E82-10396
CR-169185

AgRISTARS

SR-P2-04301
NAS9-15466

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

Supporting Research

May 1982

Technical Report

Characteristic Variations in Reflectance of Surface Soils

by E.R. Stoner and M.F. Baumgardner

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(E82-10396) CHARACTERISTIC VARIATIONS IN REFLECTANCE OF SURFACE SOILS (Purdue Univ.) 8 p HC A02/MF A01 CSCL 08M

N82-32818

Unclas
G3/43 00396

SR-P2-04301
NAS9-15466
LARS 121881

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Star Information Form

1. Report No SR-P2-04301	2. Government Accession No	3. Recipient's Catalog No
4. Title and Subtitle Characteristic Variations in Reflectance of Surface Soils		5. Report Date May 1982
		6. Performing Organization Code
7. Author(s) E.R. Stoner and M.F. Baumgardner		8. Performing Organization Report No LARS 121881
9. Performing Organization Name and Address Purdue University Laboratory for Applications of Remote Sensing 1220 Potter Drive West Lafayette, IN 47906-1399		10. Work Unit No
		11. Contract or Grant No. NAS9-15466
12. Sponsoring Agency Name and Address NASA Johnson Space Center Earth Resources Research Division Houston, TX 77058		13. Type of Report and Period Covered Technical
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

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Five distinct soil spectral reflectance curve forms were identified according to curve shape, the presence or absence of absorption bands, and the predominance of soil organic matter and iron oxide composition. These curve forms were further characterized according to genetically homogeneous soil properties in a manner similar to the subdivisions at the suborder level of Soil Taxonomy. Results indicate that spectroradiometric measurements of soil spectral bidirectional reflectance factor can be used to characterize soil reflectance in terms that are meaningful to soil classification, genesis, and survey.

17. Key Words (Suggested by Author(s)) Remote Sensing, Spectroradiometry, Bidirectional Reflectance Factor, Soil Taxonomy	18. Distribution Statement		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

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

NASA - JSC

Characteristic Variations in Reflectance of Surface Soils[1]

E. R. STONER AND M. F. BAUMGARDNER[2]

ABSTRACT

Surface soil samples from a wide range of naturally occurring soils were obtained for the purpose of studying the characteristic variations in soil reflectance as these variations relate to other soil properties and soil classification. A total of 485 soil samples from the U.S. and Brazil representing 30 suborders of the 10 orders of *Soil Taxonomy* was examined. Spectral bidirectional reflectance factor was measured on uniformly moist soils over the 0.52 to 2.32 μm wavelength range with a spectroradiometer adapted for indoor use.

Five distinct soil spectral reflectance curve forms were identified according to curve shape, the presence or absence of absorption bands, and the predominance of soil organic matter and iron oxide composition. These curve forms were further characterized according to genetically homogeneous soil properties in a manner similar to the subdivisions at the suborder level of *Soil Taxonomy*. Results indicate that spectroradiometric measurements of soil spectral bidirectional reflectance factor can be used to characterize soil reflectance in terms that are meaningful to soil classification, genesis, and survey.

Additional Index Words: **remote sensing, spectroradiometry, bidirectional reflectance factor, soil taxonomy.**

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

MODERN COMPREHENSIVE soil classification (Soil Survey Staff, 1975) utilizes visible soil reflectance, or color, as a differentiating characteristic for many classes as an essential part of the definition of certain diagnostic horizons. Unlike other differentiating characteristics such as particle size distribution or base saturation, which are verifiable by established laboratory procedures, soil reflectance is determined solely by visual comparison with standard color charts. Quantitative measurements of visible as well as infrared reflectance spectra of soils are possible using spectroradiometric techniques developed to simulate the geometry of remotely sensed data (Stoner et al., 1980b).

Soil reflectance is a cumulative property which derives from inherent spectral behavior of the heterogeneous combination of mineral, organic, and fluid matter that comprises mineral soils. 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 (Ångstrom, 1925; Baumgardner et al., 1970; Bowers and Hanks, 1965; Bowers and Smith, 1972; Da Costa, 1979; Höffer and Johannsen, 1969; Karmanov, 1970 Lindberg and Snyder, 1972; Mathews et al., 1973; 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-infrared reflectance of minerals and rocks (Hunt, 1977; Hunt and Salisbury, 1970, 1971, 1976a, 1976b; Hunt et al., 1971a, 1971b, 1973a, 1973b, 1973c, 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 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.

Five soil reflectance curve forms are described here from examination of 485 bidirectional reflectance spectra of surface soils from 39 states and Brazil. Characteristic variations in the reflectance of these laboratory measured soils are discussed in terms of reflectance-related soil properties and soil taxonomy.

MATERIALS AND METHODS

Surface soil samples representing 246 soil series were collected from 481 sites within 39 of the 48 contiguous states of the U.S. and 4 sites within the state of Paraná, Brazil (Fasolo, 1978).[3] For 239 U.S. soil series, duplicate samples were obtained: one from a site near the type location for the current official series, and another at a site from 1 to 30 km distant from the first site in a different mapping delineation of the same series. Soil series were selected at random within climatic strata from among a list of more than 1,300 benchmark U.S. soil series of large geographic extent and widely applicable characteristics (Soil Survey Staff, 1972). Climatic strata followed the soil temperature regimes defined in *Soil Taxonomy* (Soil Survey Staff, 1975) and moisture zones based on the Thornthwaite (1948) moisture stress index. The resulting collection of soil samples covers a well-distributed pattern encompassing 17 continental U.S. climatic zones including soils from 28 suborders of 9 soil taxonomic orders.

The standard sieved soil fraction < 2 mm in diam was used for laboratory determination of chemical, physical, and spectral properties. Organic carbon was determined by the modified Walkley-Black procedure, while free iron was measured by the Na citrate-bicarbonate-dithionite extraction procedure (Franzmeier et al., 1977). Reflectance measurements were made on uniformly moist soils equilibrated for 24 hours at one-tenth bar moisture tension on asbestos tension tables (Stoner et al., 1980b). This procedure expedited the establishment of a standardized moisture condition for a sizeable number of samples (over 500) held in large (10 cm in diam) sample holders, while avoiding the fluctuating, uncontrolled environmental conditions of air-dry soil samples. Bowers and Hanks (1965) and Peterson et al. (1979) confirmed the predictable increase in reflectance of soil samples on dry-

[1] Journal Paper no. 8460, Purdue Univ., Agric. Exp. Stn. Supported in part by NASA Grant NAS9-15466. Received 16 Mar. 1981. Approved 21 July 1981.

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[3] P. J. Fasolo. 1978. Mineralogical identification of four igneous extrusive rock-derived soils from the State of Paraná, Brazil. M.S. Thesis, Purdue Univ., West Lafayette Ind.

Table 1—Characteristics of surface samples of 5 mineral soils (Fig. 1, curves *a* through *e*).

	Reflectance curve form				
	Organic-dominated (*a*)	Minimally altered (*b*)	Iron-affected (*c*)	Organic-affected (*d*)	Iron-dominated (*e*)
Soil series	Drummer	Jal	Talbott	Onaway	(Not given)
Horizon sampled	Ap	A11	Ap	Ap	Ap (0-10 cm)
Soil subgroup	Typic Haplaquoll	Typic Calciorthid	Typic Hapludalf	Alfic Haplorthod	Typic Haplorthox
Sample location	Champaign Co., Ill., USA	Lea Co., N. Mex., USA	Rutherford Co., Tenn., USA	Delta Co., Mich., USA	Londrina, Parana, 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 color	Black	Brown	Strong brown	Dark brown	Dark red
Contents:					
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 0.1 bar tension	41.1%	17.0%	28.2%	27.3%	33.1%

ing, and like Condit (1970), observed similar curve forms for a soil at all moisture contents.

Spectral bidirectional reflectance factor (Nicodemus et al., 1977) was measured with an Exotech Model 20C spectroradiometer (Leamer et al., 1973) adapted for indoor use with a reflectometer equipped with an artificial illumination source, transfer optics, and sample stage. Spectral readings were taken in 0.01-μm increments over the 0.52- to 2.32-μm wavelength range. A 1,000-W tungsten-iodide coiled filament lamp and paraboloidal mirror provided highly collimated incident irradiation similar to that of solar illumination. Pressed barium sulfate was used as a calibration standard to account for fluctuations in intensity of the illumination source (Robinson and Biehl, 1979). The 3/4° field of view from an altitude of 2.4 m made it possible to detect a sample area of about 3.2 cm in diam.

Reflectance measurements for all of the soil samples were placed in a digital data base together with soil taxonomic formative elements and modifiers, sampling site characteristics, and laboratory analyses. Graphic display of soil reflectance curves was achieved by means of the LARSPEC software package (Simmons et al., 1975). A compendium of laboratory measured soil parameters together with reflectance spectra of all 485 soil samples was prepared in an abbreviated presentation of data obtained in this study (Stoner et al., 1980a).

RESULTS AND DISCUSSION

Examination of soil spectra from 485 individual soil samples revealed the existence of five distinct soil reflectance curve forms identified by curve shape and the presence or absence of absorption bands. In addition, these five soil spectral reflectance curve forms could be distinguished as having in common certain differentiating characteristics pertaining mainly to the organic matter content and iron oxide content of these soils.

Reflectance spectra representative of the five curve forms are illustrated for five mineral soil samples (Fig 1). Characteristics of these specific surface soils are detailed for comparison of reflectance-related soil properties (Table 1). 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 characteristic concave curve shape from 0.5 to 1.3 μm. Strong water absorption bands are present at 1.45 and 1.95 μm in this and most other curve

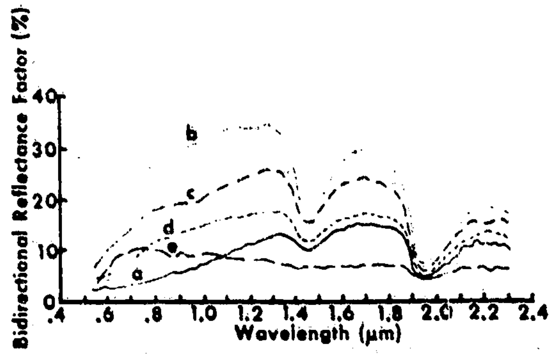

Fig. 1—Representative reflectance spectra of surface samples of 5 mineral soils (Table 1): (*a*) organic-dominated (high organic content, moderately fine texture); (*b*) minimally altered (low organic, medium iron content); (*c*) iron-affected (low organic, medium iron content); (*d*) organic-affected (high organic content, moderately coarse texture); and (*e*) iron-dominated (high iron content, fine texture).

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 a characteristic convex curve shape from 0.5 to 1.3 μm. 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 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 et al., 1971a). 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, labeled the organic-affected form, typically has a higher overall reflectance than the organic-dominated form. It exhibits a concave shape

Table 2—Differentiating characteristics of 5 soil spectral reflectance curve forms.

Differentiating characteristics	Reflectance curve form: Organic-dominated	Minimally altered	Iron-affected	Organic-affected	Iron-dominated
Vegetational effects					
Mineral soils†	High organic matter content	Low organic matter content	Low organic matter content	High organic matter content	Varied organic matter content
Organic soils	Fully decomposed organic fibers			Organic fibers preserved	
Iron oxide content‡	Low	Low	Medium§	Low	High
Texture	Fine to moderately fine textured soils	Varied	Varied	Medium- to coarse-textured soils	Fine-textured
Natural drainage	Poor to good	Good	Good	Poor to good	Good
Mineralogy	Commonly montmorillonitic	Mixed	Mixed	Mixed	Commonly kaolinitic

† Low organic matter content = 0 to 2%, high = 2+%.
‡ Low iron oxide content = 0 to 1%, medium = 1 to 4%, high = 4+%.
§ Soils with low iron oxide contents occurring as coatings on coarse-textured soil particles exhibit the same curve form.

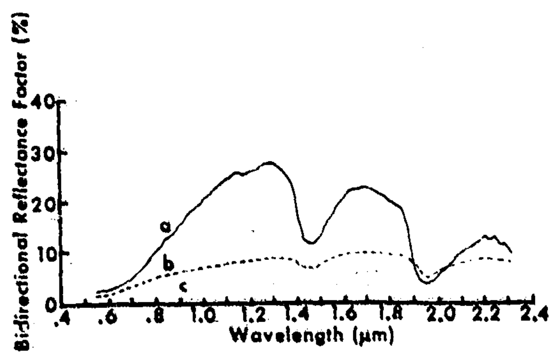

Fig. 2—Representative reflectance spectra for organic soils with: (*a*) minimally (fibric), (*b*) partially (hemic), and (*c*) fully (sapric) decomposed organic fibers (Table 3).

from 0.5 to 0.75 μm with a convex shape from 0.75 to 1.3 μm.

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 infrared wavelengths is so strong that the 1.45 and 1.95 μm water absorption bands are almost obliterated.

Soil parameters characteristic for specific reflectance properties serve to differentiate soil spectral reflectance curve forms (Table 2). Mineral soils with the organic-dominated curve form have high organic matter contents (> 2%) well dispersed as coatings on the fine to moderately fine soil grains. In the case of organic soils, the decomposition state of plant remains determines the reflectance curve form. Fully decomposed organic fibers reflect in the manner of the organic-dominated form, while well-preserved fibers exhibit the higher reflecting organic-affected form. The high reflectance of fibric soil materials in the infrared region resembles the infrared reflectance of senesced leaves (Gausman et al., 1975). This increased infrared reflectance has been attributed to tissue morphology in which an increased number of air voids provide more air-cell interfaces for enhanced reflection. Reflectance spectra for three organic soil samples illustrate these differences for fibric, hemic, and sapric soil materials (Fig. 2, Table 3).

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

Table 3—Characteristics of surface samples of 3 organic soils (Fig. 2).

Soil series	Rifle	Kenner	Terra Ceia
Horizon sampled	Oi1 (fibric material)	Oe1 (hemic material)	Oap (sapric material)
Soil subgroup name	Typic Borohemist	Fluvaquentic Medisaprist	Typic Medisaprist
Sample location	Delta Co., Mich., USA	Jefferson Parish, La., USA	Palm Beach Co., Fla., USA
Climatic zone	Humid frigid	Humid thermic	Humid hyperthermic
Parent material	Herbaceous fibers dominated by *Sphagnum* spp.	Herbaceous plant remains with clayey alluvium	Nonwood fibrous hydrophytic plant remains
Drainage class	Very poorly drained	Very poorly drained	Very poorly drained
Decomposition state of plant remains	Slight (fibers well preserved)	Intermediate (fibers preserved but destroyed by rubbing)	Complete (fibers nearly absent)
Moist Munsell color	7.5YR 3/2 (dark brown)	10YR 2/1 (black)	N 2/0 (black)
Organic matter content	84.8%	54.4%	76.4%
Iron oxide content	Trace	0	0
Moisture content (0.1 bar tension)	217.0%	73.1%	137.0%

clay minerals are not responsible for the character of soil reflectance curves (Lindberg and Snyder, 1972), but mineralogy is interrelated 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 and mineralogy are seen to vary for these soils.

Medium iron oxide contents (from 1 to 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 (> 4%) which appear capable of masking out even the effects of high organic matter contents.

Mineral soils with the organic-affected curve form differ from those with the organic-dominated form principally because of coarser soil textures. Coarse soil grains uncoated by organic matter were evident from the appearance of samples of these soils. Lower moisture contents of the coarser textured soils would

Table 4—Identity according to reflectance curve forms for 485 surface soil samples representing 30 suborders of the 10 orders of *Soil Taxonomy* (Soil Survey Staff, 1975).

	Reflectance curve form					
	Organic-dominated	Minimally altered	Iron-affected	Organic-affected	Iron-dominated	Total samples
Aqualf	1	2	2	3		8
Boralf	3		6	11	2	22
Udalf	2	9	21	5	2	39
Ustalf	—	4	6	2	—	12
Alfisol	6	15	35	21	4	81
Argid		27	3	2		32
Orthid		8	10	—		18
Aridisol		35	13	2		50
Aquent	9	5		4		18
Fluvent	2	20	3	1		26
Orthent		12	2	8		22
Psamment	2	—	2	8		12
Entisol	13	37	7	21		78
Hemist				2		2
Saprist	4			2		6
Histosol	4			4		8
Aquept	4	2	2	8		16
Ochrept	1	7	2	6		16
Umbrept	—	—	—	4		4
Inceptisol	5	9	4	18		36
Alboll	4					4
Aquoll	23	1		4		28
Boroll	16	5		5		26
Udoll	14			2		16
Ustoll	34	8	2	20		64
Xeroll	2	2	—	4		8
Mollisol	93	16	2	35		146
Humox					1	1
Orthox					3	3
Oxisol†					4	4
Aquod	4			4		8
Orthod	—	4	4	14		22
Spodosol	4	4	4	18		30
Aquult	2					2
Humult	2					2
Udult	2	10	20	8		40
Ultisol	6	10	20	8		44
Udert	2					2
Ustert	6					6
Vertisol	8					8
					Grand total	485

† From Brazil.

also 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 suborder (Table 4). 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 nonaquic 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 suborder 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 fiber 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*.

SUMMARY

The diversity of soil reflectance among a wide range of naturally occurring surface soils has been represented by five characteristic soil spectral reflectance curve forms. These curve forms are identified by curve shape and the presence or absence of absorption bands. Soil properties associated with each curve characterize soil reflectance in a manner which facilitates comparison with higher categories of *Soil Taxonomy*. Spectroradiometry provides both comparison with remotely sensed data from nonvegetated soils and a laboratory tool for quantitative characterization of visible as well as infrared soil reflectance.

Controlled laboratory reflectance measurements serve to define the extent to which intrinsic spectral information is available from soils as a consequence of their composition. Characterization of soil reflectance has important implications for soil genesis, classification, and survey.

ACKNOWLEDGMENTS

The authors acknowledge with gratitude the contributions of the following persons: soil scientists of the Soil Conservation Service who provided samples from 39 states; B. F. Robinson and L. L. Biehl for assistance with the spectroradiometric measurements; L. M. Nash for laboratory analysis; and Drs. D. P. Franzmeier, J. B. Peterson, L. F. Silva, and R. A. Weismiller for project support.

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