurring soils (Angstrom 1925; Baumgardner *et al.* 1970; Bowers and Hanks 1965; Bowers and Smith 1972; da Costa 1979; Hoffer and Johannsen 1969; Karmanov 1970; Lindberg and

Snyder 1972; Mathews *et al.* 1973b; Montgomery 1976; Myers and Allen 1968; Obukhov and Orlov 1964; Peterson *et al.* 1979; Planet 1970; Schreier 1977; Shields *et al.* 1968; Stoner 1979).

Extensive literature exists describing the characteristic variations in visible and near-infra-red reflectance of minerals and rocks (Hunt and Ross 1967; Hunt and Salisbury 1970, 1971, 1976a, b; Hunt *et al.* 1971a, b, 1973a, b, c, 1974). Hunt's studies reveal the intrinsic spectral features that appear in the form of bands and slopes in the bidirectional reflectance spectra of minerals as caused by a variety of electronic and vibrational processes. Reflectance measurements of 160 soil samples from 36 states of the United States are the basis for an investigation by Condit (1970, 1972) that classifies all soil spectra into three general types with respect to their curve shape. However, Condit does not discuss these three general soil spectral curve types in relation to soil characteristics or soil classification. Cipra *et al.* (1971) conducted field spectroradiometric studies and described the properties and classification of seven soil series in terms of Condit's spectral curve types.

Stoner's (1979) examination of soil spectra (0.52-2.38 μm) from 485 soil samples representing 30 sub-orders of the 10 orders of Soil Taxonomy revealed the existence of five distinct soil reflectance curve forms. These curves, derived from spectral data obtained by an Exotech Model 20C spectroradiometer, are differentiated by slope characteristics and the presence or absence of absorption bands. The differentiating elements relate mainly to the organic matter and iron oxide differences of these soils (Stoner and Baumgardner 1981). A description of the bidirectional reflectance factor and its applications to characterizing soil reflectance have been given by DeWitt and Robinson (1974).

Reflectance spectra representative of the five curve forms are illustrated for five mineral soil samples (Fig. 3). Characteristics of these specific surface soils are detailed for comparison of reflectance-related soil properties (Table 2). The first three curve forms are identical to those described by Condit (1970, 1972) as Types 1, 2, and 3, but here are renamed to express the distinguishing soil characteristics. The organic dominated form (Condit Type 1) exhibits a low overall reflectance with a gradually increasing slope from 0.5 to 1.3 μm, which imparts a characteristic concave curve shape. Strong water absorption bands are present at 1.45 and 1.95 μm in this and most other curve forms. The broadness of these bands indicates the presence of water molecules in relatively unordered sites, probably as water films on soil particle surfaces (Angstrom 1925; Hunt and Salisbury 1970).

The minimally altered form (Condit Type 2) is characterized by overall high reflectance and gradually decreasing slope from 0.5 to 1.3 μm, giving this curve a characteristic convex shape. In addition to the strong water absorption bands at 1.45 and 1.95 μm, weak water absorption bands may be present at 1.2 and 1.77 μm. These weak absorption bands correspond to the absorption bands observed in transmission spectra of relatively thick water

Table 2. Characteristics of surface samples of five mineral soils (Fig. 3, curves a-e).

	Reflectance curve form				
	organic dominated (a)	minimally altered (b)	iron affected (c)	organic affected (d)	iron dominated (e)
Soil series	Drummer	Jal	Talbot	Onaway	(not given)
Horizon sampled	Ap	A11	Ap	Ap	A11p
Soil subgroup	Typic Haplaquoll	Typic Calciorthid	Typic Hapludalf	Alfic Haplorthod	Typic Haplorthox
Sample location	Champaign Co. IL, USA	Lea Co. NM, USA	Rutherford Co. TN, USA	Delta Co. MI, USA	Londrina. Paraná, Brazil
Climatic zone	humid mesic	semiarid thermic	humid thermic	humid frigid	humid hyperthermic
Parent material	loess over glacial drift	fine textured alluvium or lacustrine	clayey limestone residuum	glacial drift	basalt
Drainage class	poorly drained	well drained	well drained	well drained	excessively drained
Textural class	silty clay loam	loamy fine sand	silty clay loam	fine sandy loam	clay
Moist soil	10YR 2/1	10YR 5/3	7.5YR 4/6	7.5YR 3/2	2.5YR 3/6
Munsell colour	black	brown	strong brown	dark brown	dark red
Contents of:					
Organic matter	5.61%	0.59%	1.84%	3.3%	2.28%
Iron oxide	0.76%	0.03%	3.68%	0.81%	25.6%
Moisture at .1 bar tension	41.1 %	17.0 %	28.2 %	27.3 %	33.1 %

Source: Stoner and Baumgardner (1981).

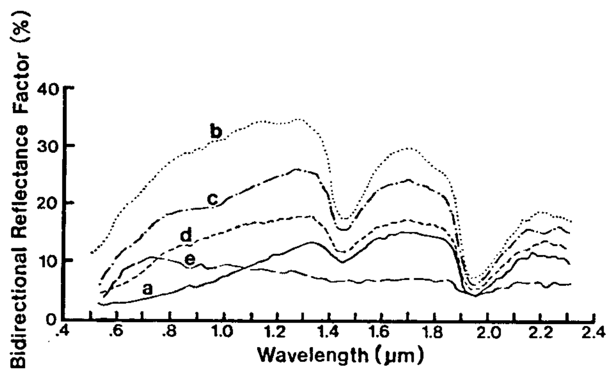

Fig. 3. Representative reflectance spectra of surface samples of five mineral soils (Table 2):
a. organic-dominated (high organic content, moderately fine texture)
b. minimally altered (low organic, medium iron content)
c. iron-affected (low organic, medium iron content)
d. organic-affected (high organic content, moderately coarse texture)
e. iron-dominated (high iron content, fine texture)

films of the type that may be expected to fill the voids between fine sand grains (Lindberg and Snyder 1972).

The Type 3 curve form of Condit is identified here as the iron-affected form, being distinguished by a slight ferric iron absorption band at 0.7 μm together with the stronger 0.9 μm iron absorption band (Hunt and Salisbury 1971b). The 2.2 μm hydroxyl absorption band can be seen in this specific sample, but does not exhibit a consistent relationship with any particular curve form or soil property.

A fourth curve type, labelled the organic-affected form, typically has a higher overall reflectance than the organic-dominated form. It exhibits a gradually increasing slope from 0.5 to 0.75 μm and decreasing in steepness from 0.75 to 1.3 μm, giving a concave/convex appearance.

The fifth curve type, the iron-dominated form, is unique in that reflectance actually decreases with increasing wavelength beyond 0.75 μm. In some soils, such as the one shown here, absorption in the middle infra-red wavelengths is so strong that the 1.45 and 1.95 μm water absorption bands are almost obliterated.

Mineral soils with the organic-dominated curve form have high organic matter contents (greater than 2%), well dispersed as coating on the fine to moderately fine soil grains. The organic-dominated curve form is often associated with montmorillonitic clay mineralogy, while soils with the iron-dominated curve form have been seen to exhibit kaolinitic mineralogy. Inherent spectral properties of clay minerals are not responsible for the character of soil reflectance curves (Lindberg and Snyder 1972), but mineralogy is inter-related with organic matter content, iron oxide content, and texture which directly affect soil reflectance.

Soils with the minimally altered curve form are characterized by low organic matter content, low iron oxide content, and good drainage. Texture as well as parent material and mineralogy are seen to vary for these soils.

Medium iron oxide contents (1-4%) distinguish soils with the iron affected curve form from those with the minimally altered form. Soils with the iron-dominated curve form have high iron oxide contents (greater than 4%) which appear capable of masking out even the effects of high organic matter contents. These high iron soils are often fine-textured and are derived from basic rocks.

Mineral soils with the organic-affected curve form differ from those with the organic-dominated form principally because of coarser soil textures. Lower moisture contents and the presence of sand and silt grains uncoated by organic matter would explain the higher reflectance of the organic-affected curve form.

Soil spectral reflectance curve forms were identified for all 485 surface soil samples and were tabulated according to soil sub-order. All Vertisol soil samples and a majority of Mollisol soil samples exhibited the organic-dominated curve form. Aquic moisture regime soils of the Alfisol, Entisol, Inceptisol, Mollisol, Spodosol and Ultisol orders show a predominance of organic-dominated and organic-affected curve forms. A majority of Aridisols and non-aquic Entisols have a minimally altered curve form. Among Alfisols and Ultisols with a humid moisture regime, a majority exhibit the iron-affected curve form. Although the iron-dominated curve form is typical of Oxisol soil samples, two Boralfs and two Udalfs also revealed this curve form.

The differentiating characteristics used to describe the five soil spectral reflectance curve forms are similar in nature to those used to define the genetically homogeneous subdivisions at the sub-order level of Soil Taxonomy (Buol *et al.* 1973). These subdivisions are based on the presence or absence of properties associated with wetness, soil moisture regimes, parent material and vegetational effects, including organic fibre decomposition stage, in Histosols. Although the soil samples in this study represent only the soil surface as it might be viewed by remote sensors, the characteristic variations in the reflectance of these soils can be interpreted in terms of soil properties diagnostic for the higher categories in Soil Taxonomy.

The spectral curves for five specific soils have been presented to illustrate the great differences in curve forms. Several environmental effects on soil reflectance will now be considered.

Comparison with Munsell Designations

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

Three soils that have the same dark red Munsell colour designation of 2.5 YR 3/6 are quite different in their infra-red reflectance characteristics (Fig. 4). The Dill soil from Oklahoma is a loamy fine sand with 0.6% organic matter and 0.8% iron oxide. The Arroyo soil from Spain is a clay with 1.28% organic matter and 2.0% iron oxide. The soil from Londrina, Paraná State, Brazil, is a highly aggregated clay with 2.28% organic matter and 25.6% iron oxide. All three soil reflectance curves show varying degrees of evidence of ferric iron absorption at 0.7 and 0.9 μm. Visible reflectance is very similar for the Dill and Arroyo soils while the Londrina soil has a generally lower reflectance in the visible than the other two.

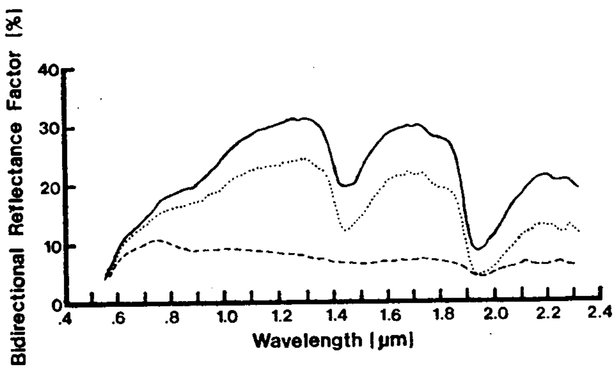

Fig. 4. Reflectance curves for three dark red soils having moist Munsell colour notations 2.5YR3/6 (Stoner 1979):

Soil	*Curve*	*% Organic matter*	*% Fe_2O_3*
Dill (Oklahoma, USA)	————————	0.6	0.87
Arroyo (Spain)	....	1.28	2.00
Londrina (Brazil)	-------------------	2.28	25.6

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

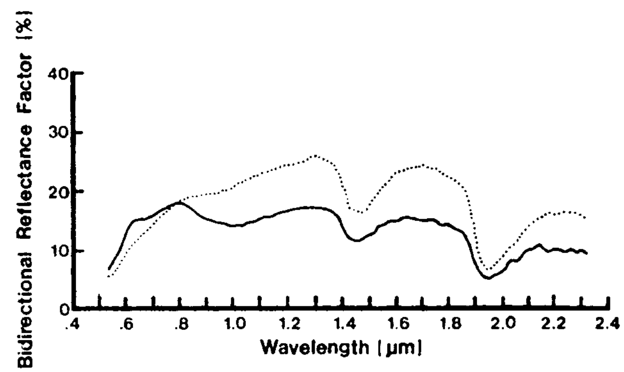

Fig. 5. Reflectance curves for two yellowish brown soils having moist Munsell colour notations 7.5YRS/6:
Bahia (Brazil) ————————
Talbot (Tennessee ....

reflectance properties. Munsell colour evaluation gives the erroneous notion that the reflectance properties of these two soils are similar.

Iron Oxides

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

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

Most of the well-resolved electronic features of iron oxides in minerals and rocks can be attributed to transitions in the iron cations (Hunt *et. al.* 1971b). Typically, the ferrous ion produces the band near 1.0 μm due to the spin allowed transition between the E_g and T_{2g} quintet levels into which the D ground state splits in an Octahedral crystal field. For the ferric ion, the major bands produced in the spectrum are a result of transition from the $^{G}A_{1g}$ ground state to $^{4}T_{1g}$ at about 0.87 μm; and to $^{4}T_{2g}$ at 0.7 μm. Whereas only 1% by weight of finely powdered haematite was found to alter a clayey, yellow

Oxisol from 10YR to 5YR in colour (Resende 1976), as little as 0.0005% of iron by weight was capable of producing a perceptible iron band at 0.87 μm in a highly transparent calcite mineral (Hunt and Salisbury 1971a). In addition to the ferrous iron band at 1.0 μm, another absorption band near 1.0 μm has been identified in a sample of gibbsite as a second overtone and combination of stretching modes of the hydroxyl radical (Hunt *et al.* 1971b).

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

Mineralogy

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

Stoner and Baumgardner (1980) averaged soil spectra for soils belonging to four mineralogy classes (Fig. 6). Soils with gypsic mineralogy reflect more

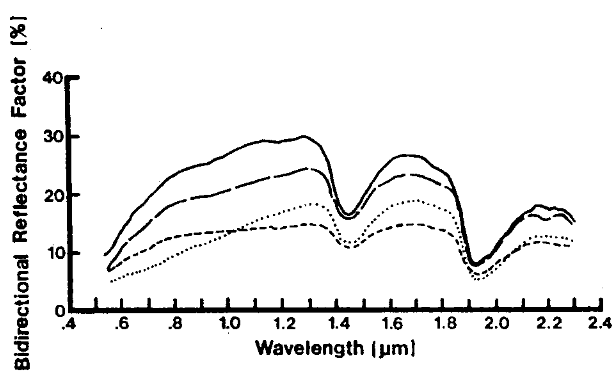

Fig. 6. Averaged reflectance spectra for soils having specified mineralogies:
nitic ....
Kaolinitic ——
Micaceous
Gypsic

at all wavelengths than any other class, whereas montmorillonitic soils reflect the least from the visible to 1.0 μm. Micaceous mineralogy soils display a very flat reflectance curve beyond 0.8 μm and reflect the least of all classes in the middle infra-red. The lower visible reflectance of montmorillonitic soils may be associated with higher organic matter contents in these soils, while the higher reflecting gypsic mineralogy soils may derive their reflectance properties directly from the highly reflecting gypsum (Hunt *et al.* 1971c). Kaolinitic mineralogy soils have a broad ferric iron absorption band at 0.9 μm, indicative of higher free iron contents associated with these soils.

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

Drainage

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

Stoner grouped soils by spectra by internal drainage class (Fig. 7). The curves for well-drained and moderately well-drained soils were so similar they were combined. Very poorly drained soils reflect considerably less than any of

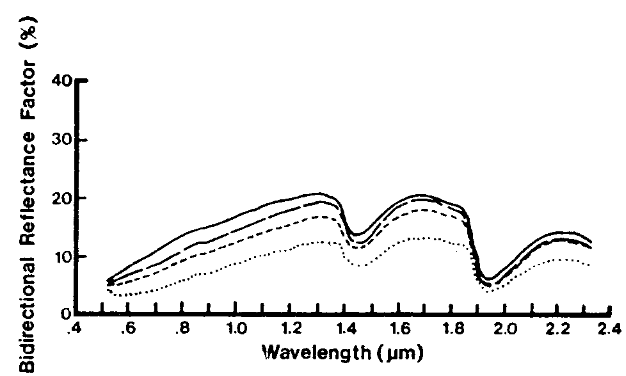

Fig. 7. Averaged reflectance spectra for soils having specified conditions of internal drainage:
———— well and moderately well drained
— — somewhat poorly drained
------ poorly drained
.... very poorly drained

the other drainage classes at all wavelengths. Whereas the well-drained and moderately well-drained soils show evidence of ferric iron absorption at 0.9 μm, all three poorly drained soil classes lack the ferric iron absorption band. As a site characteristic integrating the effects of climate, local relief, and accumulated organic matter, soil drainage characteristics can be expected to be closely associated with reflectance properties of surface soils.

Erosion Assessment

Preliminary results from studies of soil spectra from several test sites in the mesic humid region in the state of Indiana indicate that analysis of surface soil spectra may be useful in assessing erosion losses. Latz (1981) examined the changes in surface reflectance related to the severity of erosion as revealed by spectral characteristics of surface soil samples obtained in four areas along several eroded toposequences (Fig. 8). An example of one of these studies is

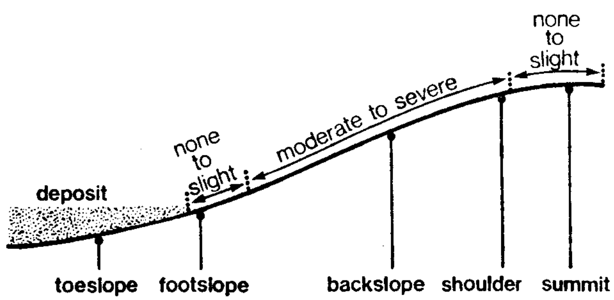

Fig. 8. Toposequence with varying degrees of erosion (Latz 1981).

the set of spectral curves for the Sidell (Mesic Typic Arguidoll) toposequence (Fig. 9).

Curves for this toposequence are easily separated spectrally. There is decreasing reflectance with decreasing severity of erosion. The least reflectance is for the depositional soils at the toeslope. For other toposequences the relationship between reflectance and severity of erosion was not so straightforward and predictable.

Soil-Related Applications

Data acquired from earth observation systems are being used to inventory and monitor changes in crops, range lands and forest resources. In each of these applications the soil background is an important component of the scene being observed. In too many cases in the analysis and interpretation of data in these applications, soil has been treated as a constant. Much research is needed to quantify the effects of the variation in the radiation characteristics of soils on the spectral variation of the vegetative cover.

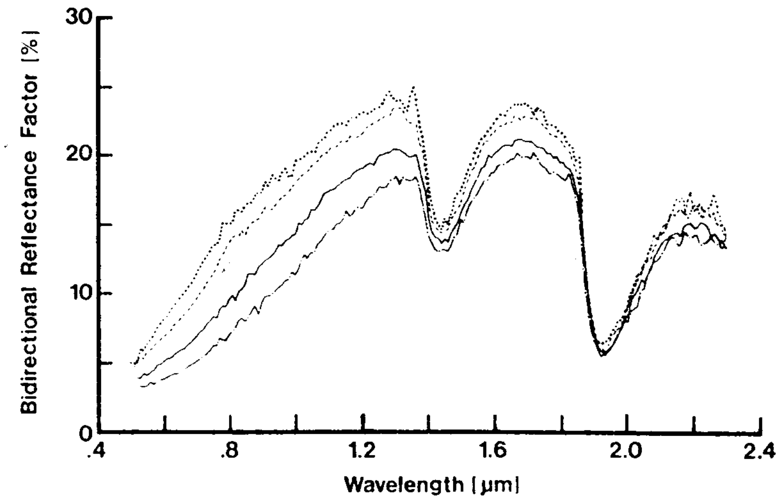

Fig. 9. Reflectance curves for soils of an eroded Sidell toposequence (Latz 1981):
——— none to slightly eroded
- - - - - moderately eroded
· · · · · · · severely eroded
— · — depositional materials

The Future

As we look at the future, we must consider the question: Where do soil information needs and the capabilities of remote sensing intersect? We are just beginning to scratch the surface of the potential use of aerospace earth observation systems as one of the tools for developing, managing and conserving earth resources. As we consider how remote sensing technology will impact soils research specifically and land resource management in general during the next two decades, it might be useful to state several assumptions, based on trends of the past three decades. It can be reasonably assumed that:

Significant advances will be made in data acquisition technology, i.e., cameras, multispectral scanners, field spectroradiometers and radar.

Rapid improvements will be made in data storage, retrieval and analysis techniques.

Methods of extracting and delivering useful information to the user will be greatly improved and accelerated.

The unit cost of acquiring and analysing data and delivering information will decrease significantly.

If these assumptions are true, the 1980s and 1990s will see great advances in the development and utilization of digital data management systems. The demand for more efficient methods of extracting useful information from geographically referenced data bases is accelerating rapidly. The soil scientists and other information users need to be aware of these developments and to participate in the definition of kinds of resource data which are needed.

If soil scientists, mineralogists, geologists and other resource scientists are to gain optimum benefit from current and future remote sensing technology, attention must be given to the formulation of research priorities and to the implementation of appropriate research in the 1980s. Four general areas of research are suggested:

1. *Understanding the landscape scene.* Our past and current understanding of the landscape is coloured largely by past and current methods of acquiring data. With repetitive earth observation systems and supporting field observations, what new insights can we gain about the dynamics of and relationships among earth surface features? How can we best use remotely sensed data to supplement and improve our understanding of soil mineralogy and its relationships to soil productivity and land degradation?

2. *Representing variations in the landscape by quantitative measurements.* Do current sensors obtain the quantitative measurements most useful for soil mineralogical studies? What spectral bands obtain the most useful data for specific applications? What are the optimum spatial and spectral resolutions of sensors for obtaining data about land resources? What new laboratory and field instruments and techniques are needed for quantitative characterization of soil and other variations in the landscape?

3. *Storage, retrieval and analysis of earth resources data.* How can we store, retrieve and overlay a wide variety of kinds and sources of data related to a specific geographic location? What kinds of soil data should be included in data bases for resource management?

4. *Extraction and delivery of useful information to the resource decision-makers.* Who are the users of information about the earth resources? What information do they want? When do they want it? How do they want it delivered? What format do they prefer? How do they use the information? What will be the cost of a desirable information delivery system of the future?

We can draw some conclusions about information from our experiences in the 1970s. Accurate, timely, useful information about our land, crop, range, forest, mineral and water resources is becoming even more critical and valuable to the decision-maker. Long-range research designed to use the best in data acquisition, data analysis and communications technology to improve the efficiency of the flow of essential information to decision-makers involved in resource management will be a good investment.

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