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FINAL REPORT

Spatial and Temporal Variability of Soil Temperature, Moisture and Surface Soil Properties

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J.H. Dane

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SPATIAL AND TEMPORAL VARIABILITY OF SOIL TEMPERATURE MOISTURE AND SURFACE SOIL PROPERTIES

Investigators

B. H. Hajek
J. H. Dane

OVERALL OBJECTIVES:

(1) Relate in-situ measured soil-water content and temperature profiles to remotely sensed surface soil-water and temperature conditions; to model simultaneous heat and water movement for spatially and temporally changing soil conditions.

(2) Determine the spatial and temporal variability of surface soil properties affecting emissivity, reflectance, and material and energy flux across the soil surface. This will include physical, chemical, and mineralogical characteristics of primary soil components and aggregate systems.

(3) Develop surface soil classes of naturally occurring and distributed soil property assemblages and group classes to be tested with respect to water content, emissivity and reflectivity.

This document is a report of studies conducted during the period of funded by NASA grants. The project was designed to be conducted over a five year period. Since funding was discontinued after three years, some of the research started was not completed.

Additional publications are planned whenever funding can be obtained to finalize data analysis for both the arid and humid locations.

REPORT

Objective 1

Studies Conducted on the E.V. Smith Research Station, Macon County, Alabama

60 neutron probe access tubes have been installed and neutron probe readings were obtained, at 20-cm depth intervals to a depth of 100-cm, about once a week to study spatial and temporal variability of soil-water content.

soil-water retention curves, saturated hydraulic conductivity values and bulk density values were obtained on undisturbed soil samples collected at all 60 locations at depths of 14, 26, 34, 46, 54, 66, 74, 86, 94, 106, and 114 cm.

soil texture, concentrations of major ions, bulk density values and neutron probe calibration curves were determined on undisturbed samples collected at all 60 locations at depths of 20, 40, 60, 80, and 100 cm.

temperature probes were constructed to measure soil temperature at all 60 locations at depths of 0 (surface), 2, 6, 15, 30, and 50 cm.

tensiometers and pressure transducers were constructed and modified, respectively, to allow measurements of soil-water pressure head at all 60 locations at depths of 15 and 30 cm.

gypsum blocks were acquired to obtain soil-moisture measurements at all 60 locations at depths of 15 and 30 cm.

data acquisition boards were designed, constructed and tested in the laboratory for use in the field to allow automation of the temperature, pressure, and gypsum block measurements.

the bulk density data were subjected to a newly developed statistical technique: bootstrapping. The bootstrap technique allows estimation of soil parameters and sample size without a priori knowledge of the sampling distribution.

Objective 1, The Bootstrapping Procedure

Undisturbed soil samples were collected on 2 occasions as a functions of depth at 60 locations in a bounded landscape (0.5-ha agricultural field). Properties determined from these samples were bulk density (16 depths), soil texture (5 depths), soil water retention curves (11 depths), concentrations of Ca, Mg, K, and P (5 depths), organic matter content (1 depth), and saturated hydraulic conductivity (11 depths). The Cramer-von Mises test proved extremely useful

in pooling data obtained at the 2 occasions (many properties are likely to change over time or are influenced by the conditions during sampling and/or the analysis). Extended data sets could thus be created, as is desirable for spatial variability studies.

The pooled data sets (except the water retention data, which still need to be analyzed) were analyzed for mean, variance, range, and sample size needed to meet a present error criterion at a specified confidence level by both classical statistics and the nonparametric procedure bootstrapping. Despite large deviations from normality of many of the empirical sampling distributions, results from the 2 methods were very similar. Correlograms determined for the chemical data showed spatial interdependency to exist in only a few cases. Even in these cases, however, were the results of the 2 methods very much the same, indicating that, as long as the area sampled is much larger than the distance of spatial interdependency, classical statistics is still applicable.

Soil water content and temperature readings were obtained as a function of depth and time with a neutron probe and temperature transducers, respectively. A ranking procedure (Friedman test) showed that, over a period of several years, the ranking from high to low water content was quite consistent with the respective locations. (publication reprint included in the Appendix)

Spatial Statistical Analysis

A simplified explanation of the linear prediction technique of kriging was derived from a statistical point of view. The kriging technique allows values of a given, spatially dependent, variate to be predicted at points where no measurements were made. It is then possible to construct a contour map for that variate. Based on the theoretically developed equations computer programs were written to carry out the predicitions. Besides assisting the computer user, the aim of this research was also to point out the similarities between kriging and standard least squares, of which it is indeed a special case. Instead of determining a semi-variogram to specify the spatial interdependency of a given variate, a more general, crossvalidation method was developed to determine the range parameter as needed in the kriging equations. In addition to simple kriging, equations and computer programs were developed for universal kriging, i.e. kriging under a lack of stationarity. These equations and programs were subsequently extended to cokriging to improve the estimation process by using information on auxiliary variates. Finally, a procedure was developed to optimize sampling schemes with the use of kriging and cokriging, i.e. determine the locations in the field and their minimum required number according to preset criteria.

The developed computer programs (a total of 6) were applied to the data collected The programs were developed in such a manner that data sets obtained at two different times could be combined into one for prediction purposes. A published bullitin is included in a packet attached to the back cover of this report.

Near Surface Soil Temperature Measurements

A real-time temperature and moisture sensing station was installed at the E.V. Smith site . Near-surface air temperature data were collected to evaluate a profile method of obtaining soil surface temperature and for comparison with soil temperature profiles. In addition, temperature profile data was collected at random points in this test area to determine variability and reliability

of data from real-time measurements. After reliability was checked, the station was relocated to the Geneva County, Alabama site to collect background data in preparation for comparison with Landsat 5 MSS and TM data. The station was allowed to collect real-time air temperature profiles from August through June. These data were analyzed in relation to maximum-minimum daily averages as it relates to soil temperature.

Objectives 2 and 3

TIMS image data, Soil emissivity, temperature, mineralogy relationships, Geneva, County, Alabama

Relationships between surface properties of Coastal Plain soils in southeast Alabama and thermal infrared image data collected using the Thermal Infrared Multispectral Scanner (TIMS) were studied. The studies included measurement of soil emissivity and diurnal soil temperature from TIMS image data and soil mineralogy and soil temperature data from laboratory and field analyses. The accuracy of TIMS soil temperature and the observed relationship between emissivity and soil mineral composition were addressed. The emphasis was on the potential value of multispectral thermal infrared imagery in studies of soil temperature and soil mineralogy in spatial distribution studies of soil properties.

Thermal Infrared Multispectral Scanner (TIMS) image data were evaluated to determine if the image data contained information useful for the characterization of surface soils. Image data were collected over a study site in southeast Alabama on 5 May, 1984, at 0500 h, and were used to compute surface soil temperature and soil emissivity data. Concurrent to the collection of TIMS data, thermometer measured soil temperature data were collected to verify TIMS derived temperature data.

Multispectral thermal infrared image data was found to contain information useful in the characterization of surface soil. A summary of the main observations of this study are:

(1) Soil temperature could be imaged and estimated using TIMS image data. Soil thermal radiance data from TIMS band 5 (10.28 to 11.06 um) was used to compute soil temperature to within 2 C of ground based thermometer measured soil temperature. Of the six TIMS bands, radiance data from 5 produced the most accurate estimate of soil temperature.

(2) Using ground based thermometer measured soil temperature, soil emissivity was computed for the field sites, and ranged from 0.87 in TIMS band 2 (8.56 to 8.94 um) to 0.99 in band 5 (10.28 to 11.06 um).

(3) A numerical model was developed to compute the relative difference in soil emissivity between two TIMS bands, based completely on blackbody radiance data computed from Planck's blackbody equation. The delta emissivity model is significant because it allows emissivity data to be computed without a priori knowledge about soil temperature or soil emissivity. TIMS band 2 and band 5 were selected to compute delta emissivity because the largest delta emissivity for soil was observed between these two bands. For all field sites, delta emissivity between band 2 and band 5 ranged from 0.04 to 0.15.

(4) Soil emissivity and delta emissivity data were observed to be correlated with soil quartz content in a nonlinear and direct manner with delta emissivity between TIMS band 2 and TIMS band 5. Thus by computing delta emissivity between for a soil from TIMS data, soils with

high quartz content could be differentiated from soils with low quartz content. Further analysis needs to be conducted to test the generality of the delta emissivity model on soils of dissimilar mineral composition, such as carbonate or smectite soils.

(5) Soil compostion data indicate that the surface soil is approximately 90% quartz, with the remaining soil components (kaolinite/HIV, gibbsite, organic matter, iron oxides) displaying a strong negative correlation to the quartz component. In this manner, the detection of quartz distribution using TIMS derived delta emissivity data allows many of the remaining soil attributes to be inferred, and a general characterization of the soil can then be performed.

(6) From a qualitative interpretation, multispectral thermal infrared imagery provides a large amount of unique information on the surface cover and features of an area such as bare soil, vegetated areas, water bodies, roads, houses and towns. Further analysis needs to be done to study combinations of image data such as night , day, and delta emissivity data, which is believed to contain very useful surface cover and feature information.

Although many useful forms of information can be derived from the TIMS image data, there are also several disadvantages using thermal infrared image data, some of which are:

(1) Collection of ground emitted thermal infrared radiance from a remote platform (aircraft of satellite) inherently includes atmospheric attenuation, which may be significant depending on the atmospheric conditons at the time of data collection. The atmospheric correction of thermal infrared data involves detailed atmospheric energy parameter, and complicated image processing techniques to reduce the atmospheric influence.

(2) The effects of soil composition, surface roughness, vegetation, and temperature variations on soil emissivity are very similar, and are potentially the source of many misinterpretations about the meaning of emissivity variation in multispectral thermal infrared data. All of these conditons must be further studied such that quantitative models can be developed to aid the interpretation of thermal infrared data. (Ochoa, M.C. 1986. Evaluation of thermal infrared multispectral scanner image data for characterization of surface soil. M.S. Thesis, Auburn University, Alabama. 90 pages.)

Humid Land Site, Geneva County, Alabama

Image data were collected over a small test area in Geneva County, Alabama, during a morning pass of Landsat 5 on October 3, 1987. Processing of data was done at NASA's Stennis Space Center using the Earth Resources Laboratory Applications Software (ELAS). MSS bands 1-3-2 and TM bands 2-4-3 were used to make a land cover classification of the test site. The number of classes defined by MSS and TM data was 7 and 8, respectively. The additional class, using TM data, was attributed to the division of the MSS class, "Trees", into two classes, "Pines" and "Bottomland Hardwoods", and was noted because of the greater resolution achieved with TM instrumentation. Ground truth data (cover type) wee collected at the time of the flight and were used in the evaluation of the land cover classification from Landsat image data. Due to the timing of the test date, some difficulty arose in distinguishing pasture from fallow areas and bare soil from harvested, residue-covered fields. Near surface vertical temperature profiles were recorded in 4 fields of differing cover classes. These profiles ranged from nearly uniform within a soybean canopy to highly variable and curvilinear over a residue-covered peanut field. The intensity of data in TM band 6 was evaluated with respect to cover class and temperature.

Tables and Figures , Data for the Humid Lands Site

Evaluation of Land Classes and Surface Temperature with Landsat 5 MSS and TM Imagery

Steven W. Cleland

TM Spectral Band Applications

Band	Principal Applications
1	Soil/Vegetation Differentiation Deciduous/Coniferous Differentiation
2	Green Reflectance by Healthy Vegetation
3	Chlorophyll Absorption for Plant Species Differentiation
4	Biomass Surveys Water Body Delineation
5	Vegetation Moisture Measurement
6	Plant Heat Stress Management Thermal Mapping
7	Hydrothermal Mapping

LANDSAT 5 SPECIFICATIONS

Altitude -- 705 km
Coverage Cycle Duration -- 16 days
Swath Width -- 185 km

Thematic Mapper

Band	Wavelength (microns)
1	0.45 - 0.52 (blue)
2	0.52 - 0.60 (green)
3	0.63 - 0.69 (red)
4	0.76 - 0.90 (near IR)
5	1.55 - 1.75 (mid IR)
7	2.08 - 2.35 (mid IR)
6	10.40 - 12.50 (thermal IR)

Ground Resolution (IFOV) -- 30 x 30 meters (Bands 1-5 & 7)
120 x 120 meters (Band 6)

Multispectral Scanner

Band	Wavelength (microns)
1	0.5 - 0.6 (green)
2	0.6 - 0.7 (red)
3	0.7 - 0.8 (near IR)
4	0.8 - 1.1 (near IR)

Ground Resolution (IFOV) -- 82 x 82 meters

LAND CLASS STATISTICS (TM CLASSIFICATION)

Mean Digital Number

Class	TM Band 1	2	3	4	5	6	7
1	69.87	25.39	23.81	63.72	57.91	123.02	18.56
2	70.01	25.85	23.68	78.71	64.92	122.91	19.52
3	78.92	34.28	35.15	99.47	96.35	130.80	34.36
4	98.03	46.86	69.25	72.63	166.10	141.46	90.95
5	79.06	33.13	37.77	76.63	101.55	132.09	39.42
6	84.84	37.53	46.47	76.71	119.12	134.89	53.33
7	104.93	53.35	75.35	94.53	166.66	138.13	87.79
8	74.61	30.66	28.94	69.58	70.41	128.36	24.61

Standard Deviation of Digital Number

Class	TM Band 1	2	3	4	5	6	7
1	2.46	1.64	2.76	8.62	12.73	4.60	30.16
2	2.31	1.60	2.58	6.64	9.67	4.38	23.62
3	3.09	2.55	4.28	16.84	12.67	3.77	19.97
4	6.47	3.86	5.79	5.89	15.16	4.40	12.36
5	2.97	1.78	4.12	2.82	13.15	3.94	18.20
6	6.15	4.59	8.25	13.41	22.88	5.04	29.39
7	12.10	8.06	14.92	11.22	24.19	4.15	22.16
8	1.93	1.01	1.14	14.92	19.39	3.76	30.04

1=Hardwoods; 2=Pines; 3=Soybeans; 4=Peanuts;
5=Pasture; 6=Fallow; 7=Bare Soil; 8=Water

TEST FIELD STATISTICS (MSS)

Mean Digital Number

	MSS Band			
Field	1	2	3	4
1	22.80	22.67	57.20	65.80
2	29.00	40.12	51.12	55.00
3	22.25	25.50	46.38	52.75
4	33.25	46.50	60.25	59.50

Standard Deviation of Digital Number

	MSS Band			
Field	1	2	3	4
1	2.65	6.39	2.01	2.78
2	3.66	7.62	2.23	2.78
3	1.75	3.96	2.97	2.31
4	4.03	3.00	4.57	3.32

1=Soybeans; 2=Peanuts; 3=Pasture; 4=Bare Soil

TEST FIELD STATISTICS (TM)

Mean Digital Number

Field	TM Band 1	2	3	4	5	6	7
1	76.71	35.58	36.18	96.57	97.14	130.44	36.85
2	100.09	50.06	77.55	82.36	185.27	145.43	96.37
3	81.33	34.88	41.79	76.65	110.85	134.30	41.92
4	108.00	55.10	80.59	90.54	173.02	140.56	101.02

Standard Deviation of Digital Number

Field	TM Band 1	2	3	4	5	6	7
1	2.03	1.31	2.62	4.90	4.52	2.42	10.01
2	2.94	3.18	4.98	5.97	4.91	3.14	4.66
3	2.91	2.39	3.90	5.25	11.06	0.94	14.68
4	2.94	2.81	5.93	5.81	7.00	1.45	6.39

1=Soybeans; 2=Peanuts; 3=Pasture; 4=Bare Soil

LAND CLASS STATISTICS (MSS CLASSIFICATION)

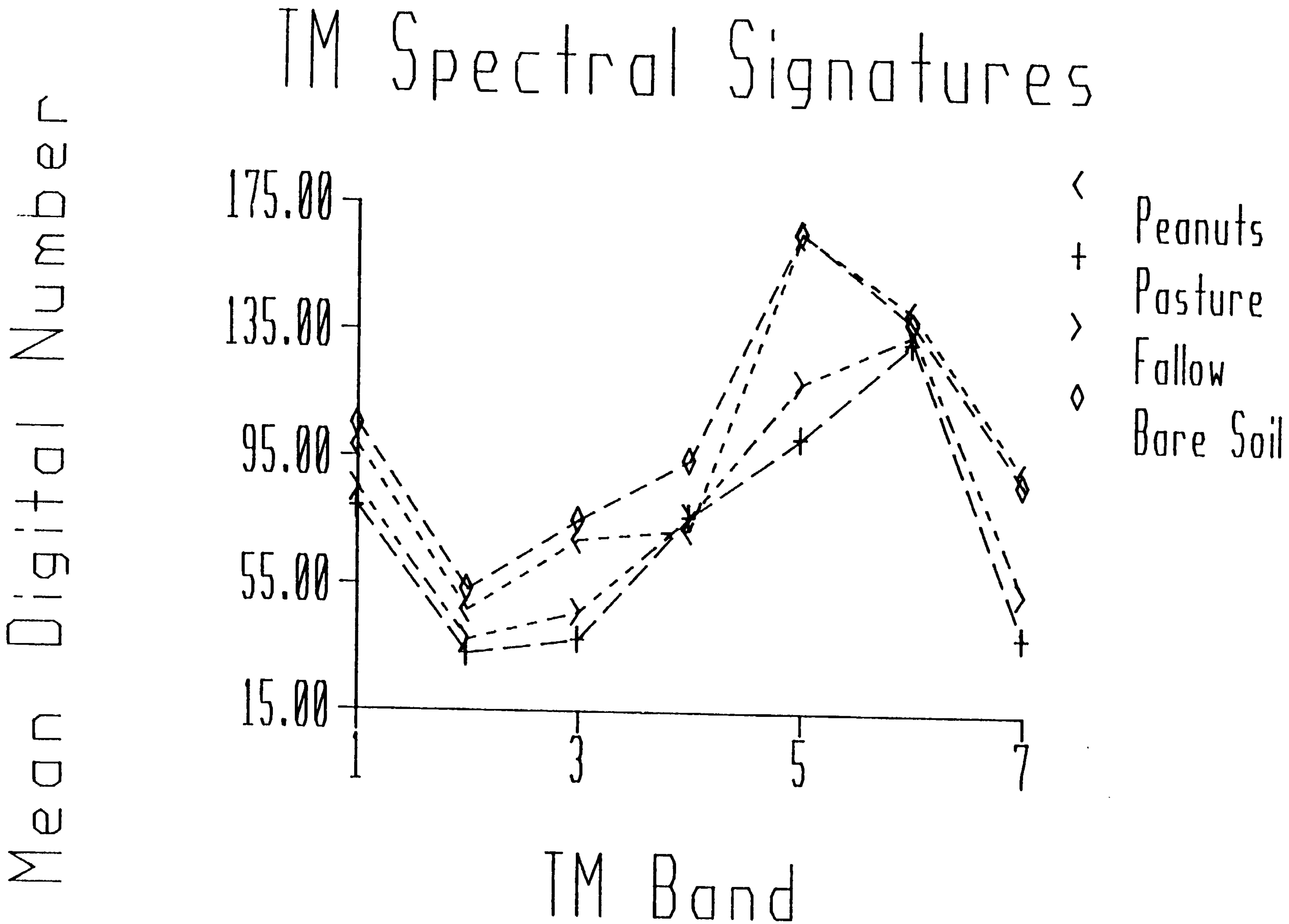
Mean Digital Number

Class	MSS Band 1	 2	 3	 4
1	16.46	12.93	38.61	47.84
2	21.26	19.22	58.18	67.57
3	29.42	39.02	49.11	50.92
4	20.73	21.15	45.02	52.19
5	23.71	26.49	47.82	53.19
6	34.05	44.17	65.22	65.81
7	19.29	16.10	38.09	44.74

Standard Deviation of Digital Number

Class	MSS Band 1	 2	 3	 4
1	1.39	2.04	4.48	6.03
2	1.67	2.70	8.89	10.79
3	2.37	3.76	4.62	5.71
4	0.98	2.41	1.97	3.12
5	2.63	4.58	7.86	8.59
6	5.13	9.88	6.44	6.39
7	0.92	1.21	5.90	7.98

1=Trees; 2=Soybeans; 3=Peanuts; 4=Pasture;
5=Fallow; 6=Bare Soil; 7=Water


TM Spectral Signatures
175.00
135.00
95.00
55.00
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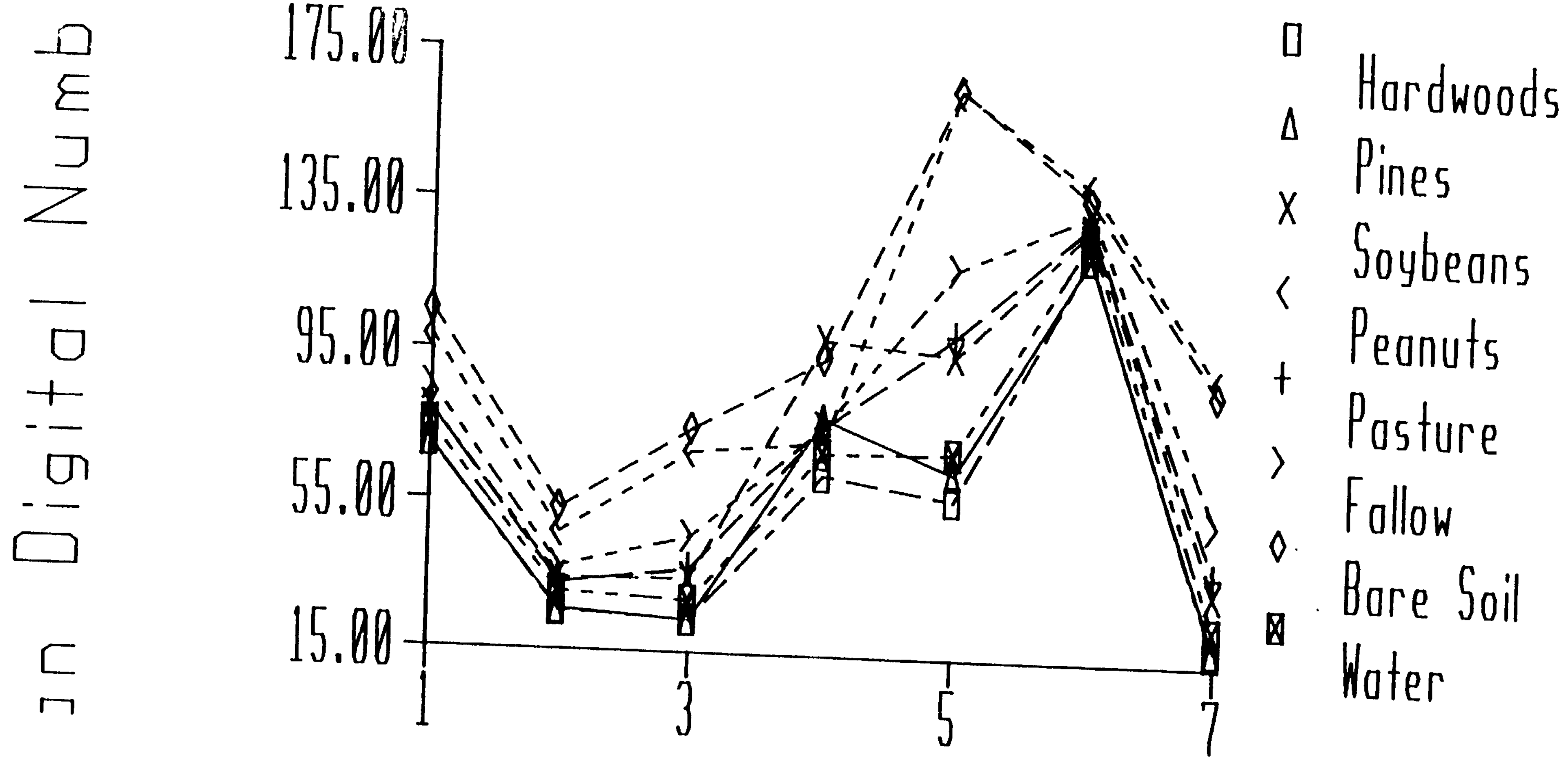
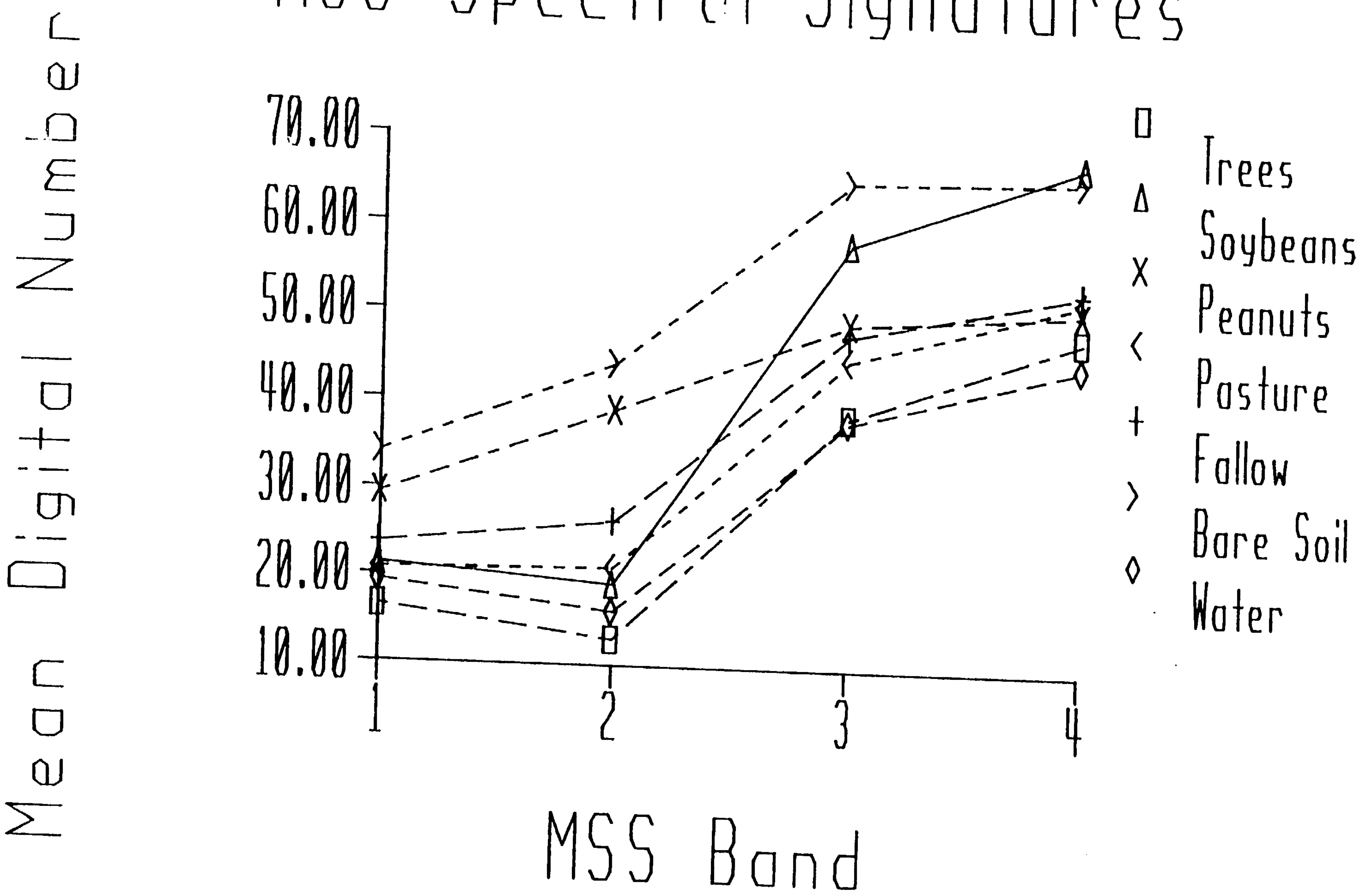
1
3
5
7
Mean Digital Number
TM Band
‹ Peanuts
+ Pasture
› Fallow
◊ Bare Soil

TM Spectral Signatures

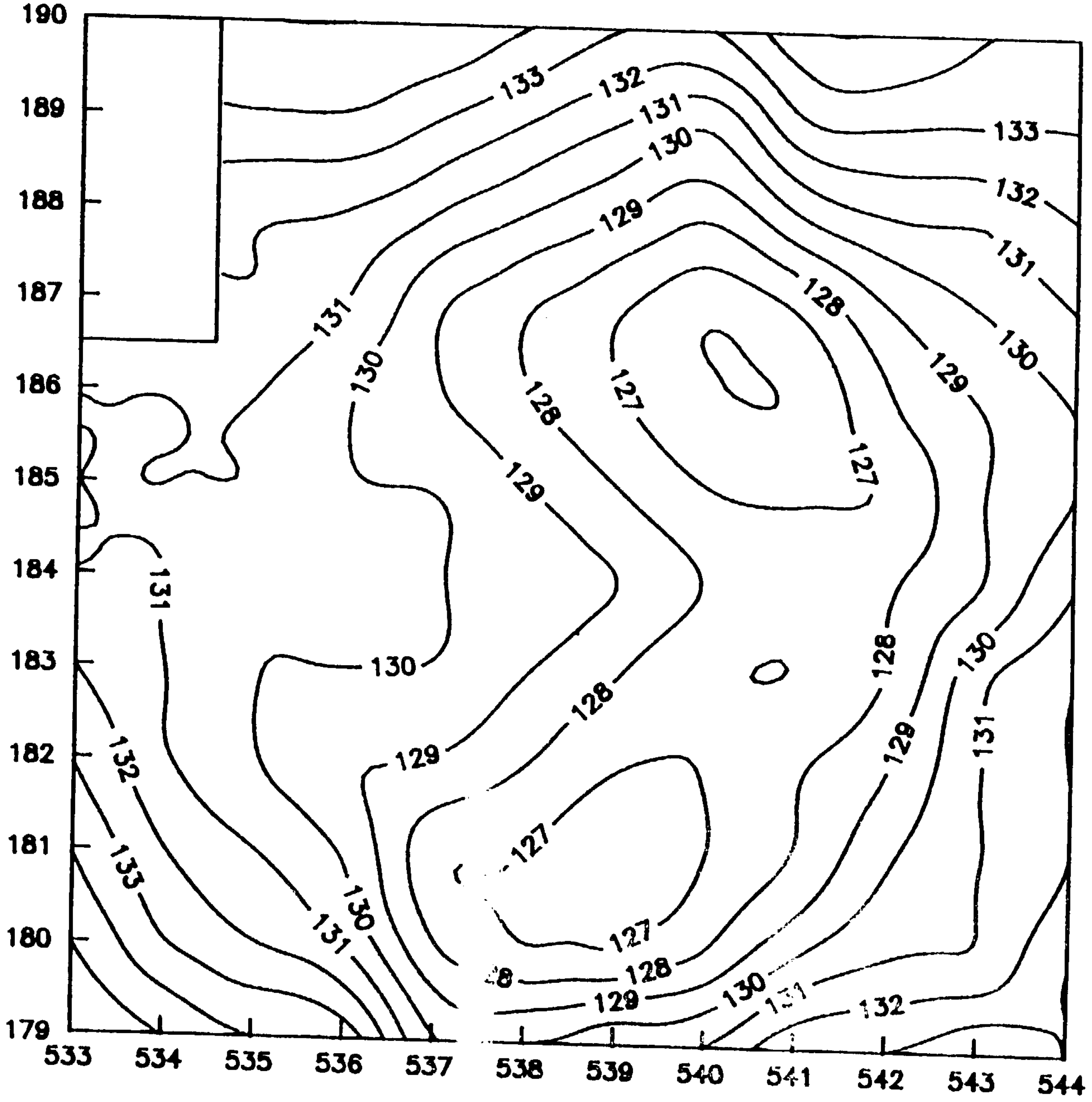


MSS Spectral Signatures

MSS Spectral Signatures



SOYBEAN FIELD -- TM BAND 6 RELATIVE INTENSITY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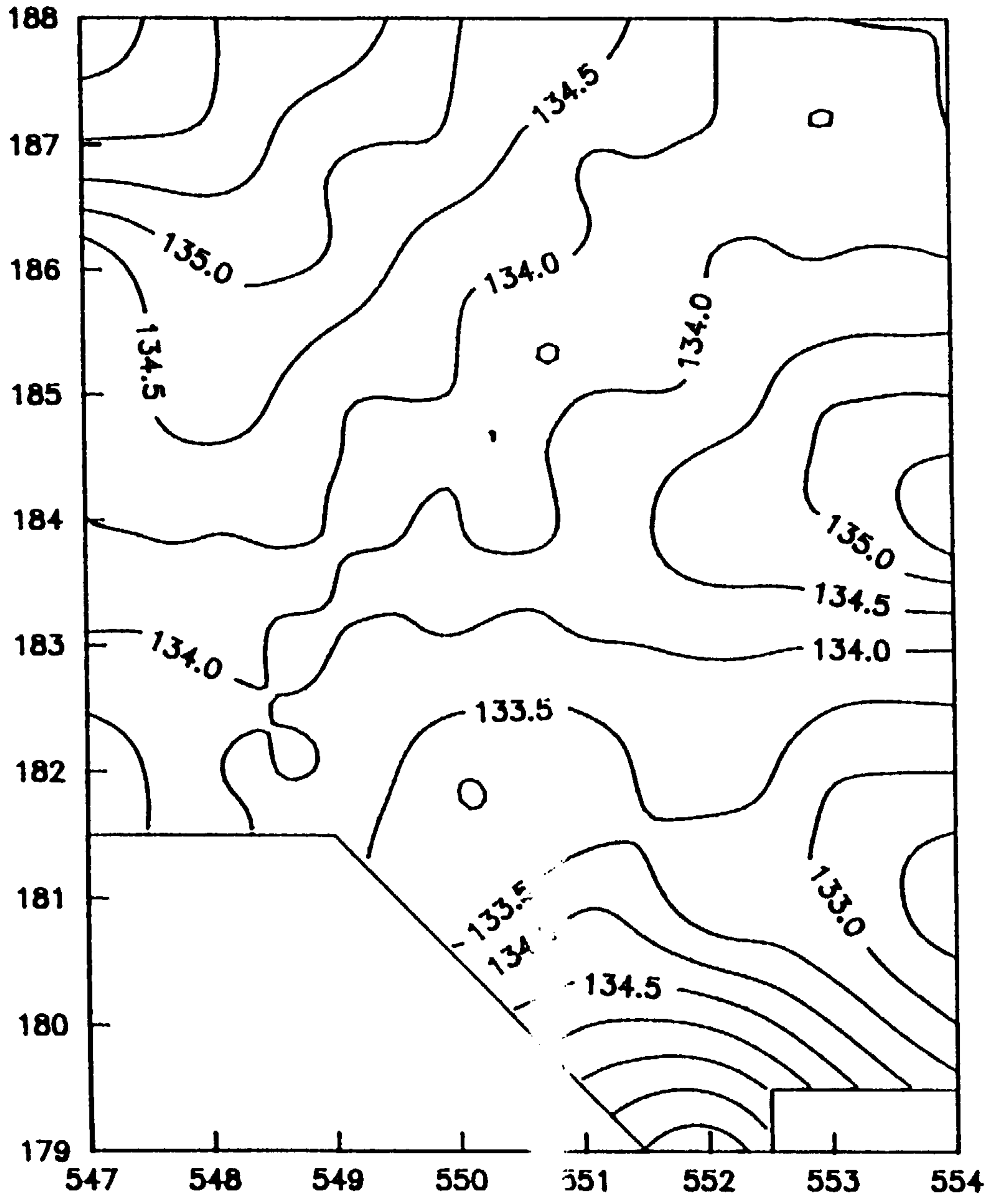
PASTURE -- TM BAND 6 RELATIVE INTENSITY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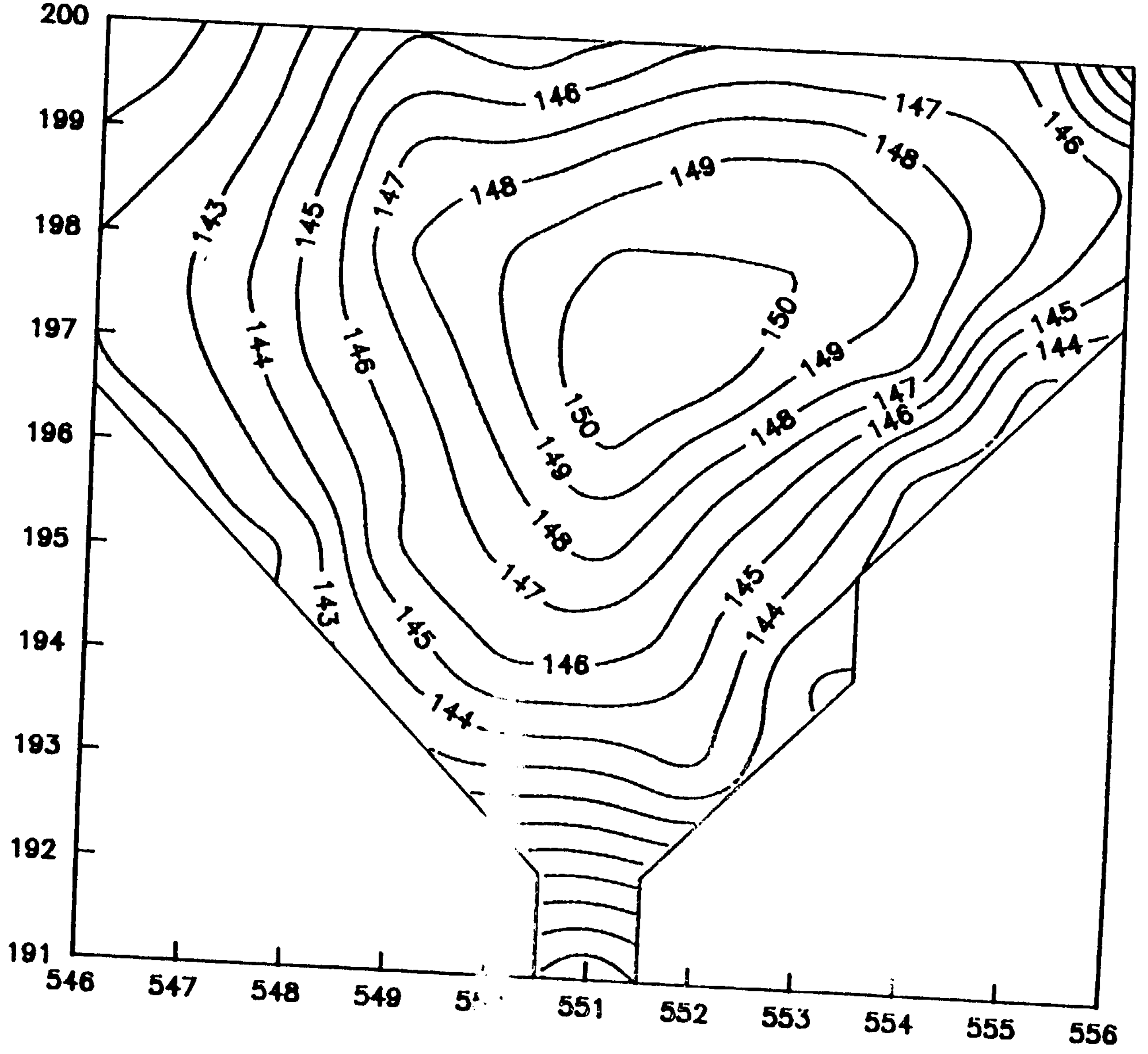
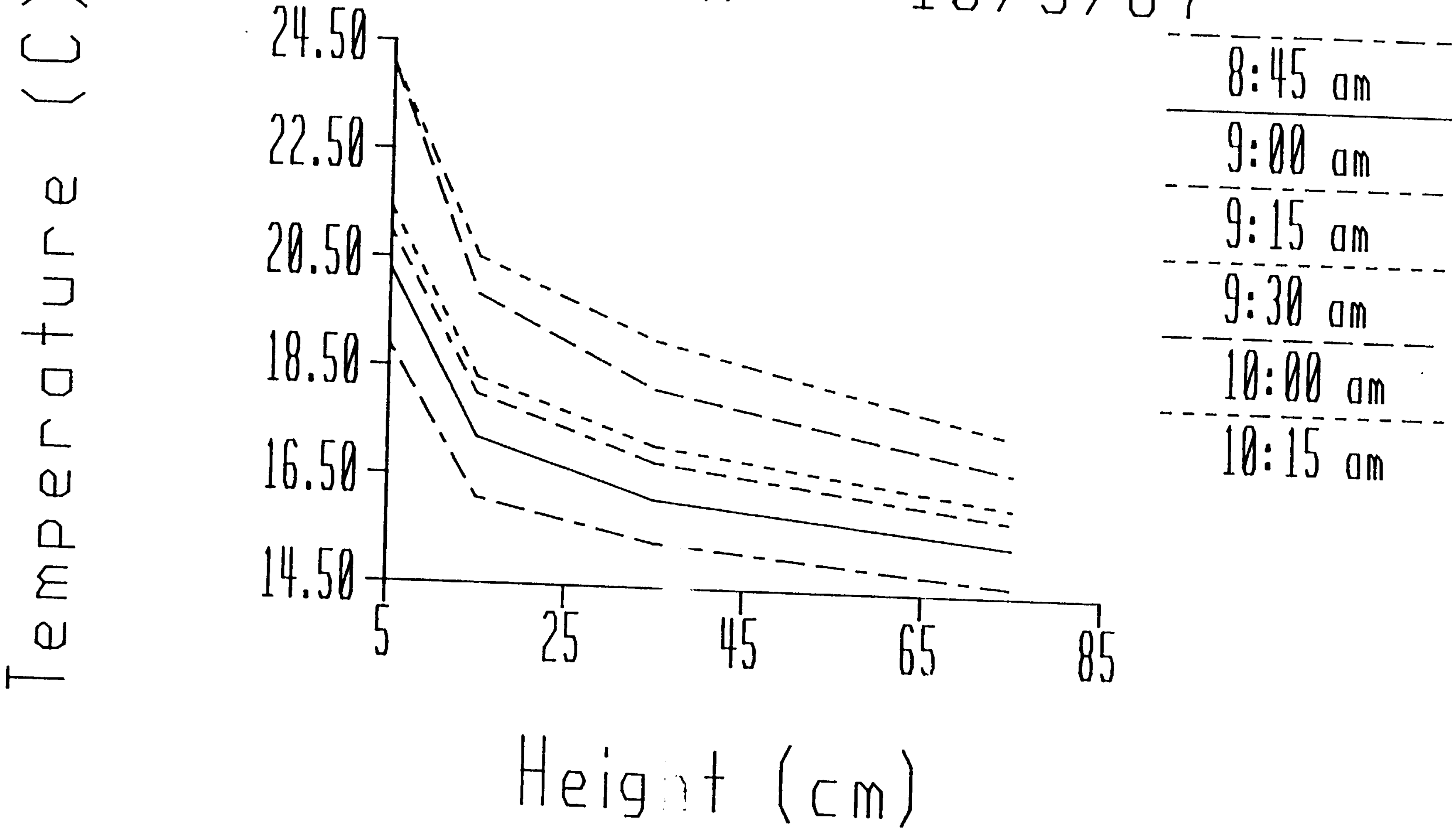
PEANUT FIELD -- TM BAND 6 RELATIVE INTENSITY

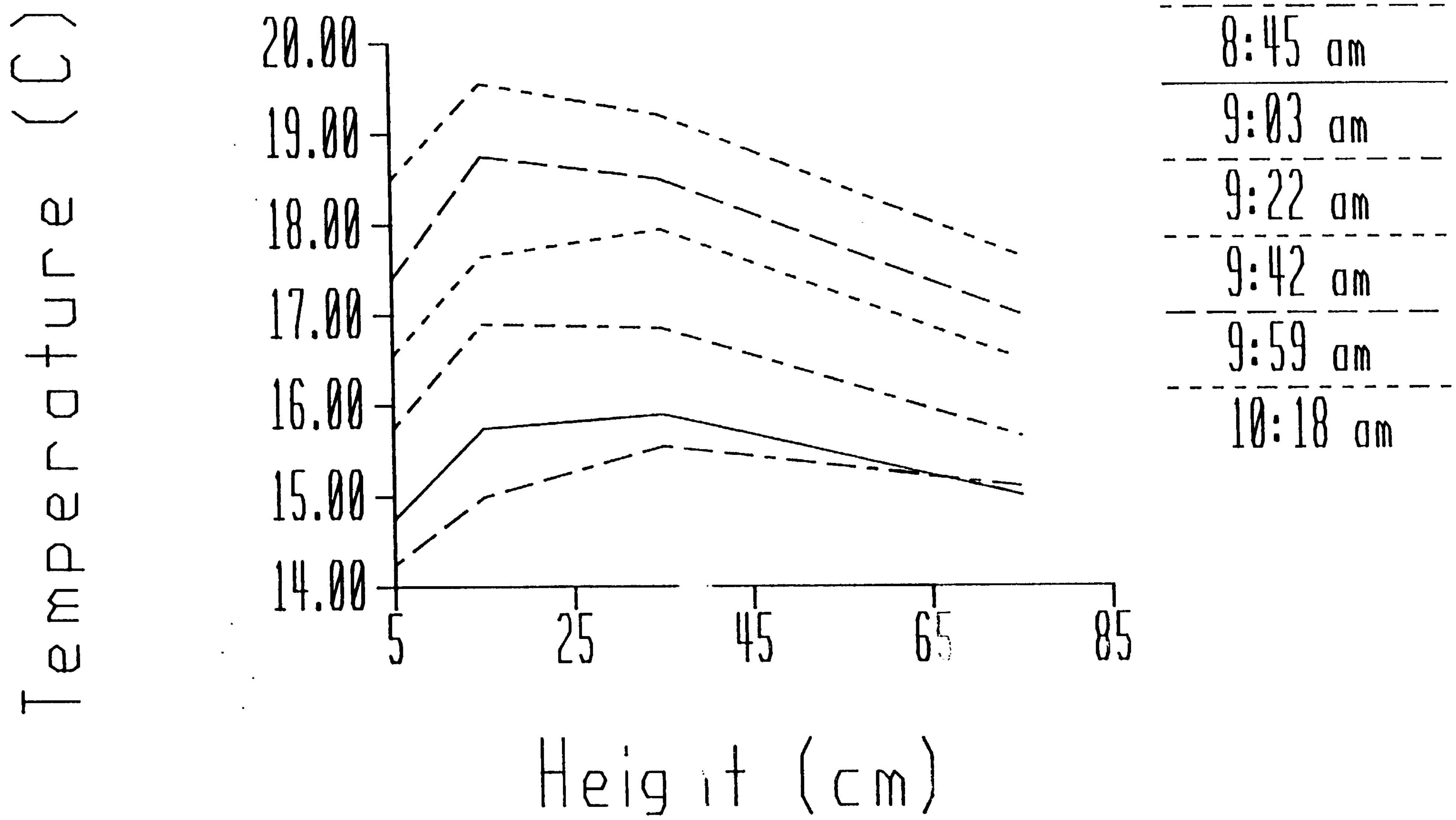


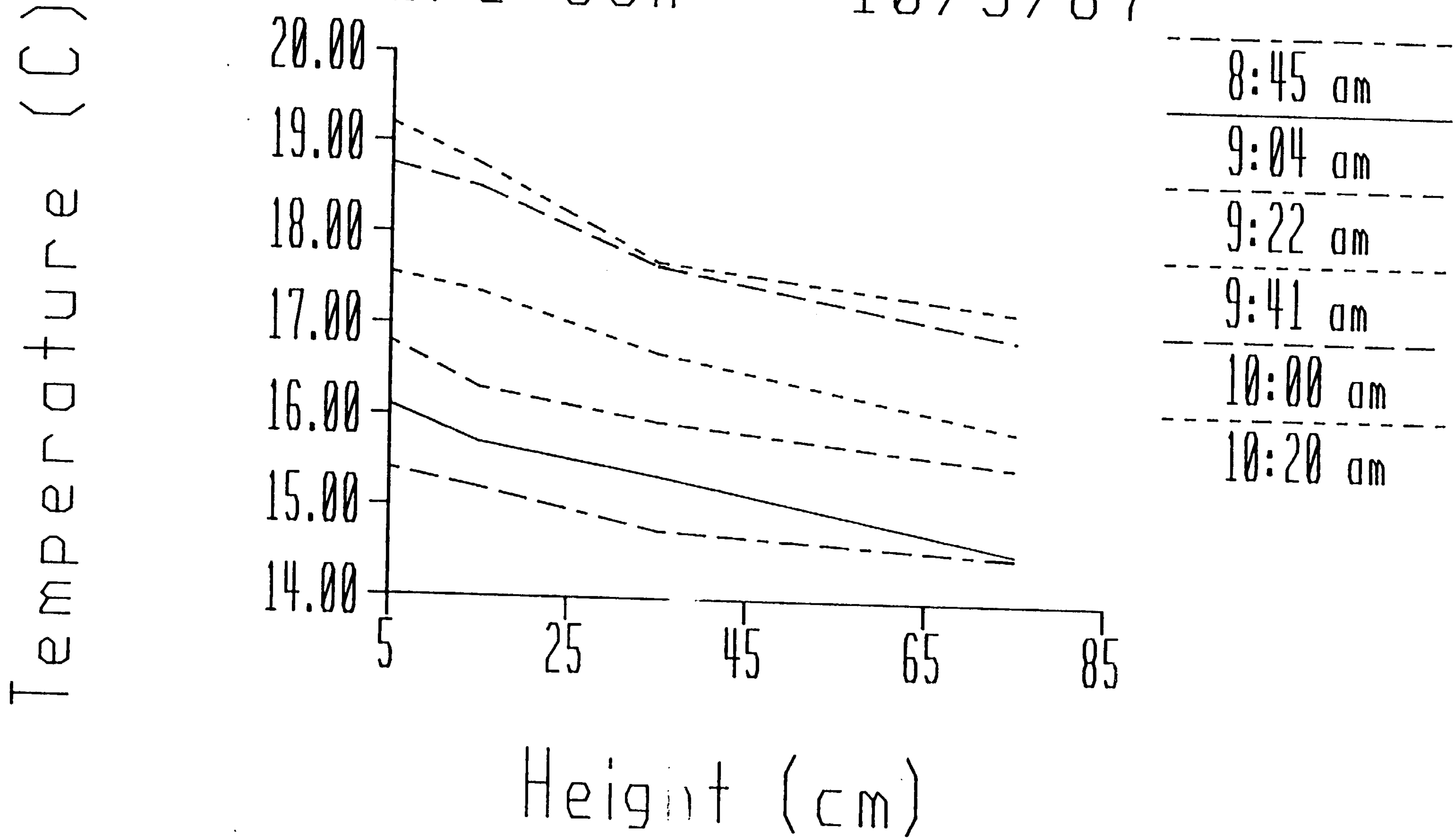
Temperature Profile

Main Station -- 10/3/87



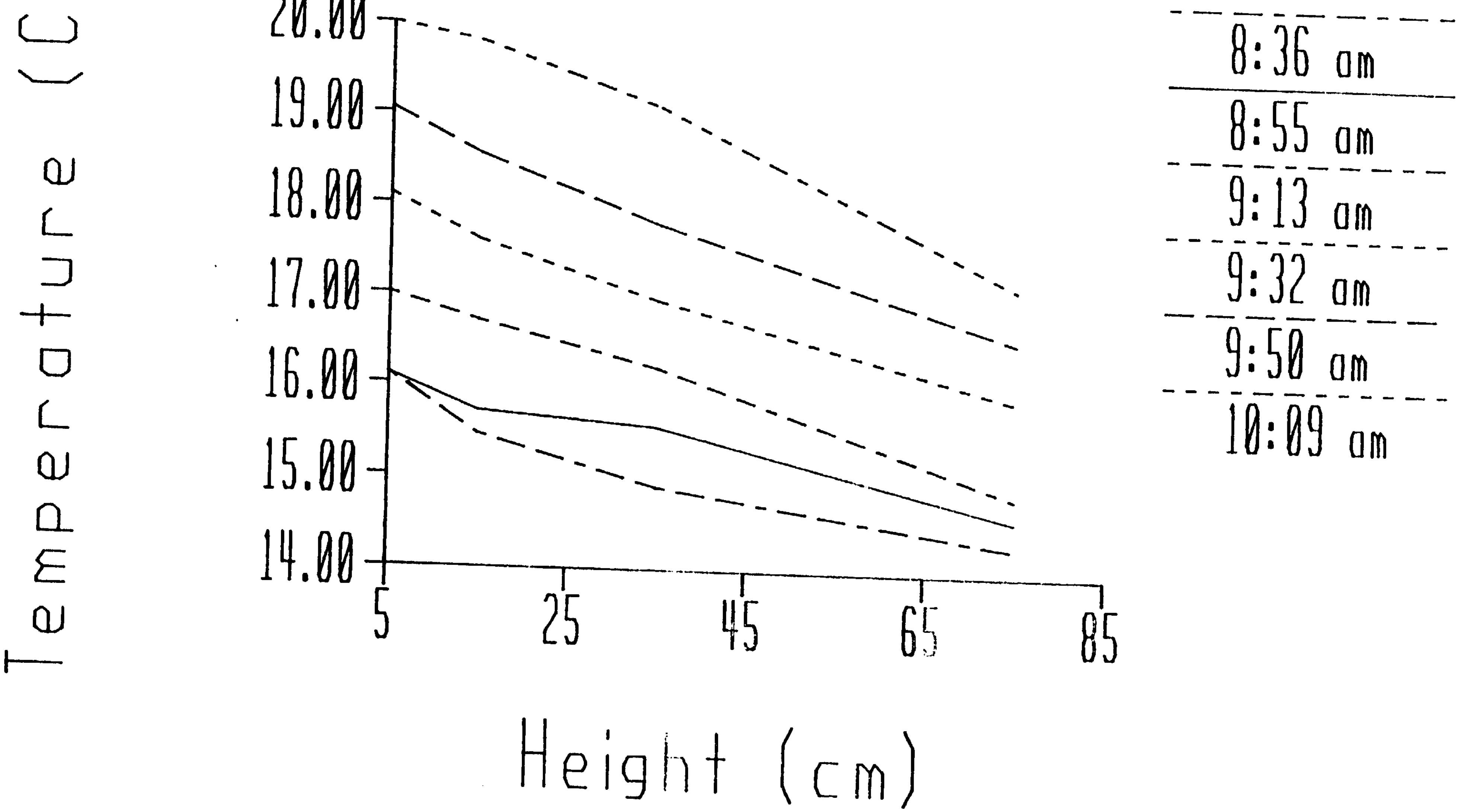
Temperature Profile
Pasture -- 10/3/87



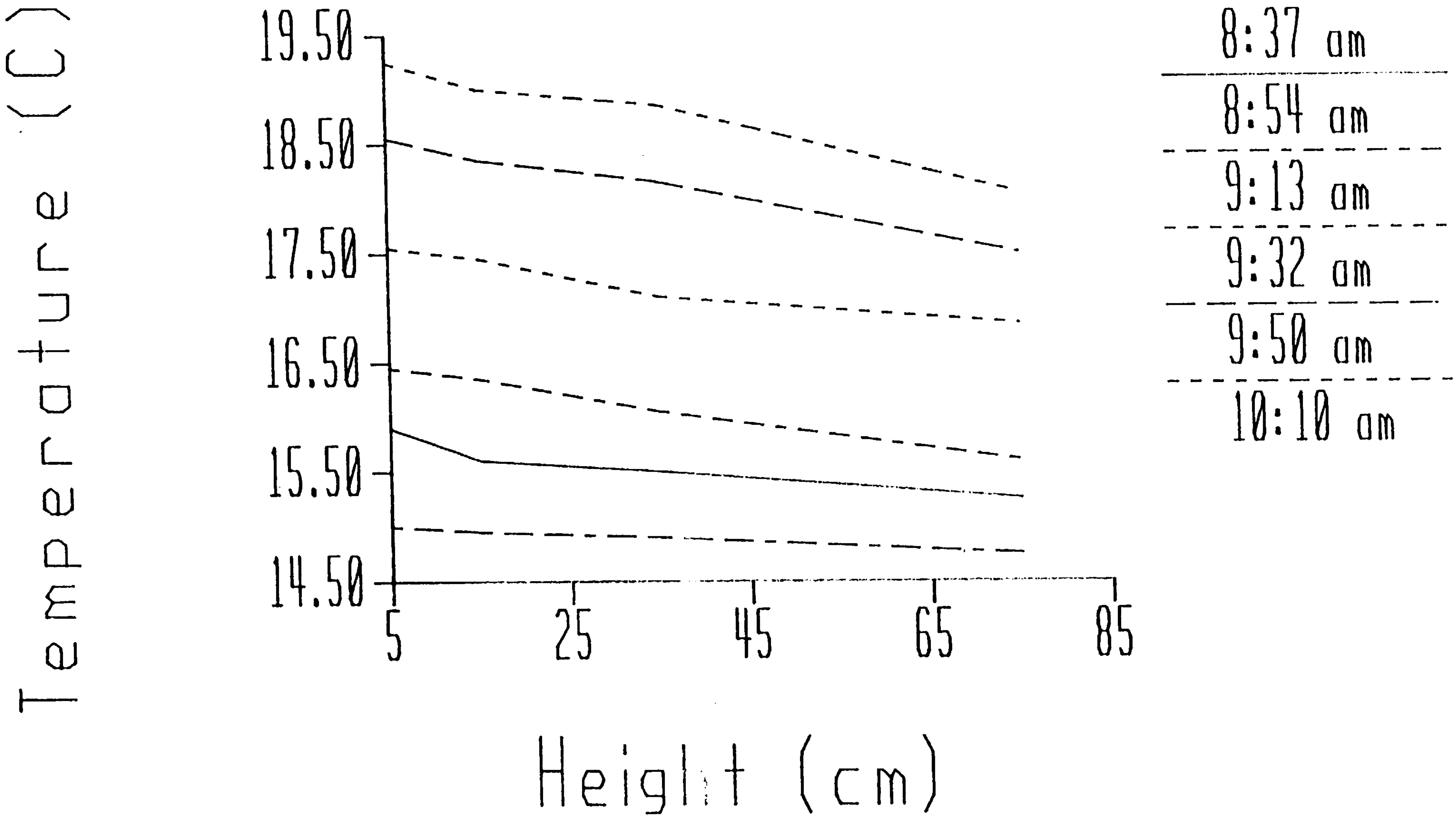


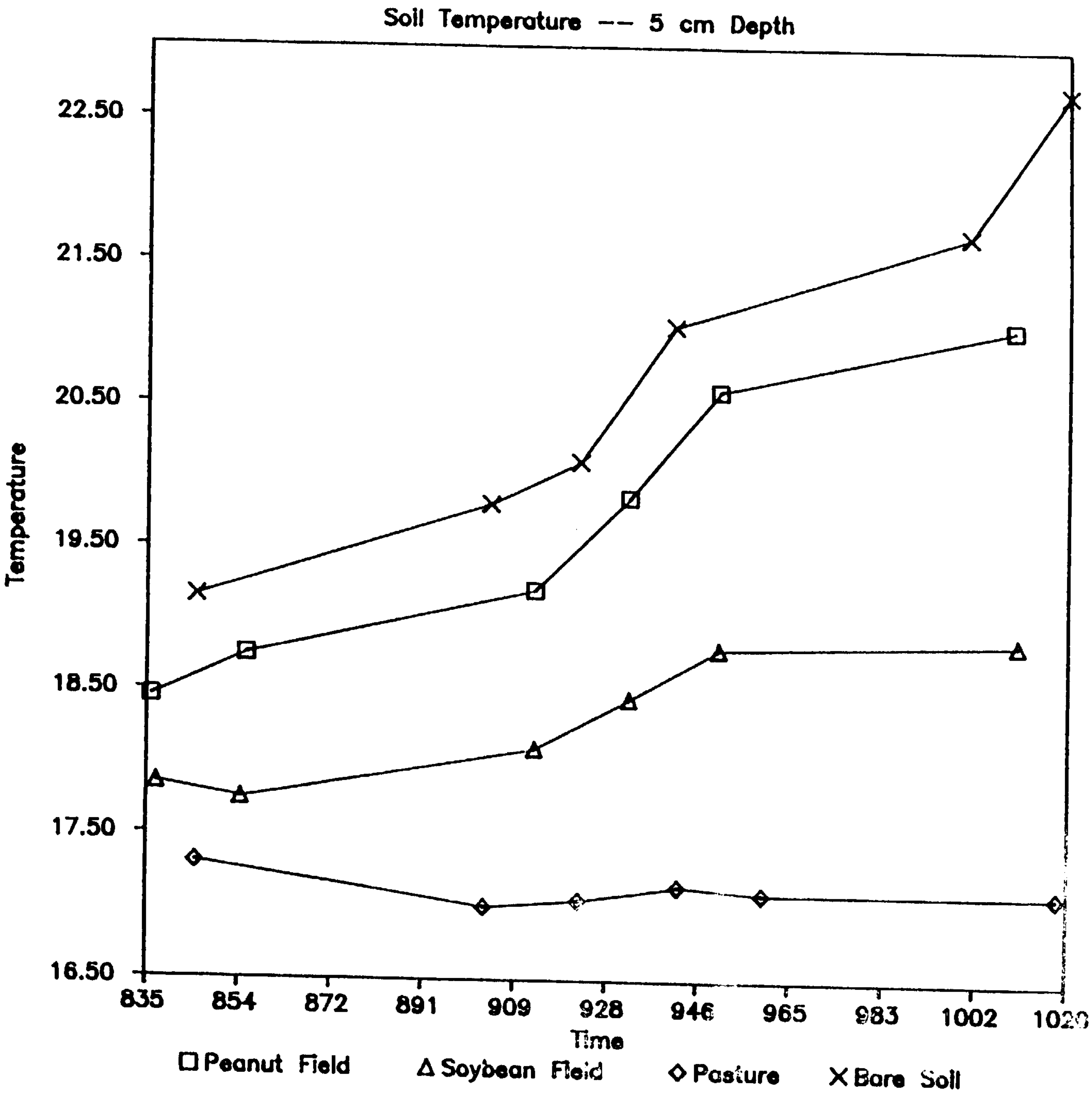
Temperature Profile
Bare Soil -- 10/3/87

Temperature Profile
Peanut Field -- 10/3/87



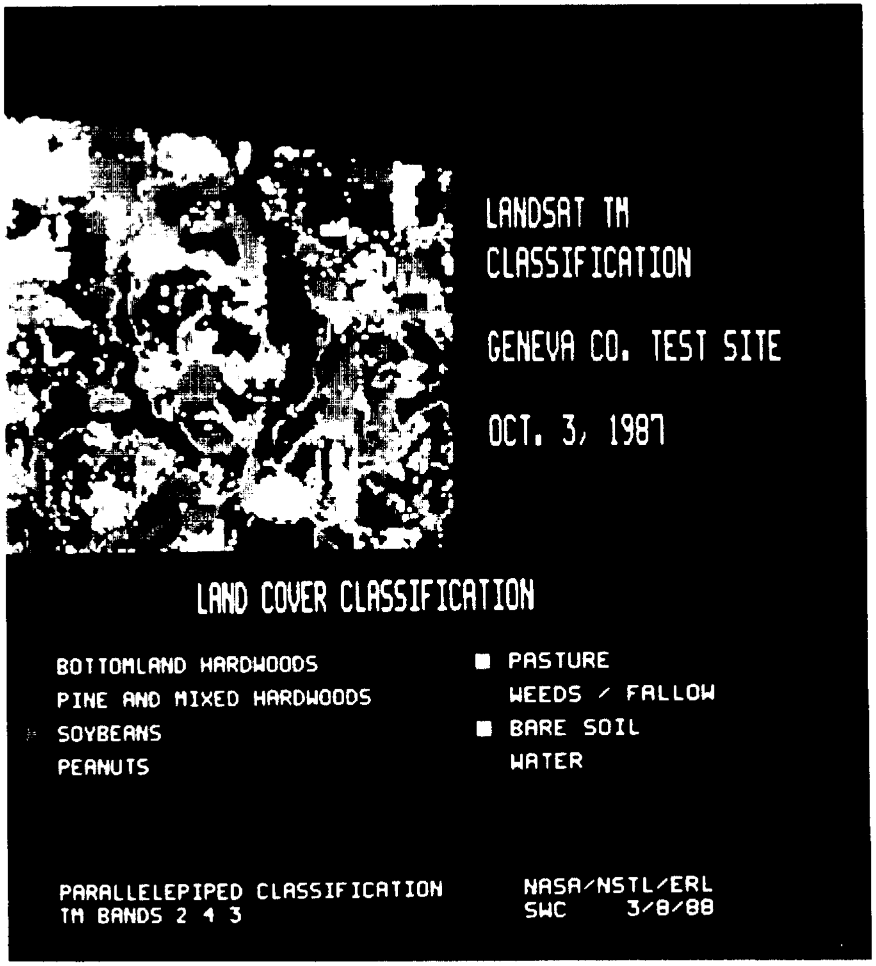
Temperature Profile
Soybean Field -- 10/3/87

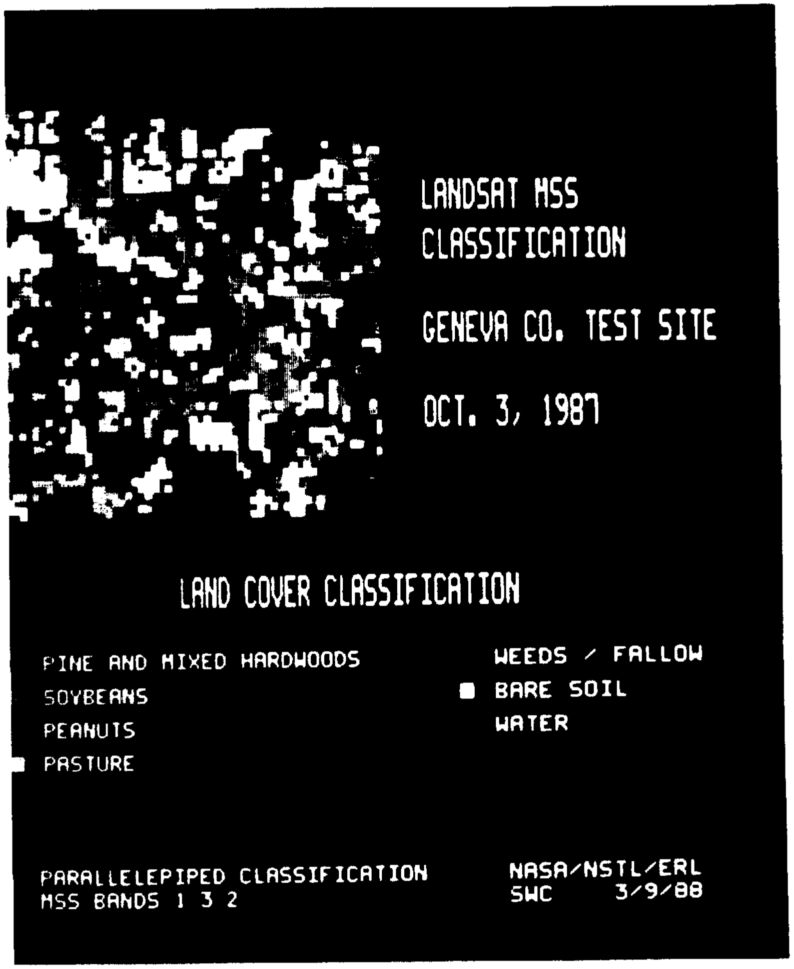



Soil Temperature -- 5 cm Depth
Temperature
22.50
21.50
20.50
19.50
18.50
17.50
16.50
835
854
872
891
909
928
946
965
983
1002
1020
Time
□ Peanut Field
△ Soybean Field
◇ Pasture
× Bare Soil

HUMID CLIMATE SITE, GENEVA COUNTY, ALABAMA

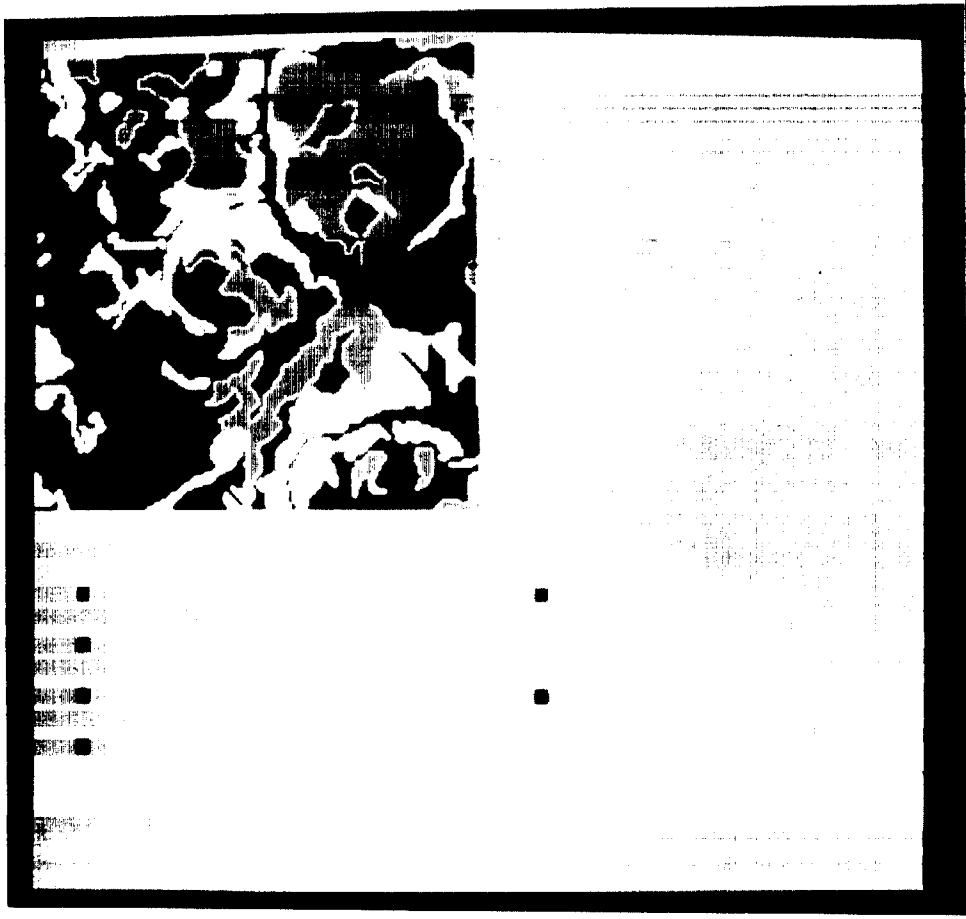
LANDSAT IMAGERY: TM and MSS Land Cover Classes

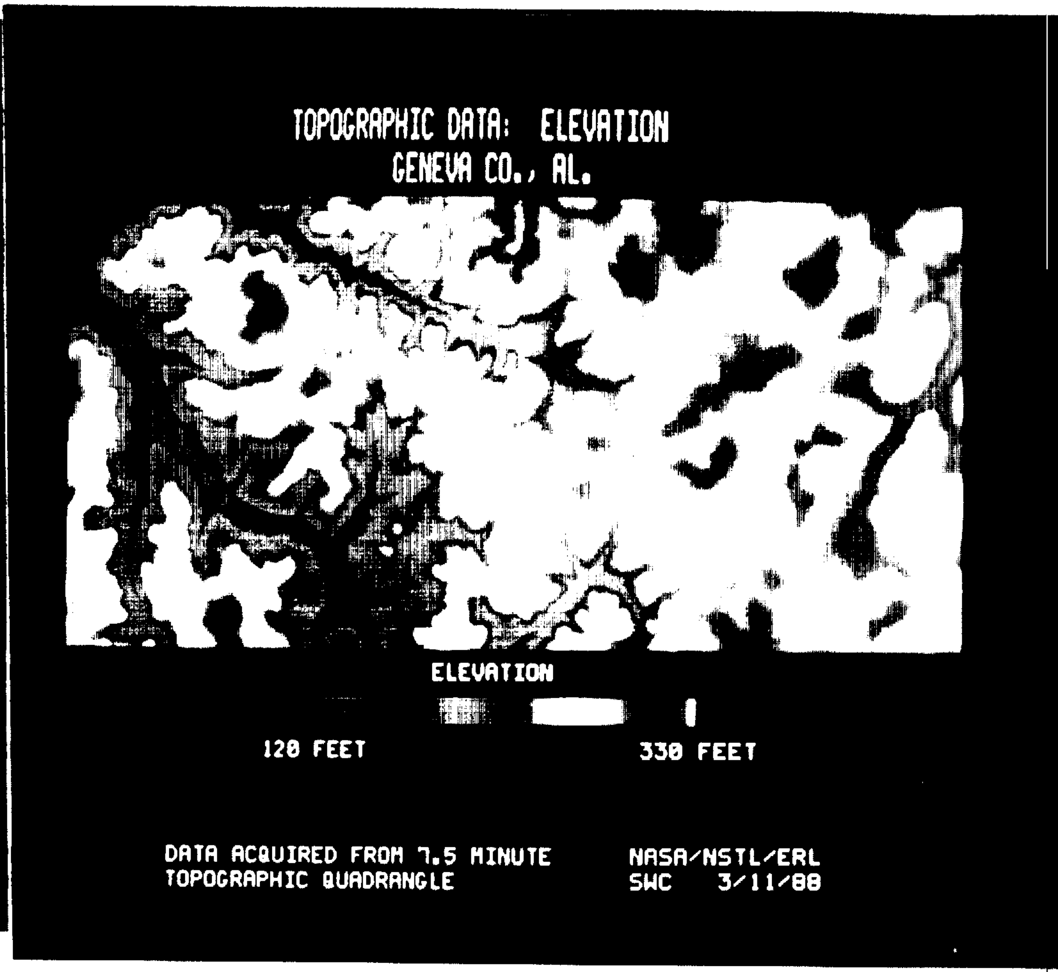

LANDSAT TM
CLASSIFICATION
GENEVA CO. TEST SITE
OCT. 3, 1987
LAND COVER CLASSIFICATION
BOTTOMLAND HARDWOODS
PINE AND MIXED HARDWOODS
SOYBEANS
PEANUTS
■ PASTURE
WEEDS / FALLOW
■ BARE SOIL
WATER
PARALLELEPIPED CLASSIFICATION
TM BANDS 2 4 3
NASA/NSTL/ERL
SWC 3/8/88


LANDSAT MSS
CLASSIFICATION
GENEVA CO. TEST SITE
OCT. 3, 1987
LAND COVER CLASSIFICATION
PINE AND MIXED HARDWOODS
SOYBEANS
PEANUTS
PASTURE
WEEDS / FALLOW
■ BARE SOIL
WATER
PARALLELEPIPED CLASSIFICATION
MSS BANDS 1 3 2
NASA/NSTL/ERL
SWC 3/9/88

HUMID CLIMATE SITE, GENEVA COUNTY, ALABAMA

LANDSAT IMAGERY: Topography and Soils

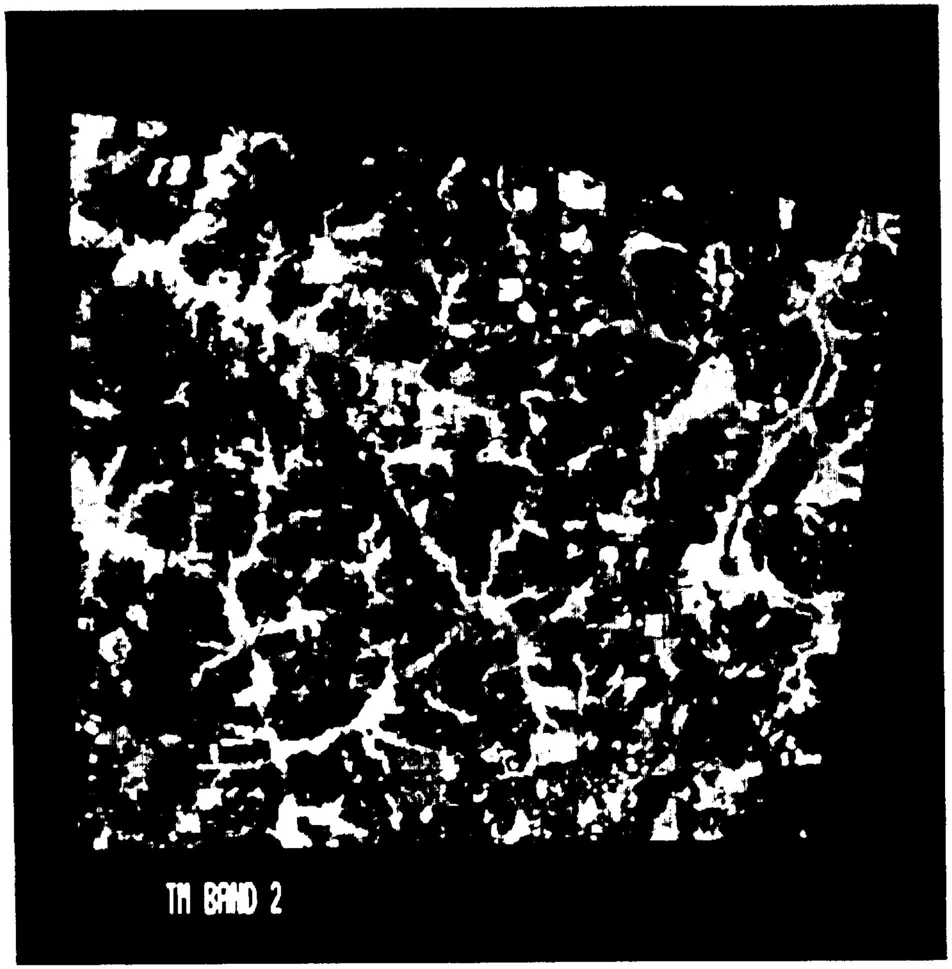


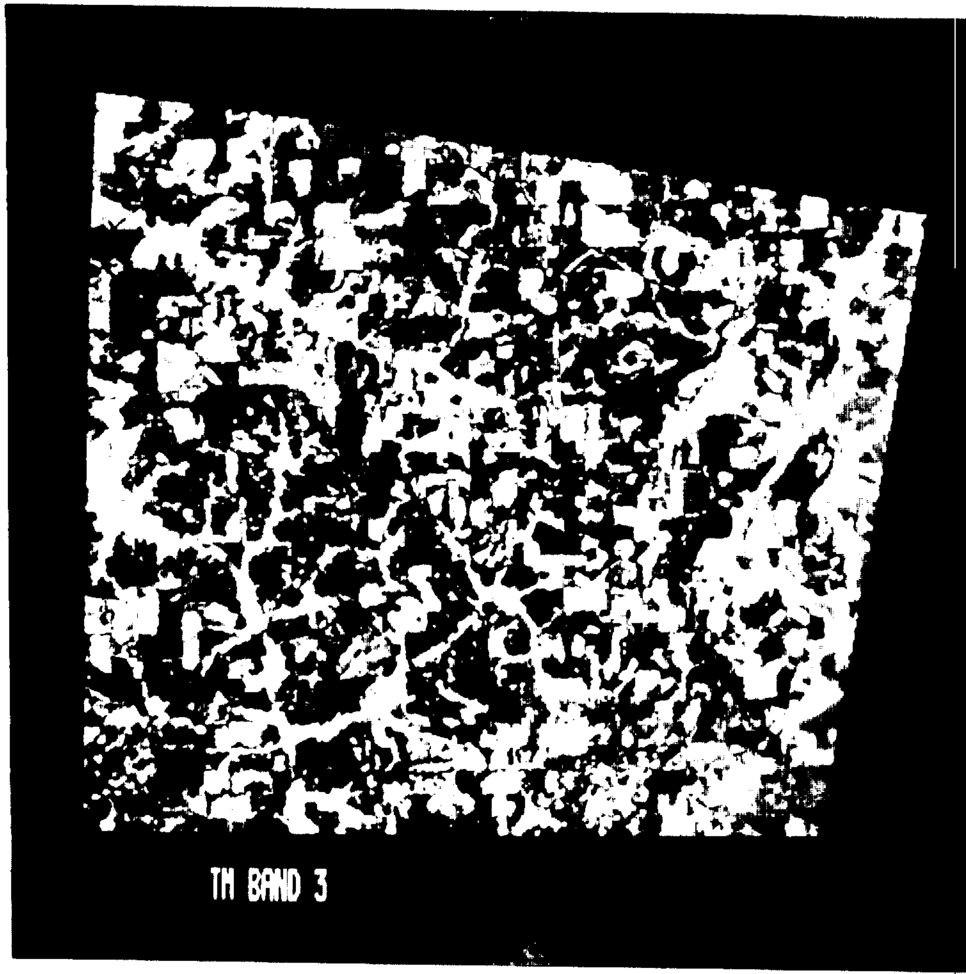

TOPOGRAPHIC DATA: ELEVATION
GENEVA CO., AL.
ELEVATION
120 FEET
330 FEET
DATA ACQUIRED FROM 7.5 MINUTE
TOPOGRAPHIC QUADRANGLE
NASA/NSTL/ERL
SWC 3/11/88

ORIGINAL PAGE
COLOR PHOTOGRAPH

HUMID CLIMATE SITE, GENEVA COUNTY, ALABAMA

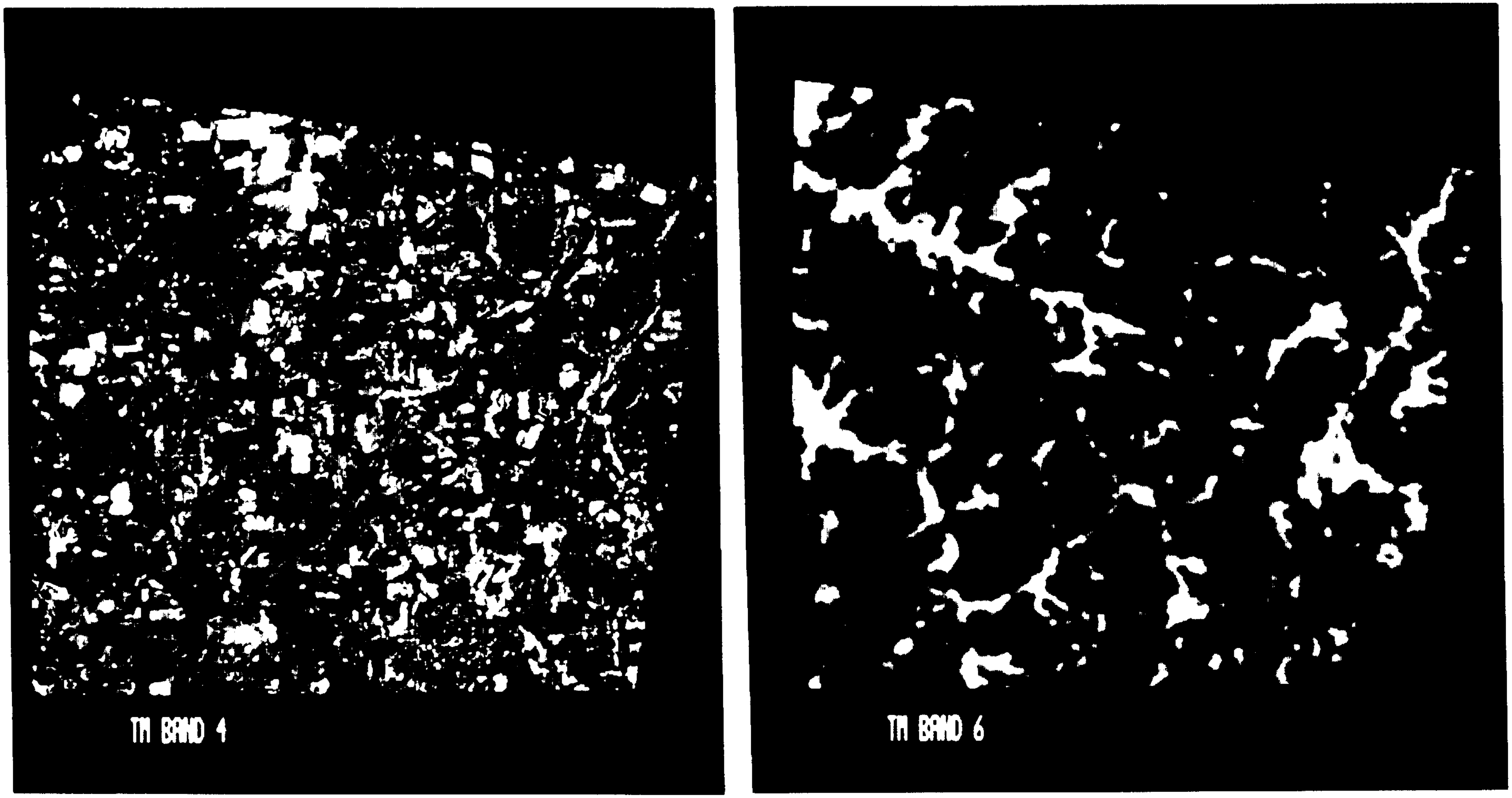
LANDSAT IMAGERY: TM Bands 2 and 3





HUMID CLIMATE SITE, GENEVA COUNTY, ALABAMA

LANDSAT IMAGERY: TM Bands 4 and 6


TM BAND 4
TM BAND 6

Landdsat MSS and TM Imagery Analysis, Arid Land Site

Soil samples were collected from the arid lands site in Dona Ana County, NM. Total elemental analysis, XRD, and thermal analyses methods are being used to characterize the mineral assemblages of arid land soil surfaces. Several types of remotely sensed data are available for this site and were evaluated in relation to basic soil components.

Spectral Characteristics of Arid Land Soils - Spectral, particle size, and mineralogical properties were determined for surface soils collected from 14 locations on the Jornado test site in Dona Ana County, New Mexico. Sample site locations wee based on analysis of TM data obtained and analyzed by NASA in previous studies on this site. The objective was to determine if remotely sensed spectral data could be used to differentiate soils with different mineralogical composition and consequently different taxonomic classification.

All soils in this area are composed of a basic matrix of quartz, feldspars, and mica. A mineralogical classification must consider which other minerals, and in which concentrations this matrix is enriched with or is deficient in. The other minerals of any consequence are smectite (montmorillonite), gypsum, calcium carbonate, and free iron oxides present as coatings on surfaces of all other minerals. TM data clearly distinguished the following classes:

smectite-iron oxides
smectite-calcium carbonate
iron oxide coated
gypsum-calcium carbonate
calcium carbonate-iron oxide
calcium carbonate

Samples were submitted to the U.S. Army Engineer Topographic Laboratories for spectral analysis. A draft of their report is includrd in this report.

DRAFT

Laboratory Spectral Analysis of Soil Samples
Jornada Experimental Range, Las Cruces, NM

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Procedures.

Spectral reflectance measurements were taken of 14 soil samples that had been collected from the U.S. Department of Agriculture, Jornada Experimental Range, near Las Cruces, New Mexico, by Dr. Hajek, Agronomy Dept., Auburn University. A gypsum sand sample collected near the White Sands National Monument was included in this set of soil samples. In the laboratory, each sample was placed on clean dry paper and allowed to air dry for at least 14 days. The sample was then passed through a 20.3 cm diameter soil sieve with openings of 2000 micrometers (um). Materials held on the 2000 um sieve were discarded and only the fraction passing this sieve was analyzed in this study. Each sieved sample was mixed thoroughly and a 20 gram (gr) to 30 gr subsample was placed into a labeled, 6 cm diameter, tared weighing dish. This is hereafter called the composite sample. A 100 gr to 200 gr subsample was placed on a nested series of 20.3 cm diameter soil sieves having openings of 500, 210, and 74 um, and the pan. This subsample was shaken for 3 to 5 minutes using a CENCO, No.

1840, mechanical sieve shaker. The portion held on a specific sieve was removed and placed into a labeled, 6 cm diameter, tared weighing dish. The sieved portions are hereafter called the soil separate. Fragments of organic matter/debris were removed from the sample composite and separates. No attempt was made to break up the soil aggregates within a sample separate, thus the separates were a mixture of soil particles and aggregates of smaller soil particles.

The reflectance spectra, 360 nanometers (nm) to 2500 nm, of each composite sample and sample separates were measured in the laboratory, using a Geophysical Environmental Research, Inc., spectroradiometer, model Mark IV, SN FBV-024. This is a dual beam scanning spectroradiometer with a 4 degree field of view (FOV). The radiometer's spectral resolution is approximately 1.5 nm in the 360 nm to 1300 nm region and 3.5 nm to 4.5 nm in the 1300 nm to 2500 nm region. A nadir radiometer viewing angle was used and the viewing height was 48.5 cm above the sample surface. The sample was positioned so it filled one half of the radiometer's FOV. A pressed Halon reference standard, "Spectralon," a 25.4 cm x 25.4 cm x 1.0 cm plate, was positioned so that it filled the other half of the radiometer's FOV. The reflectance standard is commercially available from Labsphere, North Sutton, NH, model SRS-99-100. The standard's calibration curve is relatively flat across the 300 nm to 2500 nm spectrum and it reflects approximately 97% to 99% of the incident light. The sample and the Halon standard were simultaneously illuminated by a Lowel tota, 500 watt, Tungsten-Halogen lamp, model FDN, at a color temperature of 3200 degrees K. Each composite sample or sample separate was positioned on the horizontal viewing stage in the spectroradiometer's field of view. The surface of each sample or separate was relatively "flat," although the surface was not smoothed manually. Each spectral scan required approximately 60 seconds to complete. Light energy passing either side of the split objective lens is alternately focused on the silicon and lead sulfide detectors using a rotating mirror device. In this manner the sample and the Halon reflectance standard were viewed almost simultaneously.

The radiance spectra of the sample and the Halon were automatically recorded on the radiometer's internal 3 megabyte bubble memory. After data acquisition, the radiance data were transferred to a Zenith lap top PC computer for computations of the sample's reflectance spectra. This procedure includes the manufacturer's detector calibration functions. The resulting high resolution spectral reflectance data were smoothed using a 5 point weighted average, simplified least squares curve fitting procedure (Salik and Golay, 1964, Analytical Chem. 36:1627-1639). The mean reflectance for each 5 nm waveband over the 360 nm to 2500 nm spectrum was calculated as the intergrated average beneath the high resolution spectral curve. The 5 nm waveband reflectance data are LOW resolution spectra, because their spectral resolution is less than what was initially determined. The radiometer has a detector change at about 1150 nm. Noise in the spectral data that was associated with the detector change required smoothing the reflectance curve between 1100 nm and 1200 nm, using a curve slope fitting algorithm.

The reflectance spectra were taken of the composite and sieved separates in three separate moisture conditions; air dry, wet, and oven dry. The air dry condition was created by allowing each composite sample and associated sample separates to air dry on the laboratory bench for at least 14 days at room temperature. The sample plus tare weight was determined and the sample's reflectance spectra was taken. The wet condition was created by slowly applying small amounts of de-ionized water to each air dried sample until the sample was wet, that is the sample did not contain enough water to make it glisten. The wet sample was covered and allow to equilibrate for approximately 6 hours. The wet sample plus the tare weight was determined, then the reflectance spectra was taken. The oven dry condition was created by oven drying each wet sample for 24 hours at 105 degrees Celcius. The spectra of the oven dry sample was measured after the sample had cooled to room temperature.

The spectra were taken only of those composite samples and sample separates in which the soil material covered the weighing dish to a depth of 0.5 cm or more. The percent moistures for the air dried and wet composite samples and the sample separates were determined gravimetrically on an oven dry weight basis.

The mean reflectance of each composite sample and each sieve separate was calculated for the wavebands corresponding with those of the Landsat Thematic Mapper sensor; band 1 (450 nm to 520 nm), band 2 (520 nm to 600 nm), band 3 (630 nm to 690 nm), band 4 (700 nm to 900 nm), band 5 (1550 nm to 1700 nm), and band 7 (2080 nm to

2350 nm). No attempt was made to approximate the Landsat Thematic Mapper sensor digital data.

Results.

(The following is a cursory evaluation of these spectral data.)

Three sets of spectral reflectance data were collected for the 14 soils and the gypsum sand. These are summarized by mean reflectance in the six Landsat Thematic Mapper bands occurring within the 400 nm to 2500 nm spectrum. The data for the air dry samples are summarized in Table 1; the wet samples in Table 2; and the oven dry samples in Table 3. Graphics illustrating the reflectance of each sample in air dry, wet, and oven dry conditions are provided. The sample's index number and the associated letter have continuity between the three tables, as well as the three spectral data sets. The index number is a laboratory sample identification number. The letter designates a particular range of particle sizes for a sieve separate or the composite sample are:

A- 500 to 2000 um
B- 210 to 500 um
C- 74 to 210 um
D- <74 um
E- composite

For example, index number 80 and letter A, represents the 500 um to 2000 um separate of soil sample number AU-01 in the tables and the graphics. The percentages of water held in the sample at the air dry and wet conditions are given in Tables 1 and 2 respectively.

Surface condition. The sample surfaces varied in their physical states depending on the moisture content. The surfaces of the air dry samples were irregular, caused by the individual soil particles or aggregates. Wetting the surfaces disintegrated most of the soil aggregate, resulting in a rather smooth sample surface. Samples composed of substantial percentages of sand-size particles did not exhibit the same degree of surface smoothing as the samples comprised of high percentages of silt and clay-size particles. Wetting the surface of samples comprised primarily of particle agggregates reduced the spectral differences between the sample's separates.

The surface smoothing brought about by the sample wetting also affected the surfaces of the oven dry samples, and the spectral measurement sequence was 1) the air dry samples, 2) the wet samples, and 3) the oven dry samples. Insufficient soil sample size did not permit replication of the composite sample nor the sample separates for each moisture condition. Even so, the initial results show a need to further investigate surface conditions as they affect soil reflectance contrast between different sized soil particles or aggregates.

Air Dry Soils. Generally, there was a trend for the amplitudes of the sample's and subsample's reflectance spectra to vary inversely with particle size, i.e., the smaller sized particles often had higher reflectance, e.g., Sample AU-01. Some samples e.g., AU-02, did not exhibit this trend in that the composite and separates had similar reflectance spectra. All samples and separates showed water absorption bands centered near 1440 nm, 1900 nm, and 2200 nm. Many sample did not have spectral differences in the 400 nm to 650 nm regions. Most differences between the samples and subsamples were found in wavebands longer than 650 nm. The shapes of some spectral curves in the 400 to 800 nm region show color differences associated with iron oxide staining of soil particles and with parent material differences. Sample AU-08 and the gypsum sand sample show the distinct absorptions associated with gypsum in the 1300 to 2500 nm region. Some spectral differences occurred between the separates of these two samples in the 400 to 1300 nm region; particularly the curve's amplitudes, in the 400 to 700 nm region and absorption bands in the 700 to 1300 nm region.

Wet Soils. Water applied to the samples was enough that the soil could easily fall within a subjective moisture range of moist to wet. The soil moisture potential at this condition was not determined since this was very a subjective determination of the water's effects on the soil's reflectance spectra. In all instances, water applied to a soil or soil separate brought about lower reflectance than was found for the air dried sample. The reduction varied between sample and separates of a particular soil sample. The reflectance spectra of the wet samples were from 10% to 40% less than the reflectance of the same sample or separate in the air dry condition. Small differences were found in the visible region, while large differences often occurred in the NIR-MIR region. Another major affect was the reduced reflectance contrast between the composite sample and its separates. Differences were generally less than 10% for most samples.

The water absorption bands centered at 1440 nm and 1900 nm were much deeper and wider in comparision to the air dried samples. The distinct difference for the wet samples was the much lower reflectance in the spectral regions adjacent to the water absorption bands. The small water absorption band centered at 2200 nm was not as obvious for many samples, although it was seen in both the air dry and oven dry samples. Other unique absorptions bands associated with gypsum sand and gypsiferous soil were apparent. The absorptions associated with color and iron staining were still seen in the 400 to 700 nm region.

Oven Dry Soils. Generally, the reflectances of the oven dry soils and separates had applitudes that were similar to those of the same sample in the air dry condition, although they tend to be slightly less reflective than the air dry samples. The reflectance contrast between the composite sample and its separates was usually small and similar to that observed for the wet samples. The oven dry soils show small water absorption bands centered at 1440 nm, 1900 nm, and 2200 nm, which may be indicate matrix water or hydroxyl bonds. The reflectance contrast between sample separates and the composite sample are less than found for the air dry samples.

Summary Observations.

1. Generally the sample's NIR-MIR reflectances varied inversely with particle size. Visible reflectance did not show clear relations with particle size or soil wetting.

2. Reflectance contrast between samples and separates of a sample is reduced by soil wetting and by oven drying, in comparison to the reflectance contrast found for the air dried samples.

3. For wet soils and soil separates, the water absorption bands at 1440 nm, 1900 nm, and 2200 nm lowered the reflectance in the adjacent spectral regions.

4. In the 400 nm to 700 nm region, sample reflectances appear to be affected by other soil factors and were little affected by moisture content.

5. Unique absorptions bands in the 1300 to 2500 nm region were apparent regardless of the water contents, although, reflectance in this region was lowered for wet samples.

Table 1. Air dry soil samples: Soil water content and mean reflections in thematic mapper bands for soil samples and separates, Joranado Experimental Range, Las Cruces, NM.
Obtained by Melvin B. Satterwhite and J. Ponder Henley. U.S. Army Engin. Topo. Lab., Ft. Belvoir, VA 22060-5546

File Name	Index.No.	Sep	Water %	Thematic Mapper Bands					
				Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
				450-520	520-600	630-690	760-900	1550-1750	2080-2350
				wavelength in nanometers					
AU 87 1	80	A	2.8	19.17	25.25	31.60	35.89	40.77	37.98
AU 87 2	81	B	2.8	19.28	25.57	32.32	36.90	43.53	41.50
AU 87 3	82	C	2.0	17.91	25.16	34.20	41.32	55.69	56.26
AU 87 4	84	D	2.4	18.25	25.26	33.63	39.77	49.88	48.29
AU 87 5	1	A	0.8	15.84	21.28	28.28	33.97	44.15	41.00
AU 87 6	2	B	0.6	14.03	19.10	26.16	30.86	36.61	35.21
AU 87 7	3	C	1.0	13.56	19.42	28.22	33.89	42.04	40.54
AU 87 8	4	D	2.0	13.56	19.62	27.96	33.69	45.08	44.82
AU 87 9	5	E	0.8	14.63	20.53	28.98	34.94	45.14	44.14
AU 87 10	55	A	51.8	6.43	9.32	14.44	19.60	33.16	31.68
AU 87 11	56	B	0.5	7.75	13.54	20.80	26.46	39.09	37.47
AU 87 12	57	C	0.9	7.22	11.66	19.71	25.59	37.49	36.60
AU 87 13	58	D	2.8	7.53	12.09	19.75	25.67	37.62	37.14
AU 87 14	59	E	0.8	7.88	11.51	19.07	24.79	35.83	34.70
AU 87 15	60	A	0.5	9.51	14.79	24.06	30.29	40.68	39.04
AU 87 16	61	B	0.6	7.94	12.90	22.13	28.42	38.77	37.23
AU 87 17	62	C	1.0	7.79	12.97	22.62	28.87	38.21	37.07
AU 87 18	63	D	1.7	10.48	18.00	31.24	39.46	58.26	57.20
AU 87 19	64	E	0.8	7.95	12.94	22.22	28.39	38.32	37.36
AU 87 20	6	A	0.6	15.97	20.42	25.90	32.78	44.69	40.93
AU 87 21	7	B	0.6	13.84	18.30	24.39	29.79	39.07	38.10
AU 87 22	8	C	0.8	12.36	16.92	23.42	29.20	39.16	38.92
AU 87 23	9	D	1.8	13.28	18.50	25.71	32.55	46.28	46.90
AU 87 24	10	E	0.9	13.22	17.92	24.31	30.19	40.65	39.84
AU 87 25	11	A	2.9	18.25	22.01	26.42	30.19	34.86	32.02
AU 87 26	12	B	1.9	19.15	23.33	28.58	33.06	40.19	37.41
AU 87 29	15	E	2.4	18.10	23.01	29.44	35.30	44.82	43.13
AU 87 30	66	B	0.2	9.47	14.56	23.06	29.28	39.50	38.55
AU 87 31	67	C	0.5	9.94	15.95	26.30	33.30	44.69	43.93
AU 87 32	69	E	0.5	10.14	15.94	25.70	32.34	43.50	43.08
AU 87 33	85	A	8.6	20.40	26.49	33.92	41.26	44.41	34.11
AU 87 34	86	B	4.1	19.42	25.00	32.12	37.60	42.32	36.04
AU 87 35	87	C	5.5	20.33	26.49	34.52	40.99	47.94	41.00
AU 87 36	88	D	11.8	24.81	33.32	44.82	53.25	64.39	56.42
AU 87 37	89	E	7.6	23.02	30.39	40.19	47.75	55.95	47.66
AU 87 38	50	A	5.9	9.30	11.91	17.00	20.27	17.63	15.18
AU 87 39	51	B	4.3	8.97	11.90	17.74	21.33	20.24	18.69
AU 87 40	52	C	4.2	9.12	12.24	18.69	23.43	24.05	23.63
AU 87 41	54	E	5.2	8.82	11.63	17.70	20.54	18.71	16.77
AU 87 42	17	B	0.8	13.00	17.06	22.89	28.32	38.81	38.45
AU 87 43	18	C	0.8	12.56	17.31	24.44	30.70	41.35	41.03
AU 87 44	19	D	1.5	12.87	18.27	26.01	32.36	43.71	44.48
AU 87 45	20	E	1.0	13.15	17.91	24.69	30.36	41.03	41.31
AU 87 46	70	A	0.9	13.97	18.44	25.00	30.77	36.86	34.15
AU 87 47	71	B	0.7	13.75	18.66	25.85	31.52	38.88	37.17
AU 87 48	72	C	1.1	13.22	18.61	29.45	42.32	53.21	52.14
AU 87 49	73	D	2.3	13.37	21.00	32.17	44.36	58.13	58.63
AU 87 50	74	E	1.3	13.40	18.38	27.55	38.69	47.40	46.06
AU 87 53	23	C	1.0	14.75	20.08	27.82	33.43	0.19	41.04
AU 87 54	24	D	1.7	14.20	20.05	28.70	35.36	47.04	48.30
AU 87 55	25	E	1.3	15.02	20.32	27.82	33.61	41.53	40.76
AU 87 56	75	A	2.9	11.68	16.95	25.70	30.25	30.17	29.69
AU 87 57	76	B	2.8	11.17	16.39	25.20	30.22	31.78	32.09
AU 87 58	77	C	3.0	10.35	15.80	25.94	32.77	37.94	40.34
AU 87 59	78	D	2.4	10.81	15.59	27.61	35.09	42.29	45.23
AU 87 60	79	E	2.9	11.18	17.07	27.97	35.10	39.84	41.79
AU 87 61	27	B	0.5	15.15	19.73	25.36	30.30	37.94	37.47
AU 87 62	28	C	0.7	14.43	18.80	24.38	28.97	36.72	36.50
AU 87 63	29	D	2.8	15.55	21.51	29.67	37.07	58.89	54.74
AU 87 64	30	E	0.7	14.37	18.68	28.97	28.78	56.91	36.43
AU 87 65	32	B	24.4	48.66	55.08	59.22	61.41	37.59	12.82
AU 87 66	33	C	24.5	50.76	58.00	63.15	65.49	45.72	18.72
AU 87 67	36	E	24.3	52.41	60.76	67.02	70.79	46.08	14.42

Sep: Soil size separates: A = 500-2000um, B = 210 - 500um, C = 74 - 210um, D = <74um E = composite

Table 2. Wet soil samples: Soil water content and mean reflections in thematic mapper bands for soil samples and separates, Joranado Experimental Range, Las Cruces, NM.
Obtained by Melvin B. Satterwhite and J. Ponder Henley. U.S. Army Engin. Topo. Lab., Ft. Belvoir, VA 22060-5546

File Name		Index.No.	Sep	Water %	Thematic Mapper Bands					
					Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
					450-520	520-600	630-690	760-900	1550-1750	2080-2350
					wavelength in nanometers					
AUW	1	80	A	39.9	7.01	10.44	15.09	19.51	22.16	15.83
AUW	2	81	B	44.2	8.17	11.72	16.57	21.33	23.77	16.11
AUW	3	82	C	0.0	8.31	12.15	17.15	22.88	27.62	20.34
AUW	4	84	E	28.5	7.03	10.51	15.47	20.43	24.84	18.28
AUW	5	1	A	17.8	7.06	10.21	15.39	20.29	21.49	14.29
AUW	6	2	B	25.1	6.73	9.69	14.69	18.50	16.22	10.18
AUW	7	3	C	25.1	5.40	8.33	13.38	17.42	18.74	13.22
AUW	8	4	D	27.4	6.43	9.39	13.88	17.40	19.81	14.48
AUW	9	5	E	19.9	6.06	9.09	14.02	17.92	19.19	13.53
AUW	10	55	A	88.3	6.82	9.63	15.48	19.81	20.00	18.13
AUW	11	56	B	26.1	4.55	6.83	11.37	14.86	14.44	8.79
AUW	12	57	C	28.9	4.57	6.83	11.18	14.41	15.16	10.23
AUW	13	58	D	39.2	4.67	6.64	9.98	12.75	14.83	10.46
AUW	14	59	E	27.3	4.59	6.69	10.60	13.58	13.81	8.49
AUW	15	60	A	27.7	5.77	8.52	13.71	17.80	15.33	9.81
AUW	16	61	B	23.5	5.35	8.05	13.52	17.16	14.65	8.51
AUW	17	62	C	28.0	4.85	7.56	12.97	16.33	15.38	9.82
AUW	18	63	D	36.0	5.11	7.92	12.80	15.85	16.84	12.25
AUW	19	64	E	21.4	4.70	7.20	11.94	14.98	15.54	9.42
AUW	20	6	A	26.5	5.89	7.64	10.35	15.35	17.62	11.16
AUW	21	7	B	26.3	5.62	7.72	10.98	14.71	14.42	8.80
AUW	22	8	C	27.3	5.29	7.47	11.05	14.70	16.14	10.66
AUW	23	9	D	31.2	6.10	7.94	10.80	13.93	16.92	12.82
AUW	24	10	E	19.3	5.34	7.43	10.74	14.60	18.47	13.87
AUW	25	11	A	32.5	7.66	10.14	13.77	17.89	19.90	12.98
AUW	26	12	B	33.8	7.05	9.48	13.23	17.39	19.13	12.28
AUW	27	13	C	27.8	6.81	9.53	13.60	17.88	21.39	15.52
AUW	28	14	D	33.6	9.75	13.19	17.72	22.17	25.45	18.72
AUW	29	15	E	33.4	7.02	9.40	12.98	16.91	18.40	11.88
AUW	30	65	A	18.4	5.20	7.39	11.53	16.87	18.55	11.37
AUW	31	66	B	23.4	5.36	8.16	13.67	17.59	14.42	8.50
AUW	32	67	C	22.6	5.46	8.62	14.37	18.03	18.02	12.43
AUW	33	69	E	20.2	5.32	7.87	12.47	15.56	15.43	10.06
AUW	34	85	A	75.3	8.62	12.07	16.39	21.81	17.01	9.25
AUW	35	86	B	29.8	8.79	12.63	18.41	23.88	23.36	14.50
AUW	36	87	C	43.8	8.78	12.69	18.75	24.77	24.25	14.80
AUW	37	88	D	47.3	11.12	15.52	22.07	28.49	27.43	16.71
AUW	38	89	E	42.7	9.59	13.35	18.86	24.27	21.78	12.34
AUW	39	50	A	56.9	6.33	9.32	15.16	18.98	15.11	10.28
AUW	41	52	C	45.0	6.02	9.03	15.27	19.72	17.34	13.07
AUW	42	54	E	45.2	6.25	9.29	15.55	19.98	15.52	10.99
AUW	43	17	B	22.9	5.67	7.67	11.03	14.81	16.91	11.84
AUW	44	18	C	22.7	5.65	8.64	13.50	17.73	22.78	18.29
AUW	45	19	D	33.1	6.50	8.51	11.76	14.91	17.70	13.31
AUW	46	20	E	21.1	5.43	7.75	11.67	15.96	20.89	16.54
AUW	47	70	A	21.5	6.26	9.23	13.82	17.81	18.04	11.99
AUW	48	71	B	27.4	5.98	8.69	13.43	17.36	15.85	9.66
AUW	49	72	C	21.4	5.79	9.12	15.00	19.63	22.36	17.23
AUW	50	73	D	34.5	6.11	9.27	14.48	19.07	22.76	17.58
AUW	51	74	E	21.7	7.59	11.53	16.57	22.60	25.15	16.24
AUW	52	21	A	34.7	6.22	8.54	12.30	16.59	18.88	12.80
AUW	53	22	B	31.1	6.04	8.30	12.05	15.88	17.56	12.60
AUW	54	23	C	28.7	6.20	8.87	13.31	17.35	18.76	13.58
AUW	55	24	D	35.4	7.01	9.48	13.31	16.56	17.82	13.70
AUW	56	25	E	24.1	6.34	8.98	13.10	16.72	18.69	14.46
AUW	57	75	A	34.3	5.39	7.78	12.91	16.87	16.30	14.25
AUW	58	76	B	36.2	5.19	7.71	13.00	17.07	16.58	14.36
AUW	59	77	C	21.7	6.98	9.85	15.93	20.63	20.16	18.20
AUW	60	78	D	26.2	6.75	9.88	14.91	19.32	19.53	13.03
AUW	61	79	E	30.8	5.36	7.73	12.78	16.48	15.68	13.67
AUW	62	27	B	23.2	7.05	9.36	12.55	15.57	14.09	9.33
AUW	63	28	C	26.9	6.89	9.39	12.68	15.49	16.76	11.73
AUW	64	29	D	80.3	6.71	8.99	12.32	15.72	19.01	14.16
AUW	65	30	E	20.0	6.10	8.07	10.80	13.54	14.63	10.49
AUW	66	31	A	51.4	34.24	41.35	46.92	48.51	14.74	4.66
AUW	67	32	B	54.0	37.21	44.46	49.81	51.74	17.12	5.73
AUW	68	33	C	52.3	37.08	43.68	48.74	50.81	22.43	9.12
AUW	69	35	E	51.9	33.90	40.45	46.06	48.76	17.24	5.50

Sep: Soil size separates: A = 500-2000um, B = 210 - 500um, C = 74 - 210um, D = <74um E = composite

Table 3. Oven dry soil samples: Soil water content and mean reflections in thematic mapper bands for soil samples and separates, Joranado Experimental Range, Las Cruces, NM.
Obtained by Melvin B. Satterwhite and J. Ponder Henley. U.S. Army Engin. Topo. Lab., Ft. Belvoir, VA 22060-5546

File Name		Index.No.	Sep	Water %	Thematic Mapper Bands					
					Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
					450-520	520-600	630-690	760-900	1550-1750	2080-2350
					wavelength in nanometers					
AUD	1	80	A	0	16.20	22.43	29.45	34.69	41.61	38.75
AUD	2	81	B	0	17.81	24.47	32.15	37.41	45.64	43.62
AUD	4	84	E	0	15.85	21.83	28.67	33.82	41.50	40.27
AUD	5	1	A	0	14.57	20.17	27.73	33.18	41.57	40.45
AUD	6	2	B	0	14.17	19.65	27.50	32.45	39.69	39.51
AUD	7	3	C	0	12.25	17.89	26.34	31.84	39.75	39.10
AUD	8	4	D	0	14.39	20.49	28.59	33.82	42.59	42.32
AUD	9	5	E	0	13.21	18.98	27.04	32.50	40.73	40.21
AUD	10	55	A	0	6.80	10.33	16.26	21.27	32.81	31.46
AUD	11	56	B	0	7.28	11.76	19.80	25.63	37.82	37.80
AUD	12	57	C	0	7.34	11.72	19.43	24.93	37.38	37.66
AUD	13	58	D	0	8.38	12.85	19.93	25.44	36.86	37.05
AUD	14	59	E	0	7.86	12.46	20.46	26.22	39.67	40.03
AUD	15	60	A	0	8.98	13.97	22.22	27.90	35.03	33.75
AUD	16	61	B	0	7.80	12.92	22.36	28.86	39.77	39.18
AUD	17	62	C	0	8.28	13.70	23.57	29.98	40.93	40.59
AUD	18	63	D	0	9.24	14.44	22.99	28.81	38.63	38.18
AUD	19	64	E	0	8.07	12.93	21.58	27.25	36.23	35.82
AUD	20	6	A	0	11.64	15.56	20.55	27.52	40.33	38.19
AUD	21	7	B	0	11.92	16.34	22.57	28.22	39.10	39.31
AUD	22	8	C	0	12.18	17.06	24.18	30.08	41.99	42.55
AUD	23	9	D	0	14.55	19.34	25.41	30.44	39.06	38.40
AUD	24	10	E	0	11.92	16.48	22.67	28.28	38.71	38.71
AUD	25	11	A	0	17.35	22.52	29.31	34.92	44.42	42.96
AUD	26	12	B	0	16.45	21.15	27.56	33.09	42.38	40.89
AUD	27	13	C	0	15.37	20.39	27.23	32.95	42.30	40.93
AUD	28	14	D	0	20.55	25.46	31.59	36.60	44.41	42.85
AUD	29	15	E	0	15.49	20.30	26.68	32.26	41.40	40.10
AUD	30	65	A	0	12.51	18.95	29.95	37.86	54.95	54.55
AUD	31	66	B	0	9.41	14.90	24.30	30.62	41.87	42.32
AUD	32	67	C	0	9.11	14.68	24.30	30.60	40.80	40.86
AUD	33	69	E	0	9.57	15.02	23.99	29.83	40.04	40.03
AUD	34	85	A	0	23.47	29.49	36.28	42.99	48.80	43.13
AUD	35	86	B	0	22.92	29.23	37.12	42.72	49.17	46.71
AUD	36	87	C	0	24.02	29.90	37.22	42.69	49.47	47.21
AUD	37	88	D	0	33.56	41.48	50.81	56.95	65.09	63.31
AUD	38	89	E	0	28.27	34.89	42.88	48.55	54.87	52.23
AUD	39	50	A	0	10.19	13.94	21.03	25.39	24.93	24.19
AUD	40	51	B	0	10.97	14.84	22.18	27.01	26.80	26.51
AUD	41	52	C	0	9.77	13.63	21.11	26.10	26.69	26.91
AUD	42	54	E	0	12.81	17.47	25.61	30.71	30.07	29.37
AUD	43	17	B	0	13.47	17.79	23.80	28.92	38.25	38.14
AUD	44	18	C	0	10.84	15.48	22.52	28.19	38.64	39.18
AUD	45	19	D	0	13.52	18.73	25.77	31.20	41.64	41.73
AUD	46	20	E	0	12.28	16.83	23.05	28.10	37.07	36.80
AUD	47	70	A	0	13.47	18.46	25.19	29.64	35.13	33.06
AUD	48	71	B	0	13.32	18.35	26.03	31.31	39.14	38.22
AUD	49	72	C	0	12.08	17.44	25.85	31.44	39.89	39.77
AUD	50	73	D	0	14.90	20.74	28.92	34.69	43.61	42.80
AUD	51	74	E	0	16.46	22.95	31.70	38.17	46.94	45.88
AUD	52	21	A	0	14.00	18.68	24.80	29.82	37.87	35.98
AUD	53	22	B	0	15.27	19.77	25.87	30.24	35.88	34.69
AUD	54	23	C	0	14.73	20.35	28.44	34.19	42.83	43.22
AUD	55	24	D	0	15.62	21.13	28.71	34.13	41.61	41.84
AUD	56	25	E	0	14.96	20.38	28.06	33.51	41.64	42.21
AUD	57	75	A	0	12.24	18.02	28.25	34.09	35.50	35.92
AUD	58	76	B	0	11.53	17.10	27.22	33.09	34.78	35.58
AUD	59	77	C	0	12.43	17.82	27.51	33.36	33.99	34.20
AUD	60	78	D	0	12.97	18.50	28.45	34.44	37.30	38.69
AUD	61	79	E	0	10.53	15.46	24.80	30.79	34.06	35.81
AUD	62	26	A	0	14.34	18.48	23.84	28.84	40.12	39.13
AUD	63	27	B	0	14.46	19.12	24.84	29.64	37.32	37.85
AUD	64	28	C	0	15.19	20.22	26.13	30.43	40.24	39.98
AUD	65	29	D	0	15.77	21.38	28.59	34.91	48.40	49.73
AUD	66	30	E	0	15.20	20.08	26.33	31.59	43.38	44.55
AUD	67	31	A	0	64.02	68.57	72.02	73.37	71.56	48.84
AUD	68	32	B	0	66.96	71.08	74.01	74.75	73.63	53.97
AUD	69	33	C	0	65.89	70.82	75.08	77.11	78.90	58.89
AUD	70	35	E	0	65.16	69.70	73.29	74.86	75.01	53.36

Sep: Soil size separates: A = 500-2000um, B = 210 - 500um, C = 74 - 210um, D = <74um E = composite

Table 3 (oven dry samples)

Soil Water Content and Mean Reflectance in Thematic Mapper Bands for Soil Samples and Separates, Jornada Experimental Range, Las Cruces, NM

File Name	Index No	Sep	Water %	Thematic Mapper Bands					
				band 1	band 2	band 3	band 4	band 5	band 7
				450-520	520-600	630-690	760-900	1550-1750	2080-2350
				wavelength in nanometers					
AUD 01	30	A	0 0	16 20	22 43	29 45	34 69	41 61	38 75
AUD 02	31	B	0 0	17 21	24 17	30 15	37 41	45 64	43 62
AUD 04	34	E	0 0	15 95	21 33	23 87	33 32	41 50	40 27
AUD 05	1	A	0 0	14 57	20 17	27 73	33 18	41 57	40 45
AUD 06	2	B	0 0	14 17	19 67	27 52	32 45	39 69	39 51
AUD 07	3	C	0 0	12 25	17 92	26 14	31 34	39 75	39 10
AUD 08	4	D	0 0	14 30	20 49	29 59	33 30	40 59	40 22
AUD 09	5	E	0 0	11 21	18 38	27 24	32 50	40 71	40 21
AUD 10	35	A	0 0	6 50	13 23	16 24	21 27	32 31	31 16
AUD 11	36	B	0 0	7 22	11 72	19 20	25 63	37 20	37 30
AUD 12	37	C	0 0	[illegible]	11 70	19 47	24 93	37 38	37 56
AUD 13	38	D	0 0	[illegible]	12 55	19 31	25 44	36 36	37 25
AUD 14	39	E	0 0	[illegible]	13 46	20 46	26 20	39 67	40 07
AUD 15	40	A	0 0	8 32	13 37	20 20	27 90	35 03	33 75
AUD 16	41	B	0 0	7 20	13 30	20 26	28 36	39 77	39 13
AUD 17	42	C	0 0	8 23	13 70	23 57	30 98	40 93	40 59
AUD 18	43	D	0 0	7 24	[illegible] 44	20 70	28 81	38 63	38 13
AUD 19	44	E	0 0	8 17	12 37	21 52	27 35	36 23	35 32
AUD 20	6	A	0 0	[illegible]	17 36	20 35	27 52	40 33	38 19
AUD 21	7	B	0 0	11 20	15 34	20 57	28 02	39 10	39 31
AUD 22	8	C	0 0	12 19	17 28	24 13	30 03	11 99	42 55
AUD 23	9	D	0 0	14 55	19 34	25 41	30 44	39 06	38 40
AUD 24	10	E	0 0	[illegible] 02	16 18	22 67	28 28	38 71	38 71
AUD 25	11	A	0 0	17 25	22 50	29 11	34 92	44 40	42 96
AUD 26	12	B	0 0	16 12	21 15	27 56	33 09	42 38	40 39
AUD 27	13	C	0 0	17 37	20 19	27 23	32 05	42 30	40 93
AUD 28	14	D	0 0	[illegible] 30	25 46	[illegible] 59	36 60	44 41	42 35
AUD 29	15	E	0 0	17 40	20 20	[illegible] 62	32 28	41 40	40 10
AUD 30	55	A	0 0	11 15	18 93	29 05	37 36	54 95	54 55
AUD 31	56	B	0 0	9 41	14 90	24 [illegible]	30 60	41 37	42 32
AUD 32	57	C	0 0	9 11	14 68	24 [illegible]	30 50	40 30	40 36
AUD 33	59	E	0 0	9 77	15 22	23 39	29 33	40 04	40 03
AUD 34	45	A	0 0	33 17	20 49	36 28	12 99	48 30	43 13
AUD 35	46	B	0 0	22 32	29 23	37 12	42 72	49 17	46 71
AUD 36	47	C	0 0	21 00	29 90	37 22	[illegible] 69	49 47	47 21
AUD 37	48	D	0 0	23 56	41 48	30 91	55 95	65 03	63 31
AUD 38	49	E	0 0	28 27	34 89	40 29	43 55	51 37	52 23
AUD 39	50	A	0 0	10 19	13 34	21 09	45 69	24 93	24 19
AUD 40	51	B	0 0	10 37	14 24	22 16	37 04	26 30	26 51
AUD 41	52	C	0 0	9 77	13 62	21 11	[illegible] 10	26 69	26 91
AUD 42	54	E	0 0	11 31	17 47	25 41	30 71	30 07	20 37
AUD 43	17	B	0 0	13 47	17 79	23 30	28 92	38 25	38 14
AUD 44	18	C	0 0	10 34	[illegible] 48	22 32	28 19	38 64	39 18
AUD 45	19	D	0 0	13 52	[illegible] 73	25 77	31 20	41 64	41 73
AUD 46	20	E	0 0	12 28	16 33	23 65	28 10	37 07	36 80
AUD 47	70	A	0 0	13 47	13 46	25 19	29 94	35 13	33 06
AUD 48	71	B	0 0	[illegible] 22	13 37	26 03	31 21	30 14	38 22
AUD 49	72	C	0 0	12 08	17 44	25 25	31 44	39 39	39 77
AUD 50	73	D	0 0	14 30	20 74	28 92	34 69	43 61	42 84
AUD 51	74	E	0 0	15 46	22 95	31 70	33 17	46 94	45 38
AUD 52	21	A	0 0	11 [illegible]	19 68	24 90	20 82	37 87	35 09
AUD 53	22	B	0 0	15 [illegible]	19 77	25 27	30 24	35 38	34 69
AUD 54	23	C	0 0	14 [illegible]	27 33	28 44	34 19	40 33	43 22
AUD 55	24	D	0 0	[illegible]	[illegible]	28 71	34 13	41 61	41 84
AUD 56	25	E	0 0	[illegible]	[illegible]	28 26	33 51	41 64	42 21
AUD 57	[illegible]	A	[illegible]	[illegible]	[illegible]	29 25	34 29	35 50	35 92
AUD 58	[illegible]	B	[illegible]	[illegible]	[illegible]	27 22	33 09	31 73	35 59
AUD 59	[illegible]	C	[illegible]	[illegible]	[illegible]	27 51	33 36	30 39	34 20
AUD 60	[illegible]	D	[illegible]	[illegible]	[illegible]	23 45	34 14	37 30	38 63
AUD 61	[illegible]	E	[illegible]	[illegible]	[illegible]	24 30	30 73	34 36	35 81
AUD 62	26	A	[illegible]	[illegible]	[illegible]	21 84	28 94	40 12	30 11
AUD 63	27	B	[illegible]	[illegible]	[illegible]	21 14	20 64	17 22	17 35
AUD 64	28	C	[illegible]	[illegible]	[illegible]	20 13	20 41	40 34	30 33
AUD 65	29	D	[illegible]	[illegible]	[illegible]	22 53	24 31	42 40	48 73
AUD 66	30	E	[illegible]	[illegible]	[illegible]	22 11	21 73	43 38	44 55
AUD 67	31	A	[illegible]	14 22	[illegible]	72 22	73 17	71 50	48 94
AUD 68	32	B	[illegible]	[illegible]	71 38	74 01	71 75	73 63	53 97
AUD 69	33	C	0 0	[illegible]	[illegible]	75 08	77 11	73 90	58 59
AUD 70	[illegible]	E	[illegible]	[illegible]	[illegible]	73 20	71 36	75 01	53 36

Sep = A [illegible] um B [illegible]

AIR DRY SOILS

Soil Water Content and Mean Reflectance in Thematic Mapper Bands

Soil No.	Sieve Separate	Water (%)	Thematic Mapper Bands					
			band 1	band 2	band 3	band 4	band 5	band
			450-520	520-600	630-690	760-900	1550-1750	2080-2
			wavelength in nanometers					
1	5	2.40	18.25	25.26	33.63	39.77	49.88	48.29
2	5	0.80	14.63	20.53	28.98	34.94	45.14	44.14
3	5	0.80	7.32	11.51	19.07	24.79	35.83	34.70
4	5	0.80	7.95	12.94	22.22	28.39	38.32	37.36
5	5	0.90	13.22	17.92	24.31	30.19	40.65	39.84
6	5	2.40	18.10	23.01	29.44	35.30	44.82	43.13
7	5	0.50	10.14	15.94	25.70	32.34	43.50	43.08
8	5	7.60	23.02	30.39	40.19	47.75	55.95	47.66
9	5	5.20	8.82	11.63	17.07	20.54	18.71	16.77
10	5	1.00	13.15	17.91	24.69	30.36	41.03	41.31
11	5	1.30	14.09	19.02	26.69	31.99	41.27	41.04
12	5	1.30	15.02	20.32	27.82	33.61	41.53	40.76
13	5	2.90	11.18	17.07	27.97	35.10	39.84	41.78
14	5	0.70	14.37	18.68	23.97	28.78	36.91	36.43
15	5	24.30	52.41	60.76	67.62	70.79	46.08	14.42

Sieve separates; 1= 500-2000u, 2= 210-500u, 3= 74-210u, 4= <74u and
5= composite sample

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AIR DRY SOILS

TABLE

Ratios of Mean Reflectance Values in Thematic Mapper Bands(1-5, & 7)

Soil No.	2/1	3/1	4/1	5/1	7/1	3/2	4/2	5/2	7/2	4/3	5/3	7/3	5/4	7/4	7/
1	1.38	1.84	2.18	2.73	2.65	1.33	1.57	1.97	1.91	1.18	1.48	1.44	1.25	1.21	1.
2	1.40	1.98	2.39	3.09	3.02	1.41	1.70	2.20	2.15	1.21	1.56	1.52	1.29	1.26	1.
3	1.57	2.61	3.39	4.89	4.74	1.66	2.15	3.11	3.01	1.30	1.83	1.82	1.45	1.40	1.
4	1.63	2.79	3.57	4.82	4.70	1.72	2.19	2.96	2.89	1.28	1.72	1.68	1.35	1.32	1.
5	1.36	1.84	2.28	3.07	3.01	1.36	1.68	2.27	2.22	1.24	1.67	1.64	1.35	1.32	1.
6	1.27	1.63	1.95	2.48	2.38	1.28	1.53	1.95	1.87	1.20	1.52	1.47	1.27	1.22	1.
7	1.57	2.53	3.19	4.29	4.25	1.61	2.03	2.73	2.70	1.26	1.69	1.68	1.35	1.33	1.
8	1.32	1.75	2.07	2.43	2.07	1.32	1.57	1.84	1.57	1.19	1.39	1.19	1.17	1.00	0.
9	1.32	1.94	2.33	2.12	1.90	1.47	1.77	1.61	1.44	1.20	1.10	0.98	0.91	0.82	0.
10	1.36	1.88	2.31	3.12	3.14	1.38	1.70	2.29	2.31	1.23	1.66	1.67	1.35	1.36	1.0
11	1.35	1.89	2.27	2.93	2.91	1.40	1.68	2.17	2.16	1.20	1.55	1.54	1.29	1.28	1.0
12	1.35	1.85	2.24	2.76	2.71	1.37	1.65	2.04	2.01	1.21	1.49	1.47	1.24	1.21	1.0
13	1.53	2.50	3.14	3.56	3.74	1.64	2.06	2.33	2.45	1.25	1.42	1.49	1.14	1.19	1.0
14	1.30	1.67	2.00	2.57	2.54	1.28	1.54	1.98	1.95	1.20	1.54	1.52	1.28	1.27	1.0
15	1.16	1.29	1.35	0.88	0.28	1.11	1.17	0.76	0.24	1.05	0.68	0.21	0.65	0.20	0.3

AIR DRY SOILS

TABLE

Kauth-Thomass Transformation of 6 Band Thematic Mapper Data

Soil No.	Sieve Separate	Water (%)	Brightness	Greenness	Wetness
1	5	2.4	91.39	3.19	-2.18
2	5	0.8	81.33	2.31	-2.99
3	5	0.8	60.28	0.82	-4.45
4	5	0.8	66.17	1.76	-3.63
5	5	0.9	72.03	1.56	-4.00
6	5	2.4	81.77	2.85	-2.38
7	5	0.5	76.12	1.65	-4.35
8	5	7.6	101.47	8.07	3.12
9	5	5.2	38.02	5.03	3.08
10	5	1.0	73.32	0.98	-4.56
11	5	1.3	74.99	1.81	-3.02
12	5	1.3	76.40	2.92	-2.16
13	5	2.9	75.66	3.73	-2.40
14	5	0.7	67.56	1.82	-2.69
15	5	24.3	104.90	31.77	38.70

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1760 '         Kauth-Thomass Coeff.  SAND sun/shaded/mesquite/wet
1770  DATA .1177,.2050,.3462,.41560,.5374,.6023
1730  DATA -.0002,-.0101,-.3309, .8501,.0107,-.4094
1790  DATA  .0407,-.1863,.7623,.0001, .1109,-.6085
1791 '
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AIR DRY SOILS

TABLE

Kauth-Thomass Transformation of 6 Band Thematic Mapper Data

Soil No.	Sieve Separate	Water (%)	Brightness	Greenness	Wetness
1	5	2.4	82.34	-2.05	-41.00
2	5	0.8	71.86	-1.08	-38.52
3	5	0.8	50.23	0.83	-33.16
4	5	0.8	56.15	1.25	-34.62
5	5	0.9	62.79	-0.96	-35.61
6	5	3.4	73.73	-2.13	-36.87
7	5	0.5	64.97	0.64	-39.26
8	5	7.6	95.41	-1.08	-40.25
9	5	5.2	37.57	0.77	-11.78
10	5	1.0	63.53	-1.21	-36.63
11	5	1.3	66.24	-1.33	-35.49
12	5	1.3	68.54	-1.08	-34.60
13	5	2.9	67.05	1.42	-34.57
14	5	0.7	60.39	-1.82	-31.13
15	5	24.3	131.68	-4.78	6.02

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1791 '
1795 '          Kauth-Thomass Coeff   Crist (1985) RSE 17:1301-1306
1796  DATA .2043,.4158,.5524,.5741 ,.3124,.2303
1797  DATA -.1603,-.2819,-.4934, .7940,-.0002,-.1446
1798  DATA  .0315, .2021,.3102,.1594,-.6806,-.6109
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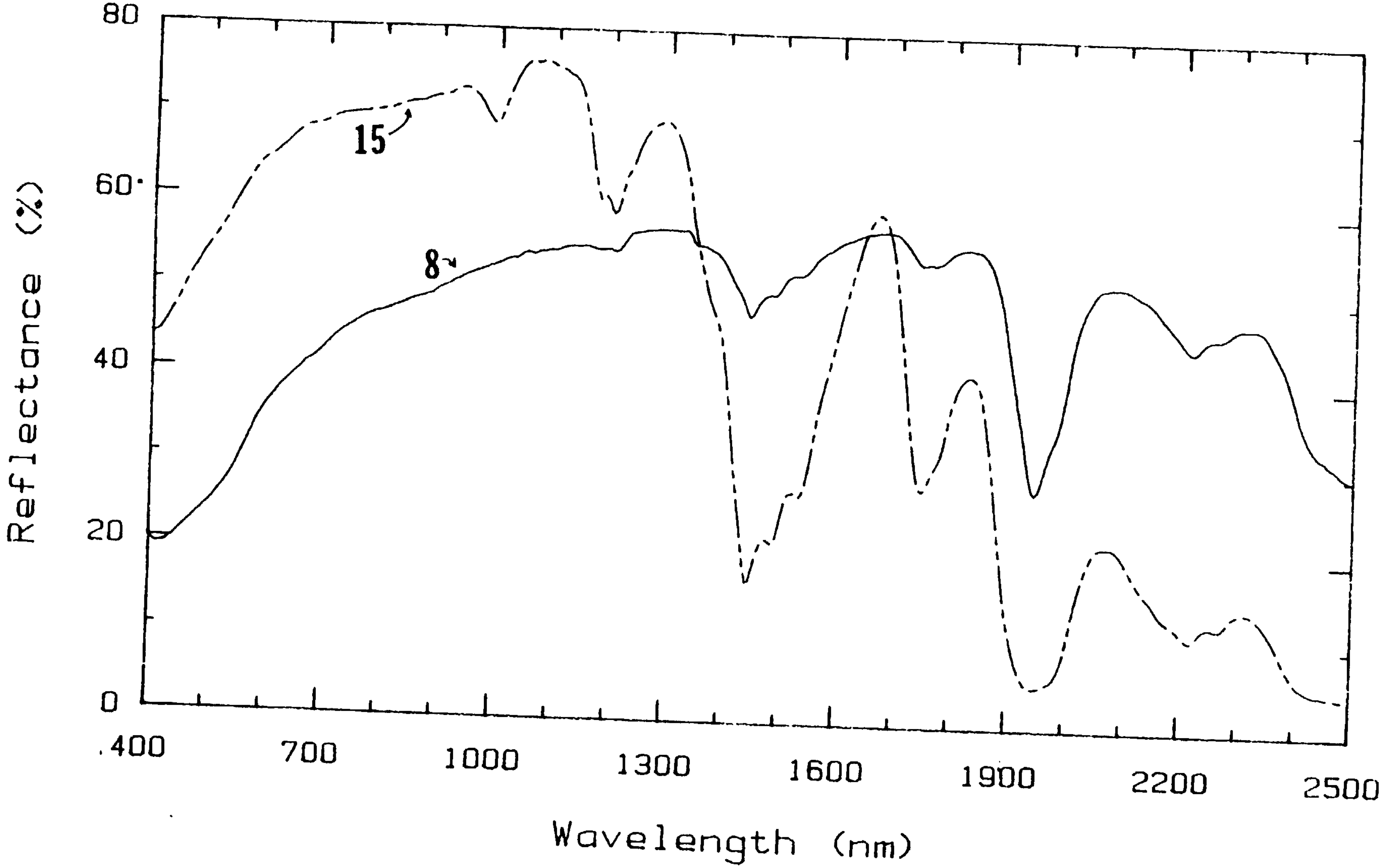

Figure 1. Reflectance Spectra of Air Dried, Very Gypsiferous Soils

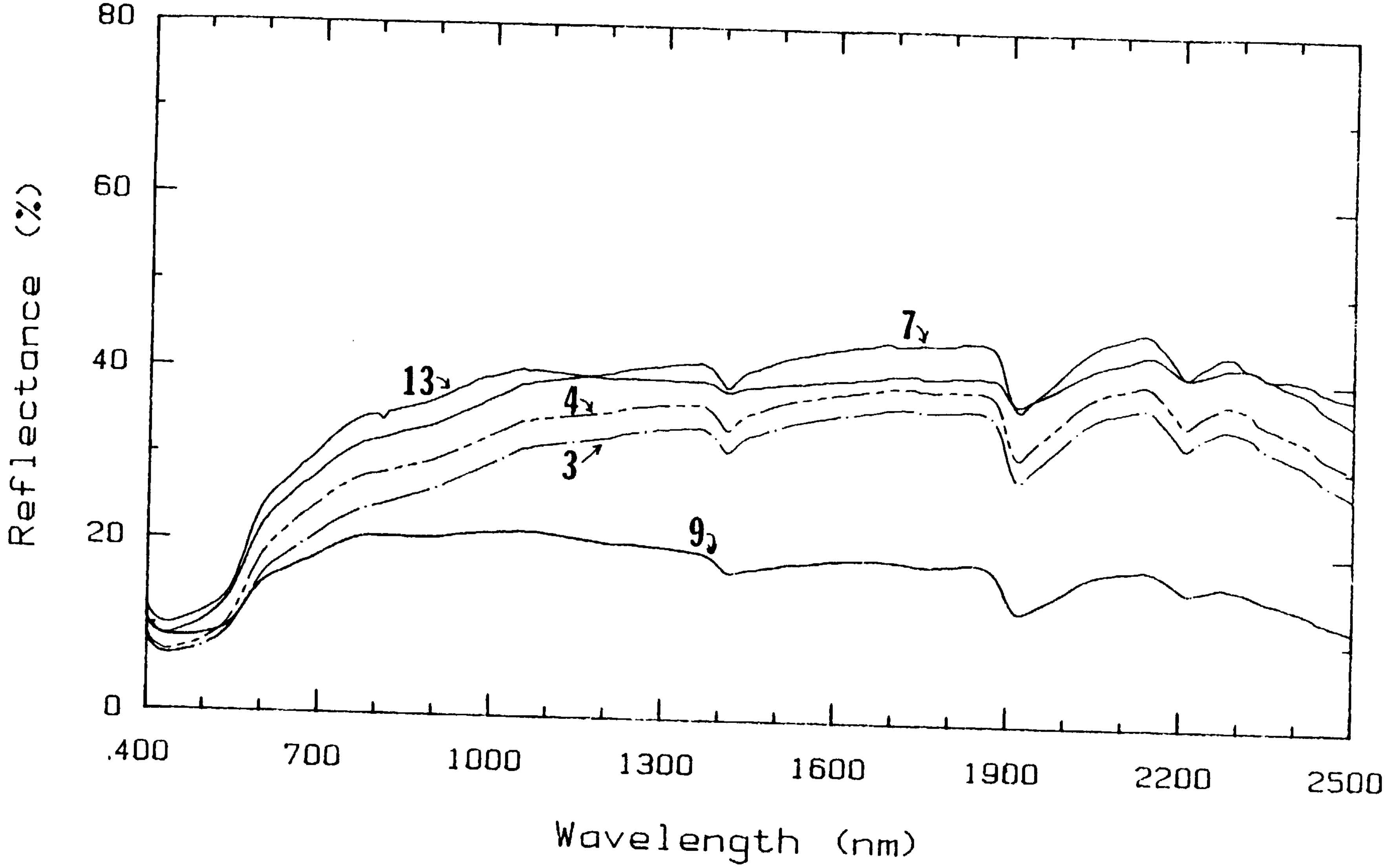

Figure 2. Reflectance Spectra of Air Dried, Ferruginous Soils

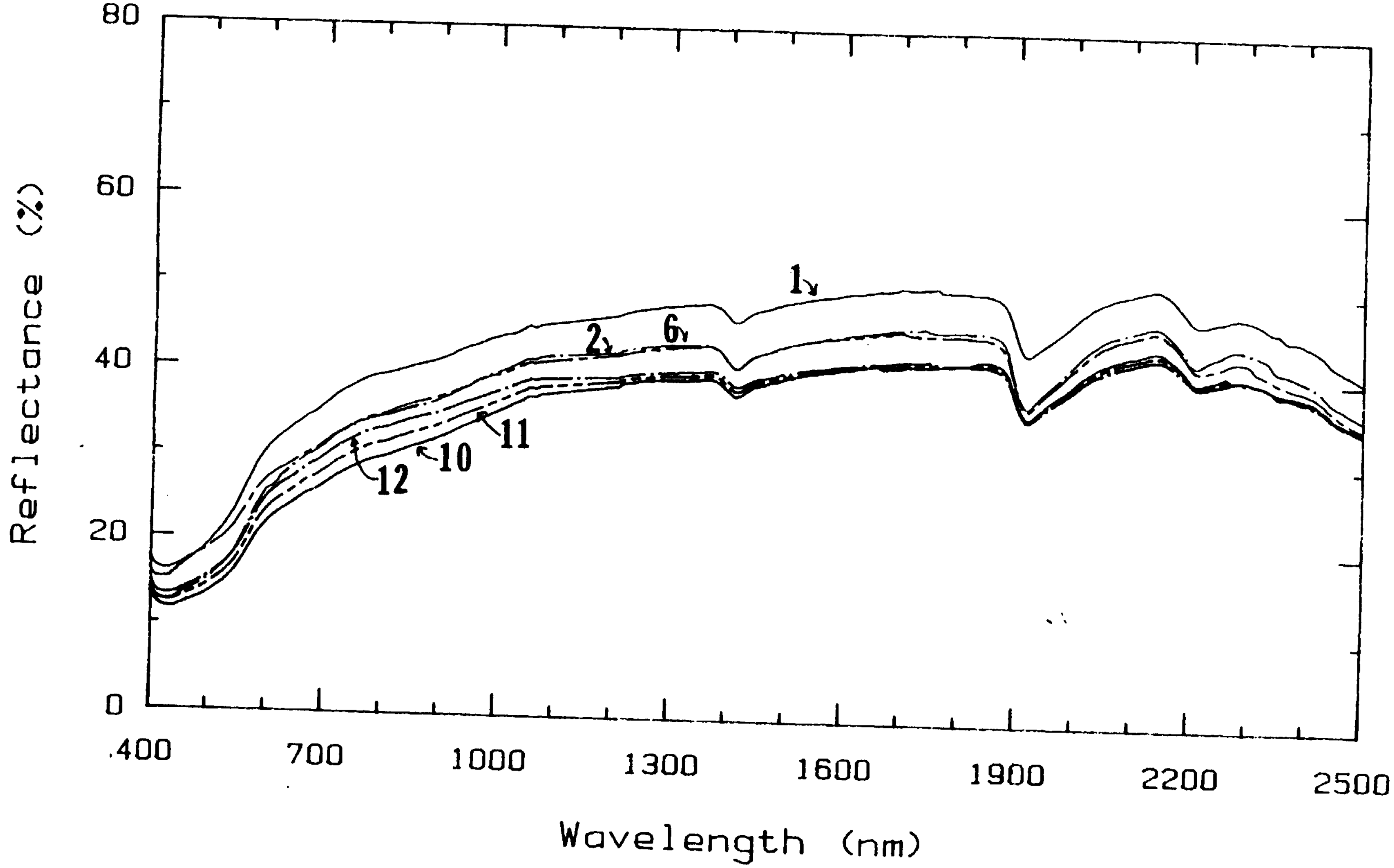

Figure 3. Reflectance Spectra of Air Dried, Very Calcareous Soils

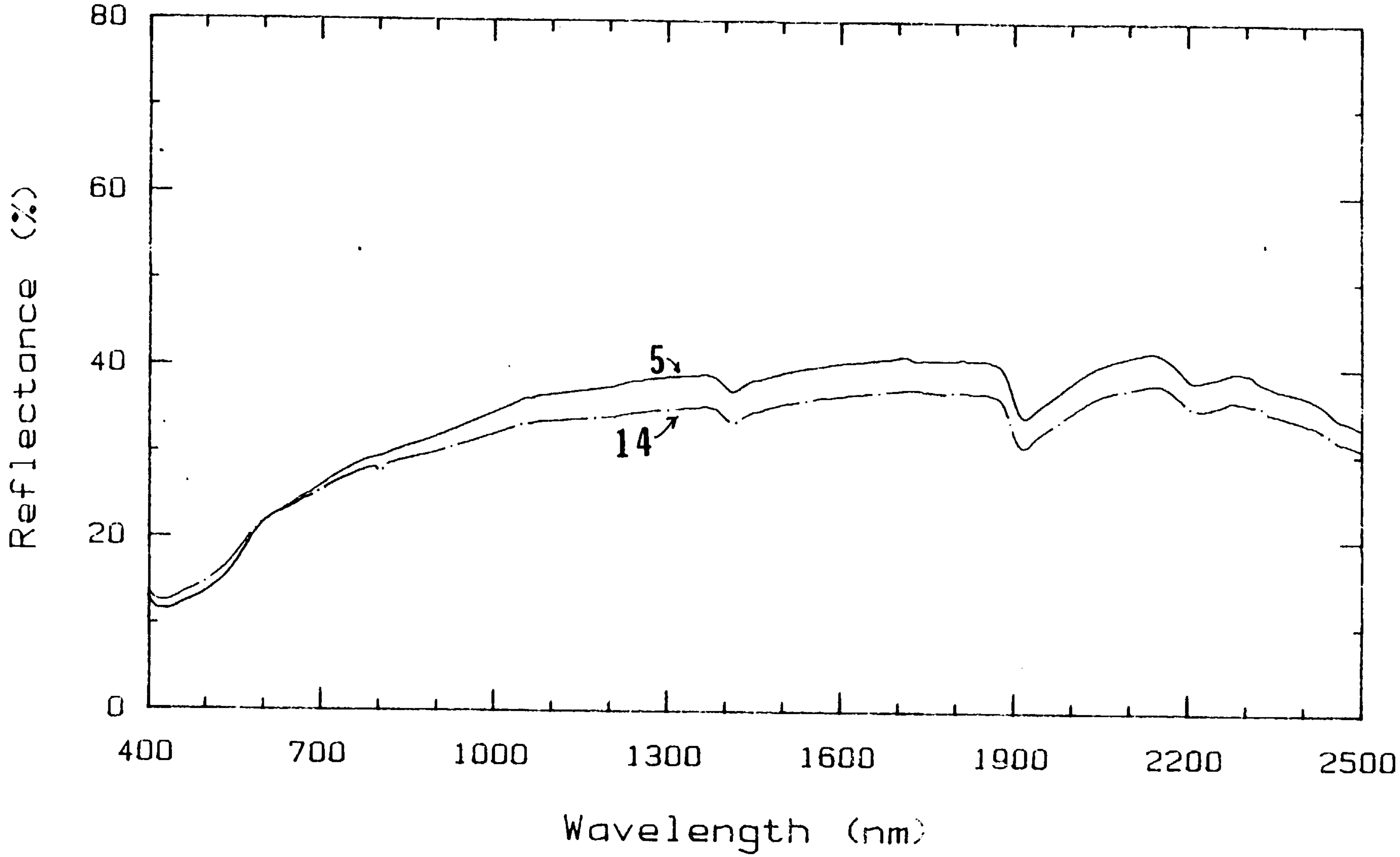

Figure 4. Reflectance Spectra of Air Dried, Slighly Calcareous Soils

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Estimating Soil Parameters and Sample Size by Bootstrapping

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Estimating Soil Parameters and Sample Size by Bootstrapping[1]

J. H. DANE, R. B. REED, AND J. W. HOPMANS[2]

ABSTRACT

Collecting large numbers of soil samples (observations) to estimate parameters of certain soil properties is not always feasible, especially for undisturbed soil samples. If the number of soil samples is small, however, the usefulness of classical statistics is often limited and an alternative procedure is required to determine statistics of interest. A recently developed, computer-intensive, statistical procedure; bootstrapping, is discussed for two bulk density applications for which relatively small numbers of observations were obtained. Bulk density was determined at 16 depths along 1.2-m long soil cores taken at each of 60 locations in a 50- by 100-m cultivated field (Norfolk sandy loam, Typic Paleudults). Initially, 16 locations were sampled. At a later date, the additional 44 locations were sampled at similar soil-water conditions. For each core, bulk density was determined at 0.20-, 0.40-, 0.60-, 0.80-, and 1.00-m depths by a paraffin technique and at 0.14-, 0.26-, 0.34-, 0.46-, 0.54-, 0.66-, 0.74-, 0.86-, 0.94-, 1.06-, and 1.14-m depths by a direct method. Semivariograms, determined for each depth, generally showed no evidence of spatial interdependence between locations. Additional statistical tests indicated that the samples for the two dates came from different populations. Bootstrapping was used to determine confidence intervals for the population mean, variance, and range by sampling date without a priori assumptions as to the distribution of bulk density in the population. Bootstrapping was further used to develop a general method for determining the minimum sample size (minimum number of observations) that can be used to estimate the population mean with a selected degree of precision and level of confidence. Application of the bootstrap method indicated not only differences in bulk density on the two sampling dates but also differences in the precision of the bulk density measurement techniques.

Additional Index Words: **spatial variability, temporal variability, semivariogram, bulk density, confidence intervals, mean, variance, range, kriging.**

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WITH INCREASED INTEREST in spatial variability by agricultural scientists, the statistical method, kriging, has been experimented with as a tool for predicting soil property values at unrecorded places (Journel and Huijbregts, 1978; Matheron, 1971; Clark, 1982). The utility of the method depends in part, however, on the accuracy of the *semivariogram*, a measure of spatial interdependence for the property.

Regardless of spatial interdependency, statistics such as the mean, variance, and range provide valuable information about a given property. Such statistics are, however, of limited value without associated measures of reliability. Most statistical methods in current use generate these reliability estimates from theoretical considerations of the pertinent sampling distributions. Often these considerations are based on unverified and/or unverifiable assumptions as to the distribution of the variable in the population. Further, since these same methods were generally developed prior to the advent of modern computers, they tend to focus only on those statistics that can be dealt with analytically.

Recently, computer-intensive methods have been developed, which can be used for virtually any statistic of interest and do not require a priori assumptions as to the distribution of the variable in the population. In this study, one of these methods, the bootstrap (Efron, 1979; 1982; Diaconis and Efron, 1983; Efron and Gong, 1983) was applied, to (i) develop sampling distributions for the mean, variance, and range of bulk density in a cultivated field, and (ii) determine the minimum sample size required to estimate mean bulk density with a given precision and level of confidence. Some consequences of temporally disjoint sampling for bulk density are also presented.

MATERIALS AND METHODS

A 50- by 100-m field was divided into 16 equal blocks (12.5 by 25 m) with the sample location at the center of each block. The soil was classified as a Norfolk sandy loam (Typic Paleudults). In November 1982, undisturbed 1.2-m long soil cores with a diameter of approximately 50 mm were extracted from each block with a hydraulic sampler mounted on the back of a pickup truck. Samples from these 16 locations comprised the first data set.

The additional 44 locations were sampled in May 1984 when in-situ soil-water conditions, as determined with the neutron probe, were similar to those in November 1982. Water content values at time of sampling ranged from about 0.125 at the 0.20-m depth to about 0.250 at the 1.00-m depth. Samples from these 44 locations comprised the second data set. To determine the additional sampling locations (Fig. 1), the existing 16 points (solid circles) were connected to form a network of triangles (solid lines), each with two sides of 14 m and one side of 12.5 m. A random process was then used to assign sampling locations to the midpoint of a tri-

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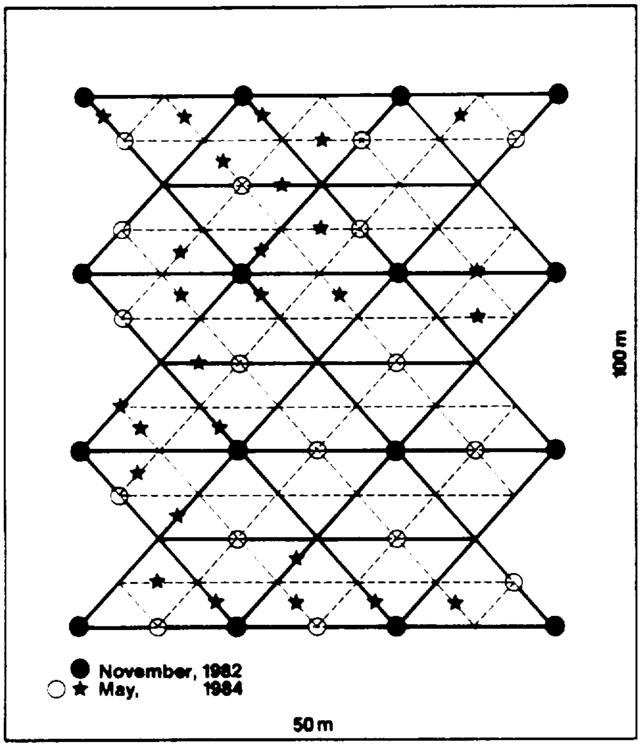

Fig. 1. Sampling scheme. Solid circles refer to sampling sites of the first 16 locations (first data set), open circles and stars to the additional 44 locations (second data set).

angle side in such a manner that each triangle had a single sampling location. If the sampling position was located on a side common to an adjacent triangle it sufficed for both triangles. Nineteen locations (open circles) were selected by this procedure. Each triangle was then subdivided into four equal triangles having two sides of 7 m and one side of 6.25 m. The remaining 25 locations (stars) were randomly allocated to the midpoints of the sides of the smaller triangles (Fig. 1). The purpose of this sampling scheme was to attain a degree of randomness while simultaneously obtaining large numbers of pairs for given lag distances to check for spatial interdependency of soil properties by means of semivariograms (Burgess and Webster, 1980).

The undisturbed cores were sliced into soil samples with an approximate height of either 50 or 75 mm. The vertical midpoints of the 50-mm long samples were taken at 0.20-, 0.40-, 0.60-, 0.80-, and 1.00-m depths, while those of the 75-mm long samples were taken at 0.14-, 0.26-, 0.34-, 0.46-, 0.54-, 0.66-, 0.74-, 0.86-, 0.94-, 1.06-, and 1.14-m depths. Bulk densities of the 50-mm long samples were determined as outlined by Blake (1969), except that complete cylindrical samples rather than soil clods were coated with paraffin. The 75-mm long samples were placed inside metal cylinders with an inside diameter of 53.5 mm and a height of 60 mm. The gap between soil sample and cylinder was filled with paraffin and both ends of each soil sample were shaved off to obtain 60-mm long soil samples. Bulk density values could thus be obtained from direct measurements of height and diameter, using a caliper with a precision of 0.05 mm, and the mass of soil determined at the end of water-retention determinations with Tempe pressure cells (Tanner and Elrick, 1958). The 50-mm long samples were also used to determine calibration curves for the neutron probe. Bulk densities obtained by the paraffin and the direct methods were treated independently during statistical analyses.

The core was discarded if >2% compaction occurred over the total length of the 1.2-m long core during sampling (determined from the difference in height between the soil surface inside and outside the soil sampling tube). Some samples were destroyed while taking laboratory measurements. Therefore, in certain instances the maximum sample number (N) by depth was <16 and 44 for the first (November 1982) and second (May 1984) data set, respectively.

Applications of Bootstrapping

Case I: Confidence Intervals by Bootstrapping

Bootstrapping is a statistical technique in which "true" sampling distributions for a statistic are simulated through repeated sampling from an empirical cumulative distribution function (cdf), i.e., one determined by the sample observations. The resultant simulated sampling distribution is generally a good approximation of the true sampling distribution (Kimura and Balsiger, 1985), and can thus be used to estimate confidence intervals for the statistic (Efron and Gong, 1983). This method of determining confidence intervals has several advantages over more conventional parametric methods: (i) no assumptions are made as to the nature of the cdf in the population being sampled, or to the form of the sampling distribution of the statistic, so the method is general, (ii) the sampling distribution of the statistic is determined directly from the sample data so mathematical complexity is not a limiting factor, and (iii) the complexities of the sampling scheme need not be explicitly accounted for, as in a parametric analysis, since they are inherent in the empirical cdf from which the sampling distribution is determined.

The construction of a bootstrap sampling distribution for a statistic is done as follows.

1. B random samples of size N are drawn with replacement from the N available observations. Each sample comprises a bootstrap replicate.
2. For each bootstrap replicate, the statistic of interest is calculated.
3. A frequency histogram is plotted of the B values of the statistic.

For each data set and depth combination, $B = 5000$ bootstrap replicates were generated and frequency histograms plotted for the means, variances, and ranges. Confidence limits for the statistics were determined empirically as the end points of the central (in terms of the median) $(1 - \alpha)$ 100% region of the distribution.

Case II: Estimates of Minimum Sample Size by Bootstrapping

When observations constitute a random sample from a population with a normal distribution, it is relatively simple to calculate the minimum sample size (Warrick and Nielsen, 1980) needed to estimate the population mean, given specified conditions for the estimator. However, such methods are unsuited when the distribution of the population being sampled is nonnormal or of unknown form. A variation of the bootstrap technique was applied to determine the minimum sample size required to estimate the mean bulk density.

The following procedure was carried out independently for each combination of data set and depth. Bootstrap replicates of sizes $B = 2, 3, \ldots N$ were generated 800 times, and the mean for each replicate calculated. For each value of B, the fraction of the 800 replicates having means within a given percentage of the mean for the N observations was calculated. A segmented function of the form

$$\begin{aligned} Y &= a + bX + cX^2, & X &< X_0 \\ Y &= d, & X &\geq X_0 \end{aligned}$$

was fit through the fractions, where Y = fraction of

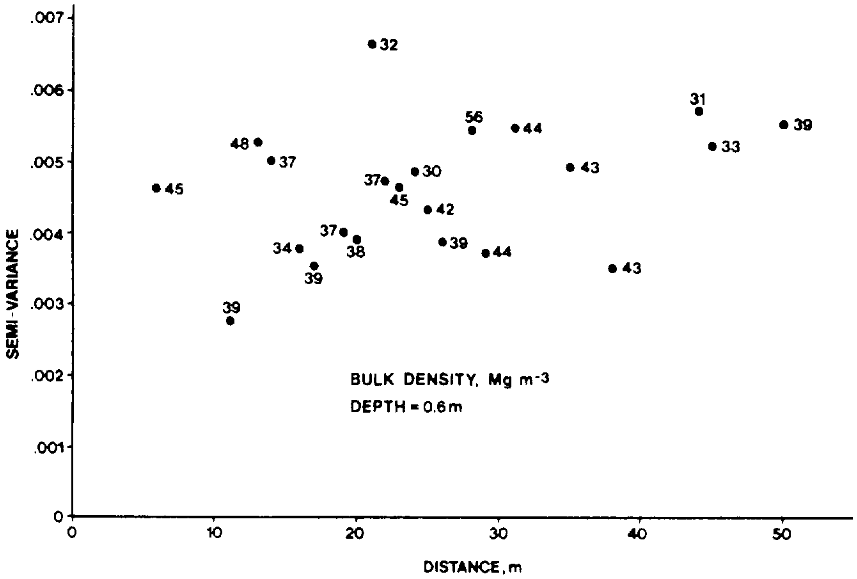

Fig. 2. Nondirectional semivariogram for bulk density values of all 60 locations at a depth of 0.6 m. The number adjacent to each data point indicates the number of pairs from which the semivariance was calculated.

800 bootstrap replicates having means within the specified percentage of the mean for the N observations, X = bootstrap sample size, i.e., 2, 3, . . .N, and a, b, c, and d are constants. The join-point of the curve segments (X_0) was taken as the minimum sample size required (fraction within maximum error stabilized).

RESULTS AND DISCUSSION

The construction of semivariograms requires large numbers of pairs at given lag distances. The bulk density values for both data sets (16 and 44 locations for November 1982 and May 1984, respectively) were, therefore, combined by depth. Lag distances were grouped into 0.5-m intervals over distances from 3 to 50 m. Nondirectional semivariograms were calculated for each depth. An example is presented in Fig. 2 for the 0.6-m depth, where each semivariance was calculated from at least 30 pairs (the number of pairs for the different distances are indicated in the figure). Since no variance structure was apparent, directional semivariograms were subsequently determined in the longitudinal and lateral directions. If the direction of the line connecting any two points differed <5° from the longitudinal or lateral direction, these pairs were included in the calculations for the respective semivariograms (Clark, 1982). The longitudinal direction had 16 lag distances (ranging from 13–50 m), with the number of pairs varying from 16 to 23, whereas in the lateral direction only two distances existed (6 and 13 m) with sufficient numbers of pairs (19 and 21, respectively) to justify some confidence in the semivariance values. All directional semivariances were, however, of the same magnitude as those shown in Fig. 2, and no variance structures seemed to be present. Results similar to those shown in Fig. 2 were obtained for all other depths.

It was initially assumed that bulk density data sets should belong to the same population, even though sampled on different dates but during similar soil water conditions, and could therefore be combined to calculate semivariograms. However, differences between the 16 and 44 soil-core data sets were revealed during additional statistical analyses (Table 1). This raised the question of the legitimacy of combining the two data sets.

Evidence of lack of normality was observed for sample populations from several depths and for both sets (Fig. 3a; Table 1, Kolmogorov-Smirnov test, $P < 0.05$). Means for the two data sets differed at the 0.2-m depth (t-test, $P < 0.0002$), while the variances differed at the 0.4-m depth (F-test, $P < 0.0083$). Though these latter two tests assume normality, conclusions about the parameters were not expected to be altered by the nonnormality observed (Scheffe, 1959). Combining data sets would only be justified if they have the same distribution.

Frequency distributions obtained with bootstrapping are presented for the 0.6-m depth of the second

Table 1. Bulk density (Mg m^{-3}) information obtained by the paraffin method for two sample sizes (N).

					Equality	
N	Mean	Range	Variance	Normality†	Mean‡	Variance§
				Depth = 0.2 m		
15	1.70	1.61–1.79	0.00300	Yes (0.63)¶	No (0.0002)	Yes (1.0000)
43	1.63	1.41–1.73	0.00300	No (0.01)		
				Depth = 0.4 m		
16	1.72	1.66–1.76	0.00120	Yes (0.08)	Yes (0.061)	No (0.0083)
43	1.69	1.55–1.89	0.00443	Yes (0.71)		
				Depth = 0.6 m		
16	1.74	1.61–1.83	0.00327	Yes (0.27)	Yes (0.38)	Yes (0.33)
43	1.72	1.53–1.81	0.00500	No (0.01)		
				Depth = 0.8 m		
16	1.77	1.62–1.84	0.00328	No (0.027)	Yes (0.35)	Yes (0.065)
43	1.80	1.66–1.90	0.00227	No (0.018)		
				Depth = 1.0 m		
16	1.78	1.72–1.85	0.00192	Yes (0.15)	Yes (0.28)	Yes (0.100)
43	1.81	1.61–1.93	0.00323	No (0.043)		

† Kolmogorov-Smirnov test.
‡ t-test.
§ F-test.
¶ Test probabilities in parentheses.

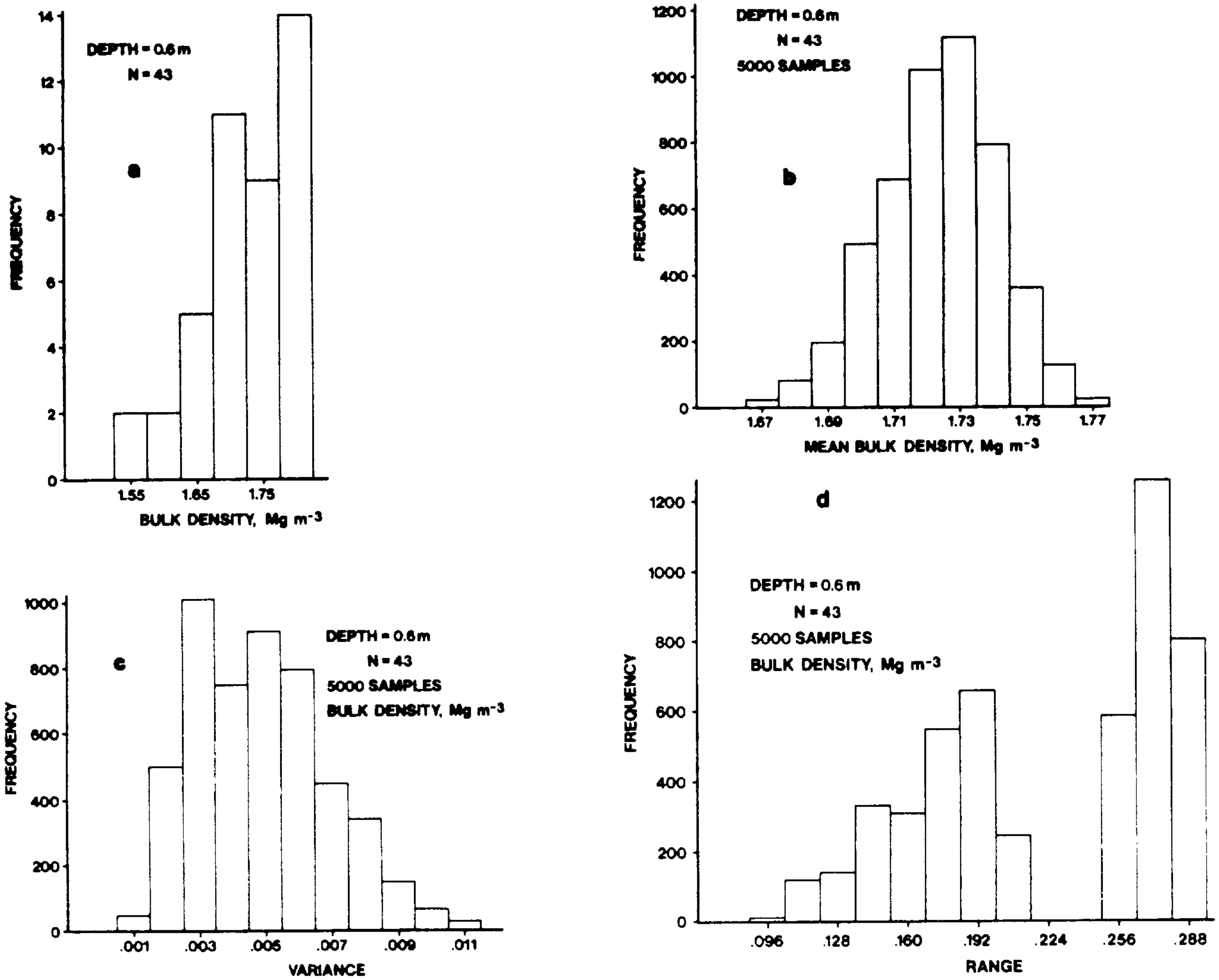

Fig. 3. Frequency distributions for bulk density based on of 43 observations (a), for 5000 bulk density bootstrap sample means (b), for 5000 bulk density bootstrap sample variances (c), and for 5000 bulk density bootstrap sample ranges (d).

(May 1984) data set in Fig. 3a, b, and c for the mean, variance, and range, respectively. As expected from the central limit theory, the mean bulk density shows a normal sampling distribution, while the variance resembles a χ^2-distribution. The range shows a rather peculiar gap in the distribution, which can be explained as follows. If no bulk density values in the original data set exist such that the difference between them is equal to one of the selected intervals of the range frequency distribution, then no such range values can be expected to occur in the bootstrap replicates. Moreover, even if a few such values do exist in the original data set, they do not necessarily make up the extreme values (ranges) in the bootstrap replicates. The presented frequency distributions resulted in estimated values for the mean of the means and the mean variance of 1.72 and 0.005, respectively. The corresponding approximate confidence intervals at the 95% level extended from 1.686 to 1.757 for the mean, and from 0.0017 to 0.0092 for the variance. The fact that the mean of the means and the mean variance are the same as the values listed for the mean and variance in Table 1 (0.6-m depth), shows that the bootstrap sampling distributions are unbiased.

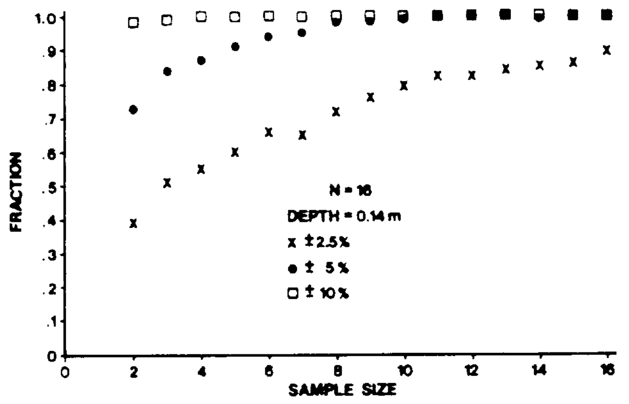

Fig. 4. Fraction of samples within the indicated percentages of the maximum error of estimate as a function of bootstrap sample size (B = 2, 3, ..., N = 16).

Bootstrapping to determine the minimum sample size (X_0) for estimating mean bulk density was carried out for maximum errors of estimate (one-half of the confidence intervals) of 2.5, 5, and 10%. Results for the first data set (November 1982) are illustrated for the 0.14-m depth in Fig. 4, while those for all depths

Table 2. Minimum sample sizes (X_0) for estimating the mean population bulk density and the corresponding fractions (Y_0) of samples within the specified error limits (1982 data set).

	Maximum error of estimate			
	2.5%		5%	
Depth, m	X_0	Y_0	X_0	Y_0
		Direct technique		
0.14	17	0.87	10	0.99
0.26	15	0.86	9	0.99
0.34	12	0.97	5	1.00
0.46	12	0.99	5	1.00
0.54	12	0.96	6	1.00
0.66	15	0.88	7	0.99
0.74	14	0.87	8	0.99
0.86	12	0.97	5	1.00
0.94	13	0.94	6	1.00
1.06	13	0.95	6	1.00
1.14	7	1.00	4	1.00
		Paraffin technique		
0.20	8	0.99	3	1.00
0.40	5	1.00	6	1.00
0.60	9	0.99	6	1.00
0.80	8	0.99	5	1.00
1.00	6	1.00	6	1.00

Table 3. Minimum sample sizes (X_0) for estimating the mean population bulk density and the corresponding fractions (Y_0) of samples within the specified error limits.

	Maximum error of estimate			
	2.5%		5%	
Depth, m	X_0	Y_0	X_0	Y_0
		Sample size = 16		
0.20	8	0.99	3	1.00
0.40	5	1.00	6	1.00
0.60	9	0.99	6	1.00
0.80	8	0.99	5	1.00
1.00	6	1.00	6	1.00
		Sample size = 44		
0.20	17	0.94	10	1.00
0.40	19	0.89	9	0.99
0.60	21	0.89	10	0.99
0.80	15	0.97	7	1.00
1.00	17	0.94	8	1.00

are reported in Table 2. The results in Fig. 4 show that the fraction of sample means within the error limits increases with sample size and eventually reaches a plateau (Y_0) beyond which little or no additional information is gained. A reduction in error limit requires a larger number of observations (X_0) to estimate the population mean. The results also point out an effect of technique in determining the bulk density. The X_0-values for the paraffin technique are generally smaller than those for the direct method (Table 2). Apparently the latter method is subject to more random variation or the former method somehow smoothed out existing variations.

Comparison of X_0-values for the two data sets based on the paraffin technique also showed differences (Table 3). Minimum sample sizes for the first data set are considerably smaller than those for the second set, suggesting either different soil conditions during the time of sampling, or, less likely, a human-related experimental effect.

CONCLUSIONS

Results of the statistical analyses of bulk density data obtained by depth from a 50- by 100-m cultivated field indicated that the final results were affected by both sampling at different times and the technique used to determine bulk density. Although soil-water conditions were similar at the two times of sampling, the results indicate differences in bulk density values. These differences were not expected for what was thought to be a static property. Other examples of combining data sets sampled at different dates were not found in the literature, mainly because such reports did not mention time periods over which sampling occurred. If large time periods are involved, however, combining data sets to determine spatial interdependency of a given soil property by means of semivariograms may be questionable, even if the same technique is used to determine that property.

The two bootstrapping techniques used in this study were useful for (i) obtaining sampling distributions for the mean, variance, and the range for bulk density values without a priori assumptions, and (ii) for determining the minimum sample size needed to obtain an estimate of the mean at a given confidence level and degree of precision. Both bootstrapping techniques should be applicable for analysis of other soil parameters. It seems entirely feasible, e.g., to use the bootstrap technique for determining confidence intervals on semivariances (Shumway, 1985).

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