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Final Report

INVESTIGATIONS OF VEGETATION AND SOILS INFORMATION CONTAINED IN LANDSAT THEMATIC MAPPER AND MULTISPECTRAL SCANNER DATA

E.P. CRIST, R. LAURIN, J.E. COLWELL, and R.J. KAUTH

Infrared and Optics Division

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16. Abstract

This document is a final report for FY84 ERIM research activities in support of the Earth Sciences and Applications Division, NASA Johnson Space Center. Two primary research thrusts are described: the TM Tasseled Cap transformation, and remote measurement of soil properties. An extension of the TM Tasseled Cap transformation to reflectance factor data is presented, and the basic concepts underlying the Tasseled Cap transformations are described. The ratio of TM Bands 5 and 7, and TM Tasseled Cap Wetness, are both shown to offer promise of direct detection of available soil moisture. In addition, some of the effects of organic matter and other soil characteristics or constituents on TM Tasseled Cap spectral response are described.

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Final Report

INVESTIGATIONS OF VEGETATION AND SOILS INFORMATION CONTAINED IN LANDSAT THEMATIC MAPPER AND MULTISPECTRAL SCANNER DATA

by

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This report describes results of research performed in support of the Earth Sciences and Applications Division, NASA Johnson Space Center.

Environmental Research Institute of Michigan
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December 1984

PREFACE

This report describes part of a comprehensive program of research concerned with advancing the state-of-the-art in remote sensing of the environment from aircraft and satellites. The research was carried out for the Earth Sciences and Applications Division of NASA's Lyndon B. Johnson Space Center, Houston, Texas, by the Environmental Research Institute of Michigan (ERIM). Dr. Jon D. Erickson was the Division Chief and Mr. James L. Dragg was Chief of the Remote Sensing Research Branch. Dr. Victor S. Whitehead, with the assistance of Mr. Kenneth Baker, served as Technical Coordinator of the reported effort. The basic objective of this multidisciplinary program was to develop remote sensing as a practical tool to provide the scientist, planner and decision-maker with extensive information quickly and economically.

Timely information obtained by remote sensing can be directly important to such people as the farmer, the city planner, the conservationist, and others concerned with problems such as crop yield and disease, urban land studies and development, water pollution, and forest management. In a longer range view, remote sensing is one of a number of tools applicable to developing an understanding of the more global physical processes affecting the earth. The scope of our program includes:

1) Extending the understanding of basic processes.

2) Discovering new applications, developing advanced remote-sensing systems, and improving automatic data processing to extract information in a useful form.

3) Assisting in data collection, processing, analysis, and ground-truth verification.

The research described herein was performed under NASA Contract NAS9-16538 by ERIM's Infrared and Optics Division headed by Jack L. Walker, Vice-President of ERIM, under the direction of Robert Horvath, Program Manager and Eric Crist, Program Scientist.

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1.0
INTRODUCTION

This final report describes progress made by the Environmental Research Institute of Michigan (ERIM) in support of the Earth Sciences and Applications Division (ESAD), NASA Johnson Space Center, during the period 1 November 1983 through 31 December 1984.

The objectives of the research reported here were:

1) To characterize and understand the information content of Landsat Thematic Mapper (TM) data.

2) To develop methods by which that information may be applied to monitoring vegetation and soils.

This report is organized on a topical rather than programmatic basis, under two major headings corresponding to the major thrusts of the research program. In order to promote more timely dissemination of research results to the scientific community, reporting in the open literature was emphasized. Thus, sections 2.1, 2.2, 3.3, and 3.4 are complete papers which have been or soon will be submitted for publication in a variety of remote sensing journals. While this format results in some degree of redundancy in this document, it achieves the important objectives of open literature publication and minimized cost.

1.1
SUMMARY OF PROGRESS

Two general areas of research comprised the ERIM FY84 effort described in this report — TM Tasseled Cap analyses, and soils analyses.

1.1.1. TM Tasseled Cap Analyses

In FY 82 and 83 a transformation, termed the TM Tasseled Cap transformation, was devised which captures the vast majority of vegetation and soils information in three spectral features, each of which can be directly associated with particular physical scene class characteristics. In FY 84, additional analyses were carried out to derive an equivalent transformation for reflectance factor data (e.g. those measured in the field using spectrometers), so that these data could be analysed in the same terms as actual satellite sensor data. This transformation is described in Section 2.2. In addition, steps were taken to better explain the fundamental concepts of the Tasseled Cap transformations of TM and MSS data, resulting in the paper reproduced as Section 2.1.

1.1.2. Soils Analyses

Several research topics were pursued under the general heading of soils-related remote sensing:

a) Using field and laboratory-measured reflectance factor spectra of a variety of soils in the 420 to 2420 nanometer range, principle components analysis was used to identify the major soil spectral differences and to analyse the interactions and correlations within and between spectral regions. Results, described in Section 3.1, indicated that the TM Tasseled Cap features Brightness and Wetness are very similar to the first two principle components using the entire reflectance spectra, and provide first indications for use in defining optimum sensor bands for soils-related remote sensing.

b) The physical causes of soil spectra variation in the Fourth TM Tasseled Cap feature were investigated, again using the field and lab spectra. No strong association could be made between Fourth Feature signal variation and any soil physical characteristic, although organic matter content (percent-by-weight) was associated with Fourth Feature response in a relative sense. Section 3.2 provides further discussion. In addition, analysis of a new set of data, described in c) below, showed that red soils were readily distinguishable from non-red soils in the Fourth Feature. These results are discussed in Section 3.4.

c) The interactions of moisture content and soil physical properties, as they affect TM band reflectance as well as response in the TM Tasseled Cap feature space, were analyzed using a new set of soil spectral measurements. A select group of soil samples, representing a range of soil textures, parent materials, etc., were measured over the 400 to 2500 nanometer spectral range at a variety of moisture contents, providing more comprehensive information than was previously available. Using these data , a ratio of TM bands 5 and 7 was shown to have potential as a means of determining available water without knowing the soil texture. In addition, the influence of organic matter on Wetness response to moisture changes was demonstrated, as were the general spectral effects of changes in soil moisture in the TM Tasseled Cap Plane of Soils. Sections 3.3 and 3.4 describe the analyses and their results.

d) The effects of soil brightness on vegetation response, as measured by several common vegetation indices, were analyzed using a Landsat Multispectral Scanner (MSS) scene. A recent rain squall had darkened (wet) the soils in a portion of this scene, providing a clear soil brightness contrast relatively uncorrelated with vegetation characteristics. Brief analysis of these data confirmed, for the most part, other studies using ground-based reflectance measurements, showing that both the magnitude and "direction" (increase or decrease) of the soil brightness effect differs between the vegetation indices considered. Section 3.5 provides details of these results.

2.0 TM TASSELED CAP ANALYSES

During fiscal years 1982 and 1983, a transformation of Landsat Thematic Mapper (TM) data was developed which captures 95% or more of the total TM reflective band data variability for vegetated scenes in three "hybrid" spectral features, each of which can be directly associated with physical characteristics of scene classes. This transformation, termed the TM Tasseled Cap transformation, provides substantial data volume reduction with little or no loss of significant information, as well as improved ability to relate spectral response directly to scene class characteristics. Section 2.1 provides a basic explanation of the key concepts of this transformation and its Landsat MSS equivalent. Section 2.2 describes a transformation by which reflectance factor data (such as those collected in the field with spectrometers) can be transformed into analogous features, providing continuity of analysis and interpretation from ground-based to space-borne sensor response.

2.1 FUNDAMENTAL CONCEPTS OF THE TASSELED CAP TRANSFORMATIONS

(submitted to *Photogrammetric Engineering and Remote Sensing* as 'The Tasseled Cap De-Mystified,' by E.P. Crist and R.J. Kauth

Abstract

The fundamental concepts on which the Tasseled Cap transformations of MSS and TM data are based – particularly the identification of inherent data structures – are explained and discussed. Emphasis on the structures present in data from any given sensor, which are themselves the expression of physical characteristics of scene classes, provides a number of advantages, including: a) reduction in data volume with minimal information loss, b) spectral features which can be applied, without re-definition or adjustment, to any data set for a given sensor, c) spectral features which can be directly associated with important physical parameters, and d) easier integration of data from multiple sensors.

Introduction

The great increase in information available from multispectral sensors carries with it a substantial increase in data volume and complexity, both of which present obstacles to the efficient extraction of the information contained in the data. As a result, numerous methods have been developed for transforming such data, deriving features which are easier to handle (less volume) and/or easier to interpret (less complex). Ratios and differences of bands, principle component analysis , and other linear combinations of bands have been applied to multispectral data with varying degrees of success. Many of these are described in Perry and Lautenschlager (1984).

The Tasseled Cap transformations of Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) data (Kauth and Thomas, 1976, Crist and Cicone, 1984c) represent examples of linear combination features which have achieved a degree of acceptance in the remote sensing community. However, although the basic concepts behind these transformations, once grasped, are actually quite simple, the degree of understanding of these concepts in the remote sensing community has not kept pace with their acceptance – in short, many researchers are either: a) using the Tasseled Cap transformations without really understanding them, b) mis-applying or extending the transformations or their underlying concepts, or c) hesitating to use the transformations because of their apparent mystery.

This paper is not intended to provide detailed descriptions of the Tasseled Cap transformations of MSS and TM data, which can be found in Kauth and Thomas (1976) and Kauth et al. (1979) for MSS, and Crist and Cicone (1984b and 1984c) for TM, nor does it provide a detailed comparison of these transformations with others currently in use. It's sole purpose is to convey an understanding of the basic principles behind the Tasseled Cap transformations, the "Tasseled Cap Concept," and thus to address the problems listed above.

The Concepts

The signals from a given sensor can be thought of as defining a multi-dimensional space where each sensor band corresponds to one dimension. For a two-band sensor, the space is a plane, or a rectangle in that plane, as shown in Figure 2.1. For a three-band sensor, the space is a rectangular box, as in Figure 2.2. In both cases, the edges of the space are determined by the minimum and maximum possible signal values of the bands. This concept can be applied equally well to sensors with more than three bands, although the resultant data space is more difficult to visualize. For the moment, we will confine ourselves to the three-band case.

If every possible combination of signal values in the three-dimensional space had an equal probability of occurrence, then one could expect that a large set of data from the sensor would be dispersed with more or less equal density throughout the cube in Figure 2.2. Such is not the case, however. Reflectance curves for scene classes, for example vegetation and soils, have particular characteristic shapes, as illustrated in Figure 2.3 (Knipling, 1970, and (Stoner and Baumgardner, 1980). Although substantial variation in spectral characteristics can and does occur within the vegetation and soil classes, most or all of the members of those classes share certain fundamental physical properties (e.g. vegetation cellular structure) which produce predictable spectral reflectance patterns. As a result, all possible combinations of signal values do not have equal probabilities of occurrence. Instead, the data tend to be concentrated in certain portions of the cube, giving "structure" to what would otherwise be an amorphous cloud.

The portions of scene class reflectance spectra influenced by a given physical characteristic of the scene class may be wide or narrow, or even disjoint. If the bands of a sensor are located such that they respond to distinct and uncorrelated physical scene class characteristics, then variation in one of those characteristics will only cause variation in one sensor band. In this case, each band can be directly associated with a particular physical scene class characteristic. Figure 2.4 will be used to schematically represent this case. The text is aligned with the band axes (edges of the rectangle) just as the spectral

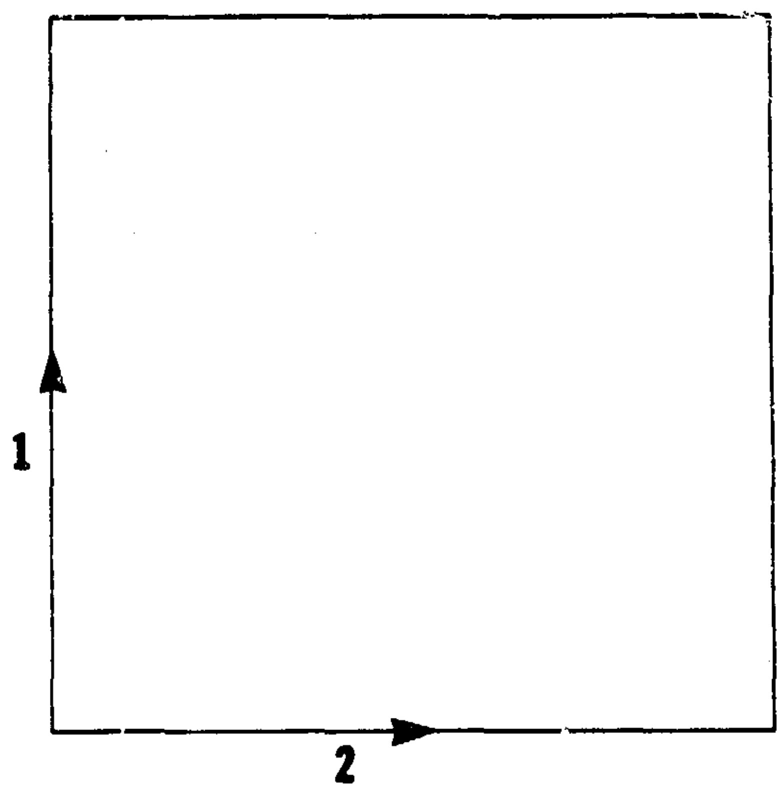

Figure 2.1. Schematic representation of two-band sensor data space.

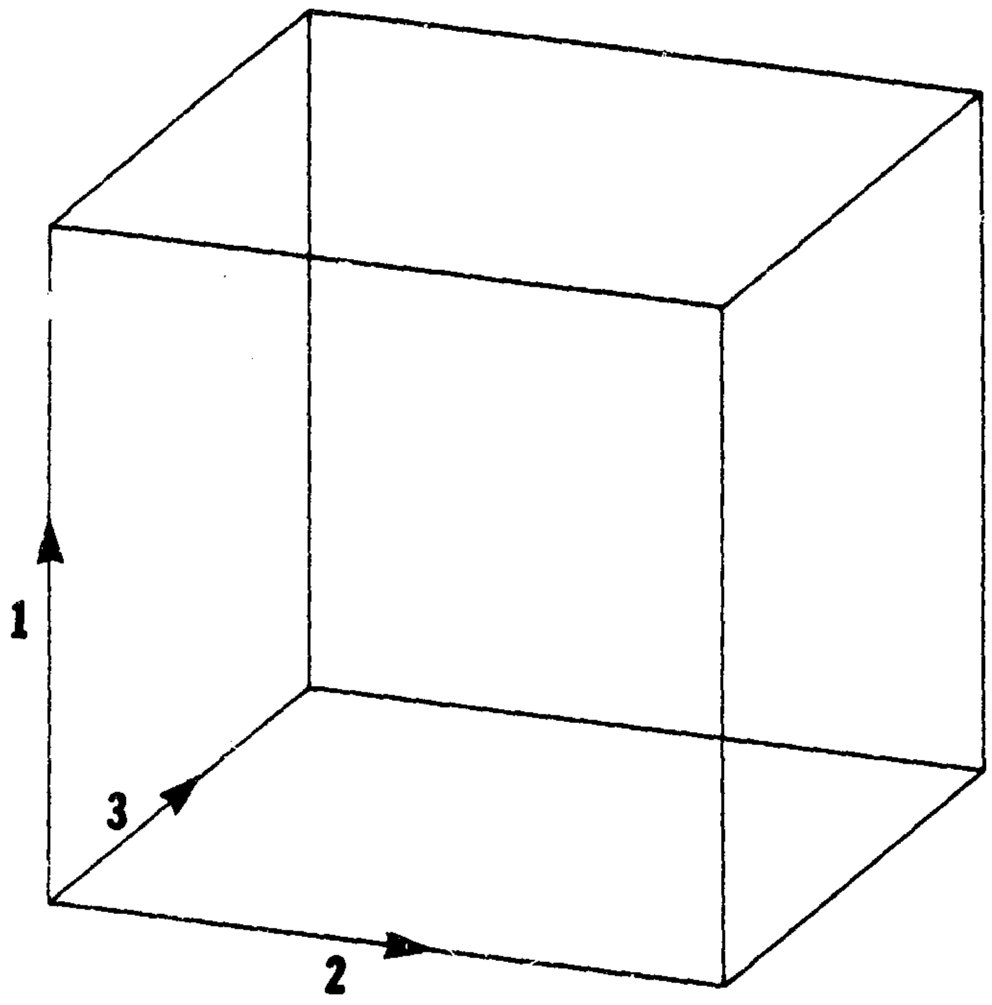

Figure 2.2. Schematic representation of three-band sensor data space.

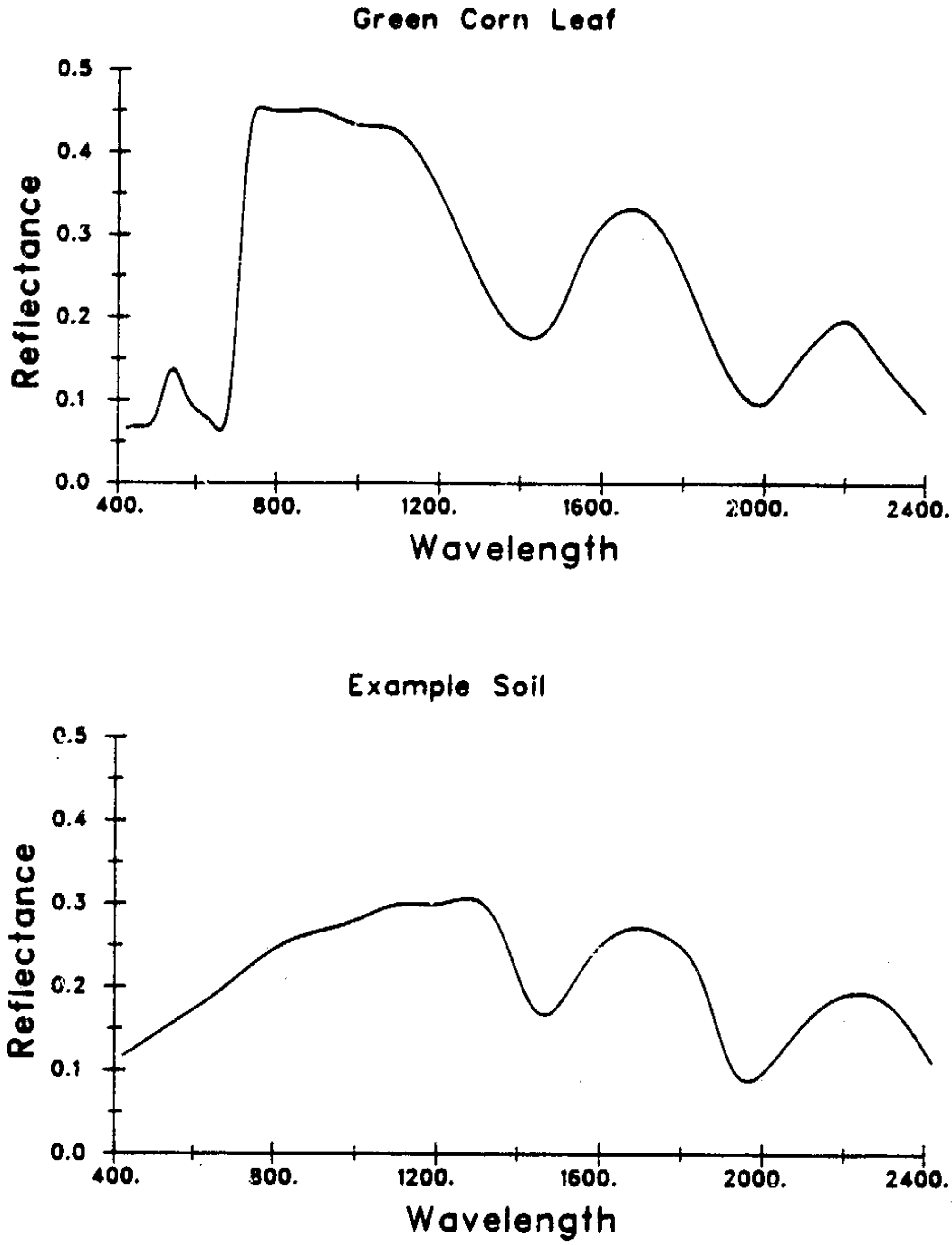

Figure 2.3. Typical vegetation and soil spectra. (Soil spectrum courtesy of Purdue/LARS)

variation induced by a particular scene class characteristic is aligned with the band axes. If the sensor bands fall such that more than one band responds to a particular scene characteristic, then variation in that characteristic will cause signal variation in more than one band, in a correlated fashion. Where such correlation is perfect for all relevant scene classes, the sensor bands could be said to be redundant. However, it is more likely that the correlations will be imperfect, which is to say that each band will contain some unique information, but that the total information will only be captured by some combination of the bands.

In the two-band sensor case, any data structures are constrained to fall in the two dimensions defined by the two bands, and will thus be viewed directly in the two-band projection. Band correlation will simply mean that the axes of primary data variation are not aligned with the band axes. This case is schematically represented in Figure 2.5. In sensors with more than two bands, band correlation, if it occurs, will result in the data structures not being aligned with any pair of band axes, so that any two-dimensional projection of the band signals (i.e. pairwise) will only provide a skewed view of the data structures. Figure 2.6 illustrates the simplest of such cases, where the data fall in a single plane. Where more complex data structures occur, the potential confusion and distortion of information is even more severe. In Figure 2.7, two perpendicular plane-like structures are joined at one edge, forming an "open book" shape.

Figure 2.8 illustrates two possible viewing perspectives on these data structures. In Figure 2.8a, the text is entirely legible, though somewhat compressed horizontally, but the geometric relationship between the two planes or pages is lost completely — the two pages appear as one. In Figure 2.8b, the geometric relationship between the pages is again largely obscured, and in addition, the text is garbled. In both cases, fundamental information is lost or distorted.

Because the structures present in data from a particular sensor are directly related to the actual physical characteristics of the scene classes (and inferring those characteristics is presumably our objective), we will be best able to extract the relevant scene class information if we view the structures in the most direct possible way, a way in which each data structure can be viewed in its entirety, and separately from the other data structures (preserving both the information in each structure and the geometric relationships between structures). The Tasseled Cap concept simply involves identifying the relevant data structures for a particular sensor and application (i.e. set of scene classes), changing the viewing perspective such that those data structures can be viewed most directly, and defining feature directions (new x-, y-, and z-axes in the cube example) which correspond to spectral variation primarily or exclusively associated with a particular physical scene class characteristic.

As a hypothetical example, suppose we find that the data from a three-band sensor seem to be concentrated in a plane-like structure, as in Figure 2.9a. We rotate the data space (change our viewing perspective) so that we can see the greatest amount of variation in the plane (view it most directly — Figure 2.9b). Now we note that scene classes A and B tend to vary primarily in the directions illustrated in Figure 2.9c. We therefore rotate the cube once again such that the directions of variation are aligned vertically and horizontally, i.e. with the x- and y-axes (Figure 2.9d). The features defined by the new

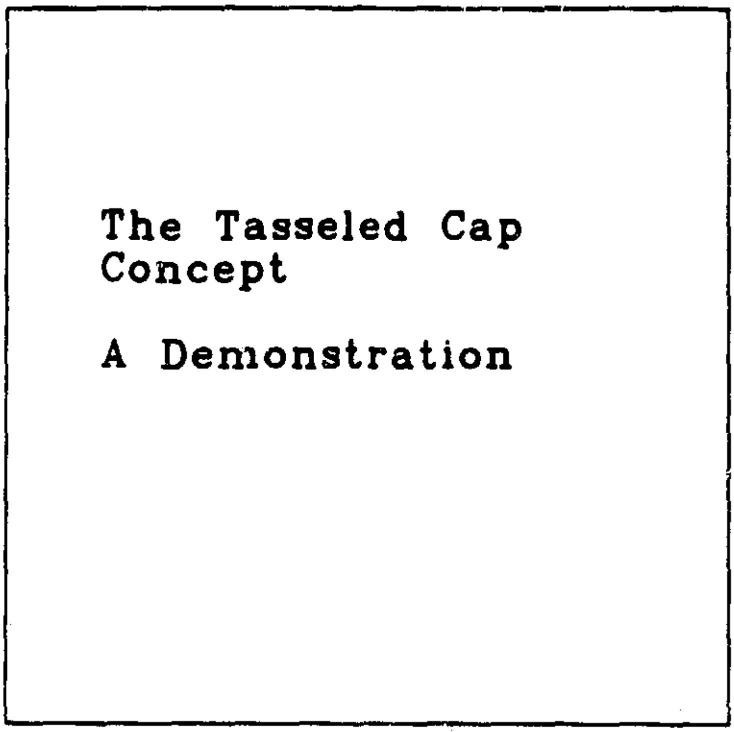

Figure 2.4. Schematic representation of two-band data with perfect association between band axes and contained information.

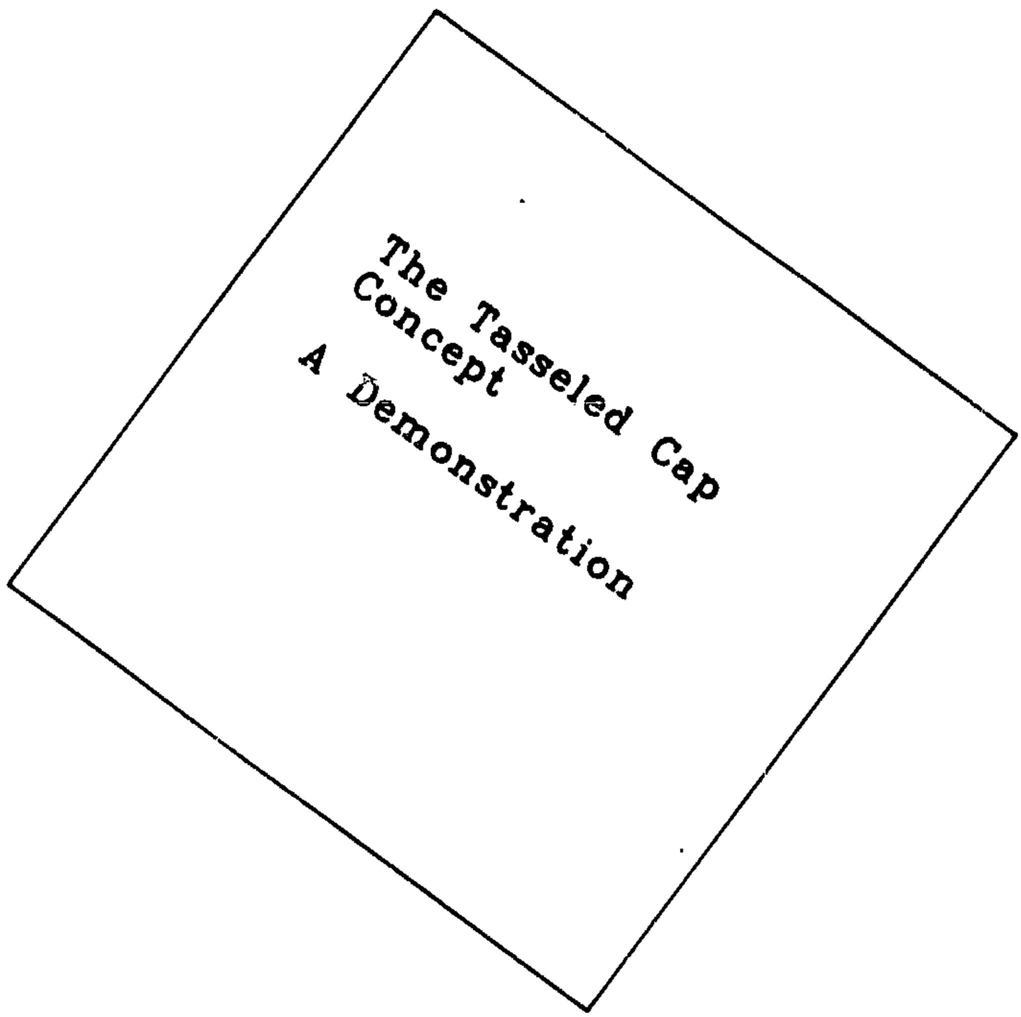

Figure 2.5. Schematic representation of three-band data with correlation.

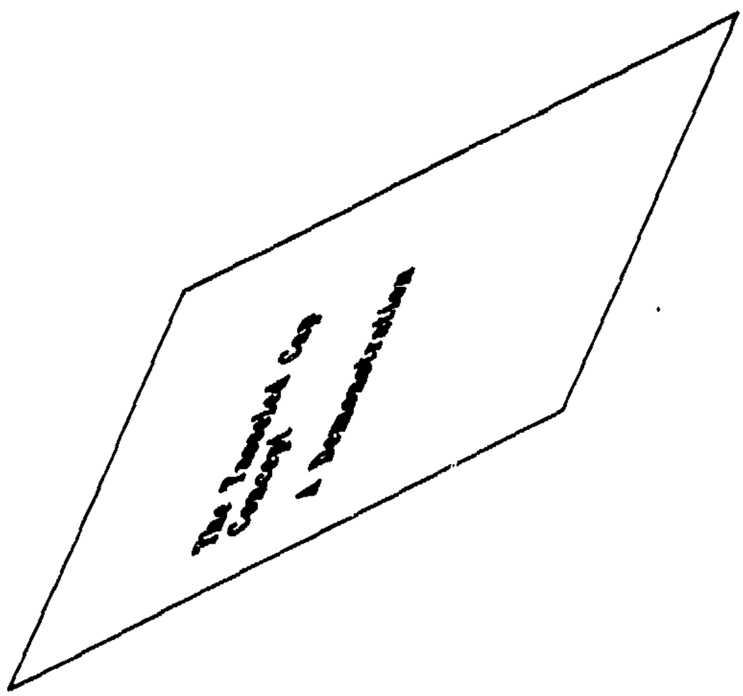

Figure 2.6. Schematic representation of three-band data with correlation.

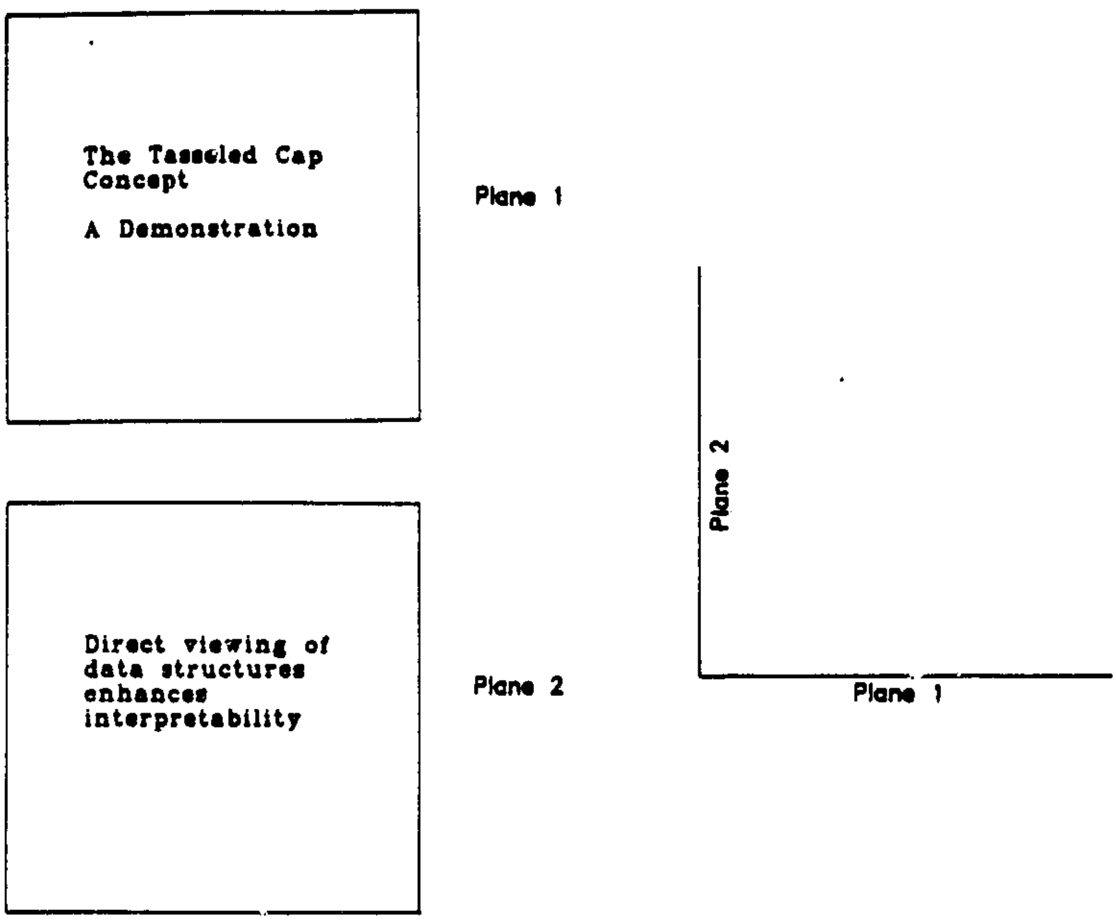

Figure 2.7. Schematic representation of complex data structures in three-band data.

(a)

(b)

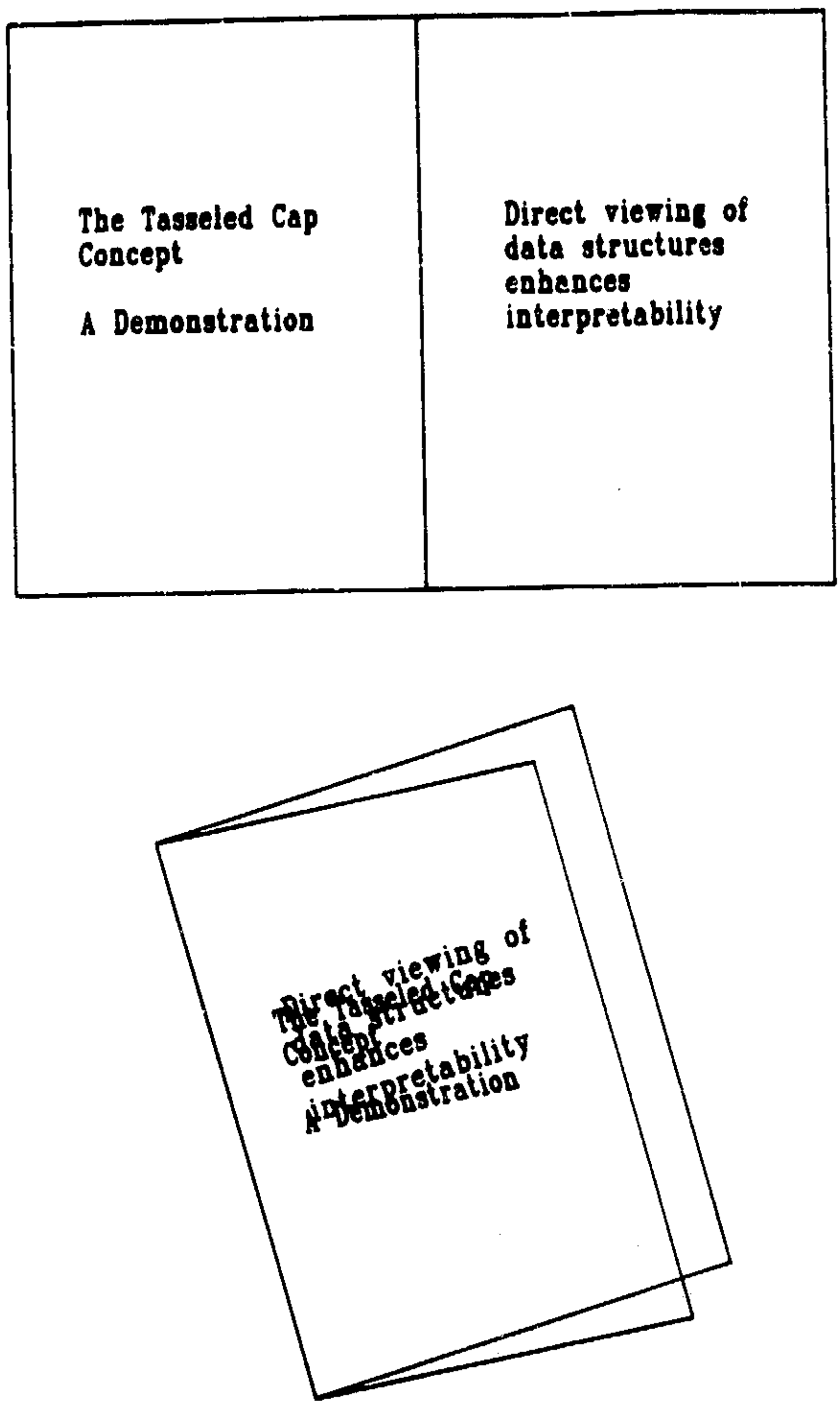

Figure 2.8. Distortions of complex data structures resulting from viewing perspective.

axes, both of which are combinations of the original three bands, now capture the greatest possible amount of data variation, and can be readily and unambiguously interpreted with respect to physical scene class characteristics.

Several additional aspects of this approach should be noted. First, all of our rotations were applied to the three-dimensional cube as a whole – the linear distances between any two points within the cube were unchanged. This means that the data are fundamentally the same before and after application of the transformation – only the viewing perspective has changed. Second, a change to a new sensor or a new application (different set of relevant scene classes) requires a re-working of the transformation, starting with identification of the data structures. One cannot safely assume, without investigation, that, for example, the data structures found in Landsat MSS data will be duplicated in TM data, or that defining features in TM data in precisely the same manner as they were defined in MSS data will necessarily capture the data structures accurately or adequately. No "cookbook" approach will suffice to define Tasseled Cap features for a new sensor – the entire process must be carried out each time (although, as will be discussed later, the physical basis of the transformations tends to result in similar data structures and features for sensors with similar spectral sensitivities). Third, and as a result of the second point, the transformation will be most generally useful if the scene classes are defined broadly, e.g. "vegetation and soils" rather than "fescue and Fincastle sandy loam". Finally, while changing to a new sensor or application requires re-working of the transformation, changing to a new set of data from the same sensor imposes no such requirement. This is because the transformation is defined based on fundamental and, for the most part, invariant physical characteristics of the relevant scene classes. Once the features of the transformation are properly aligned to respond to these characteristics, they will be applicable to any data set from the same sensor (barring changes in sensor calibration, etc.). The content of a particular data set (scene) will determine which portions of the data structures are occupied, but will not affect the data structures themselves.

The Transformations

In the case of the four-band Landsat Multispectral Scanner (MSS), vegetation and soils data were found to primarily occupy a single plane-like structure, which typically contains 95% or more of the total data variation. In that plane, a feature named Brightness was defined in the direction of soil reflectance variation, and a feature named Greenness was defined in a perpendicular direction associated with the reflectance characteristics of green vegetation.

For the Thematic Mapper (TM), data in the six reflective bands were found to primarily occupy three dimensions, defining two perpendicular plane-like structures and also occupying a region between the two planes. One plane contains fully-vegetated samples, while the other contains bare soil samples. When both soil and vegetation are visible to the sensor, the data fall in the region between the two planes. Brightness and Greenness features, analogous to those defined for MSS data, were found to be appropriate for TM data as well, although the Brightness feature in TM data is not exactly equivalent to its MSS counterpart. In addition, a feature named Wetness was defined to correspond to the observed direction of soil moisture variation in the plane occupied by bare soils

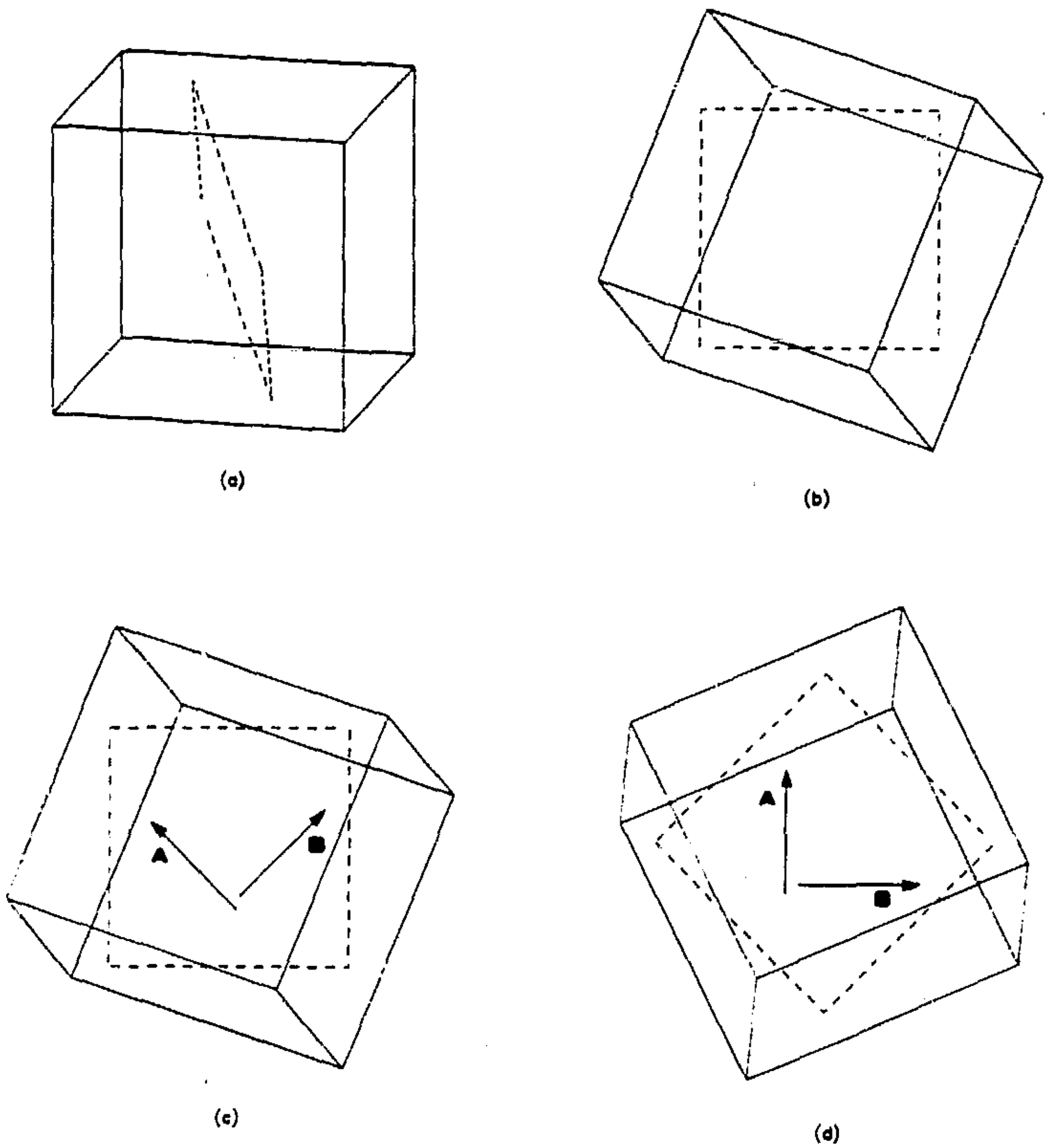

Figure 2.9. Hypothetical three-band sensor data – Tasseled Cap example.

data. Here again, the three features typically capture 95% or more of the total data variation.

While application of the Tasseled Cap concept to different sensors requires, as stated earlier, redefinition of the transformation to correspond to the observed data structures in the particular sensor's signal space, the direct association of features with physical scene class characteristics enhances the likelihood of feature similarity between sensors with similar though not necessarily identical ranges of spectral sensitivity. In the case of Landsat MSS and TM, as just described, the Greenness features are essentially identical between the two sensors, and the Brightness features are similar (Crist and Cicone, 1984a, and Crist, 1984). When the longer infrared bands of the TM are omitted (i.e. bands 5 and 7, the two bands most different from those of the MSS), the resulting Greenness and Brightness features, based on the remaining four reflective TM bands, are both identical to their MSS Tasseled Cap counterparts (Crist and Cicone, 1984a, and Crist, 1984). Simulation studies have likewise provided indications of analogous Brightness and Greenness features in data from the NOAA AVHRR and CZCS sensors (Cicone and Metzler, 1984). This similarity provides a ready mechanism by which multiple sensors may be used jointly, exploiting the particular desirable characteristics of each. In addition, it allows us to apply our considerable experience with older sensors, such as the Landsat MSS, to understanding data from other, newer sensors, providing a base of knowledge on which to build. Thus, for example, we can apply our MSS Tasseled Cap knowledge to TM Tasseled Cap features, and concentrate our new effort on fully exploiting the spectral, spatial, and radiometric enhancements embodied in the Thematic Mapper.

Conclusions

The fundamental basis of the Tasseled Cap transformations involves finding the data structures inherent to a particular sensor and set of scene classes, and adjusting the viewing perspective such that these structures can be most easily and completely observed. While this concept has been used primarily in agricultural or vegetation applications, there is good reason to expect that it could be similarly employed in geologic or urban land use applications, or in any application for which relevant scene classes have some distinctive and characteristic spectral properties. It is the identification of and emphasis on inherent data structures, rather than any particular application, which distinguishes the Tasseled Cap approach to multispectral data understanding.

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2.2
A TM TASSELED CAP EQUIVALENT TRANSFORMATION FOR REFLECTANCE FACTOR DATA

(submitted as a short communication by E.P. Crist to *Remote Sensing of Environment*)

Abstract

A transformation of TM waveband reflectance factor data is presented which produces features analogous to TM Tasseled Cap Brightness, Greenness, and Wetness. The approach to adjusting the transformation matrix to other types of reflectance factor data (different instrument or band response) is described in general terms.

Introduction

The Tasseled Cap transformations of Landsat MSS (Kauth and Thomas, 1976) and TM (Crist and Cicone, 1984a and 1984b) data provide a mechanism for data volume reduction and enhanced data interpretability by emphasizing the structures in the spectral data which arise as a result of particular physical characteristics of scene classes. The basic concepts underlying these transformations are discussed by Crist and Kauth (1985). Because the expression of the data structures is influenced by sensor calibration and detector response, the transformations are sensor dependent, i.e. the transformation matrix for MSS data cannot be applied successfully to TM data. Similarly, the transformation matrix for actual TM signal count data cannot be directly applied to reflectance factor data, even if those reflectance factor data are collected or combined in bands equivalent to those of the TM.

Scientific investigations related to the use of satellite remotely sensed data for monitoring vegetation often include use of ground level (truck-mounted or handheld) spectrometer data to supplement data from the spaceborne sensor. Such data can be collected under more controlled conditions, allowing detailed analysis of the physical characteristics of the entities being observed as well as their spectral response.

This paper presents a transformation by which one type of reflectance factor data may be converted to TM Tasseled Cap equivalent features. Others have used a "Tasseled-Cap-like" approach to defining dataset-specific transformations for reflectance data (e.g. Jackson, 1983). Some of the differences between such approaches and the Tasseled Cap transformations of MSS and TM data are discussed specifically by Crist and Cicone (1984b) and can be inferred from Crist and Kauth (1985). The transformation presented here is intended to provide features which relate as directly as possible to the corresponding TM Tasseled Cap features. Such a direct relationship allows researchers whose end goal is to better understand and use TM data to move more easily between actual satellite data and ground-measured data, thus facilitating application of the results of field experiments to actual Landsat TM data.

This paper is not intended to provide a full explanation of the basic Tasseled Cap concepts or of the particular characteristics of the MSS or TM Tasseled Cap transformations, since these have been provided elsewhere (Crist and Kauth, 1985, Kauth and Thomas, 1976, Crist and Cicone, 1984a and 1984b). Instead, a basic familiarity with at least the TM Tasseled Cap transformation is assumed.

Approach

The data set used in deriving the transformation consists of field spectrometer reflectance factor measurements (sampled at 10-nm increments from 400- to 2400-nm) of a diverse mix of crops and soils, obtained from the Laboratory for Applications of Remote Sensing (LARS) (Biehl et al., 1982). These are the same data which were used in the TM simulation and analysis of Crist and Cicone (1984a), and are described in greater detail in that paper. TM band reflectance factor values were derived by computing weighted averages of the measured reflectance factors, using as weights the pre-launch composite detector response functions of the Landsat-4 Thematic Mapper. The procedure for obtaining the transformation, which in general terms involves selective rotation and viewing of particular known scene classes in the six-dimensional spectral space, is also described in Crist and Cicone (1984a).

Results and Discussion

Table 2.1 contains the transformation coefficients derived by this analysis. The results of the transformation are illustrated for the entire data set in Figures 2.10 through 2.12, and for selected sample groups in Figures 2.13 through 2.15. Note that in all cases a subscript 'R' is used as a reminder that the features are reflectance factor equivalent features and not the actual TM Tasseled Cap features.

In evaluating the results of the transformations, one should keep in mind that the reflectance spectra used here are identical to those used in the simulation of Landsat TM signal counts which comprised the data set from which the first TM Tasseled Cap transformation was derived (Crist and Cicone, 1984a). Comparison of Figures 2.10 through 2.12 to the overall data distributions of Crist and Cicone (1984a and 1984b) demonstrates at least a general correspondence. Similarly, comparison of the transformation matrix in Table 1 to those of the previous works shows that the basic characteristics of the resultant features are similar (i.e. the same bands exert the key influences and the primary contrasts represented by the features are the same). The differences which do occur between the transformation matrices can likely be attributed to the effects of solar irradiance, atmospheric interference, and TM sensor calibration.

Further evidence of the transformations' correspondence can be found by comparing the data distributions in Figures 2.13 through 2.15 to those in Figures 2.16 through 2.18. The two sets of figures are based on the same spectra, selected from the larger group to represent particular scene classes, but the data in the first set (Figures 2.13 through 2.15) have been converted to TM inband reflectances and transformed via the reflectance factor TM Tasseled Cap transformation (Table 1), while the data in the second set have been

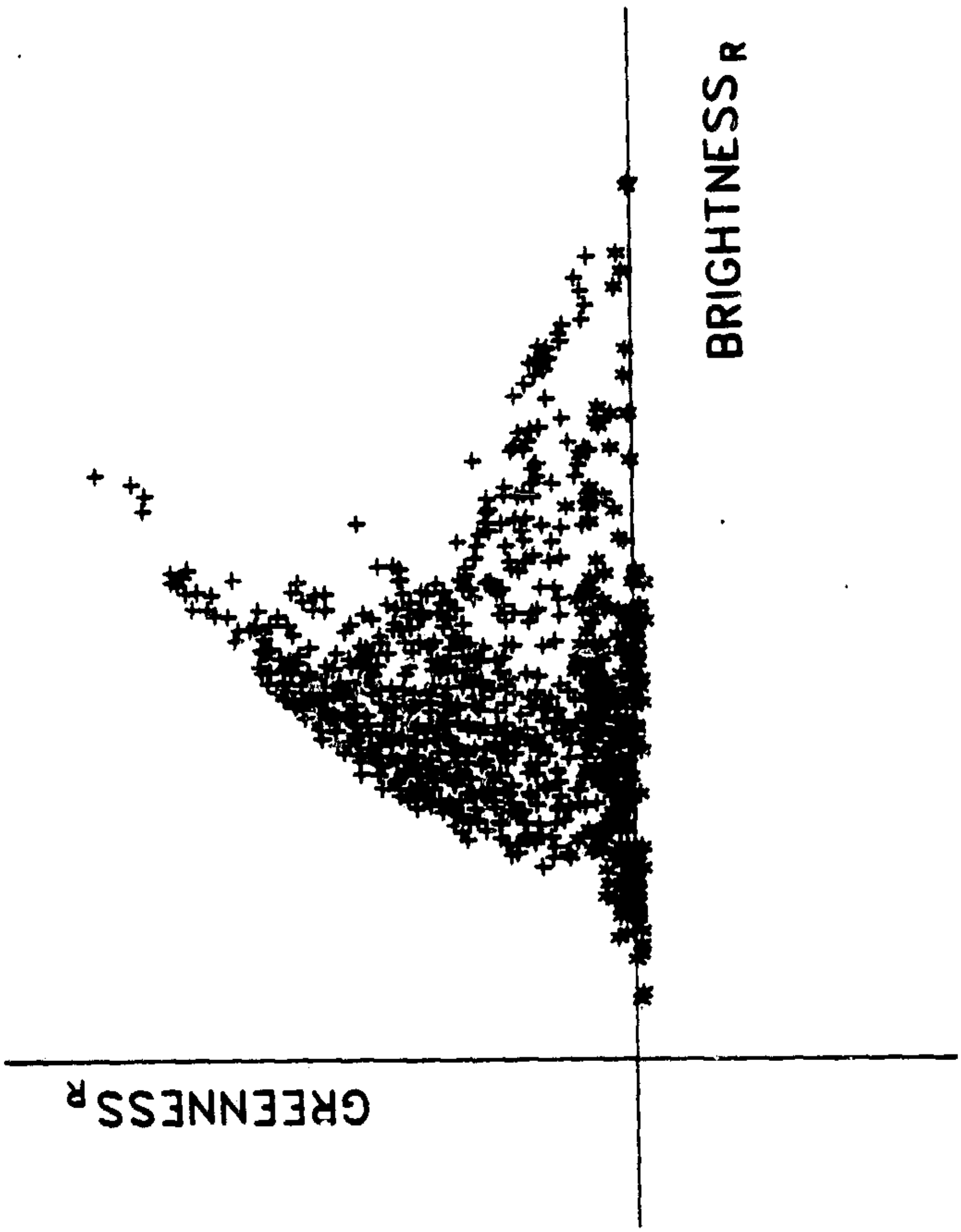

Figure 2.10. Reflectance factor TM Tasseled Cap Plane of Vegetation. All data. Key: '+' vegetation, '*' bare soil.

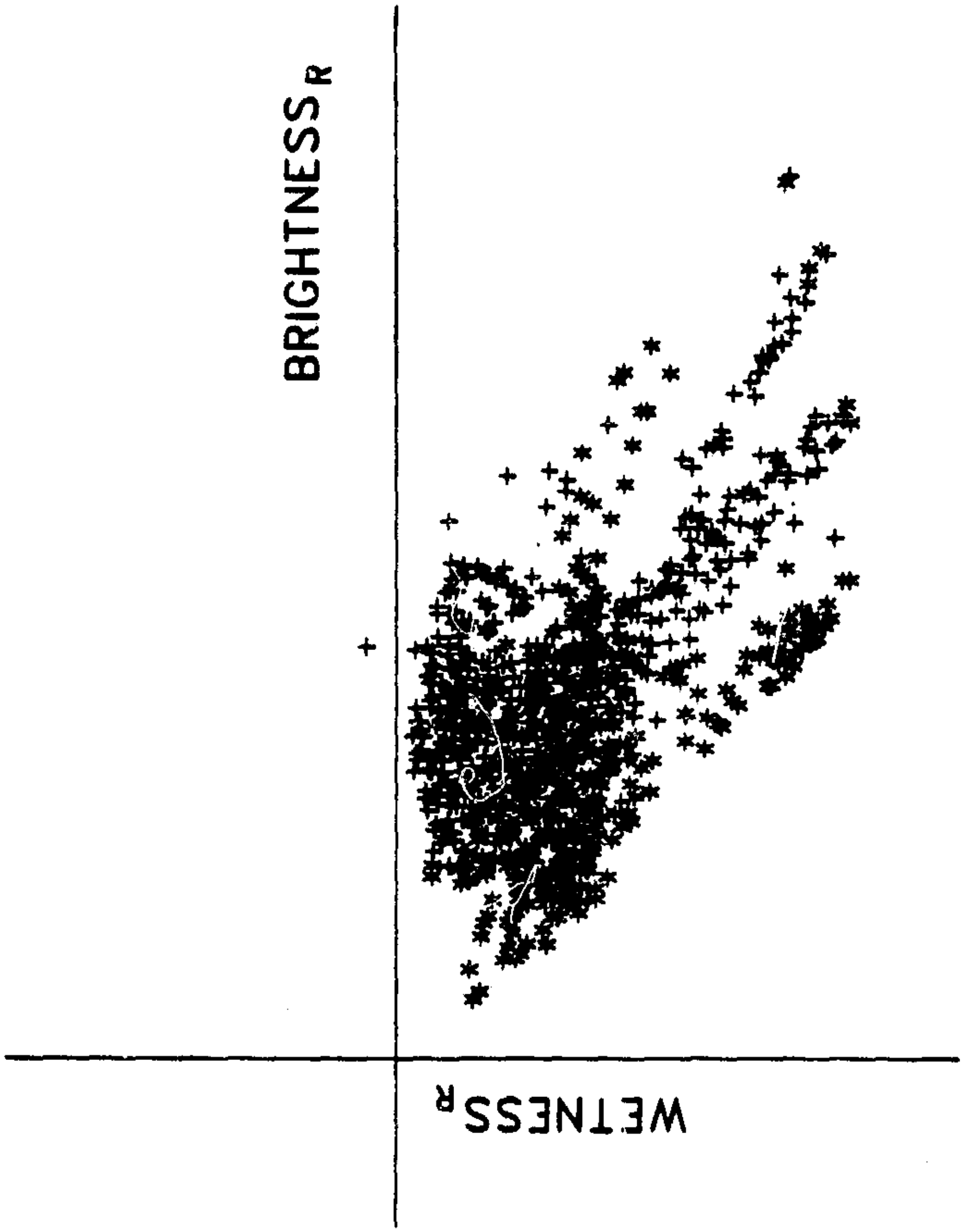

Figure 2.11. Reflectance factor TM Tasseled Cap Plane of Soils. All data. Key: '+' vegetation, '*' bare soil.

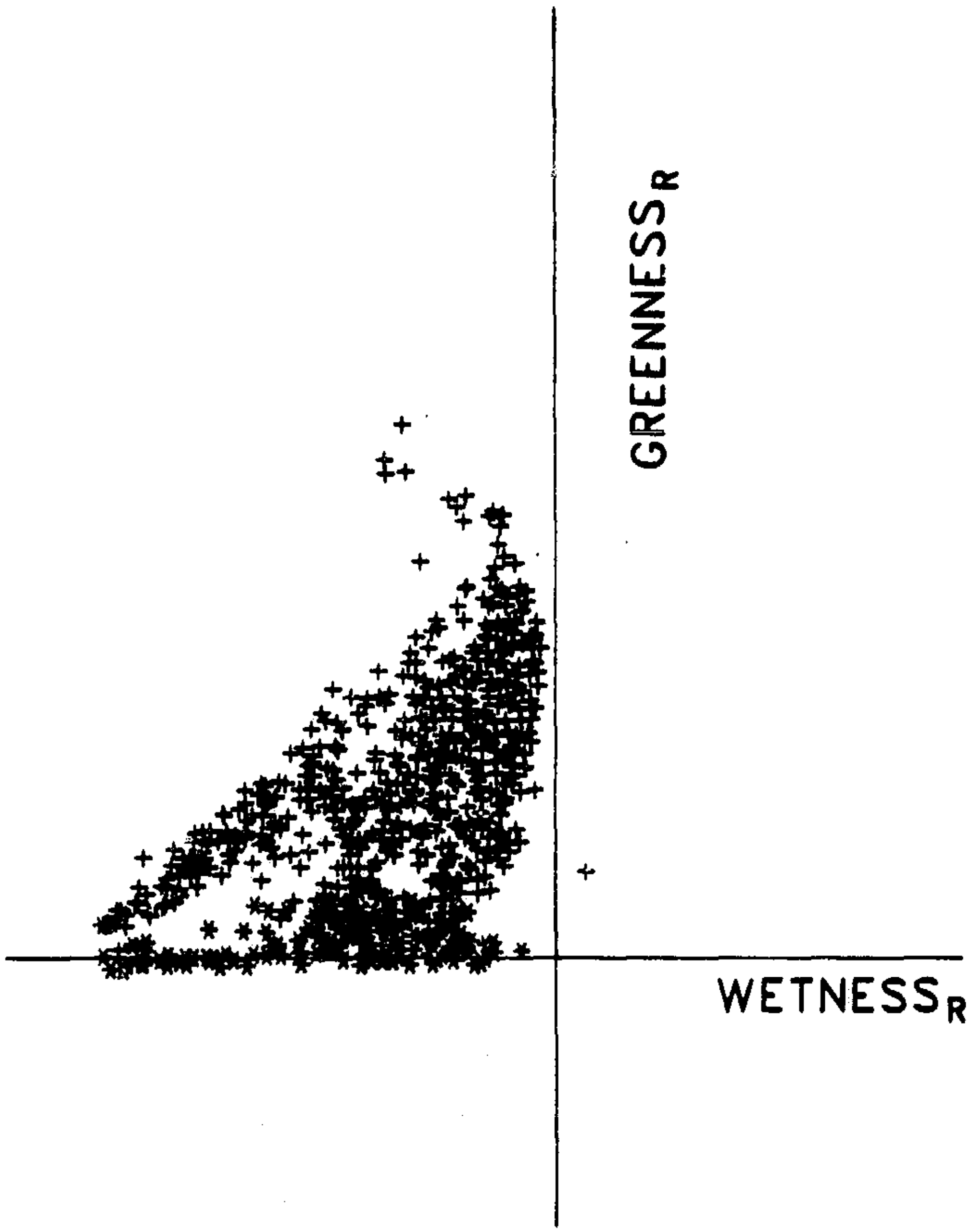

Figure 2.12. Reflectance factor TM Tasseled Cap Transition Zone. All data. Key: '+' vegetation, '*' bare soil.

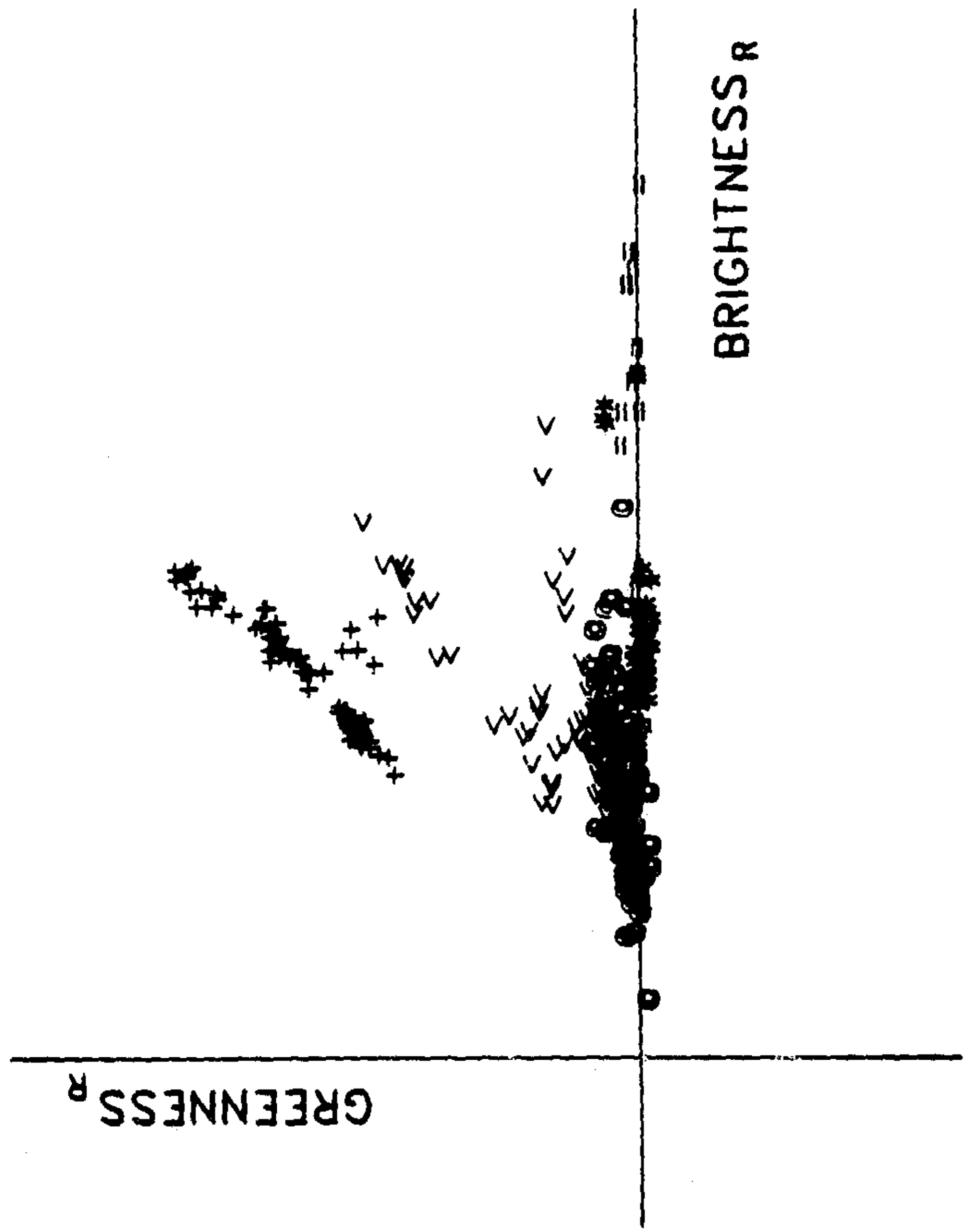

Figure 2.13. Reflectance factor TM Tasseled Cap Plane of Vegetation. Sample data. Key: '+' green vegetation, full cover; '<' brown vegetation, nearly full cover; '@' field capacity soils (lab-measured); '*' bare field soils; '=' quarry sand (field-measured)

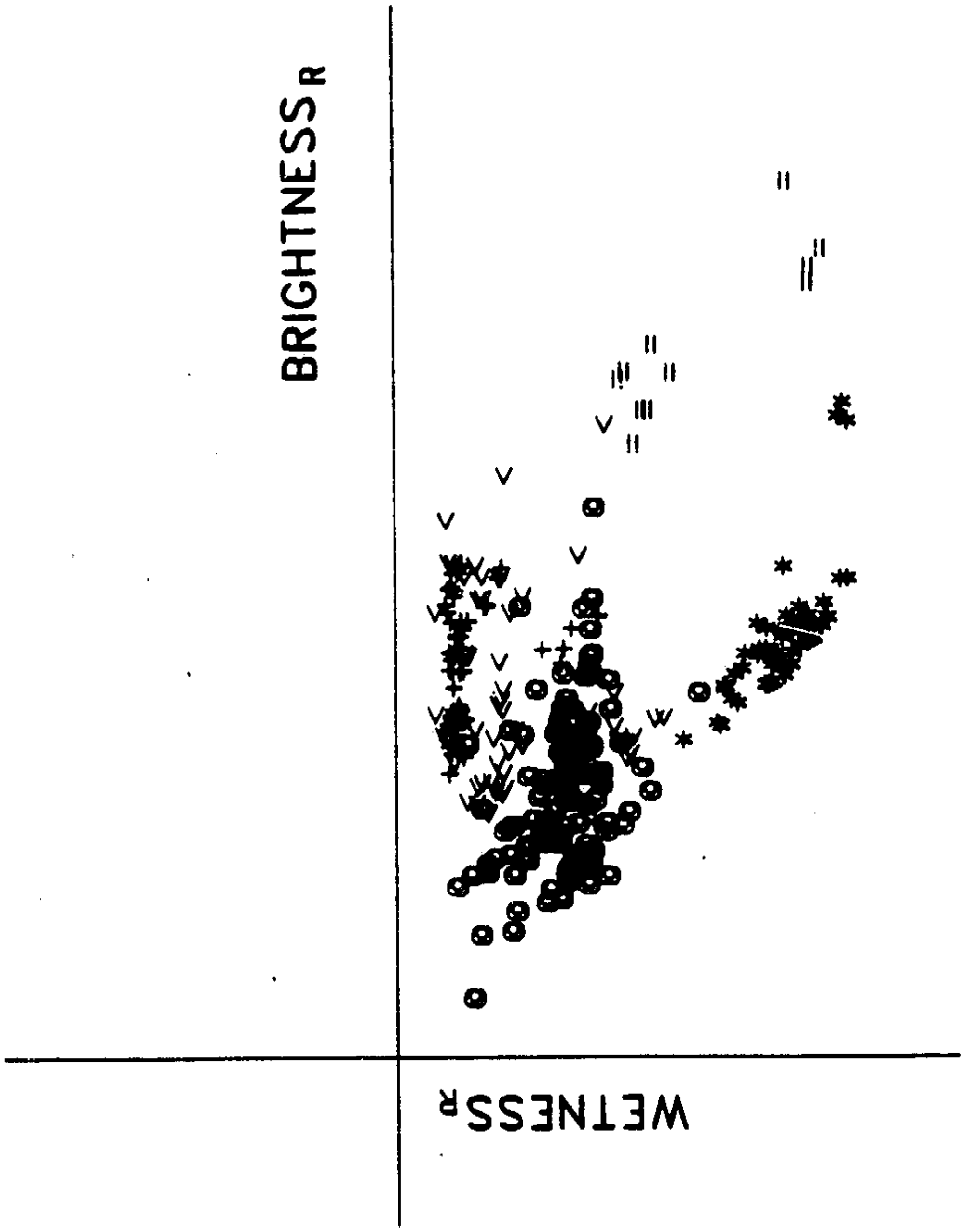

Figure 2.14. Reflectance factor TM Tasseled Cap Plane of Soils. Sample data. Key: '+' green vegetation, full cover; '<' brown vegetation, nearly full cover; '@' field capacity soils (lab-measured); '*' bare field soils; '=' quarry sand (field-measured)

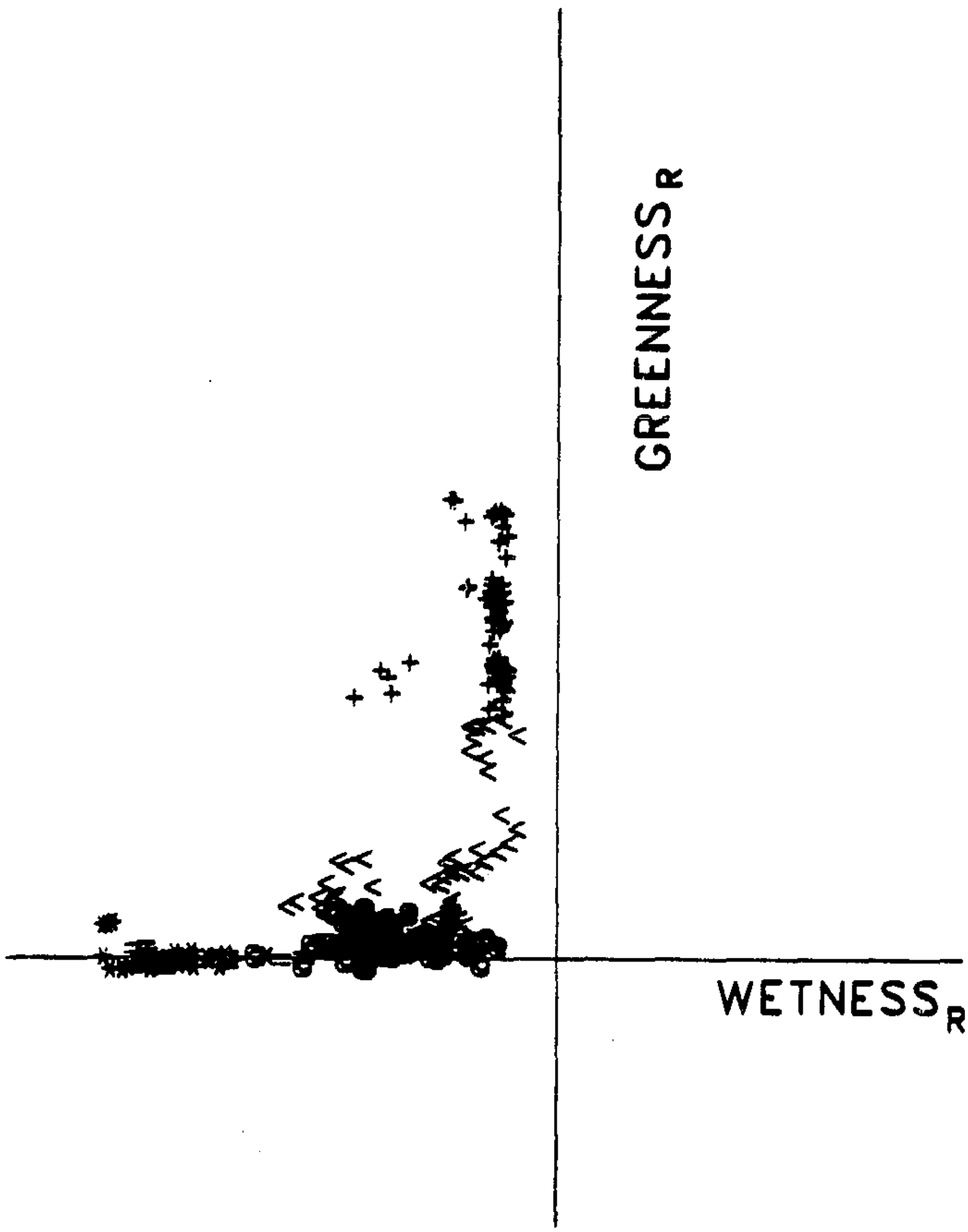

Figure 2.15. Reflectance factor TM Tasseled Cap Transition Zone. Sample data. Key: '+' green vegetation, full cover; '<' brown vegetation, nearly full cover; '@' field capacity soils (lab-measured); '*' bare field soils; '=' quarry sand (field-measured)

Table 2.1
TM Tasseled Cap Equivalent Transformation Matrix
for Band Reflectance Factor Data

Feature	TM 1	TM 2	TM 3	TM 4	TM 5	TM 7
Brightness_R	.2043	.4158	.5524	.5741	.3124	.2303
Greenness_R	-.1603	-.2819	-.4934	.7940	-.0002	-.1446
Wetness_R	.0315	.2021	.3102	.1594	-.6806	-.6109
Fourth_R†	-.2117	-.0284	.1302	-.1007	.6529	-.7078
Fifth_R†	-.8669	-.1835	.3856	.0408	-.1132	.2272
Sixth_R†	.3677	-.8200	.4354	.0518	-.0066	-.0104

†See text for cautions concerning Fourth through Sixth features.

used to simulate TM signal counts and then transformed in the manner of Crist and Cicone (1984a). Here again, comparison indicates a high degree of similarity in the transformation results. Each of the narrowly-defined scene classes occupies a similar position in the two transformed feature spaces, and the relative positions of scene classes are likewise similar between the two sets of figures. The one noticeable difference occurs between Figures 2.14 and 2.17, which provide what is termed the Plane of Soils view (Crist and Cicone, 1984b). The soils data are aligned somewhat differently with respect to the vegetation samples and the coordinate axes (particularly the Wetness direction). While the reason for this difference is not entirely understood, it should be kept in mind when evaluating transformed reflectance factor data and comparing results to actual TM data behavior.

The transformation presented in this paper is, as pointed out by the above example, comparable but not identical to the TM Tasseled Cap transformation of actual TM data. One ought not to assume, using this transformation any more than simply using inband reflectance factors, that the spectral behavior of scene classes measured on the ground will be exactly duplicated in space-borne sensor data. Whether using reflectance

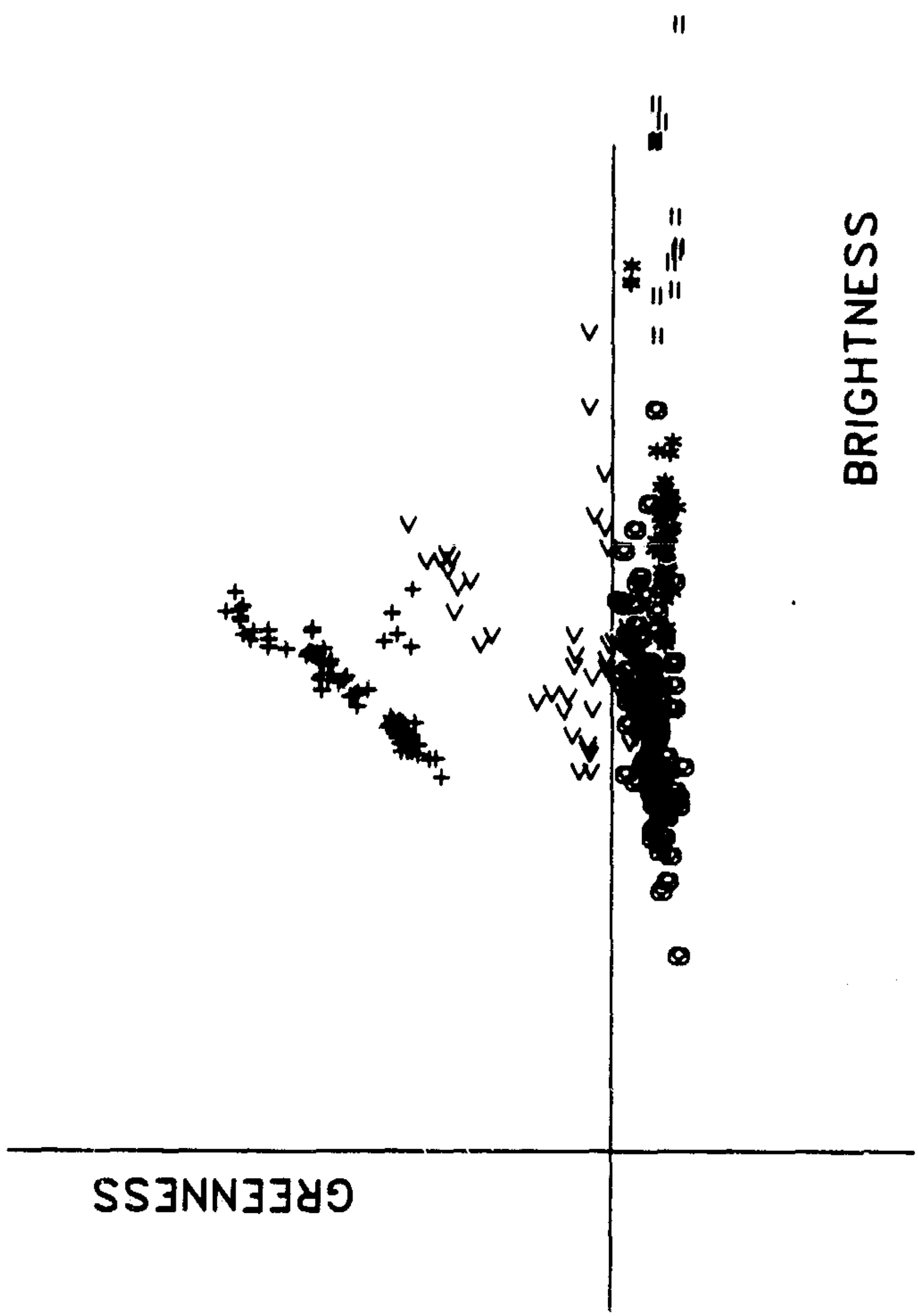

Figure 2.16. TM Tasseled Cap Plane of Vegetation. Sample data (based on simulated TM signal counts). Key: '+' green vegetation, full cover; '<' brown vegetation, nearly full cover; '@' field capacity soils (lab-measured); '*' bare field soils; '=' quarry sand (field-measured)

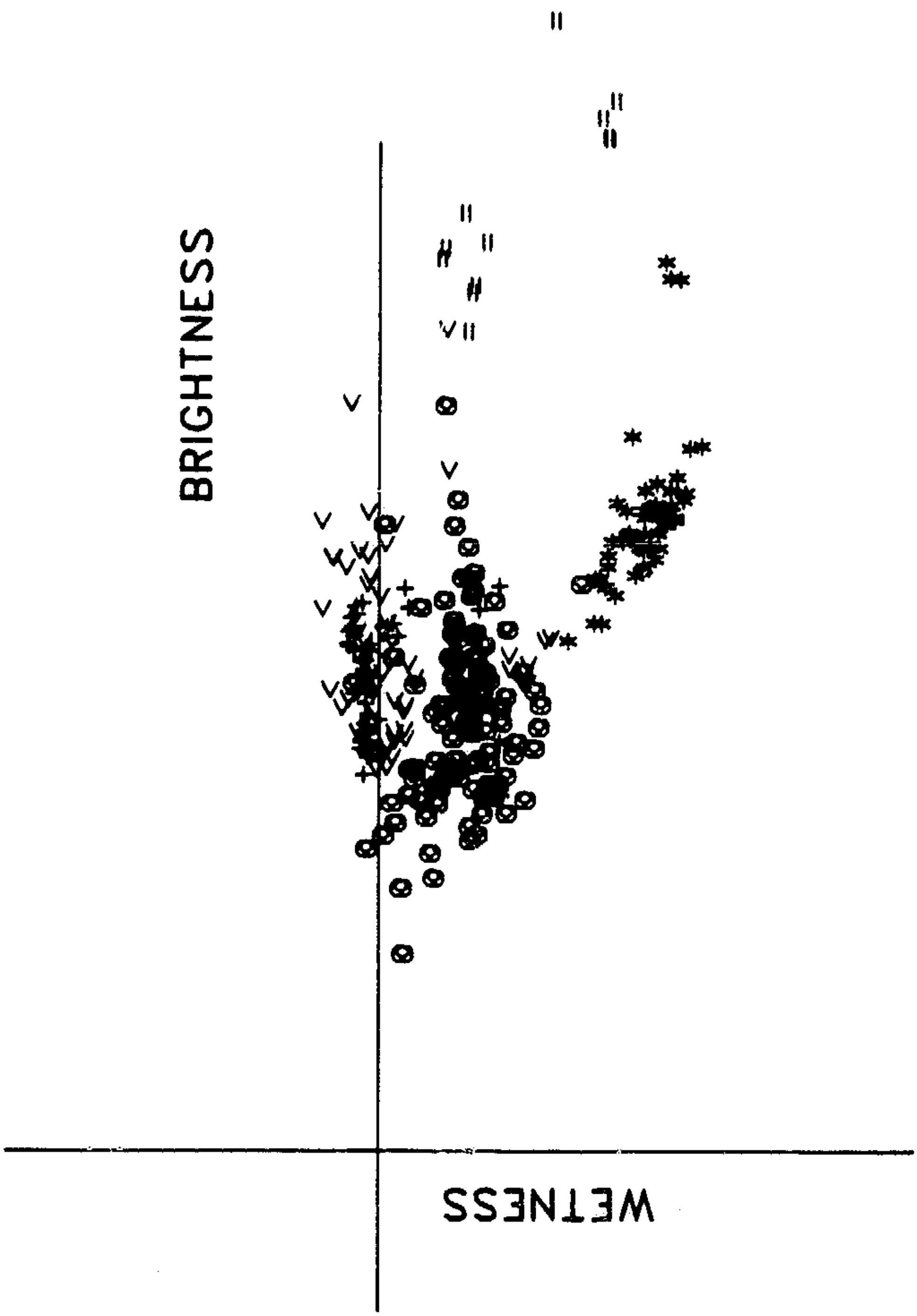

Figure 2.17. TM Tasseled Cap Plane of Soils. Sample data (based on simulated TM signal counts). Key: '+' green vegetation, full cover; '<' brown vegetation, nearly full cover; '@' field capacity soils (lab-measured); '*' bare field soils; '=' quarry sand (field-measured)

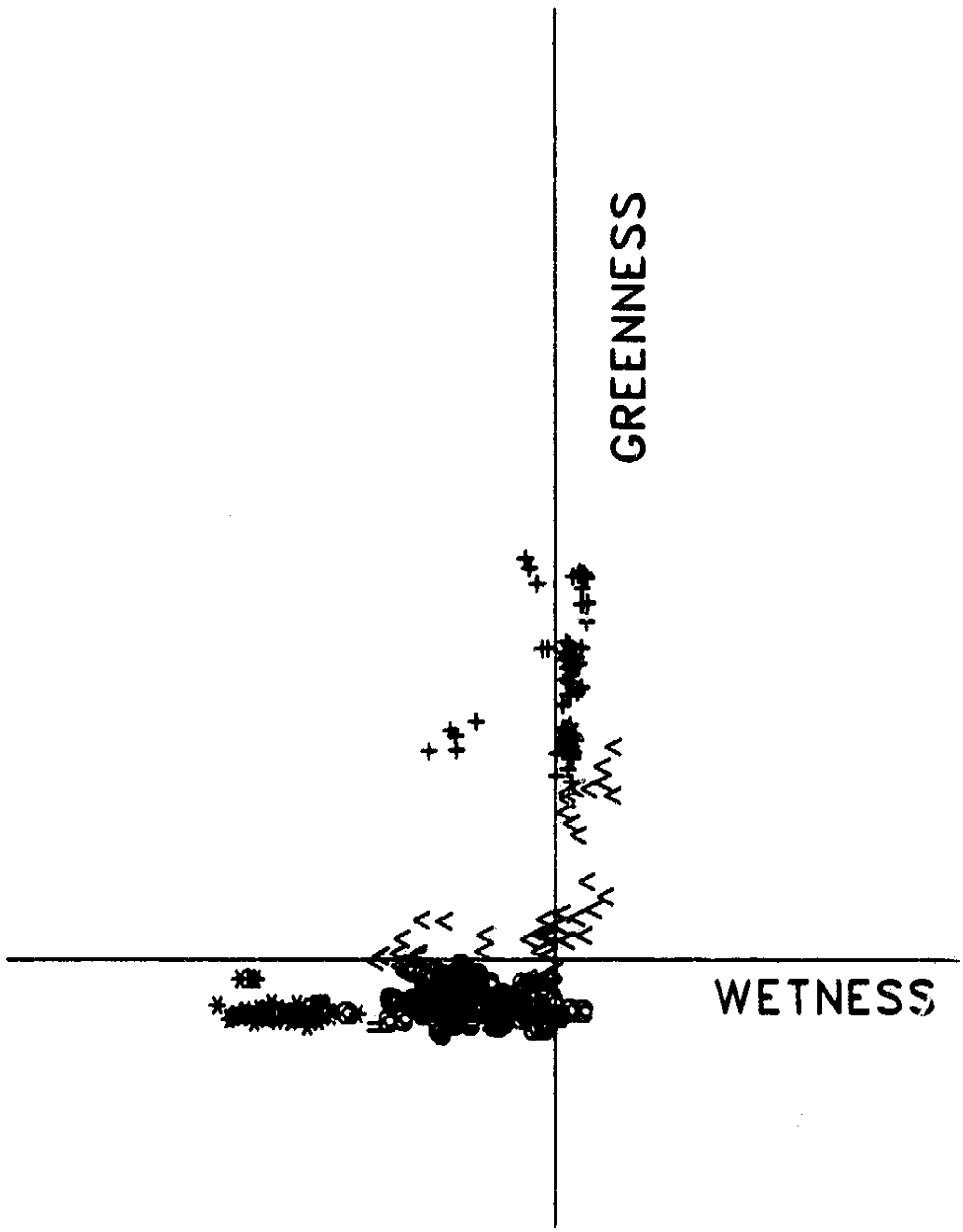

Figure 2.18. TM Tasseled Cap Transition Zone. Sample data (based on simulated TM signal counts). Key: '+' green vegetation, full cover; '<' brown vegetation, nearly full cover; '@' field capacity soils (lab-measured); '*' bare field soils; '=' quarry sand (field-measured)

factors or transformed features, ground-based results should be taken as indicators, and should always be confirmed in actual sensor data.

Crist and Cicone (1984a and 1984b) describe the physical significance of the TM Tasseled Cap features, and note that the fourth through sixth features of the transformation have as yet no known physical association. Because of this, there can be no assurance that the fourth through sixth features of this reflectance factor TM Tasseled Cap Transformation correspond to the same features in the simulated or actual signal count data transformations. Thus, while the entire matrix is included in Table 1, only the Brightness_R, Greenness_R, and Wetness_R features should be assumed to respond in the same manner as the analogous features of the previous transformations. No conclusions should be drawn, with respect to actual data response, based on reflectance factor data response in the fourth through sixth features.

Extending the Transformation

The reflectance factor TM Tasseled Cap transformation presented here is based on spectrometer data integrated over the pre-launch composite detector response functions of the Landsat-4 Thematic Mapper, and should not be routinely applied to reflectance factor data derived from some other source (e.g. a multiband radiometer) or integrated over different detector response functions (e.g. Landsat-5 TM). It is expected that the results obtained with this matrix for other reflectance factor data would be very nearly correct, depending of course on how greatly the instrument response differs from that used in this study. However, the results should be checked before proceeding with any analysis of the transformed data. The procedure for checking the transformation results, and adjusting the transformation if necessary, is outlined in general terms below.

First, the transformation matrix in Table 1 should be applied to the data. Viewing plots such as those in Figures 2.10 through 2.12, taking into account the data structures described in Crist and Cicone (1984a and 1984b), and comparing results to the figures in this and the previous papers, should give a first indication of the accuracy of the transformed results for the particular data in question. Plotting known samples from the entire data set, as in Figures 2.13 through 2.15, will give an even better measure of the transformation accuracy. If adjustment is indicated, it can be accomplished by applying three-dimensional rotations to the data (and the transformation matrix) such that the proper data alignments are achieved (again, for a more complete discussion of what "proper data alignments" are, see Crist and Cicone 1984a and 1984b). Because all the features of the transformation are orthogonal, rotations applied to a subset of features will not affect the other features, or the interrelationships between the rotated subset and the other features.

Conclusion

The reflectance factor TM Tasseled Cap transformation described here can be applied directly to many sets of reflectance factor data, and further provides a base from which similar transformations can be derived for other types of reflectance factor data. The resultant Brightness_R, Greenness_R, and Wetness_R features, though not identical to the actual data TM Tasseled Cap features, are analogous to TM Tasseled Cap Brightness, Greenness, and Wetness, and thus facilitate the application of knowledge gained through analysis of ground-based reflectance factor data to satellite-based signal count data.

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3.0
SOILS ANALYSES

Analyses in fiscal years 1982 and 1983 indicated that substantial new soils-related information was potentially available from TM data. In particular, indications of greater ability to measure the moisture condition of soils using TM data were observed. As a result, a major thrust of ERIM's FY84 research under this contract involved analysis of soils and their response in the TM wavelengths.

Section 3.1 describes a basic analysis of soil reflectance spectra in the 420 to 2420 nanometer spectral range, aimed at determining: 1) the number of distinct and significant directions of soil spectral response, 2) the suitability of the TM bands for soil monitoring, and 3) possible improvements in band placement or number in this wavelength region for the purpose of soil monitoring.

In Section 3.2, soil-related spectral variation in the Fourth TM Tasseled Cap Feature is considered. Although this variation represents a small fraction of the total TM data variability, the high radiometric quality of TM data allows for the possibility that this small variation could still be put to use. Accordingly, attempts were made to associate Fourth Feature spectral response with some physical property or condition of soils.

Sections 3.3 and 3.4 describe analysis of a new set of soil spectra, collected at ERIM under this contract specifically for the purpose of assessing the soil moisture monitoring potential of TM data. Section 3.3 describes analyses of the TM bands and TM band ratios in this context, while Section 3.4 discusses TM Tasseled Cap feature response as simulated from these new spectra.

Finally, since soil and vegetation most often appear to the sensor in some combination, it is of considerable importance to understand their joint effect. Section 3.5 describes initial analyses of the effect of soil background on some common vegetation indices, this time using Landsat Multispectral Scanner (MSS) data.

3.1
PRINCIPLE COMPONENTS ANALYSIS OF SOIL REFLECTANCE SPECTRA

Any particular sensor is of necessity designed either to a) best provide one particular type of information (e.g. for one scene class), or b) provide information on a range of scene classes, with the Landsat MSS and TM sensors falling in the second category. Since the most important and useful (information-bearing) spectral bands will likely differ, to varying degrees, from class to class, a broad-use sensor will necessarily represent a series of compromises, and will likely not be ideally suited to any one purpose.

The work reported in this section represents an initial effort at understanding the soils-related information contained in the spectral range from 420 to 2420 nanometers, without the constraints of a particular sensor, and thereby to define sensor bands which would be of greatest value with respect to soils monitoring.

Data Set.

The soil reflectance spectra of Stoner and Baumgardner (1980) comprised the base data set. These spectra cover the range from 420 to 2420 nanometers, with samples at 10-nanometer increments, and represent a wide variety of soil types at a constant (high) moisture level. For this initial analysis, the data were stratified based on atmospheric transmittance values from the atmospheric model of J.V. Dave (1978). Only those wavelength ranges with transmittance values greater than 0.80 (in Dave's Model 3 – a very clear atmosphere) were included in the analysis. The resulting wavelength intervals are listed in Table 3.1, and represent those showing the least influence of atmosphere from the perspective of satellite-based remote sensing. This stratification reduced the number of spectral samples for each soil sample to 110 at the 10-nanometer spacing.

Table 3.1 Wavelength Intervals Used in Analysis of Soil Reflectance Spectra (in nanometers)

550	to	750
780	to	910
980	to	1100
1180	to	1290
1520	to	1740
2100	to	2360

Approach

Principle components analysis (based on the covariance matrix) was performed on the 110 reflectance factor spectral samples for 569 cases (soil samples). The resulting coefficients were plotted and analyzed with respect to correlations within spectral regions, correlation to TM Tasseled Cap features, and relative importance (% variance).

Results and Discussion

Table 3.2 describes the portion of total data variability associated with the 40 computed PC's. It should be noted that, while the soils in the data set represent a wide range of texture classes, parent materials, and other characteristics, they may not a) provide equal representation of each of these characteristics, and/or b) provide a wide range of all the important reflectance-influencing soil characteristics. Thus one ought not to assume that a PC representing only a small portion of the total data variability is necessarily unimportant. The coefficients for the first six PC's are illustrated in Figures 3.1 through 3.3.

Wavelength Correlations. The visible wavelength region (400 to 700 nanometers) acted as a single unit through at least the first six PC's (i.e. all positive or all negative coefficients). Beyond that point, varying degrees of contrasts within this region were noted (e.g. "green" vs. "red"). The near-infrared region (700 to 1300 nm) was less uniform, and

Table 3.2 Percent Data Variation Associated with Soil Reflectance Principle Components.

PC	% Variance	Cum. % Var.
1	86.92	86.92
2	9.93	96.85
3	2.05	98.90
4	0.51	99.41
5	0.25	99.66
6	0.08	99.74
7	0.05	99.79
8	0.04	99.83
9	0.02	99.85
10	0.02	99.87
.	.	.
11-20	0.05	99.92
21-30	0.03	99.95
31-40	0.01	99.96

tended to include two wavelength regions (distinguished by coefficient signs). However, the boundary wavelength between the two regions was not stationary, but varied with PC. Two longer infrared regions (1500 to 1750 nm and 2000 to 2400 nm) behaved as one only through the first two PC's. The shorter of the two regions exhibited response correlation through the first seven PC's, while the longer wavelength region showed some variation within itself in the fifth PC, and considerable variation after the first seven PC's.

In the mid-range of PC's (numbers 10 through 30), much of the "action," as indicated by coefficient magnitudes, was concentrated around 900, 1300, and 2000-2400 nanometers. In the remaining PC's (numbers 31 to 40), most of the variation was in the near-infrared and first longer infrared intervals (700-1300 and 1500-1750 nm), with little variation in the visible and longest infrared ranges.

These wavelength interval correlations don't necessarily mean that, for example, only one visible band is needed in order to capture most of the important soil information. Such conclusions could only be drawn by analyzing the spectral effects of particular important soil characteristics (e.g. iron content, texture, etc.). The principle components analysis described here only provides one of many pieces of information which could be used, in combination, to specify optimum bands for soils-related remote sensing.

Correspondence to TM Tasseled Cap Features. As can be observed in Figure 3.4, the first two soil principle components are identical, in a qualitative sense, to the TM Tasseled Cap features Brightness and Wetness (coefficients in the figure are those for reflectance factor data, as described in Section 2.2, reduced by one-half to more closely match the range of the PC coefficients.) Since the TM response range corresponds closely to the

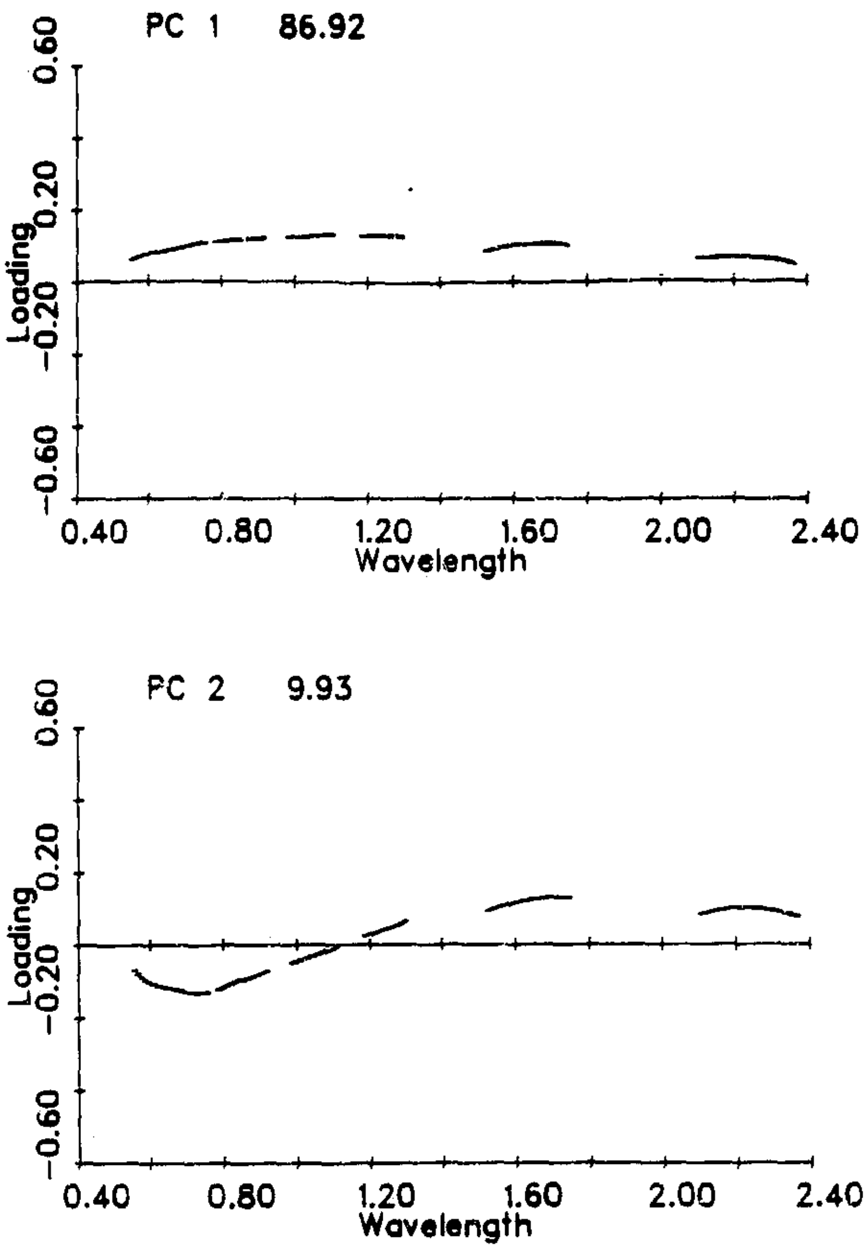

Figure 3.1. Soil reflectance principle components.

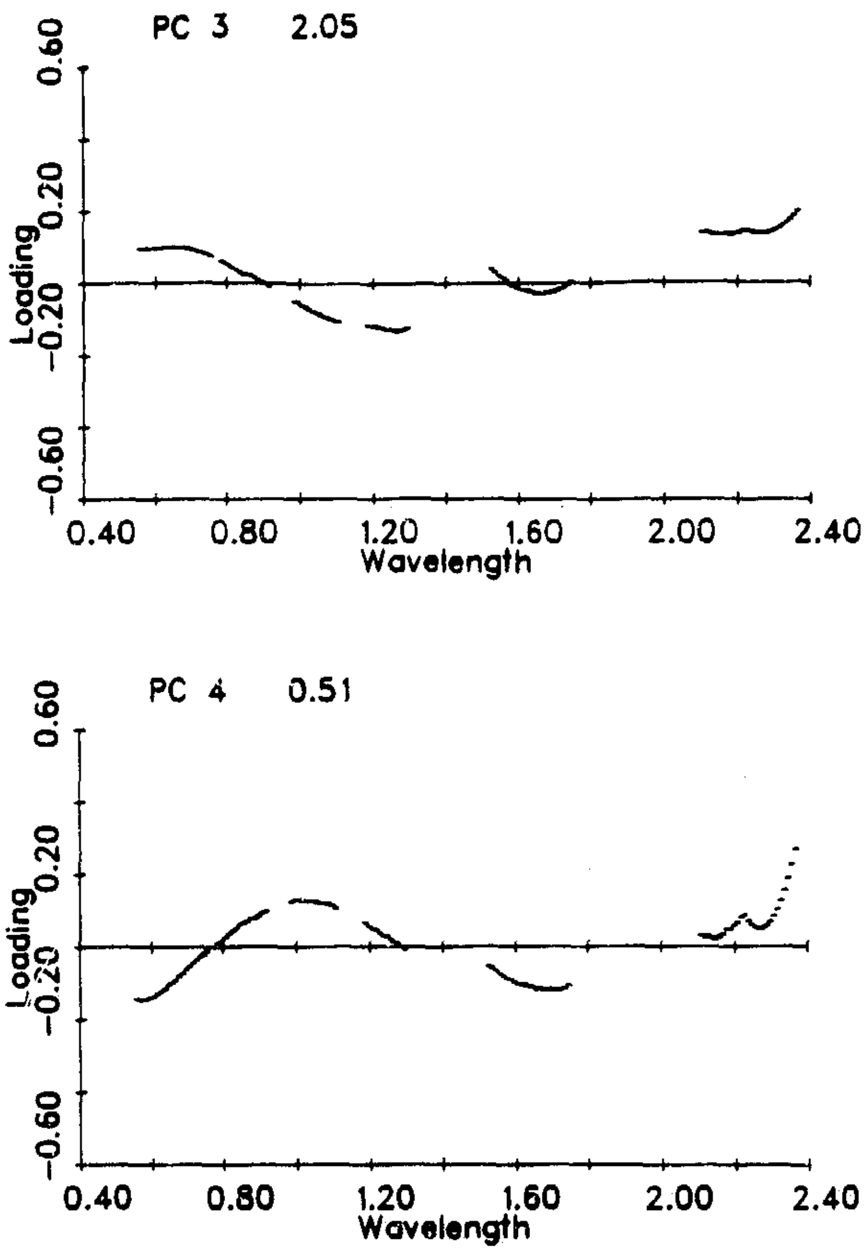

Figure 5.2. Soil reflectance principle components.

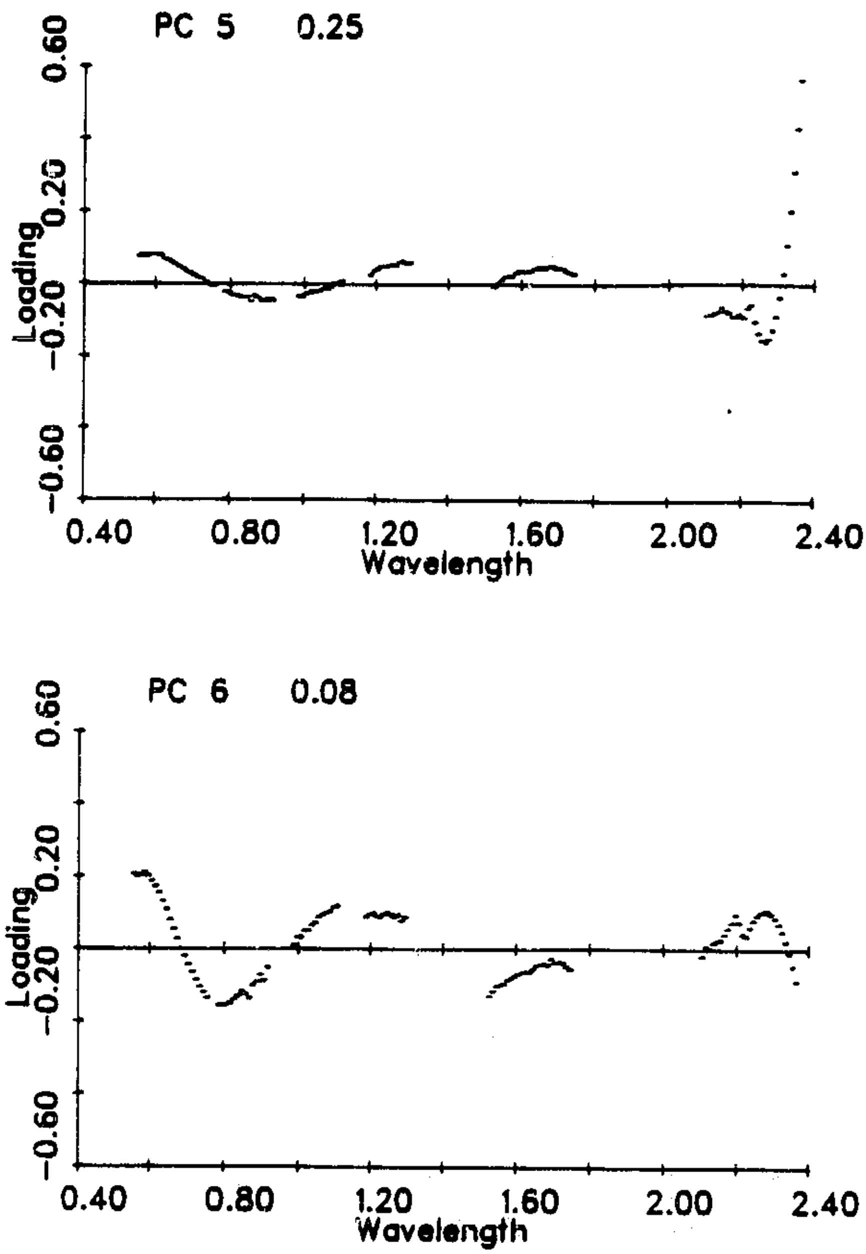

Figure 3.3. Soil reflectance principle components.

wavelength intervals used in this analysis, this result is not unexpected. It does, however, provide some confirmation of the previous TM Tasseled Cap results, and indicates that Brightness and Wetness are indeed the two primary spectral directions with respect to this diverse soils data set.

Also of note, however, is the fact that the third PC includes a contrast in the near-infrared wavelengths (approximately 750–900 nm vs. 900–1300 nm) which falls outside the range of TM band sensitivity, suggesting that, while the TM bands capture the majority of soils-related information in the 400 to 2400 nanometer range, some of that information is overlooked. Previous comparisons of TM vs MSS bands based on simulated signal counts (Crist and Cicone, 1984) have indicated little apparent loss of information associated with transition from the four MSS bands to TM bands 2,3, and 4. Since the MSS bands are sensitive from 700 to 1100 nanometers, one might expect the PC 3 contrast to be represented there. However, the coefficients of PC 3 change sign within the range of MSS 4 (800 to 1100 nm – see Figure 3.2), and so the contrast may in fact be lost, or largely suppressed, in the MSS data as well. Clearly, however, there is some soils information in the near-infrared range which cannot be captured by the TM bands, and may not be captured in the MSS bands. What is also clear is that the wealth of information potentially available in these soil principle components has by no means been fully understood by the limited analyses carried out thus far.

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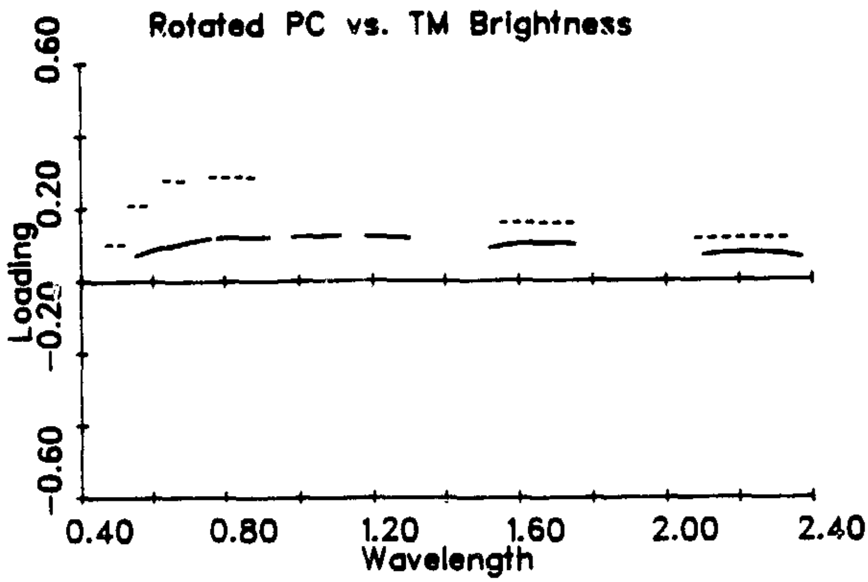

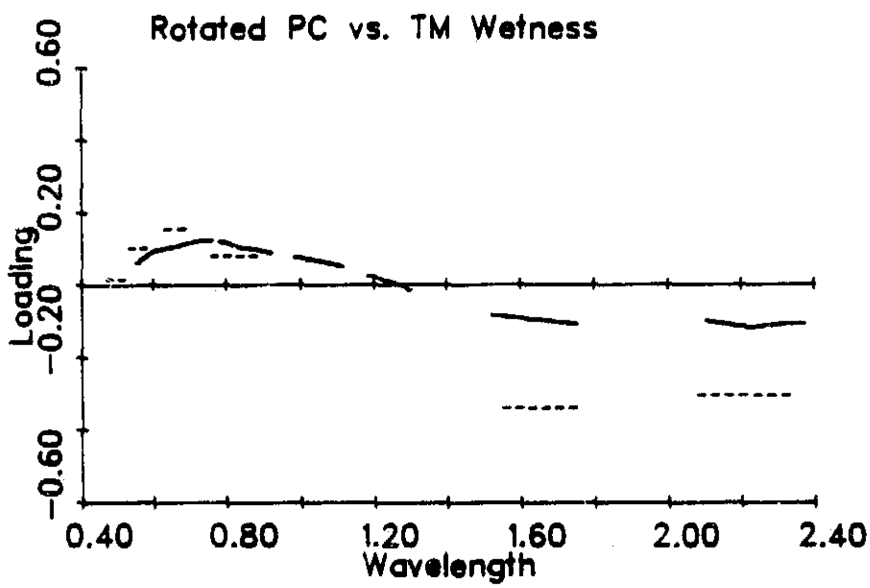

Figure 3.4. Comparison of TM Tasseled Cap features and soil reflectance principle components. Dashed lines indicate Tasseled Cap feature coefficients, scaled to fit on the graphs.

3.2
PHYSICAL CAUSES OF FOURTH TM TASSELED CAP FEATURE VARIATION

In the actual and simulated TM scenes analyzed to date, 95–99% of the total data variability is contained in the three Tasseled Cap features Brightness, Greenness, and Wetness. However, some lesser amount of variation was also observed, in the data simulated from lab-measured soil spectra, in the Fourth TM Tasseled Cap feature (Figure 3.5). Accordingly, an effort was made to associate this spectral variation with some physical property or characteristic of the lab-measured soils.

Approach

Analyses were carried out both for the entire set of lab soils (569 spectra for 294 soil series), and for a sub-sample from the larger set (46 spectra for 23 soil series). Because the soil variation in Figure 3.5 is partially expressed in the Greenness direction, a rotated Fourth Feature was defined to capture all of the observed soil variation. Table 3.3 lists the coefficients of both the original and rotated Fourth Features. Analyses were carried out using both of these features.

Two approaches were taken using the entire data set. First, the configuration of the data set is such that, for most of the soil series, two samples were included which, while representing the same series, could differ from each other in one or more important characteristics. After identifying a set of soil characteristics likely to influence or be correlated with soil spectral response (listed in Table 3.4), the soil series pairs were sorted in order to identify those series pairs which exhibited maximum variation in one property with minimum variation in the other key properties. Analysis of the spectral differences between the samples in the selected pairs thus provided the best indication of the spectral effect of a particular property.

Second, soil data in the Greenness vs. Fourth Feature projection were stratified by a variety of other soil descriptors, listed in Table 3.5, and visually examined to determine whether any clear delineation occurred as a result.

More intensive analysis of a subset of soils was also carried out. The subset was selected by stratifying the rotated Fourth Feature into "high", "medium", and "low" signal levels. Soil series for which both members of the pair fell in the same "high" or "low" category comprised the sub-sample. These soil series were then compared with respect to a) characteristics of their reflectance spectra, and b) physical or chemical properties.

Results

Change Vectors. Of all the properties listed in Table 3.4, only organic matter content was found to exert a consistent effect. Figure 3.6 illustrates this effect, while Figure 3.7 shows, for comparison, a typical result for another soil characteristic. In these figures, the arrows point in the direction of increasing values of the particular property being considered (e.g. increasing percentage of organic matter). While consistent with respect to the direction of spectral change induced by a change in organic matter content,

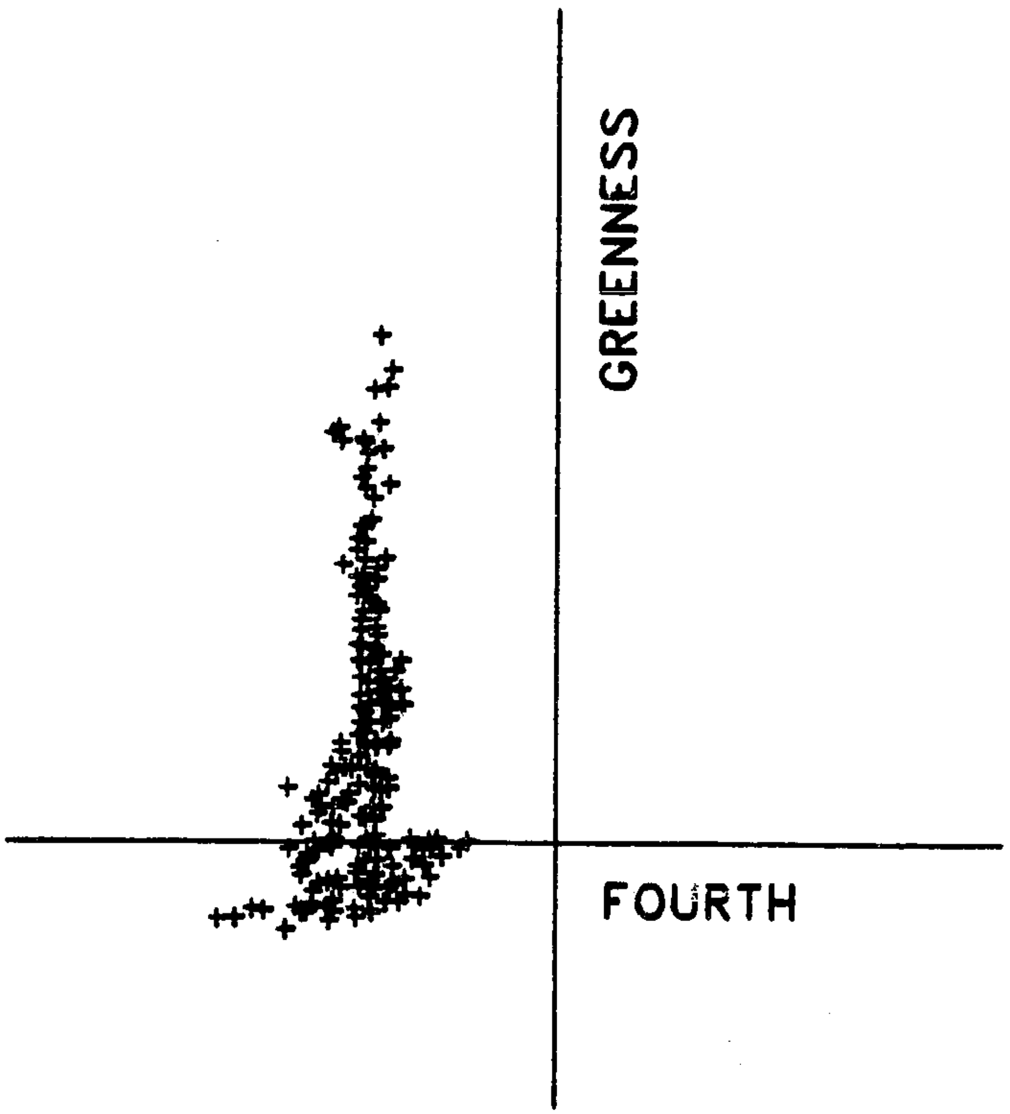

Figure 3.5. Greenness vs. Fourth Feature. Simulated data.

Table 3.3 Original and rotated Fourth Feature coefficients.

Feature	TM1	TM2	TM3	TM4	TM5	TM7
Original	-.83	.07	.42	-.08	.24	-.25
Rotated	-.86	-.00	.21	.29	.24	-.28

Table 3.4 Soil properties expected to influence reflectance

Texture	Organic matter content
Iron Oxide content	Cation exchange cap.
Sand %	Silt %
Clay %	Water content
Hue (Munsell)	

Table 3.5 Other soil characteristics used as stratifiers.

Climate	Particle size class distr.
Mineralogy class	Physiographic class
Parent material	Drainage class
Order	Temperature regime

the relationship between organic matter content and the Fourth Feature is not such that a particular signal in the Fourth Feature can be associated with a particular percentage of organic matter. Figure 3.8 illustrates this point, including the amounts (percentages) of organic matter for each point plotted. Some other factor must be responsible for, or at least interact with organic matter to determine, the absolute signal level in the Fourth Feature.

Stratification. Plots of the stratified soils data in the Greenness vs. Fourth projection, using the characteristics in Table 3.5 as stratifiers, revealed no clear relationship between any of the characteristics and Fourth Feature response.

Sub-sample Spectral Response. Comparison of the reflectance spectra and simulated TM response of the sub-samples (selected, as previously described, based on rotated Fourth Feature response), considered both actual response values. and slopes of the reflectance curves. Samples from the "low" group exhibited higher average response in the TM Band

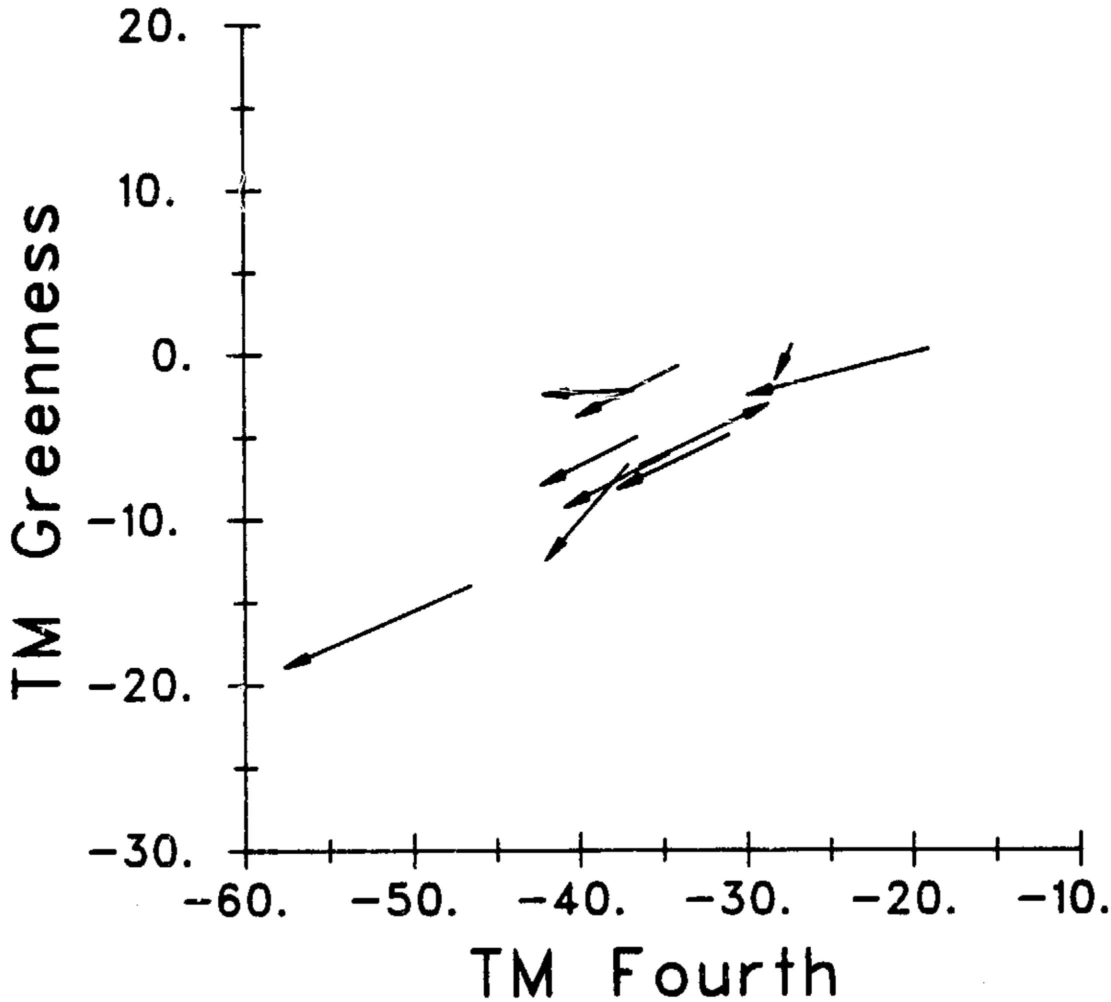

Figure 3.6. Direction of spectral change associated with changes in organic matter content.

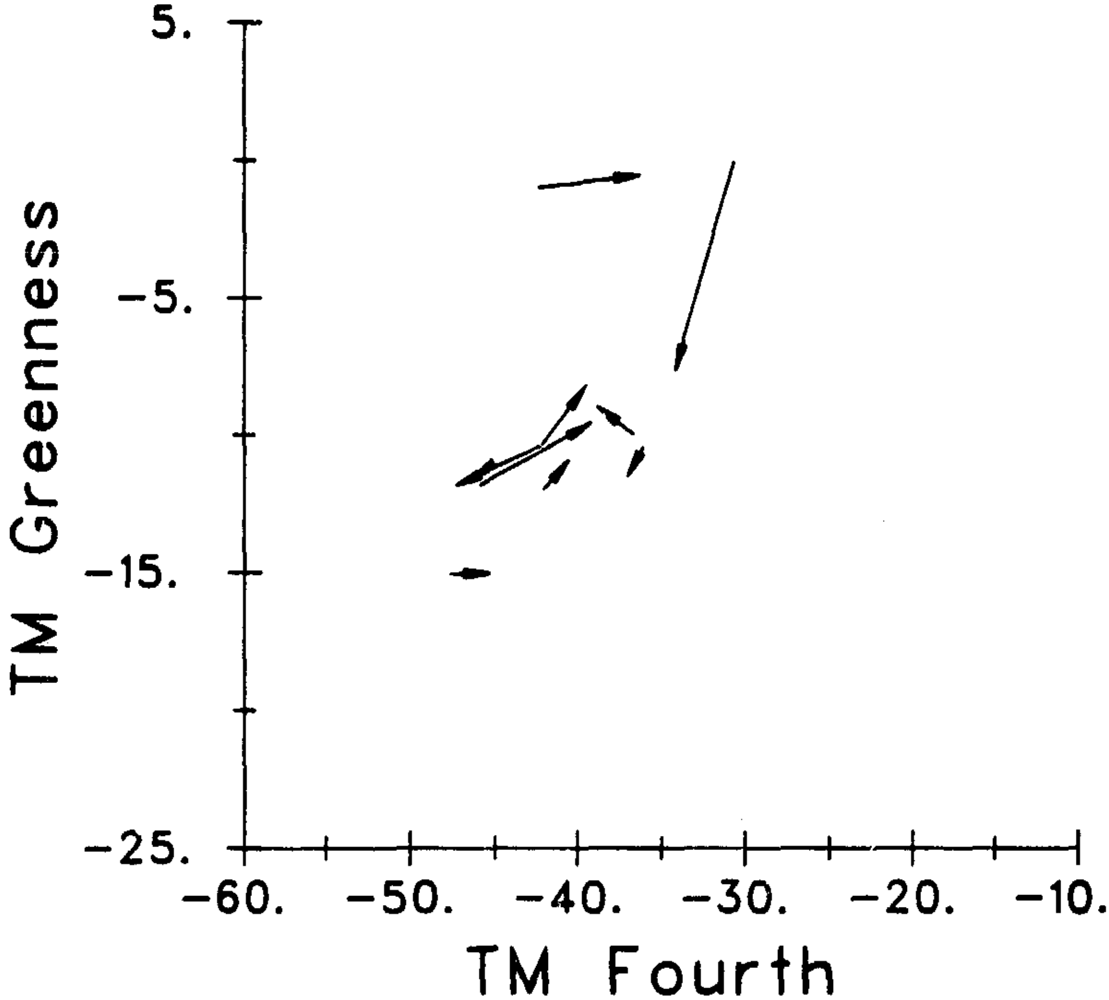

Figure 3.7. Direction of spectral change associated with changes in iron oxide content.

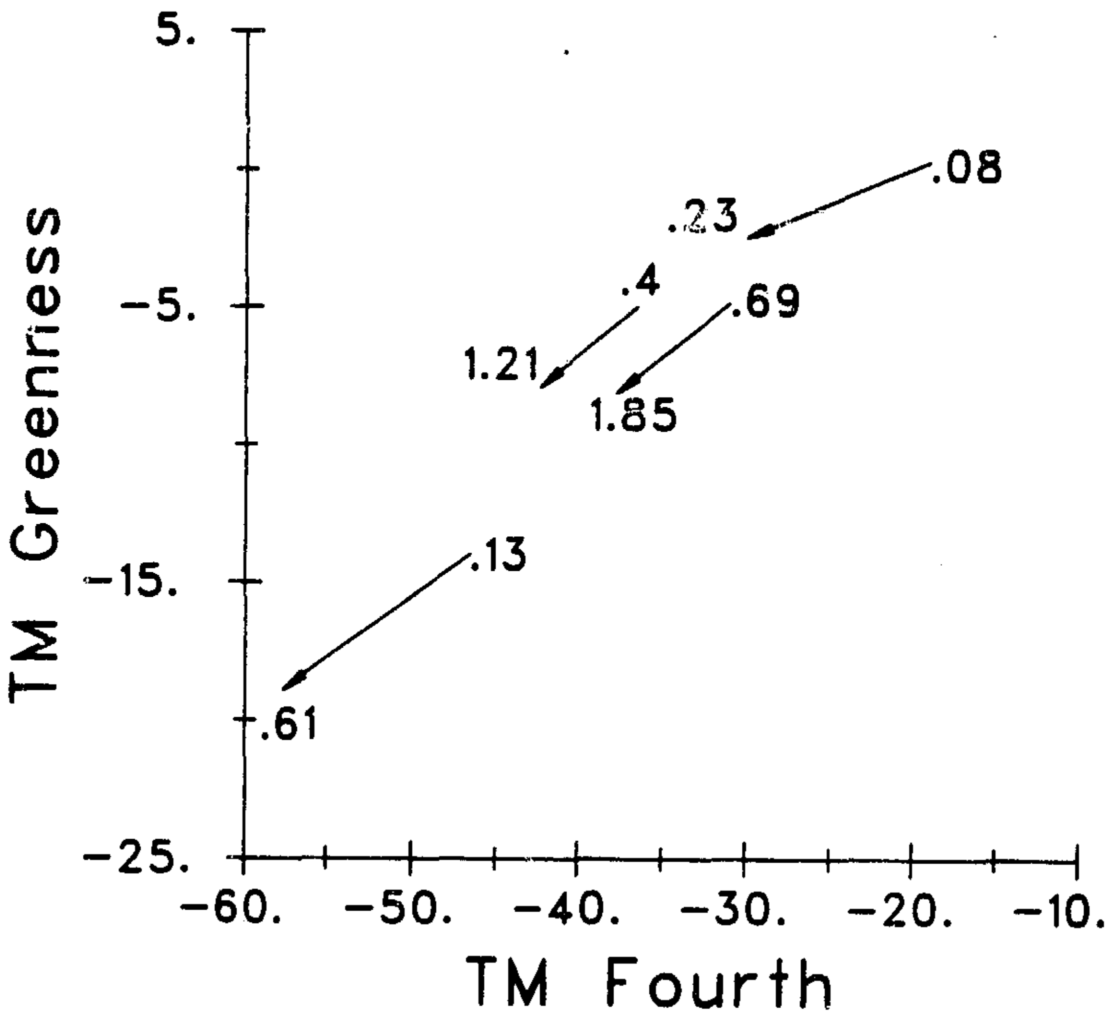

Figure 3.8. Direction of spectral change associated with changes in organic matter content. Selected samples.

1 wavelengths and, to a lesser degree, in the TM Band 2 wavelengths, as well as slightly lower average response in the TM Band 4 wavelengths. In terms of TM Tasseled Cap features, the two sub-samples had approximately equivalent Brightness and Wetness responses, while the "low" group also was characterized by lower average responses in the Fifth and Sixth TM Tasseled Cap features.

Figure 3.9 illustrates the average slopes of the reflectance spectra for the two classes. As can be seen from these data, the "low" group tends to have lower slopes through the visible bands, while the slopes of the two groups are, insofar as the TM band wavelengths are concerned, essentially identical in the infrared region. Both of these results indicate that, as might be expected based on the feature coefficients in Table 3.3, the primary difference being expressed in the Fourth Feature occurs in the visible region, and particularly in the shorter (blue-green) wavelengths.

Soil Properties Comparison. In the sub-samples, as in the entire data set, no one characteristic could be identified as being strongly correlated to Fourth Feature response. The soil series in the "high" group tended to: a) be associated with warmer temperature regimes, b) be better drained, c) have higher chroma's and more reddish hues (Munsell color), and d) contain higher concentrations of iron and aluminum oxides. The "high" group also fell mostly into the Mollisols and Alfisols, while the "low" group consisted mainly of Entisols. However, none of these differences were absolute.

Thus, in spite of fairly intensive analysis of the lab-measured soil spectra, no strong link between Fourth Feature variation and some soil characteristic could be identified. Additional analyses on a different data set specifically designed for this purpose are needed to establish the physical causes of Fourth Feature variation.

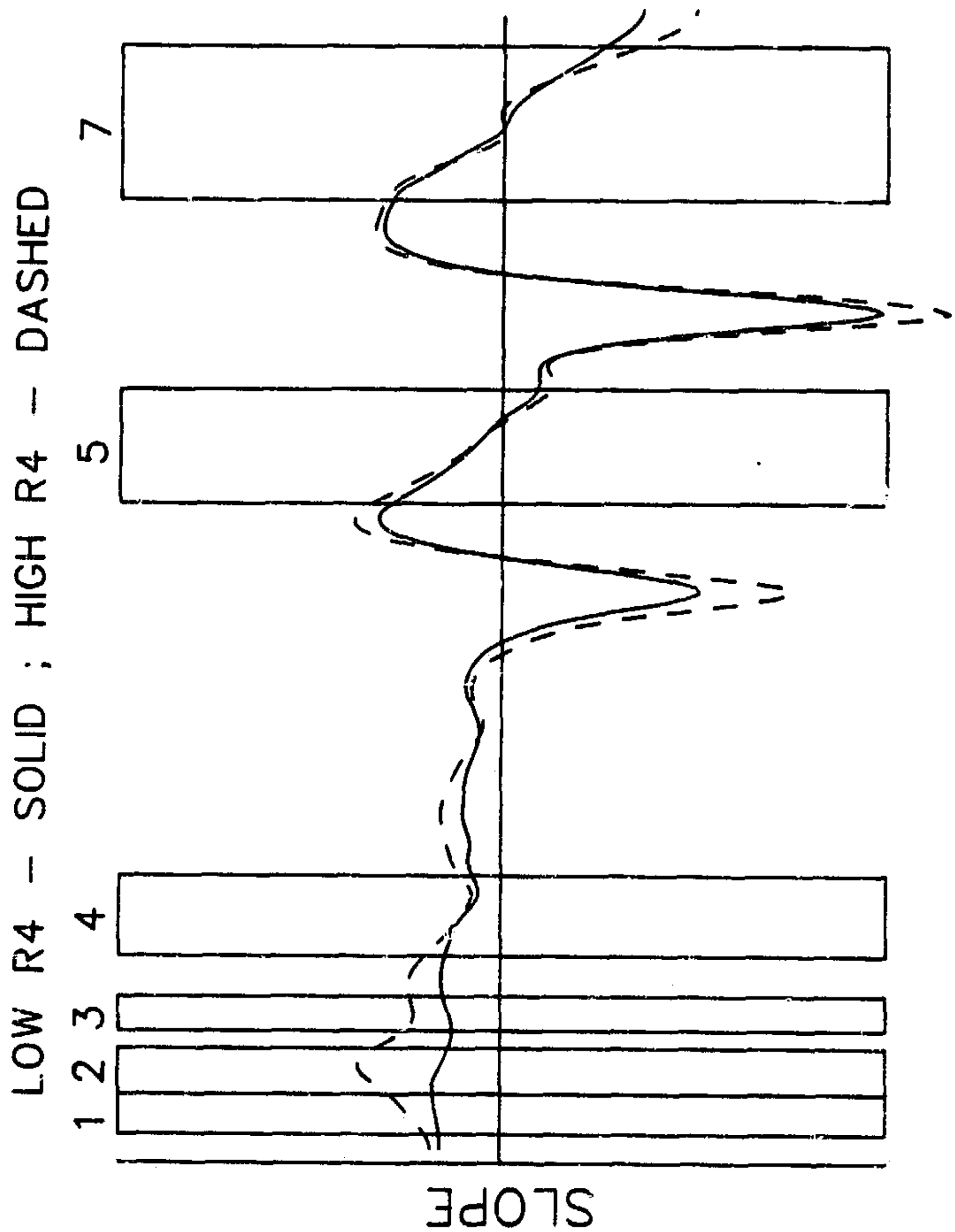

Figure 3.9. Average slopes of soil reflectance spectra.

3.3
MEASURING SOIL MOISTURE IN THE TM BAND WAVELENGTHS

Abstract

The soil moisture-related information contained in the Thematic Mapper spectral bands is investigated, using reflectance spectra from a variety of soils measured over a wide range of moisture contents. Inband reflectances for the wavelengths corresponding to TM bands 5 and 7 are found to respond in a consistent manner to changes in moisture content. A ratio of these two bands tends to correlate with a measure of available water (as opposed to absolute moisture content) for soils covering a wide texture range. If the residual variation observed can be identified and normalized through additional analysis, this technique could prove to be of considerable value for obtaining surface moisture information over a wide geographic region.

Introduction

Monitoring soil moisture is of major importance in agriculture; crop production depends in large part on the water available in the soil for carrying soluble nutrients to the root system and for maintaining the overall metabolism of plants. An adequate program of water monitoring is indispensable for economical management of irrigation, ensuring both that water can be applied to the soil before the crop is irreversibly affected by moisture stress, and that water will not be applied when it is not needed.

Several methods and systems have been developed to monitor the moisture content of the soil and evaluate its availability to plants. These methods can be divided into two groups: *in situ*, and remote. *In situ* methods include gravimetric techniques which involve soil sampling and direct measurement of water, the use of resistivity cells (gypsum or nylon blocks) which translate electrical conductivity of the soil to moisture content, tensiometers which provide direct readings of the suction force in the soil, and neutron probes which translate the loss of energy emitted by a probe into hydrogen (and thus water) content of the soil. Most of these methods are quite precise and reliable but they suffer from serious drawbacks associated with their limited spatial range, the cost of installation and maintenance of the field equipment, the amount of human effort required to perform continuous monitoring, and the limitation of measurement to easily accessible areas.

Remote sensing methods depend upon the measurement of electromagnetic energy that is either reflected or emitted from the soil surface. These methods include measurement of soil albedo and index of refraction, thermal infrared measurement of soil surface temperature, and microwave measurement of soil backscatter coefficients and dielectric properties.

Thus far, microwave techniques have received the most attention. Microwave sensors can provide surface penetration, to varying degrees, and thus can measure more than surface moisture. However, microwave techniques for soil moisture measurement are seriously affected by a number of factors including surface roughness and slope. In addition, such techniques have not yet been implemented in an operational system.

Idso et al. (1975a) demonstrated that overall soil reflectance (or albedo) is linearly related to the water content of the soil surface. As the water content increases, the reflectance decreases until a minimum reflectance is reached near the soil's saturation point. At saturation, free water begins to collect on the surface and reflectance begins to increase. However, soils vary so greatly in reflectance characteristics that a technique which used albedo for inferring soil moisture content could at best be applied to soils whose classification and some base reflectance values were known. Further, Schmugge et al. (1979) point out other drawbacks to the use of soil albedo in this regard, including the effects of surface roughness, illumination geometry, texture, and the presence of organic matter. Perhaps most importantly, soil moisture inferences based on surface reflectance can only take into account the moisture status of a thin surface layer of the soil, which may not represent the actual distribution of water throughout the soil.

Idso et al. (1975b) suggest that, in spite of these limitations, albedo measurements may still provide information of use in the calculation of soil water flux near the soil/air interface, thus facilitating understanding of the coupling of evaporative water loss with the properties of the soil surface and the supply of water to it from below.

Reginato et al. (1977) also evaluated reflective band ratios in the 400 to 1000 nanometer wavelength region as means to estimate soil moisture. They concluded, however, that such ratios were of little value in estimating moisture status, although they also suggested that ratios of longer infrared wavelength regions (including the 1400 and 1900 nanometer water absorption regions) to shorter wavelength regions might prove useful.

The launching of the Thematic Mapper (TM) aboard Landsats 4 and 5 has renewed interest in the use of reflective data for soil monitoring. In particular, bands 5 and 7 (1550 to 1750 nm and 2080 to 2350 nm) are well suited for studying absorption phenomena associated with the presence of water. Theoretical concepts backed by simulation and preliminary laboratory experiments seem to indicate that TM data could provide useful information with respect to soil moisture content and thus water availability to plants. While these bands can still not provide penetration below the soil surface, they may provide better information about surface moisture, and thus allow inference of other soil moisture conditions.

Dynamics of water in soils. The movement of water in soils and its availability to the root system of plants depend in large part on the textural makeup of the soil. This textural makeup determines the effective surface area of the soil particles and the overall size and geometry of the pores of the soil mass. Fine textured soils like clays are characterized by a very large surface area per unit volume and by an intense network of minute pores, which confer on such soils a much greater water-holding capacity than that exhibited by sandy soils.

For the same amount of water, the effective moisture available to plants will be much lower in clay soils than in sands, due to the fact that clay particles develop a greater matrix potential which allows them to hold the water more strongly than can the sandy soils. This texture-related matrix potential must be taken into consideration when assessing the actual availability of water to plants.

Although available water in soils varies continuously over a wide range, two soil moisture conditions are of particular importance. The first, field capacity, refers to the moisture content of a soil which has been saturated with water, and then allowed to drain freely, the excess water being removed gradually by the force of gravity until a state of equilibrium is reached between the natural suction force of the soil and the force of gravity. Field capacity is commonly accepted as a constant physical characteristic of a soil. This value typically ranges from 35 to 40 (percent of dry soil weight) for clayey soils and 15 to 20 for sandy soils. The second important moisture threshold is termed the wilting point. As moisture is further removed from the soil mass either through evaporation or through root uptake the matrix tension increases, making extraction of water by the plants increasingly difficult. The wilting point is reached when the suction from the soil particles exceeds the available root energy for water extraction. Beyond this point, irreversible wilting will occur. Like field capacity, the wilting point is considered an intrinsic soil property. The difference between field capacity and wilting point represents the total or maximum amount of water available to plants from a given soil, while the actual water availability at any given time is the total water content less the water content at the wilting point.

Soil moisture tension units and moisture tension/suction curves. The suction force developed by the soil particles is expressed as the height that a water column would rise from the water table against the force of gravity. This suction force primarily depends on the textural composition of the soil and is inversely proportional to the diameter of the pores. Figure 3.10 illustrates typical moisture suction curves for sandy and clayey soils. For the sandy soil, the wilting point and the field capacity correspond to 4% and 19% respectively, while in the clayey soil these states occur at 17% and 39%. In other words, at a water content (by weight) of 17%, the sandy soil will be nearly at its field capacity, while the clayey soil will be at its wilting point. These relationships underline the fact that a knowledge of the water content of a soil is not adequate in-and-of-itself for assessing the moisture available to plants — the textural makeup and soil moisture suction must also be taken into consideration.

Materials and Methods

Soil samples. Fifteen soil samples representing a wide range of mineralogical, textural, and drainage classes were selected for analysis. A list of these soils, and a brief description of their characteristics, are provided in Table 3.6.

The identification and classification of these samples were based on their locations with respect to soil map units and on field characterization, rather than on mechanical analysis. Thus there is some room for deviation, for any given sample, from the characteristics of the series with which the sample was identified.

Reflectance and moisture measurements. After being gently crushed and passed through a 2 mm sieve, each soil sample was lightly packed into a cell and brought to saturation. The saturation point was defined to be the point at which free water began to run out of the sample when the cell was tilted at about 45°. Each sample was then placed in a moisture can and allowed to dry slowly so that the moisture could be redistributed evenly throughout the samples. Water loss was monitored by weighing the cell at frequent

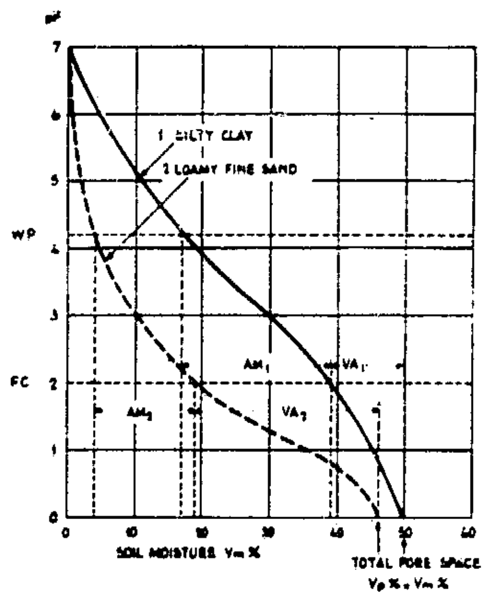

Figure 3.10. Example moisture suction curves (from Ilaco, 1981).

Table 3.6 Description of soils data set

Series name	Drainage	Color	Texture	Parent	Moisture	Temp.	Classif.
Algeria	well	red	med.-to-fine	limestone	xeric	xeric	rhodic haploxeralf
Brookston	poor	dark brown	medium	glacial loam till	aquic	mesic	typic argiaquoll
Fox	well	dark yellow-brown	medium	glacial loam till	udic	mesic	typic hapludalf
Georgia		red		mica shists			Non-soil
Kalkaska	well	dark gray brown	sandy	sandy	udic	frigid	typic haplorthod
Kenya	well	red	medium to fine	limestone	xeric	xeric	not established
Las Vegas Pink		red		weathered shale			Non-soil
Mali	well	strong brown		sandstone	ustic	thermic	ultic haplustalf
Miami	well	brown	medium	glacial loam till	udic	mesic	typic hapludalf
Morley	well	yellowish	fine	glacial loam	udic	mesic	typic hapludalf
Oakville	excessive	brown to pale brown	fine sandy	glacial outwash plains	udic	mesic	typic udipsamment
Pewamo	poor	dark grayish brown	medium to fine	glacial heavy loam till	aquic	mesic	typic argiaquoll
Spinks	very well	brown to yellowish brown	coarse	glacial outwash, sandy morains	udic	mesic	psammentic hapludalf
Vermillon	well	purple-red	fine	weathered shale	udic	frigid	inceptisol
Zambia	well	red	fine	weathered sandstone	ustic	hyper-thermic	xantic ferrasol

intervals. At predetermined moisture contents, the reflectance of each sample was measured (from 400 to 2500 nm) using a Beckman DK-2 Spectrophotometer. The reflectance curves were subsequently digitized and resampled at 10 nm increments. Inband reflectance values were computed using the pre-launch composite detector response functions for the Landsat-4 Thematic Mapper.

Moisture tension measurements. Samples of each soil were lightly packed into aluminum cylinders fitted at the bottom with filter paper and cheese cloth. The samples were then soaked overnight, weighed, and subjected to tensions of 0.05, 0.33, 1.5, and 15 bars. Moisture content was determined for each tension by comparison to the oven dry weight of the samples.

Results and Discussion

Soil moisture and single band soil reflectance. Figure 3.11 provides examples of the reflectance data collected. As expected, overall reflectance increases significantly as the soils become drier, reaching a maximum for the oven dry samples. For a given change in moisture content, the reflectance difference seems to be greatest at the longer wavelengths, and decreases with shorter wavelength until it becomes apparently insignificant at about 400 nm. In general terms, the reflectance change associated with decreasing moisture content can be characterized as a rotation about a point around 350 to 400 nm. This behavior is consistent with the known changes in water absorption, as illustrated in Figure 3.12.

Since the effects of moisture increase with increasing wavelength, one might logically expect that reflectance in TM bands 5 (1550 to 1750 nm) and 7 (2080 to 2350 nm) might be best suited to studying moisture-related spectral effects, Indeed, when the reflectance in TM bands 5 and 7 is plotted against moisture content (Figure 3.13), a consistent relationship is observed, with response in both bands decreasing in a curvilinear fashion with increasing moisture content. This relationship was further tested for a selected number of samples by measuring the reflectance of samples of unknown moisture content, inferring the moisture content based on the reflectance in TM bands 5 and 7 and curves such as those illustrated in Figure 3.13, and then determining the actual moisture content. In all cases, the moisture contents obtained through interpolation of the reflectance data were very close or identical to the measured moisture content.

The overall shape of the moisture/reflectance curves is fairly similar for the various soils. However, consistent with previous findings, there is significant difference between soils. Darker soils like Brookston exhibit low reflectance even at low moisture contents, while other soils exhibit much higher reflectance at the same moisture levels. Thus while the basic relationship between soil reflectance and soil moisture suggests that reflectance could be effectively used to measure the water content of soils, such an approach could only be used for soils whose general reflectance characteristics were already known.

Soil moisture and multi-band reflectance features. As illustrated in Figure 3.13, the reflectance values for TM bands 5 and 7, when plotted against moisture content, describe two curves which tend to converge and finally intersect at low moisture levels (2% or lower). Because this relationship is consistent both within and between soils, one might

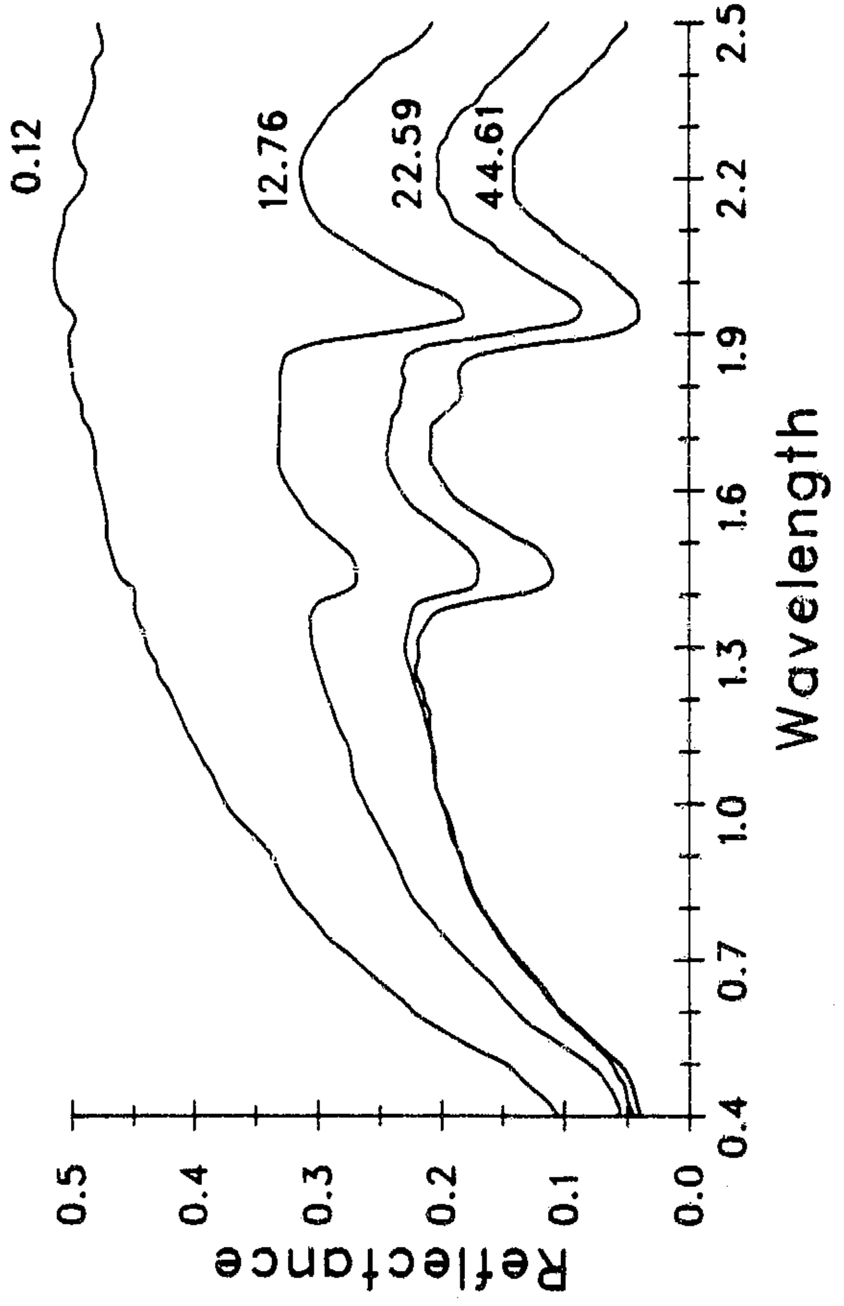

Figure 3.11. Example reflectance curves for Miami loam sample over a range of moisture contents.

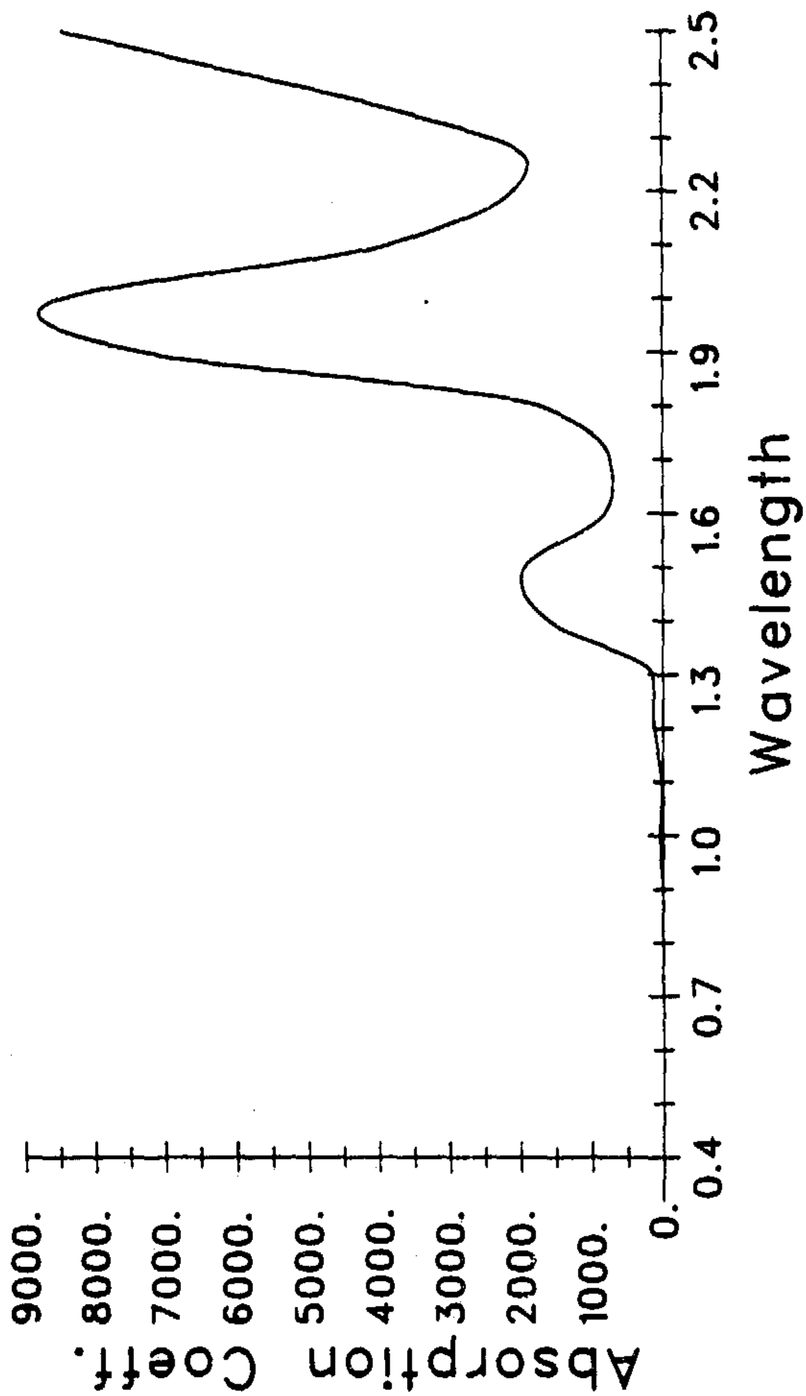

Figure 3.12. Absorption coefficient of pure water [Infrare.: Handbook, 1978].

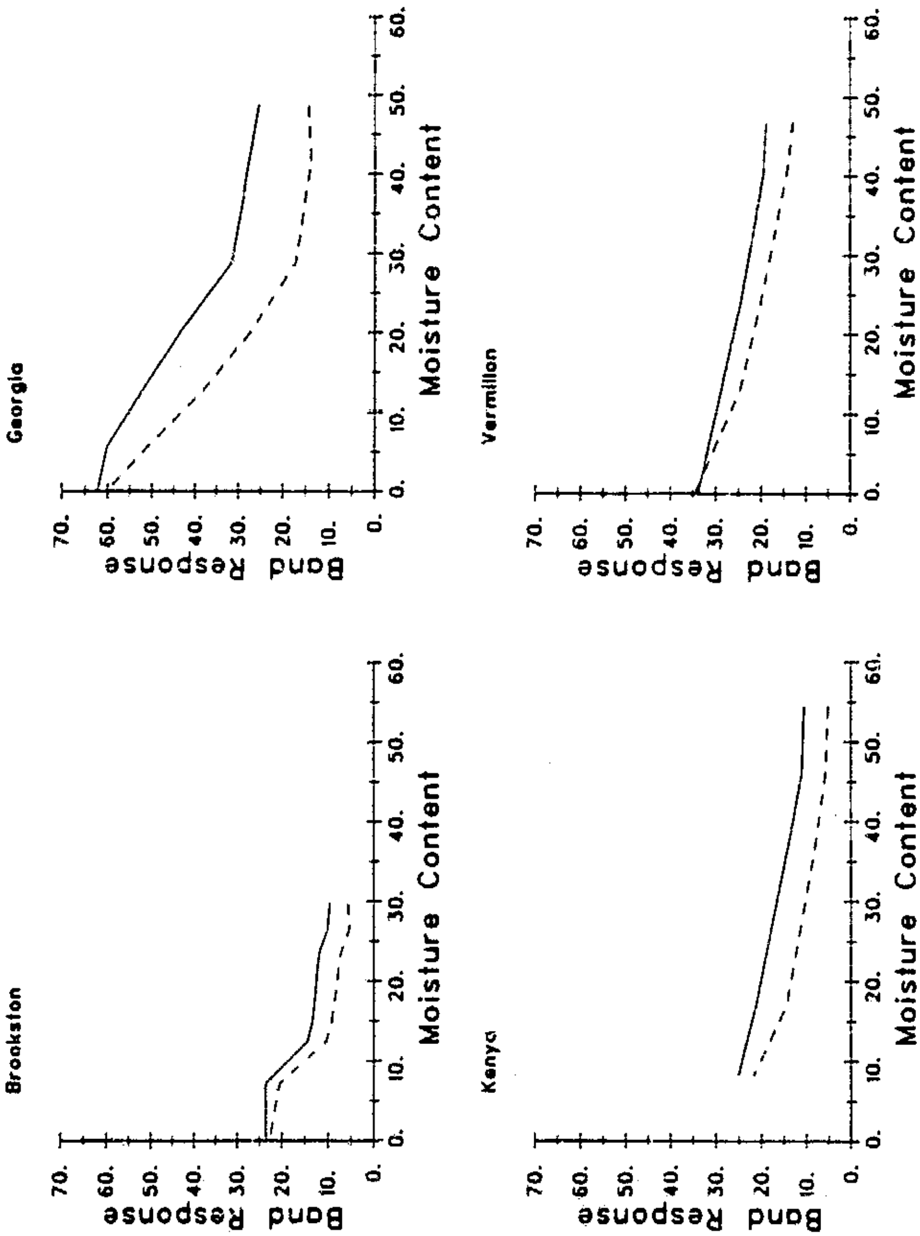

Figure 3.13. Relationship between moisture content and reflectance in TM bands 5 (dashed line) and 7 (solid line).

expect that a ratio of the two band response values could be used to infer the moisture status of a soil sample. Figure 3.14 illustrates the relationship between this ratio (TM5/TM7) and soil moisture content (on a percent of dry soil weight basis). Of note is the fact that all of the soils, in their oven dry state, exhibit ratio values centered closely around 0.94. In addition, there is a general correspondence between the slope of the curves (or a best linear fit to the data for a given soil) and the textural class of the soils: sandy soils tend to have steeper slopes while the heavy soils tend to be associated with lower slopes. On a qualitative basis, this relationship suggests that the reflectance ratio may provide information directly related to the available water or moisture tension of the soil. As previously stated, the moisture tension of a typical sandy soil at a given moisture content will be much less than that of a clayey soil at the same moisture content. Conversely, a given moisture tension will correspond to a much higher moisture content for a sandy soil than for a clayey soil.

In physical terms, one can understand this relationship by considering the surface area of a soil, and the thickness of the water layer. When water is applied to a mass of dry soil it tends to redistribute itself in thin layers around the soil particles and along the pores. For a given soil/water ratio, the thickness of the water layer will depend on the overall surface area of the soil. In sandy soils with relatively small surface area and larger pores, the water layer will be relatively thick, while in clayey soils the layer will be much thinner.

The amount of force required to pull the water from the soil is itself a function of the thickness of the water film and the size of the pores (and hence the surface area). In clayey soils, for a given amount of water, the film will be much thinner and the required suction force will be greater than that associated with a sandy soil. This explains why the same amount of water will correspond to a different pF or moisture tension value according to the textural makeup of the soil.

Similarly, the amount of spectral absorption by the soil, and hence its reflectance, is closely related to the thickness of the water layer on the soil particles. Consequently, in a sandy soil where the layer of water is thicker, the absorption will be greater than in a clayey soil where the layer is thinner. Thus textural composition affects both the tension with which the water is held (pF) and the reflectance of the soil at a given moisture content. Figure 3.15 shows the pF values for three soils ranging from sandy to clayey, while Figure 3.16 shows the TM5/TM7 values for these same soils, plotted against moisture content. The general relationships between pF and moisture content, and between moisture content and the TM5/TM7 ratio, are as expected. Finally, the actual TM5/TM7 ratio values were compared to pF values corresponding to the moisture contents associated with the various spectral measurements. These values were derived from smooth curves fit to the actual pF measurements. Figure 3.17 shows the result for all the soils, while Figure 3.18 displays the relationship for the three sample soils representing the three textural classes. A general correspondence can be seen in these figures, although with more deviation from the mean than can safely be ignored. While the amount of deviation indicates that a perfect relationship does not exist, the strong and consistent trend suggests that the relationship shows promise. If the data dispersion can be explained and normalized, based on some other physical characteristic of the soils, then

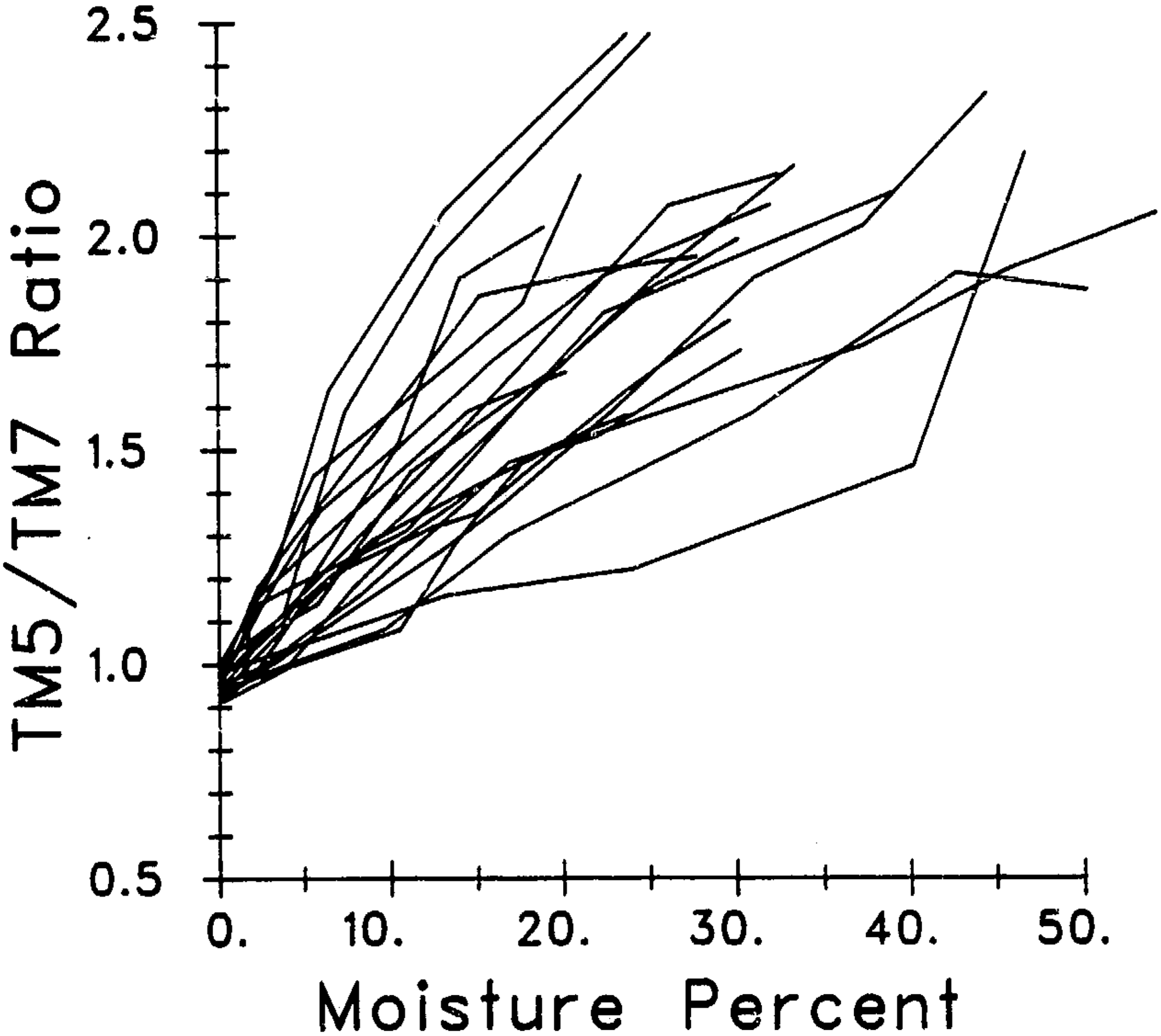

Figure 3.14. Relationship between TM5/TM7 ratio and moisture content.

this technique could provide a means by which available water, the key characteristic from a vegetation standpoint, could be inferred for soils of unknown type or textural class.

Limitations of passive reflective soil moisture assessment. As previously mentioned, soil moisture measurements based on visible and near-infrared wavelengths are limited to assessment of surface moisture only, while in fact a soil is a distinctly three-dimensional body made up of a sequence of more or less horizontal layers or horizons. The characteristics of these horizons are often quite variable, and many soils exhibit considerable vertical variability which greatly affects the overall water distribution and moisture availability. Figure 3.19 illustrates the progression of water content and distribution in a medium-textured soil following irrigation. Surface moisture content, which in this case exceeds sub-surface moisture content, can also, after redistribution of the moisture is complete, fall below the moisture level of the sub-surface horizons. Clearly then, surface moisture information is of limited usefulness in determining water availability at any given time. Nevertheless, as suggested by Idso et al. (1975b), there is still value to be gained by measurement of surface soil moisture, and while the relationship between surface and subsurface moisture is imperfect, knowledge of the surface soil moisture status should be of greater value than no soil moisture knowledge at all.

Summary and Conclusions

A functional remote sensing system aimed at monitoring the moisture status of soils must be able to 1) provide information on the relative water content of the soil, and 2) translate this information into actual water availability. This is indeed an ambitious task when one considers all the limitations to which such a system is subject, including the complexity of the dynamics of water in the soil, the spatial variability of the soil, and the very nature of soil reflectance (a cumulative property derived from the inherent spectral behavior of individual components).

Soil is indeed a very complex, often poorly defined mixture of material. The reflectance of a particular soil depends on the nature and amount of organic matter, the type and amount of clay material, the relative content of primary and accessory minerals, the texture of the soil mass, and the water content, all or most of which are interrelated. Besides the internal factors (i.e. those related to soil properties), one must also take into consideration the external factors. Laboratory experiments are conducted under strictly constant and controlled conditions of illumination and measurement. In nature, however, the external parameters are not constant, and may introduce variability that is often as important as the variability of the internal characteristics of the soil. Consequently, all such factors must be taken into consideration when the experiments are moved from the laboratory to the actual environment.

Finally, the effect of vegetative cover must be addressed. In the real world, moisture availability estimation is likely to be carried out mostly in agricultural areas for the purpose of assessing water availability to crops. The presence of vegetation will interfere with (or even mask completely) the actual reflectance of the soil. Unless techniques can be implemented for removing the effect of plant canopy reflectance (e.g. Tucker and Miller, 1977, Colwell, 1981), theoretical methods will have little practical value.

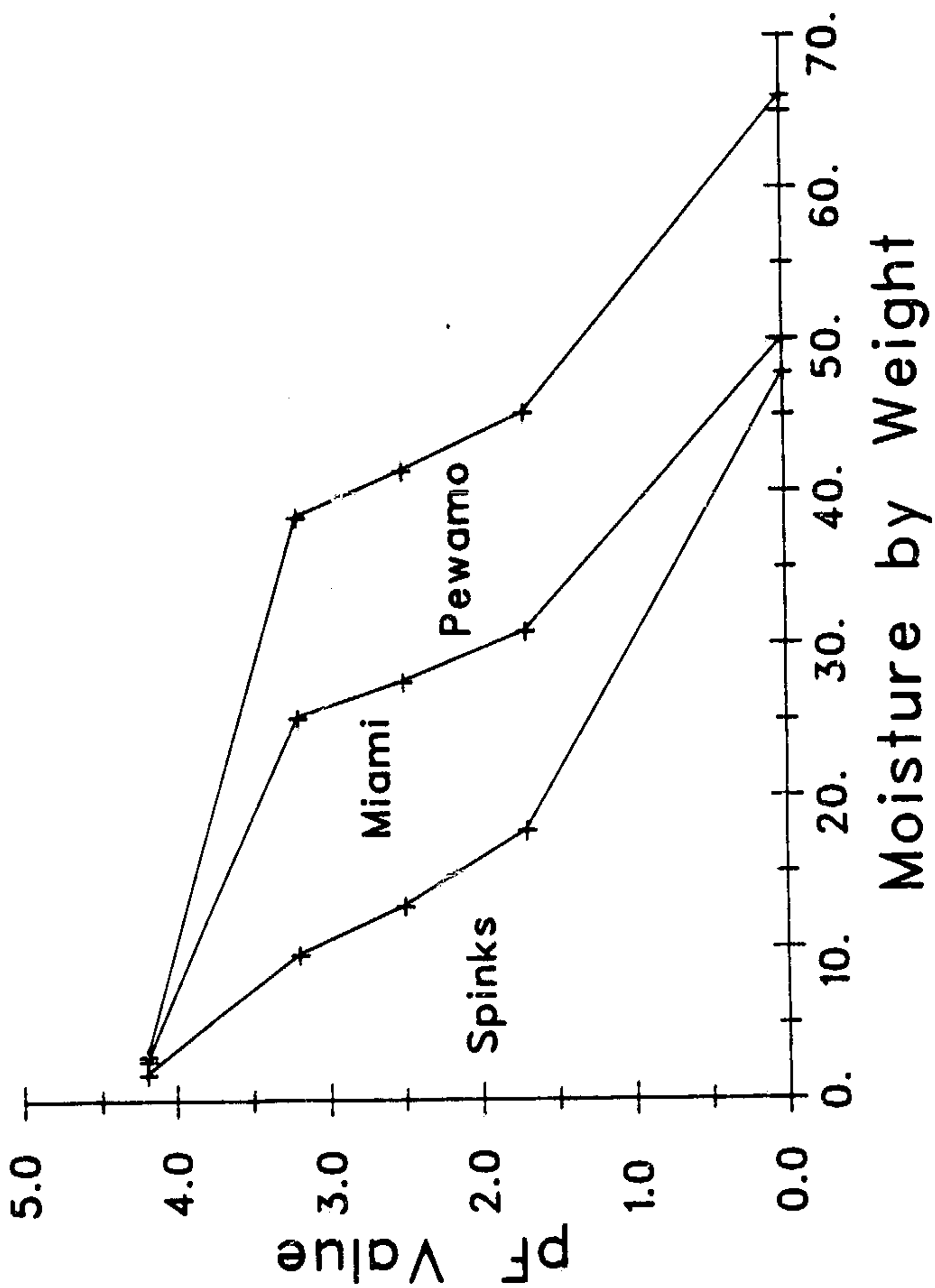

Figure 3.15. Moisture tension (pF) values for sample soils. Spinks – sandy, Miami – medium, Pewamo – clayey.

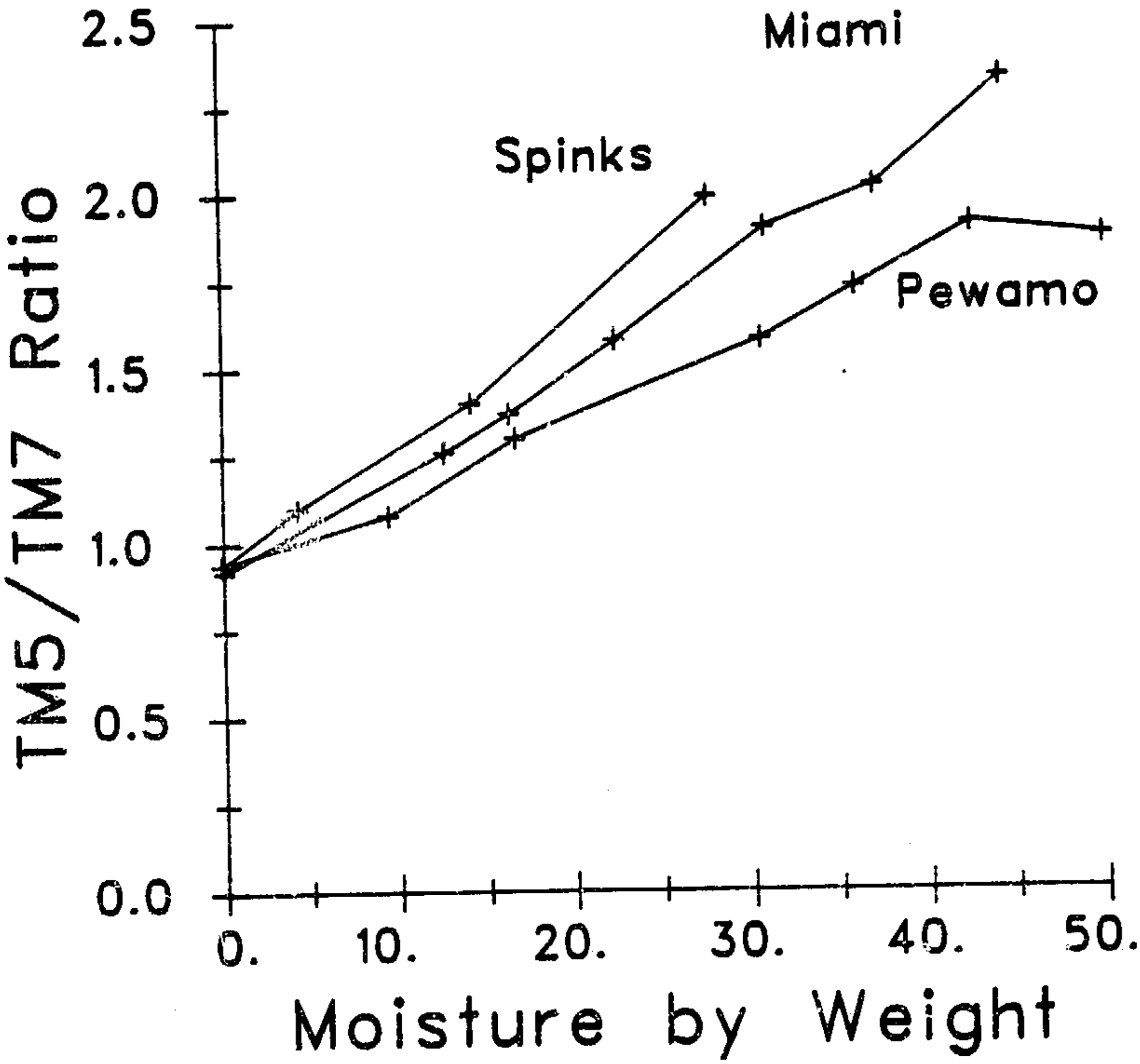

Figure 3.16. TM5/TM7 compared to moisture content for sample soils. Spinks – sandy, Miami – medium, Pewamo – clayey.

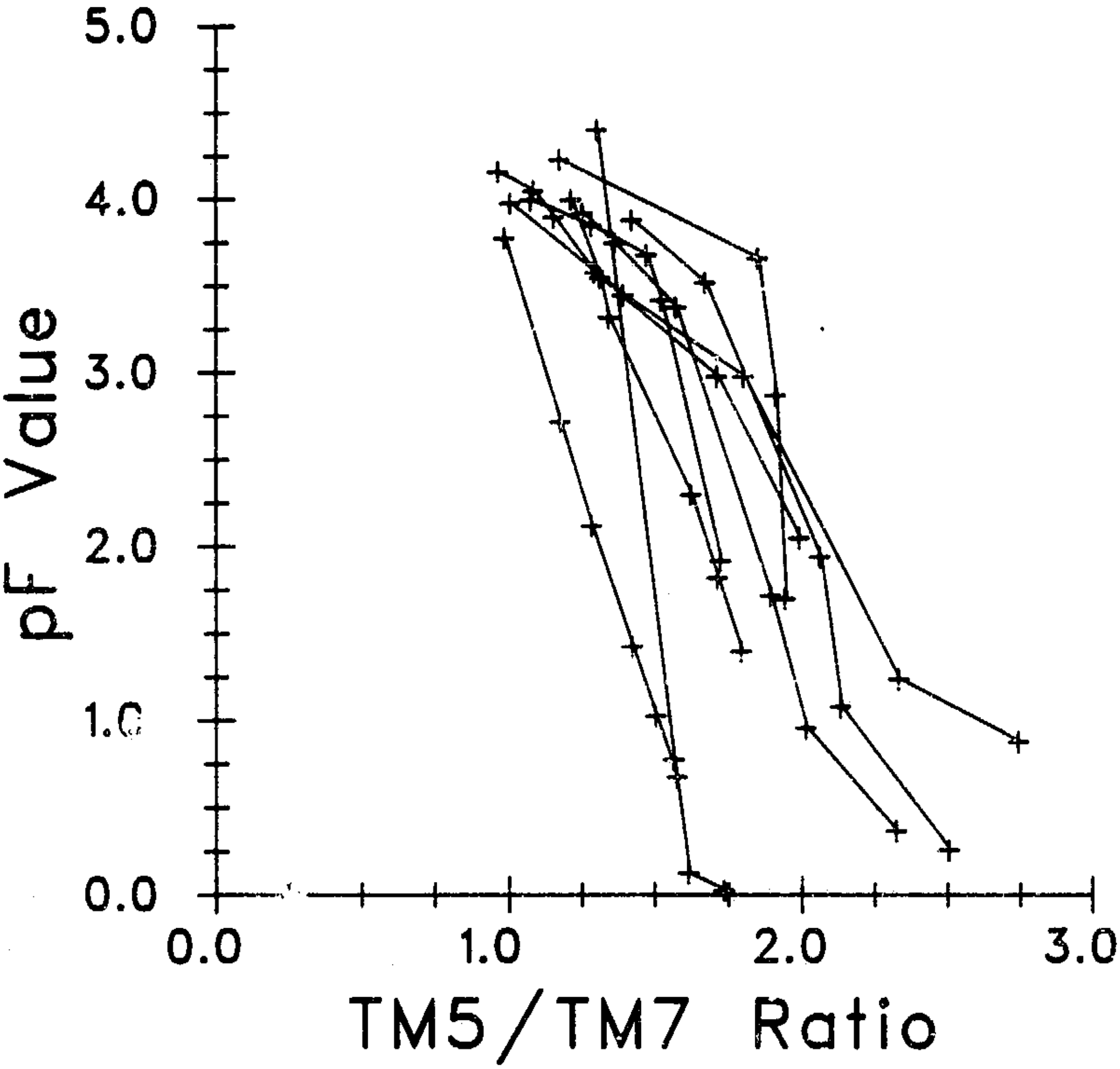

Figure 3.17. Relationship between TM5/TM7 ratio and pF value.

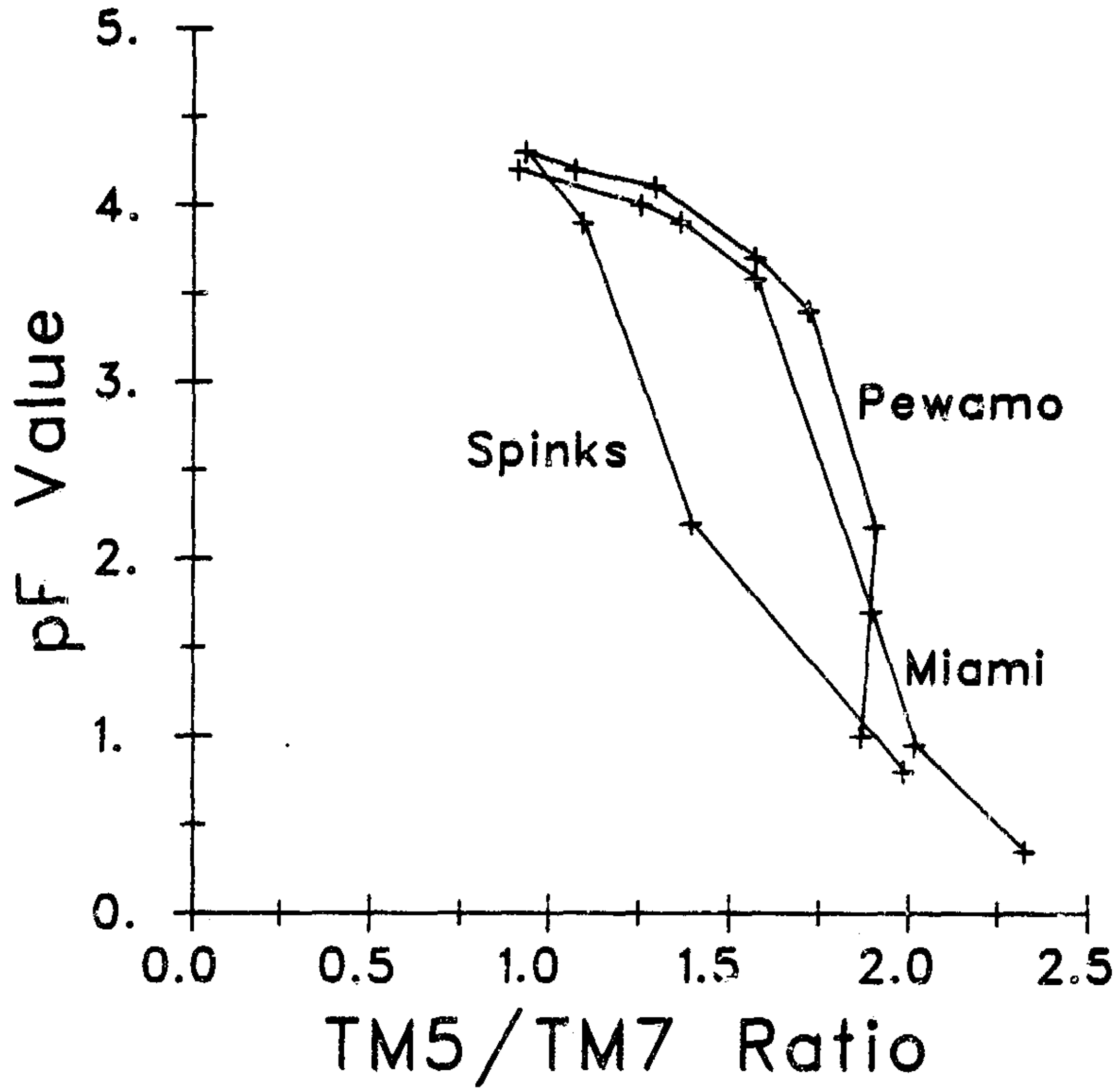

Figure 3.18. Relationship between TM5/TM7 ratio and pF value for sample soils. Spinks – sandy, Miami – medium, Pewamo – clayey.

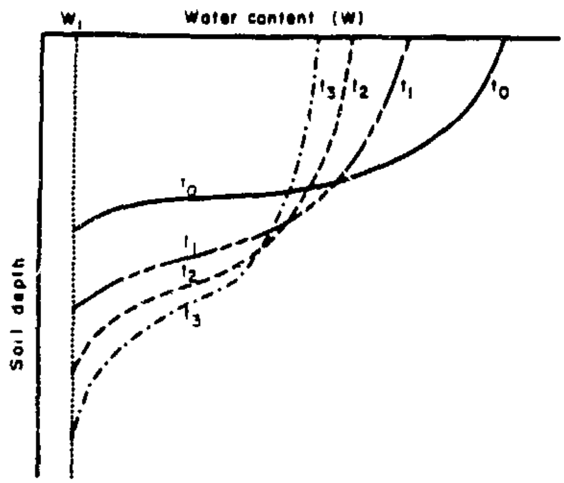

Figure 3.19. Moisture profile for a medium-textured soil following irrigation. The curves correspond to 0, 1, 4, and 14 days after irrigation, with w_1 representing the moisture status prior to irrigation [Hillell, 1971].

In spite of all the obstacles and limitations, however, the technique described in this paper offers promise of a significant advance in estimation of soil moisture using measurements of reflected solar radiation. The ability to determine available water, albeit at the surface only, for soils of unknown classification and textural makeup overcomes the problem of significant between-soil reflectance variability which is one of the key obstacles to soil moisture measurement in this wavelength region. Additional research aimed at explaining and normalizing the remaining variability between soils could result in a truly operational technique for deriving soil moisture information from Thematic Mapper data.

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3.4
SOIL EFFECTS AND INFORMATION IN TM TASSELED CAP FEATURE SPACE

Abstract

Laboratory measurements of the spectral response of soils at various moisture levels are used to simulate Landsat–4 Thematic Mapper (TM) signal counts and TM Tasseled Cap features, for the purpose of investigating the physical characteristics or conditions of the soils which dominate TM Tasseled Cap spectral response. While a consistent correlation between changes in moisture content and direction of spectral change in the TM Tasseled Cap Wetness-Brightness projection is observed, no absolute relationship between Wetness and soil moisture content can be derived, with both texture and organic matter content influencing the nature of the Wetness response. Promising correlation between Wetness and moisture tension (available water) is shown, however. In addition, soil spectral response in TM Tasseled Cap Greenness and the fourth TM Tasseled Cap feature are discussed.

Introduction

The importance and value of remote detection of soil moisture status has long been recognized, and has been the impetus for considerable research over the last ten or more years. Overall soil reflectance has been shown to be well correlated with surface moisture status for a given soil (Idso et al., 1975), but the range of overall reflectance among soils is so great that little hope exists that overall reflectance could be used to predict the moisture status of unknown soils (e.g. in a large scale satellite-based survey). Accordingly, recent research has emphasized either thermal or microwave measurements (Schmugge, 1978 provides a general discussion of both thermal and microwave techniques, while Schmugge, 1983 describes more recent microwave research). These techniques too have met with some obstacles. Vlcek and King (1983) demonstrated a strong correlation between diurnal surface soil temperature variation and subsurface soil moisture. However, they found that the nature of this relationship was dependent on soil textural class and prevailing weather conditions, thus limiting extension of the relationships only to soils of similar textural composition measured under similar weather conditions. Similarly, textural composition and surface roughness have been found to influence the microwave dielectric behavior of soils (Wang et al., 1983, and Hallikainen et al., 1984). Schmugge (1983) reports that soil texture effects on microwave soil moisture measurement can be largely removed by using percent of field capacity rather than absolute moisture content (percent of dry soil weight), and that roughness effects can be minimized by prudent choice of wavelength and view angle. He suggests that one key factor limiting development of operational microwave soil moisture monitoring techniques is the lack of a suitably extensive data set with which to test the approaches already developed.

Because soils in the four bands of the Landsat Multispectral Scanner (MSS) vary primarily in one direction related to overall reflectance, little success has been achieved in attempts to measure soil moisture using MSS data. However, the Thematic Mapper (TM) on board Landsats 4 and 5 includes two bands at longer infrared wavelengths than those of the MSS. These bands are more sensitive to moisture variation, and thus indicate a potential for improved soil moisture monitoring. Although all sensors operating in the reflective portion of the electromagnetic spectrum are limited to measuring surface soil moisture (the implications of which are summarized in Section 3.3), the availability of even surface moisture information from a system such as Landsat would represent a significant advance in our ability to monitor global processes and manage cultivated vegetation resources.

Crist and Cicone (1984a and 1984b) have described the underlying structure of TM data in the six reflective bands, relative to vegetation and soil cover types, and have derived a transformation, termed the TM Tasseled Cap transformation, which adjusts the viewing perspective on the data such that these data structures can be viewed directly and separately (for a general discussion of the Tasseled Cap concept, see Crist and Kauth, 1985). Soils in the TM Tasseled Cap feature space primarily occupy a single plane, described by the features Brightness and Wetness and labeled, for obvious reasons, the Plane of Soils.

In early studies the Wetness feature appeared to respond to changes in moisture content (hence the name), independent of the significant between-soil variation in overall reflectance as expressed in the Brightness feature. In addition, a small though still significant amount of soil-related spectral variability was observed in the TM Tasseled Cap Fourth Feature. The work described here was undertaken to: 1) further investigate the soil properties or characteristics responsible for the observed spectral variation in the TM Tasseled Cap feature space, and 2) to particularly study the relationship between soil moisture and TM Tasseled Cap Wetness.

Materials and Methods

Eighteen soil samples (different classifications, horizons, or replications) were used in this analysis. These are listed and described in Table 3.7.

These soils are ranked, in a general fashion, as to texture and organic matter content in Tables 3.8 and 3.9. Each soil was loosely packed into a sample holder, saturated with water, and then allowed to dry slowly. The samples were weighed, then their reflectance in the 400 to 2500 nm range was measured (using a Beckman DK-2 Spectrophotometer) at intervals through the drying process. Finally, the samples were baked in an oven overnight, weighed, and measured in the Spectrophotometer.
It should be noted that, as a result of the simple drying procedure used, soil samples may have been drier on the surface than below the surface. Since moisture content was determined by weight of the entire sample, this could result in some error, even though drying was allowed to proceed slowly in an effort to minimize the unevenness of the moisture distribution. One consequence of this procedure for nearly-dry samples is noted in the Results and Discussion section.

TM signal counts were simulated using pre-launch composite detector response functions for the Landsat-4 Thematic Mapper (Markham and Barker, 1983), the Dave atmospheric model for a very clear atmosphere (Dave, 1978), and pre-launch gains and offsets, again for Landsat-4 TM (Markham and Barker, 1983). These signal counts were then converted to simulated TM Tasseled Cap features using the transformation of Crist and Cicone (1984a). Smooth curves were fit to the data in the TM Tasseled Cap

Table 3.7 Description of soils data set for Tasseled Cap feature analysis

Series name	Drainage	Color	Texture	Parent	Moisture	Temp.	Classif.
Algeria	well	red	med.—to-fine	limestone	xeric	xeric	rhodic haploxeralf
Brookston	poor	dark brown	medium	glacial loam till	aquic	mesic	typic argiaquoll
Fox	well	dark yellow-brown	medium	glacial loam till	udic	mesic	typic hapludalf
Georgia		red		mica shists			Non-soil
Kalkaska	well	dark gray brown	sandy	sandy	udic	frigid	typic haplorthod
Kenya	well	red	medium to fine	limestone	xeric	xeric	not established
Mali	well	strong brown		sandstone	ustic	thermic	ultic haplustalf
Miami	well	brown	medium	glacial loam till	udic	mesic	typic hapludalf
Morley	well	yellowish	fine	glacial loam	udic	mesic	typic hapludalf
Pewamo	poor	dark grayish brown	medium to fine	glacial heavy loam till	aquic	mesic	typic argiaquoll
Spinks	very well	brown to yellowish brown	coarse	glacial outwash, sandy morains	udic	mesic	psammentic hapludalf
Vermillon	well	purple-red	fine	weathered shale	udic	frigid	inceptisol
Zambia	well	red	fine	weathered sandstone	ustic	hyper-thermic	xantic ferrasol

Table 3.8 General ranking of soils by texture.

Coarse	Kalkaska Spinks
Medium	Brookston Fox Miami
Medium-to-fine	Algeria Kenya Pewamo
Fine	Morley Vermillon Zambia

Table 3.9 General ranking of soils by organic matter content.

Medium-to-high	Brookston Kalkaska Pewamo
Medium	Brookston sandy loam Miami A Morley AB
Low-to-medium	Oakville
Low	Algeria Fox B Miami B Mali Zambia
Low-to-very-low	Kenya Vermillon
Very low	Georgia Las Vegas

Brightness and Wetness features (both plotted against moisture content), using either a second-degree polynomial or a cubic smoothing spline (DeBoor, 1978). These smoothed curves were sampled at 1% moisture increments throughout the range of the actual measurements. These samples served as the primary data set for analysis. TM Tasseled Cap Fourth Feature data were computed directly from the spectral measurements (simulated signal counts) with no smoothing or interpolation.

Results and Discussion

In general, measurements of soils at 5% moisture or less exhibited greater variability and spectral behavior which was distinctly different from that exhibited by samples with higher moisture contents. This was probably related to the observed tendency of many of the soil samples to undergo a distinct tone change at low moisture levels, as the surface actually lost all of its moisture, and, in the case of oven dry samples, formed a crust. Although the process of surface drying was not recorded for all soil samples, the unusual response at low moisture levels was characteristic of most if not all of the samples. Thus for most of the analyses reported here, samples with moisture content below 5% were excluded.

Greenness-Brightness projection. In the Greenness vs. Brightness projection, soil variation should be largely restricted to the Brightness direction. Figure 3.20 illustrates that, for this soil set, only small Greenness variation occurred. Excluding Kalkaska (the soil with the highest Greenness values) and samples with moisture contents less than 5% (for reasons previously explained), the range of soil Greenness variation is one-sixth that observed in TM Tasseled Cap Wetness, and one-twentieth that observed in TM Tasseled Cap Brightness. Table 3.10 provides descriptive information of feature variability.

The significance of this Greenness variation is dependent on the overall sensor system and sensing environment. Noise characteristics of the sensor, atmospheric and illumination geometry effects, etc. must all be considered. If the observed variation in Greenness exceeds the uncertainty resulting from the various system noise components, then soil Greenness variation could be important in some applications. For the most part, however, it would appear that the error induced by the "soil line" assumption will be of small importance in an operational setting.

Also of interest is the spectral behavior of dry or nearly-dry soil samples (less than 5% moisture). Spectral response from such samples exhibited a strong tendency to shift in the negative Greenness and positive Brightness direction, relative to the other measurements of the same soil samples. The spectral region into which the dry (and usually crusted — see previous discussion) soil sample spectra fell corresponds roughly to that occupied by concrete and other man-made materials (Crist and Cicone, 1984b).

Wetness-Brightness projection. Figure 3.21 illustrates the spectral feature effects of moisture changes for fourteen soil samples in the TM Tasseled Cap Plane of Soils. The data points in this figure are samples from the smoothed curves, representing 15, 20, 25, and 30% moisture by weight (some of the samples stop at 25%). The fourteen soils in the figure are all of those which cover the desired moisture range, with at least three data points and are free from any obviously suspicious values. In each case on the figure, the lowest Wetness and highest Brightness value corresponds to a moisture content of 15%.

Table 3.10 TM Tasseled Cap Feature variation of soils.

Data	Mean	Std. Dev.	Min.	Max.
Greenness				
All data	−9.95	5.43	−27.8	9.75
Moisture > 5%	−9.09	4.29	−16.50	9.75
Moisture > 5%, ex. Kalk.	−10.06	2.26	−16.50	−5.15
Brightness (Moisture > 5%)	144.50	45.00	69.30	265.30
Wetness (Moisture > 5%)	−23.99	18.89	−66.98	14.26

A number of observations can be made with regard to Figure 3.21. First, in each case an increase in moisture content corresponds to a reduction in Brightness and an increase in Wetness. The line segments plotted exhibit slopes which are very consistent across the soil samples. Second, the "starting points" (15% H_2O), the distance between successive points, and the total distance from wettest to driest, vary considerably from soil to soil — there can be no direct association of TM Tasseled Cap Wetness and moisture content. Third, there seem to be several sub-groupings in the figure, characterized in general by their starting Brightness and Wetness values. Finally, the spectral distance measured from the 25 to 30% values is, in nearly all cases, of a lesser magnitude than the distance from 15 to 20%. Most clear, however, are the consistency in direction of spectral change associated with a change in moisture content, and the lack of any direct connection between TM Tasseled Cap Wetness values and moisture content in an absolute sense.

Wetness vs. Moisture Content. In order to gain insight into the response of TM Tasseled Cap Wetness to moisture changes, the two values were plotted against each other, as illustrated in Figure 3.22. Here again, the lack of a direct predictive relationship between Wetness and moisture content is clear. For a moisture content of 15%, Wetness values range from −52 to −13, or 29 counts. The degree of dispersion appears to decrease at higher moisture contents.

Normalizing all the curves to the same Wetness value for 25% H_2O produces the result in Figure 3.23. This result illustrates that individual soil response in Wetness varies not only in terms of absolute Wetness value at any given moisture content (as shown in Figure 3.22), but also in the slope of the Wetness vs. %H_2O curve. In other words, the magnitude of Wetness response to a unit change in moisture varied across the soils studied. Based on the generalized characteristics of organic matter content provided in Table 3.9, both absolute Wetness value (at a particular moisture level) and particularly the slope of the Wetness vs H_2O curves are found to be correlated to organic matter

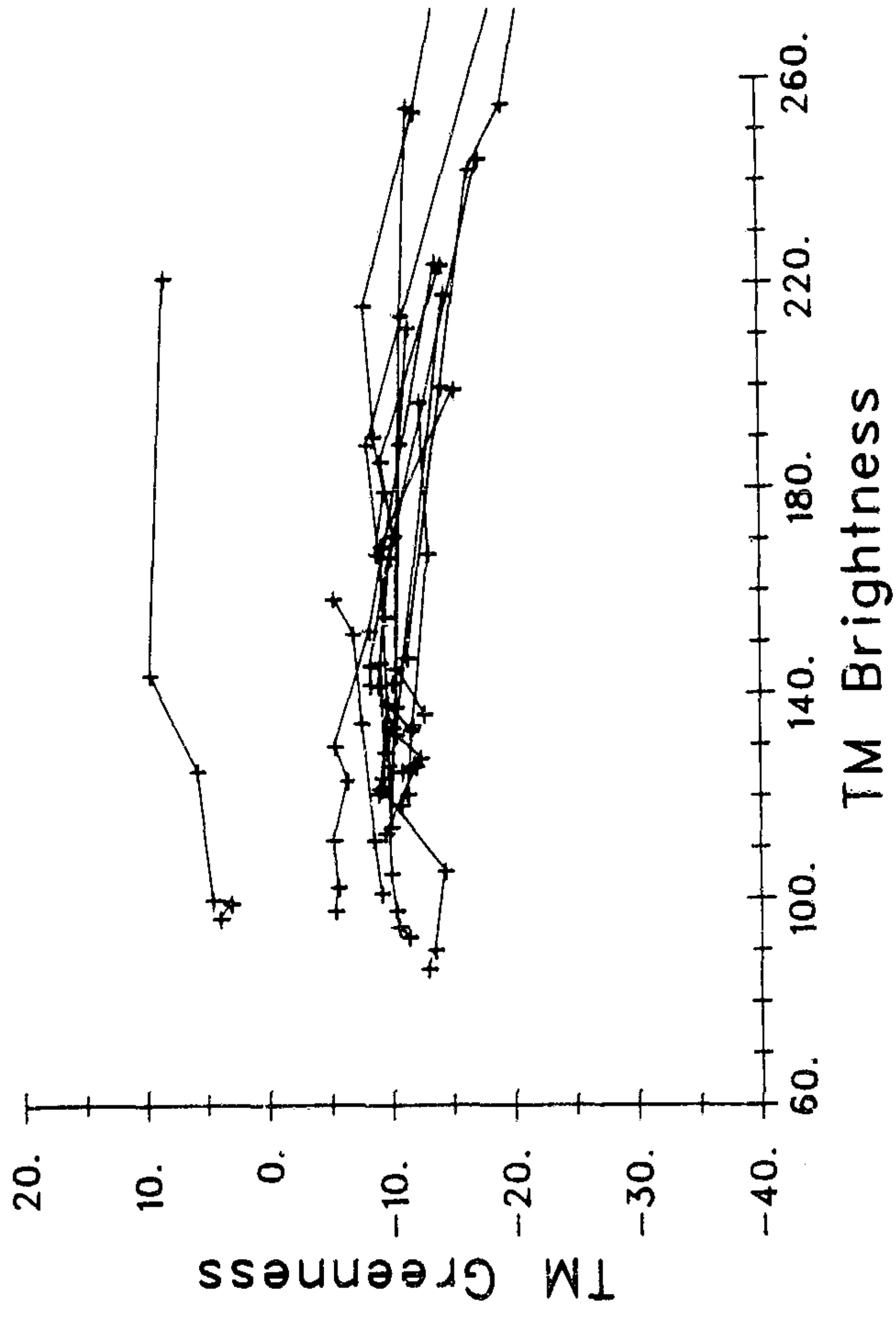

Figure 3.20. Soil variation in TM Greenness-Brightness projection. Samples with 5% or greater moisture. Note that Greenness axis is expanded to show variation.

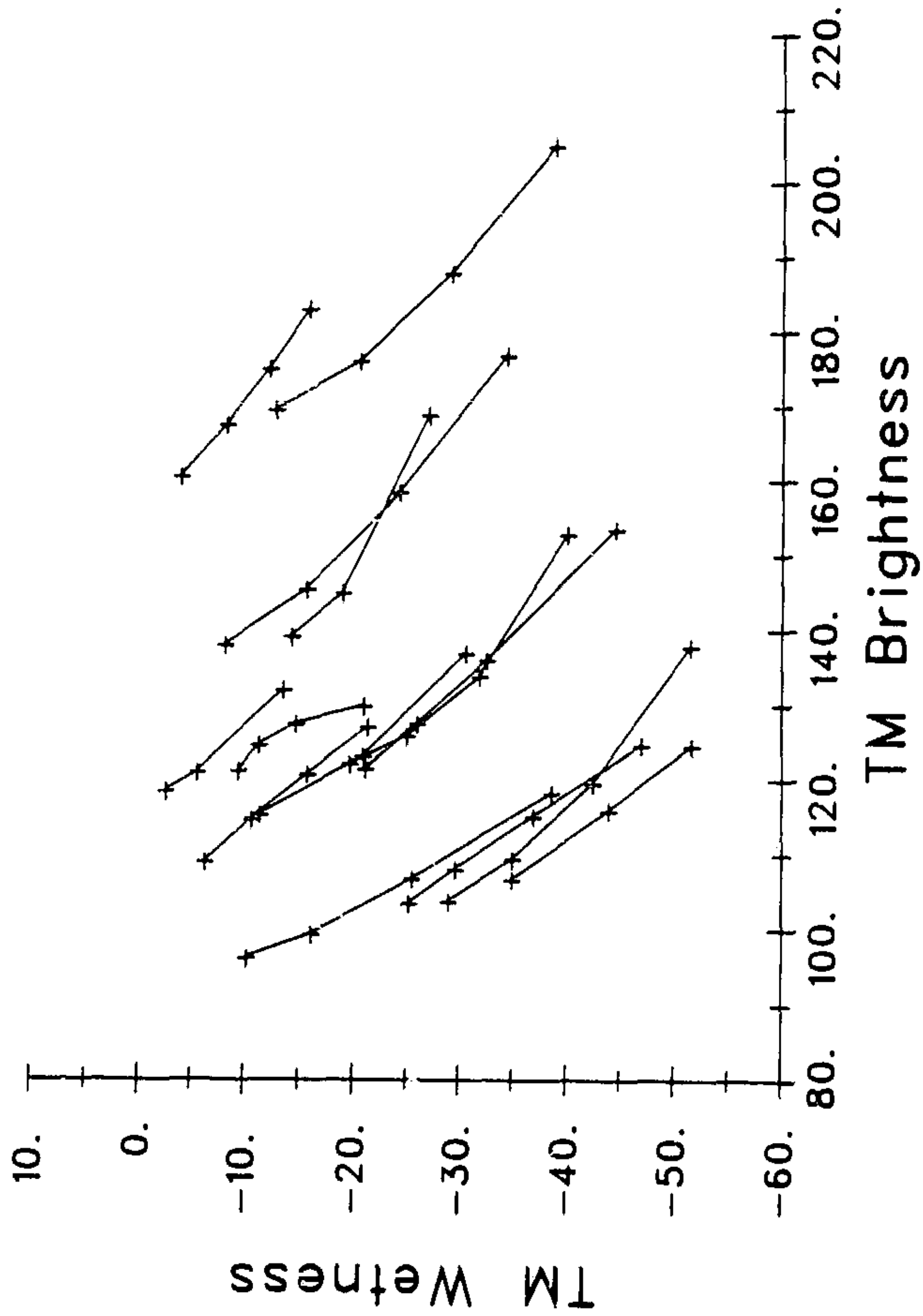

Figure 3.21. Soil moisture effects in the TM Tasseled Cap Plane of Soils.

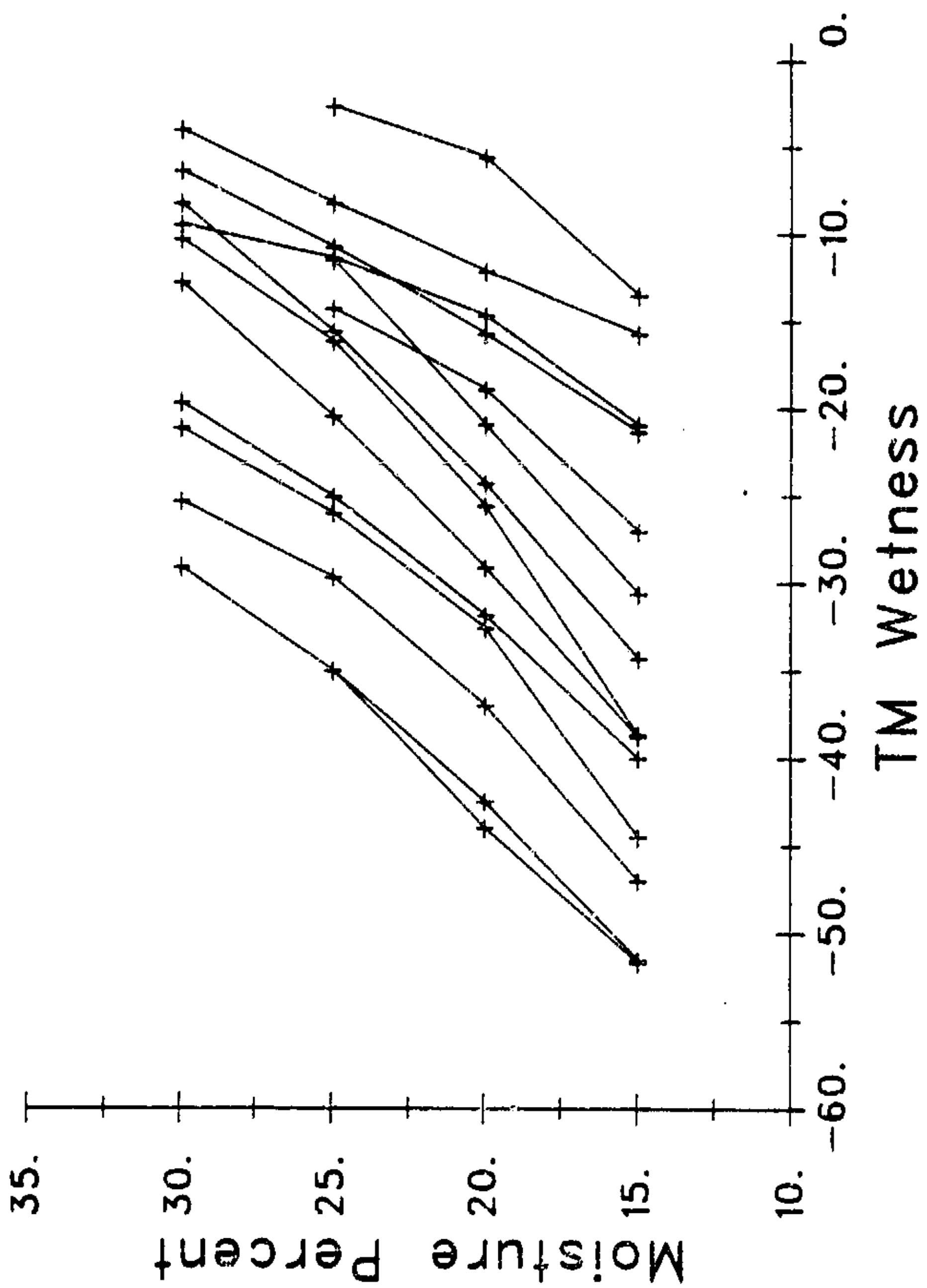

Figure 3.22. Wetness vs. moisture content. Samples from smoothed curves.

content. Soils which have higher proportions of organic matter tend to exhibit lower Wetness values at a given moisture level, and to increase in Wetness more rapidly (steeper slope) in response to unit increases in moisture content. Note that these generalizations apply only to the mid-latitude soils in the data set – the African soils appear not to behave in the same manner (although soil descriptions for these soils were less complete, limiting the analysis which could be accomplished).

Similar comparison of the Wetness vs. $\%H_2O$ results to the generalized ranking of the soils by texture, as provided in Table 3.8, shows no apparent correlation either with initial values nor with the slope of the Wetness vs. $\%H_2O$ curves.

Brightness vs. Moisture Content. Figure 3.24 shows the Brightness response of the soils in the data set to moisture changes. Again the data values are samples from the smoothed curves at 15–30% moisture (5% increments). Substantially more dispersion is noted than was seen in Wetness (Figure 3.22). The range of Brightness values at 15% moisture is 87 counts, while at 25% moisture the range is 78 counts, compared to 38 and 32 counts respectively for Wetness. Plotting the data after normalizing the Brightness values at 25% moisture (as was done in Figure 3.23 for Wetness) produces the result in Figure 3.25. Again, a slope difference between soils is apparent, although slope variation at higher moisture levels is less than was seen for Wetness.

No strong association between organic matter content and either response at a given wavelength or slope of the response line was noted for Brightness. Surprisingly, no association could be made with texture either, although one would expect, from previous analyses, to see at least an overall association between texture and Brightness at a given moisture level.

Comparisons of specific sample groupings. In addition to the overall comparisons just described, particular groupings of soils were evaluated with respect to their spectral response to soil moisture. Miami and Morley (A and AB horizons respectively) represent soils with similar mineralogy but different textures, with Morley characterized by a somewhat finer texture (more clayey) than Miami. Both fall in the medium organic matter category. As seen in Figure 3.26, the Wetness and Brightness response of the two soils is considerably different. The similarity in organic matter content may be reflected in the similarity in slope of the Wetness response lines (Figure 3.26b). Of interest as well is the convergence of the Brightness response lines in Figure 3.26c – at 25 and 30% moisture, the two soils exhibit virtually identical Brightness responses.

The second comparison uses Morley again, contrasted this time with Vermillon. Here the two soils share similar textural compositions, but derive from distinctly different parent materials (see Table 3.7). They also are considerably different with respect to organic matter content, with Morley falling in the medium category and Vermillon in the low-to-very-low category (Table 3.9). As seen in Figure 3.27, the Wetness response of the two soils is very similar, while their Brightness response, in terms of signal value associated with a particular moisture level, is very different.

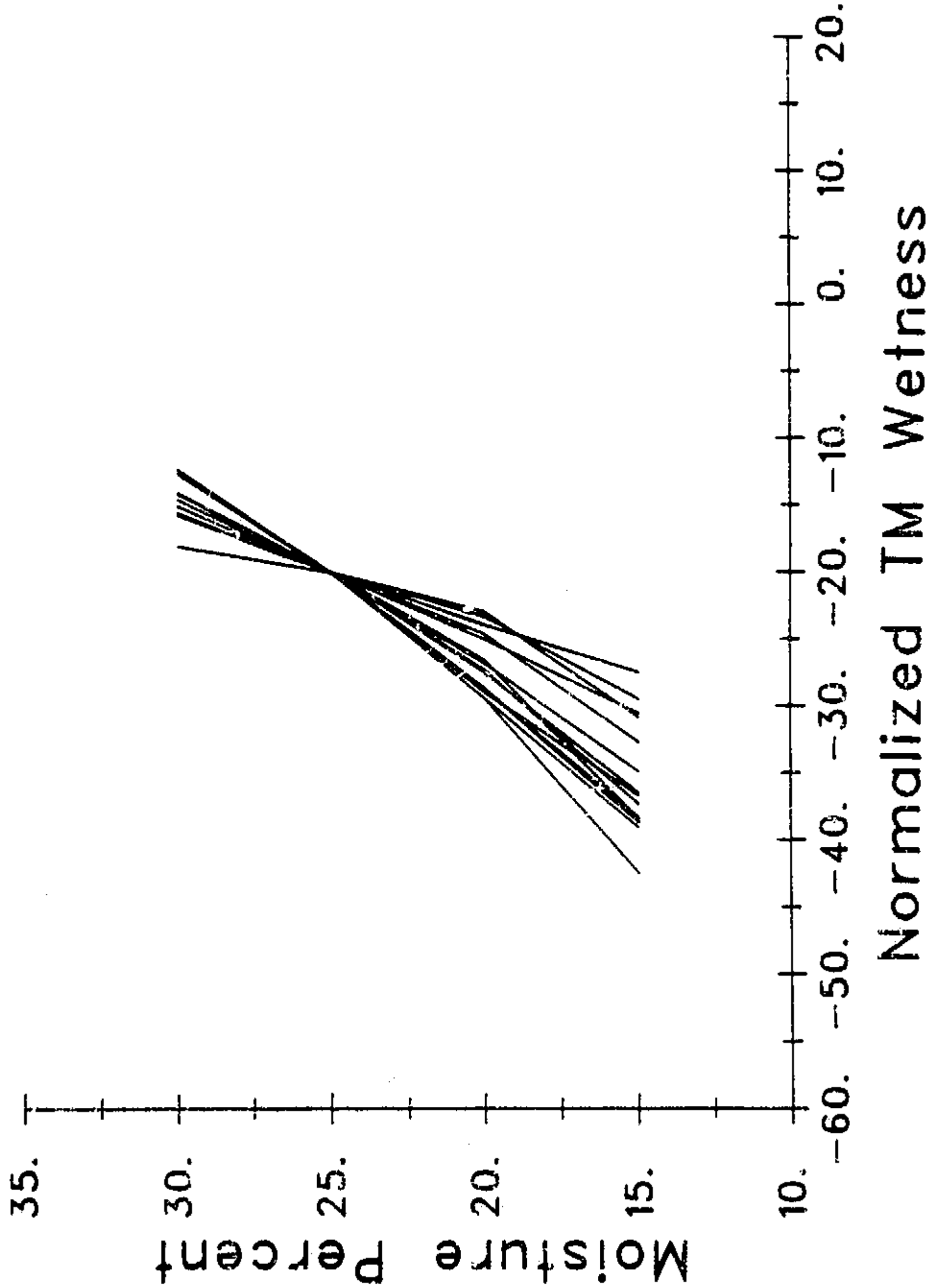

Figure 3.23. Wetness vs. $\%H_2O$. Wetness values normalized at 25% H_2O.

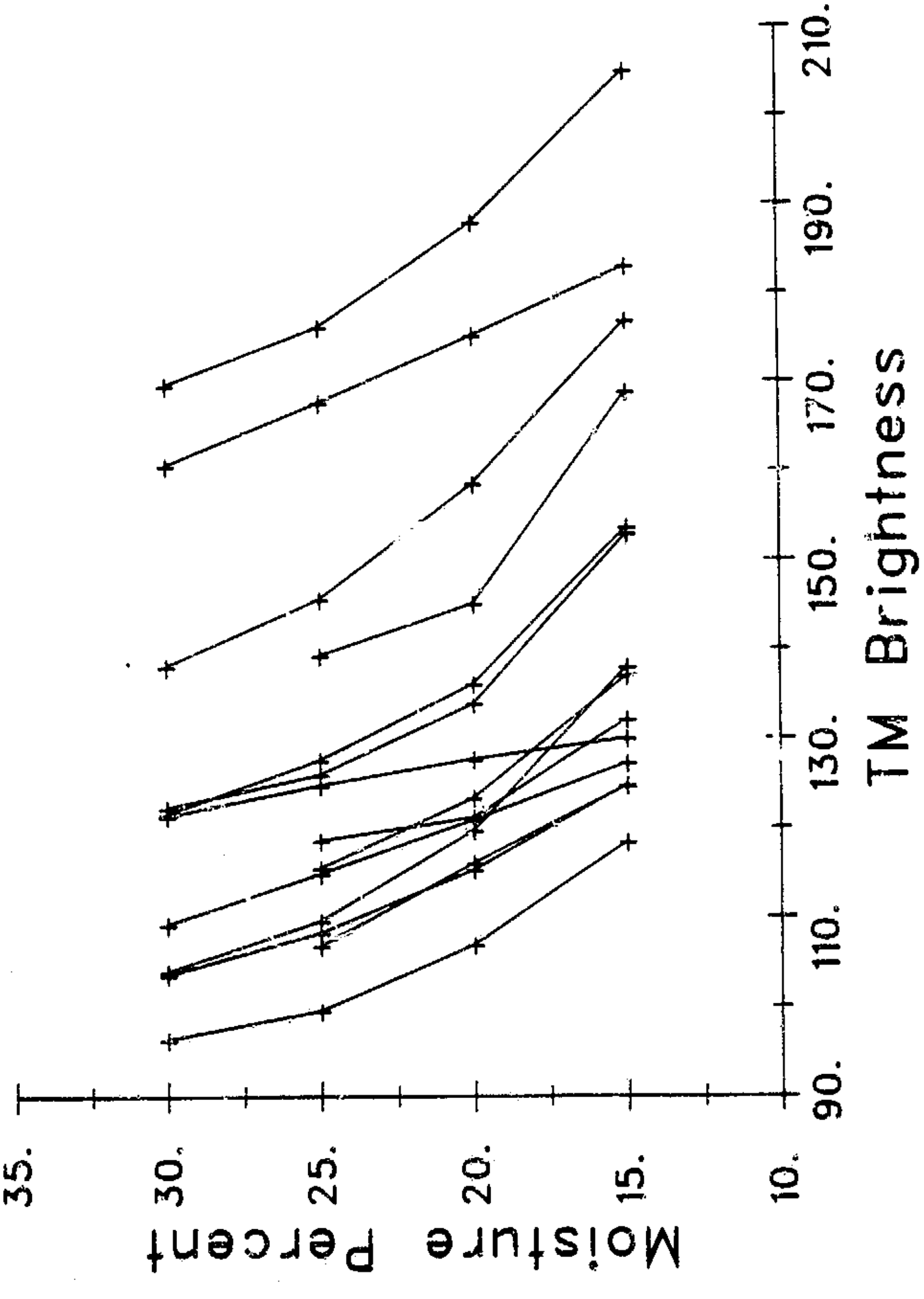

Figure 3.24. Brightness vs. $\%H_2O$. Samples from smoothed curves.

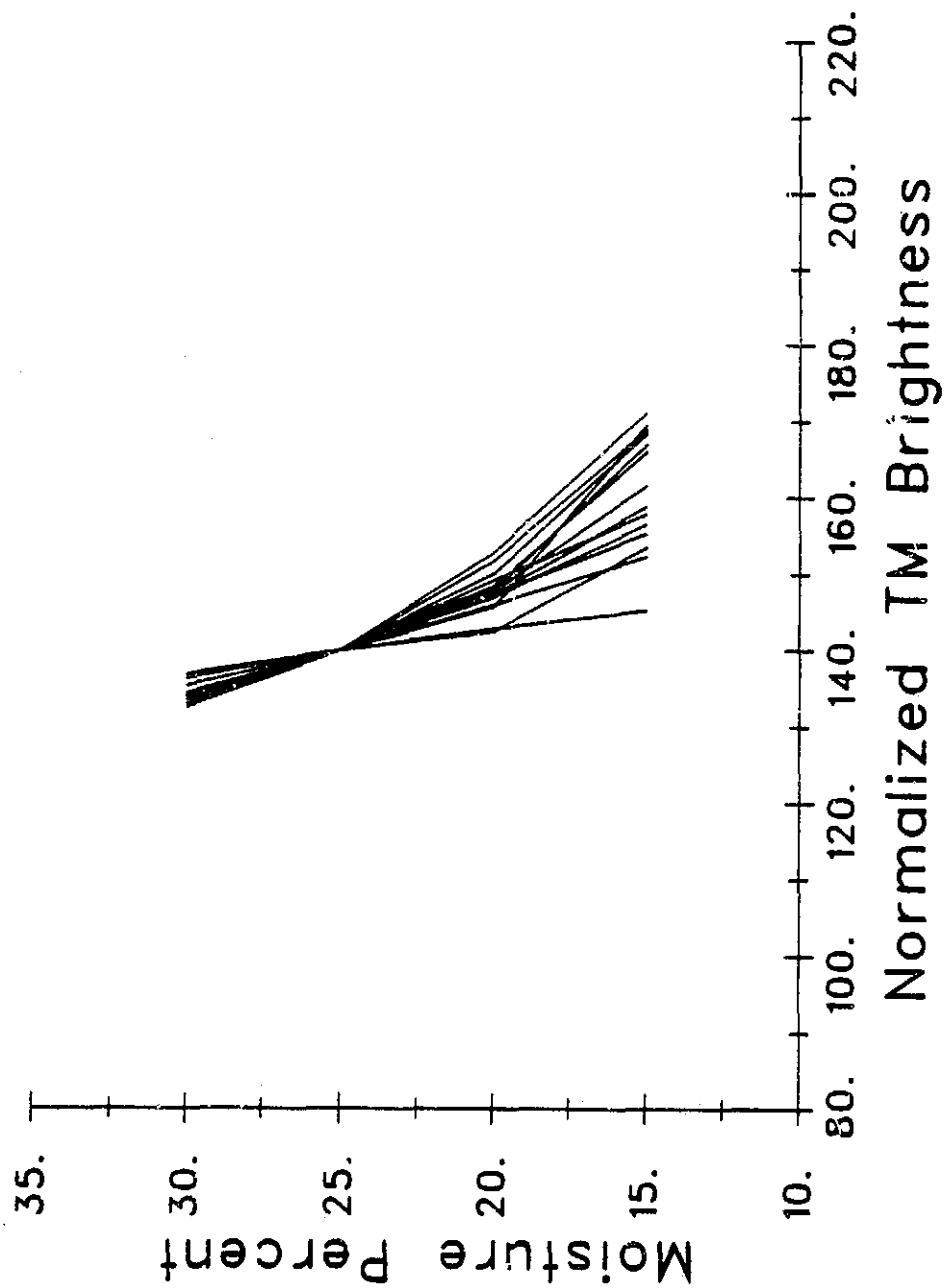

Figure 3.25. Brightness vs. $\%H_2O$. Brightness values normalized at 25% H_2O.

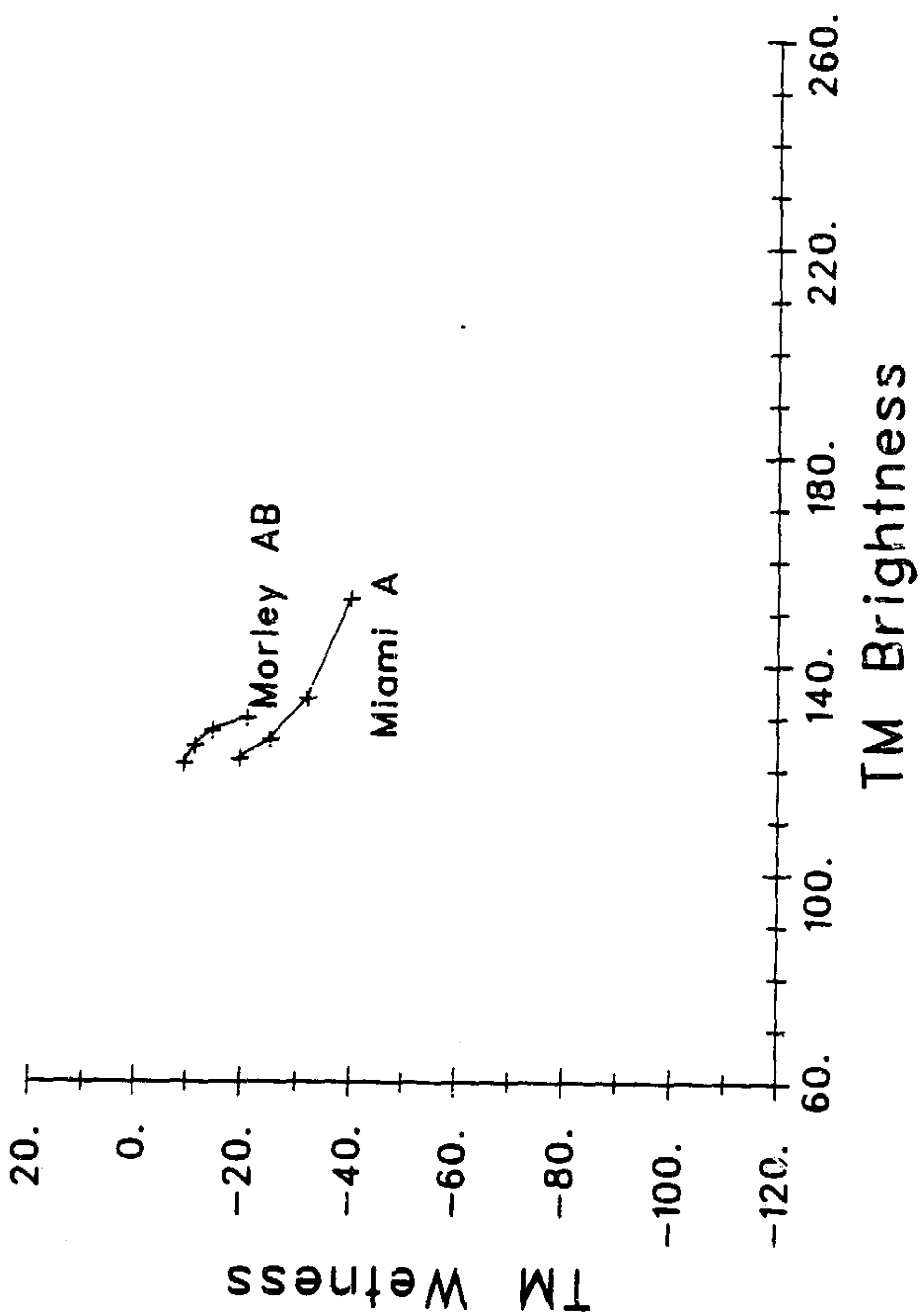

Figure 3.26a. Subgrouping comparison. Miami vs. Morley.

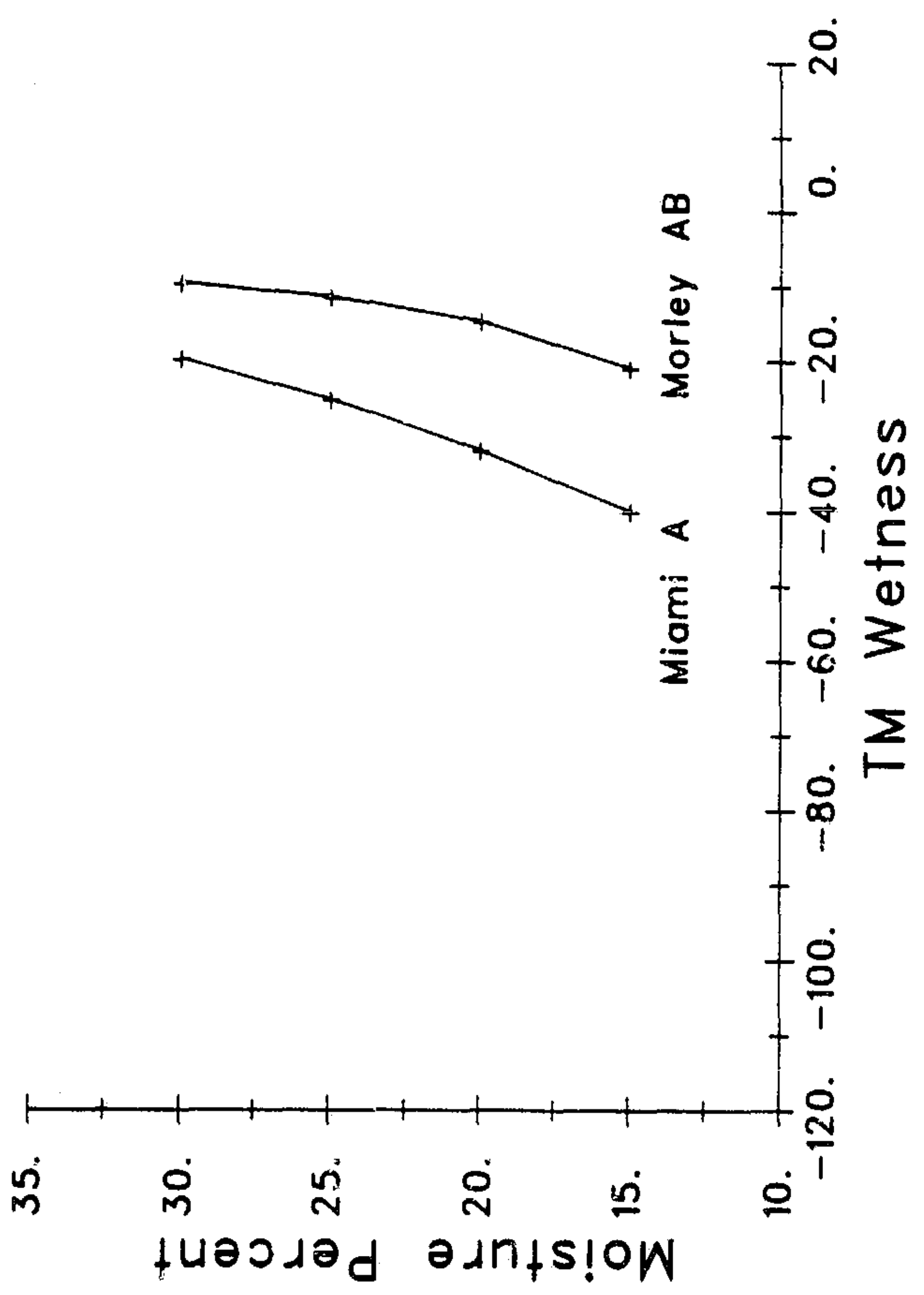

Figure 3.26b. Subgrouping comparison. Miami vs. Morley.

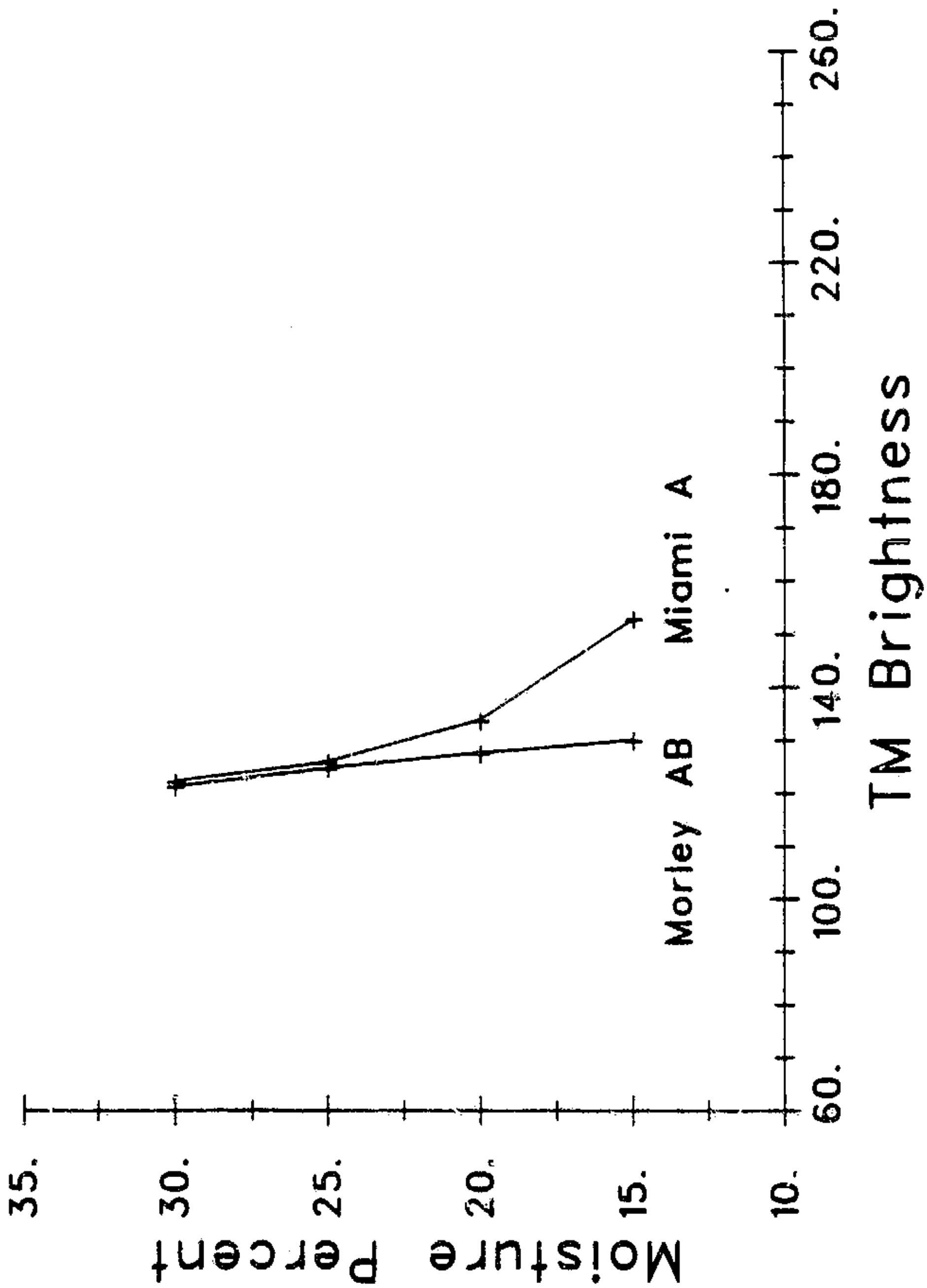

Figure 3.26c. Subgrouping comparison. Miami vs. Morley.

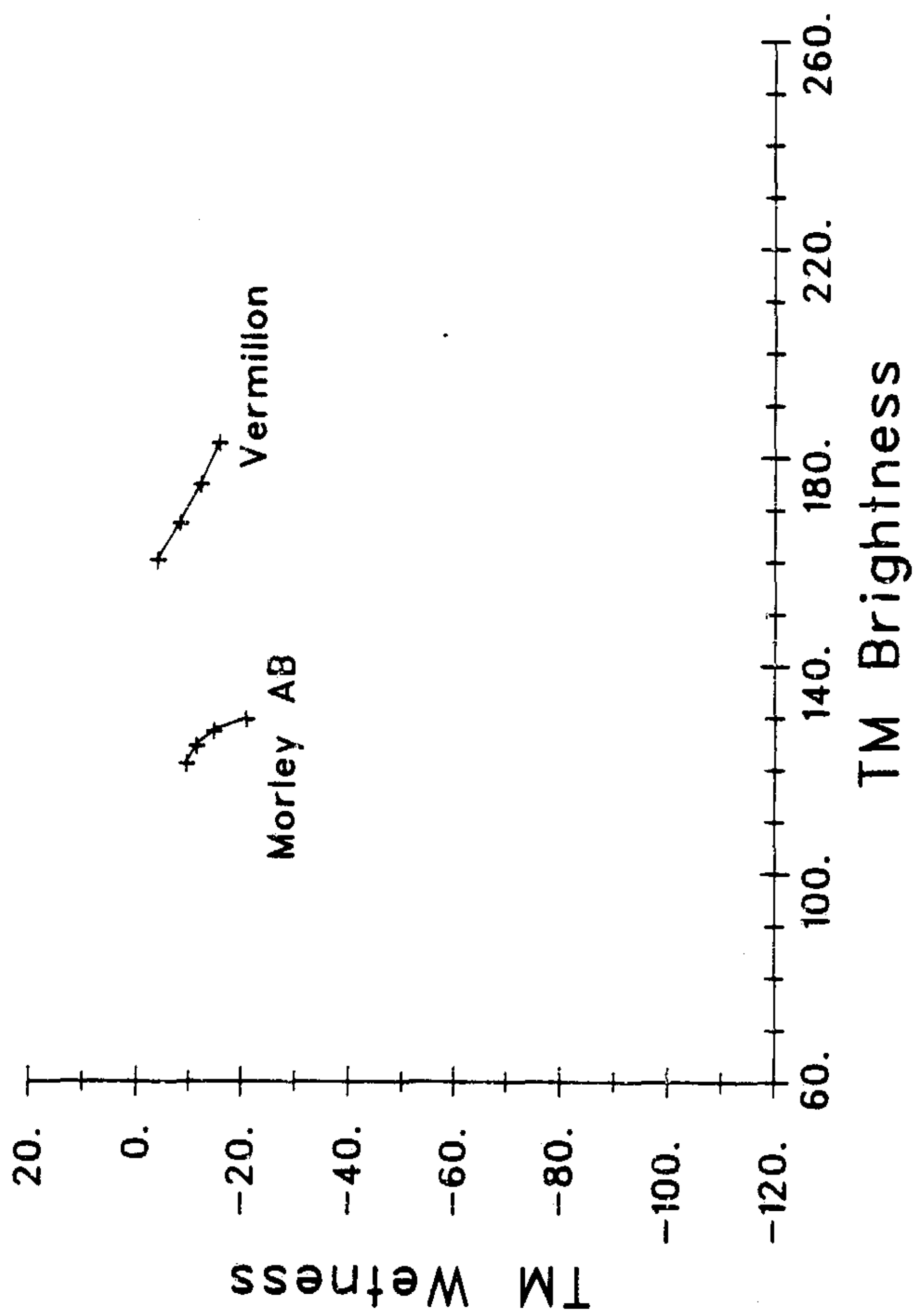

Figure 3.27a. Subgrouping comparison. Morley vs. Vermillon.

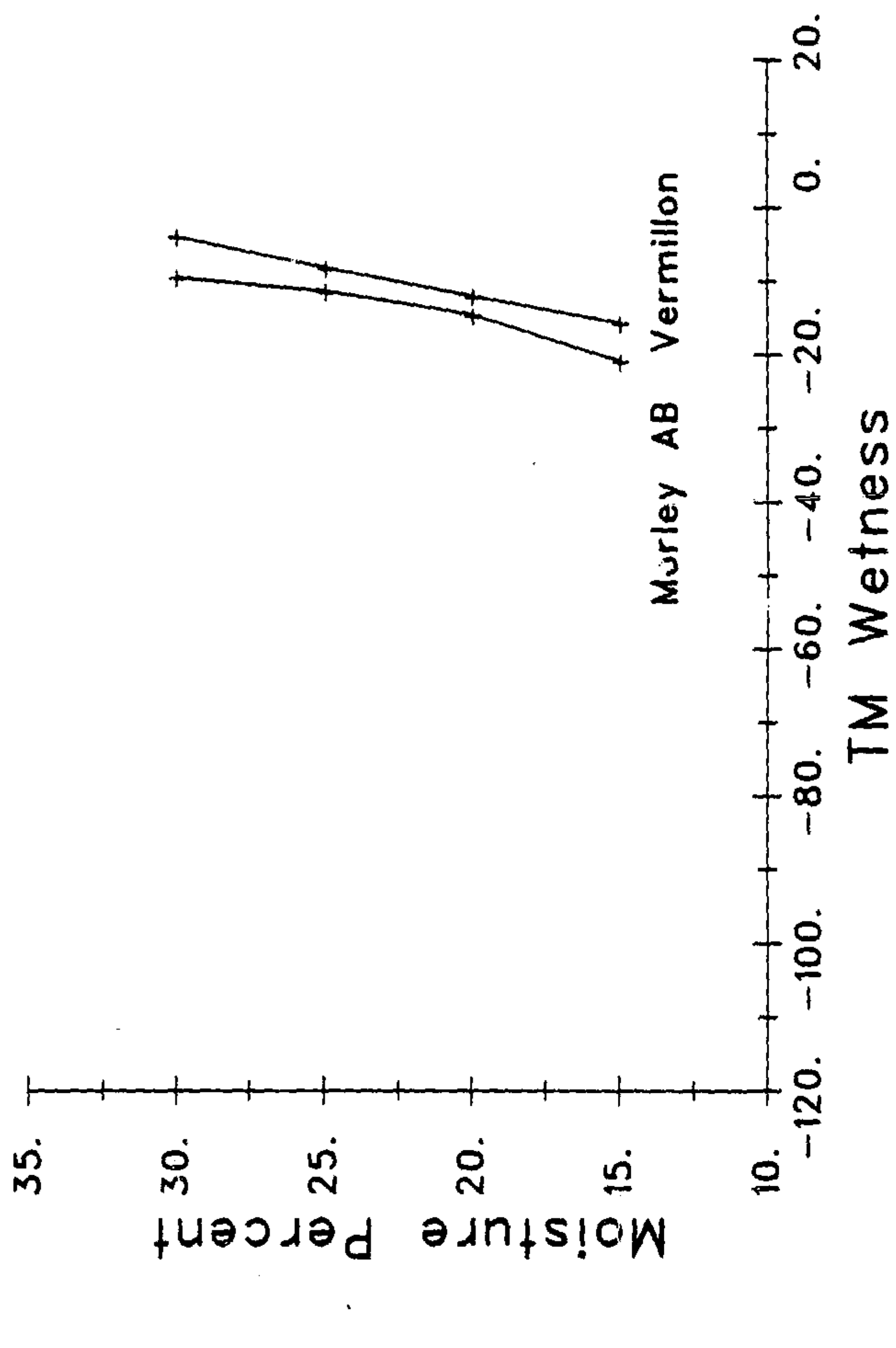

Figure 3.27b. Subgrouping comparison. Moriey vs. Vermillon.

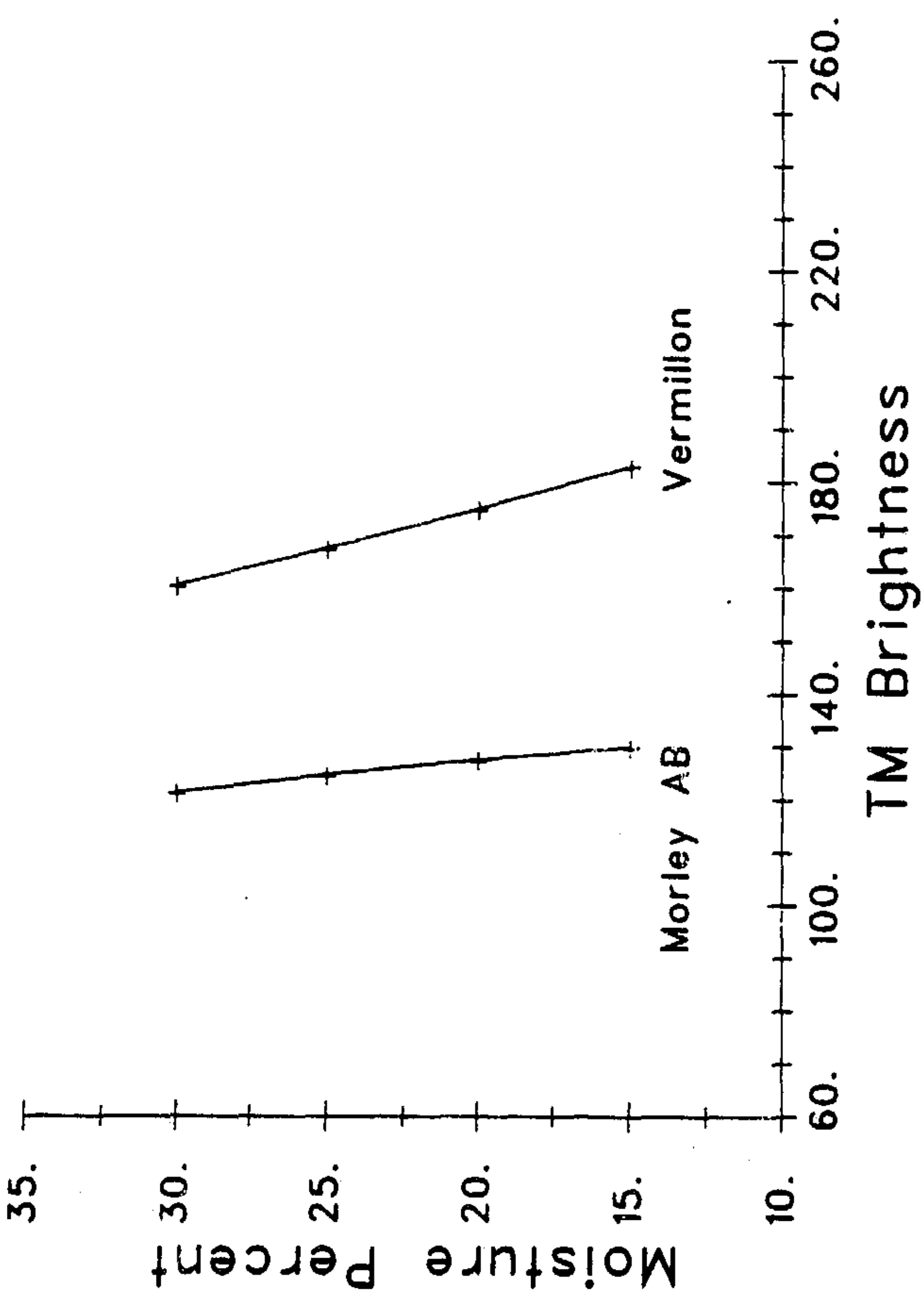

Figure 3.27c. Subgrouping comparison. Morley vs. Vermillon.

Third, we compare samples from the A and B horizons of Miami. Clearly derived from the same parent material, one would also expect the A horizon to be higher in organic matter, and of somewhat finer texture, than the B horizon. Figure 3.28 illustrates that the spectral response differences between these two samples are similar to those seen between Miami A and Morley, which likewise shared similar mineralogy with different textural makeup. This suggests some degree of correlation between textural class and TM Tasseled Cap Wetness response to soil moisture changes, in contrast with the overall result discussed earlier. Clearly the relationship between Wetness response and soil texture is neither simple nor exclusive (i.e. other factors play a part as well).

Finally, adding Brookston, Pewamo, and Fox (B horizon) to the first grouping of Miami and Morley expands the range of textural classes while maintaining similarity of mineralogy. As seen in Figure 3.29, this broader comparison yields some interesting insights. First, as indicated in Table 3.7, Brookston and Pewamo share a common classification – typic argiaquolls – which expresses their close overall similarity. Figure 3.29b illustrates that the Wetness response of these two soils is nearly identical over the range plotted, and their Brightness response (in Figure 3.29c), though not identical, is very similar as well. Further, the progression from lower to higher Wetness values at a given moisture content is perfectly correlated with the soils' rankings based on organic matter content (Table 3.9), with lower organic matter content associated with higher Wetness values at a given moisture level. Again, neither texture nor organic matter classifications were found to be correlated with Brightness response for these soils.

Other moisture metrics. One possible explanation for the lack of absolute correlation between TM Tasseled Cap Wetness and moisture content is that percent moisture by weight is not the appropriate metric. The disposition of moisture in soils is closely tied to the particle size distribution, and hence the pore size, of each particular soil. As a result, the same moisture content by weight will correspond to a wide range of available water levels, and more importantly, will be dispersed in layers (around the soil particles) of significantly different thicknesses. Since the thickness of the water layer should be directly related to the influence of the moisture on soil reflectance, there is reason to expect that a measure of actual moisture tension would be more appropriate

Figure 3.30 shows the result of plotting Wetness against pF value, a direct measure of soil moisture tension, for the seven soils for which pF data were available. While the actual signal count variation is reduced at any given level, the significance of the difference may not have changed (since a unit change in pF may be of much greater significance than a unit change of the same magnitude in moisture content by weight). However, a number of important differences, comparing this figure to Figures 3.22 and 3.29, can be noted.

First, five of the seven soils follow a very similar pattern of Wetness change with increasing pF value. Second, a clear association exists between the overall slope of the curves and textural class. Grouping the soils into four categories based on the figure yields results shown in Table 3.11. The slope (or overall curve shape) difference between groups is perfectly correlated (in this small data set) to textural differences, with coarser textured soils exhibiting flatter slopes in the Wetness vs. pF curves. There also appears to be indication of convergence of the various curves at a low pF value. Organic matter is not correlated with the groupings in Figure 3.30.

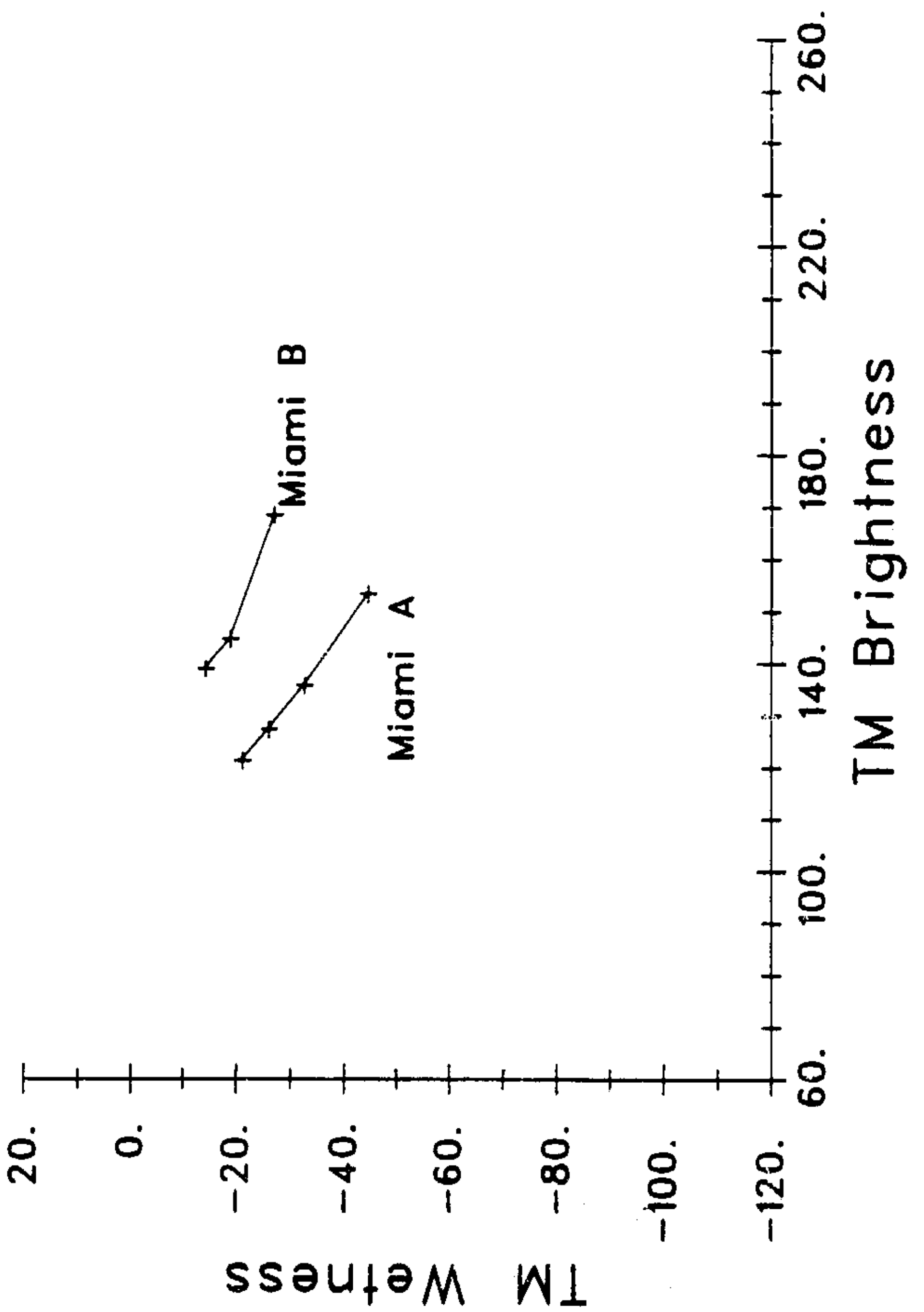

Figure 3.28a. Subgrouping comparison. Miami A and B horizon samples.

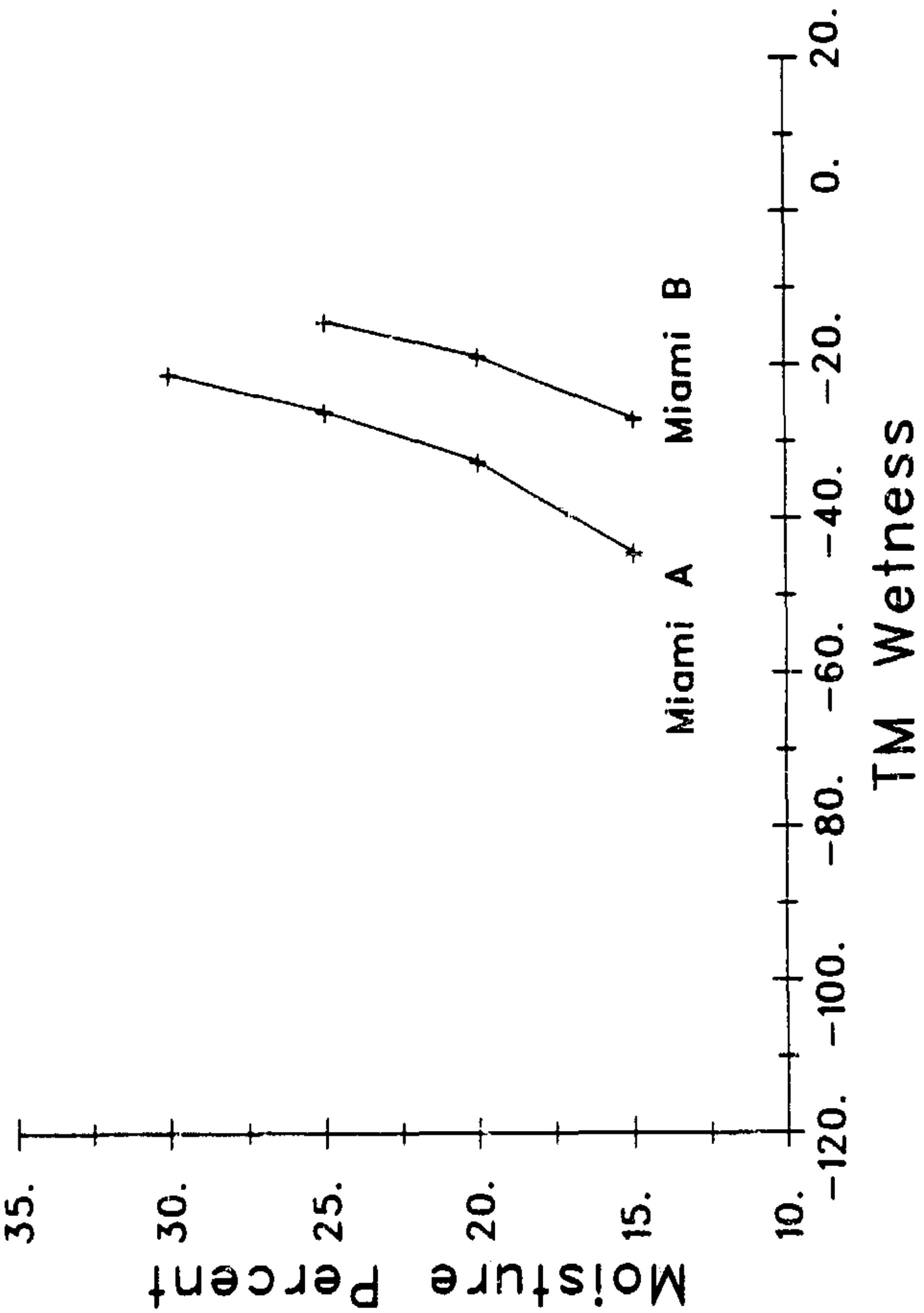

Figure 3.28b. Subgrouping comparison. Miami A and B horizon samples.

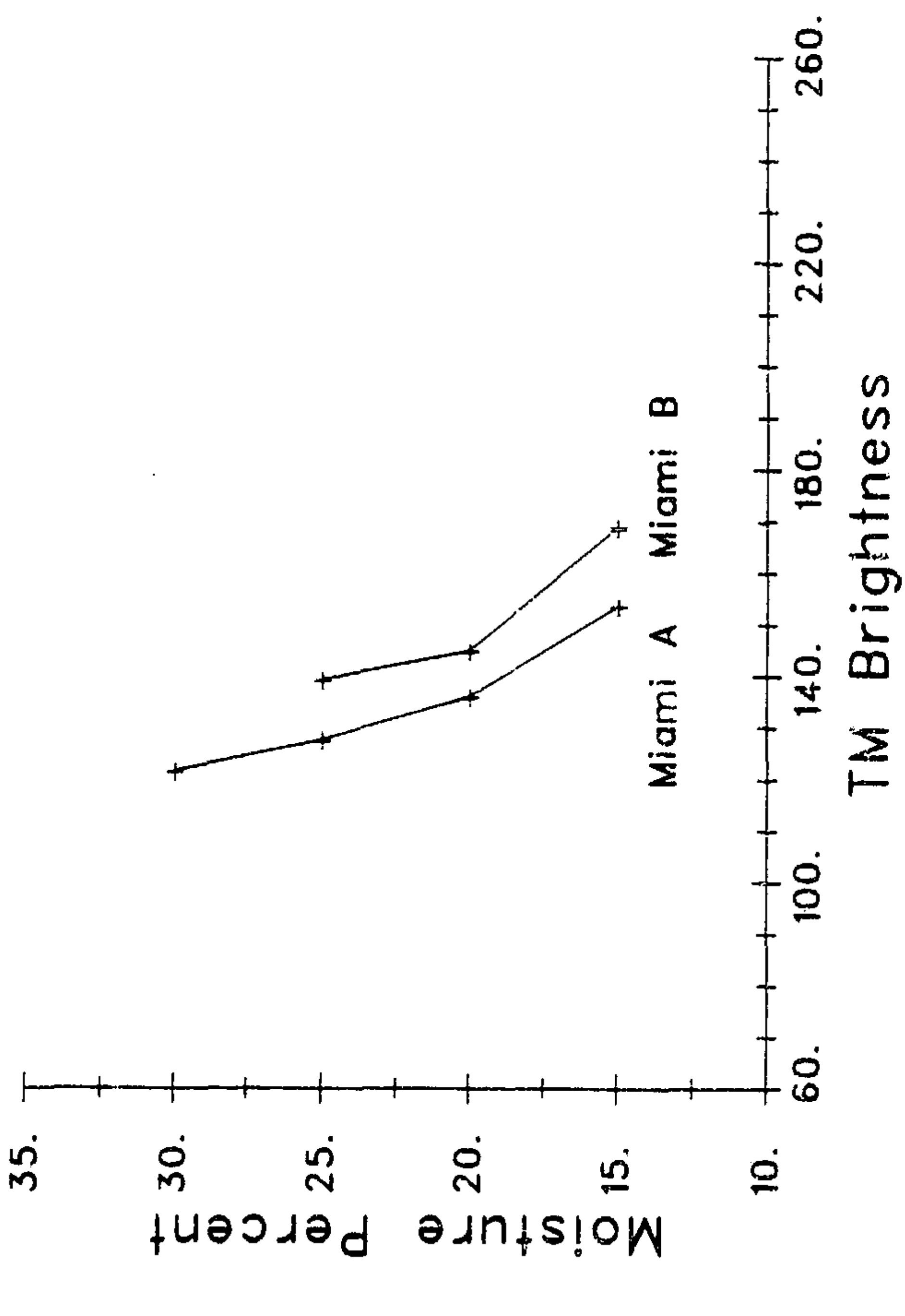

Figure 3.28c. Subgrouping comparison. Miami A and B horizon samples.

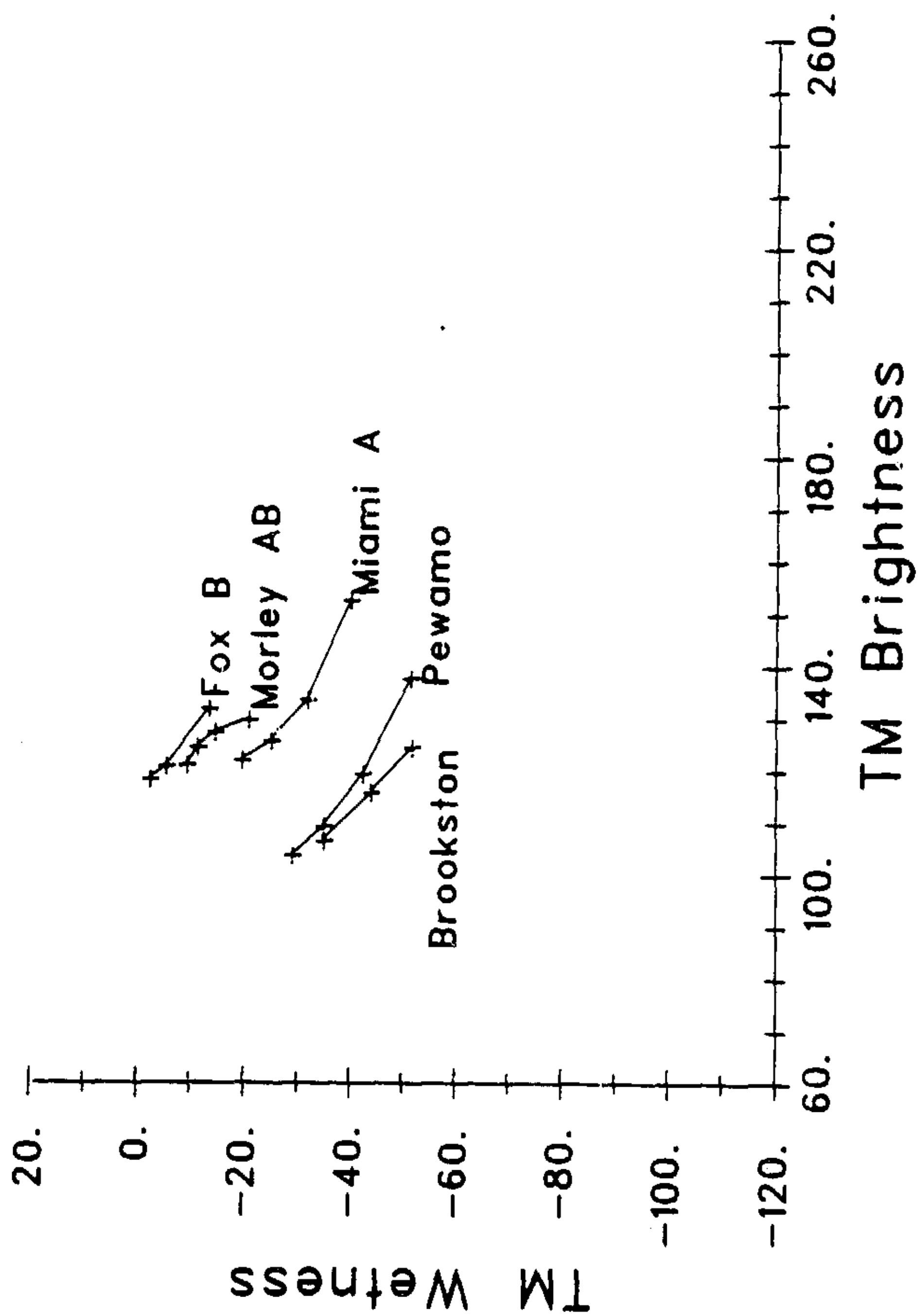

Figure 3.29a. Subgrouping comparison. Miami, Morley, Brookston, Fox, and Pewamo.

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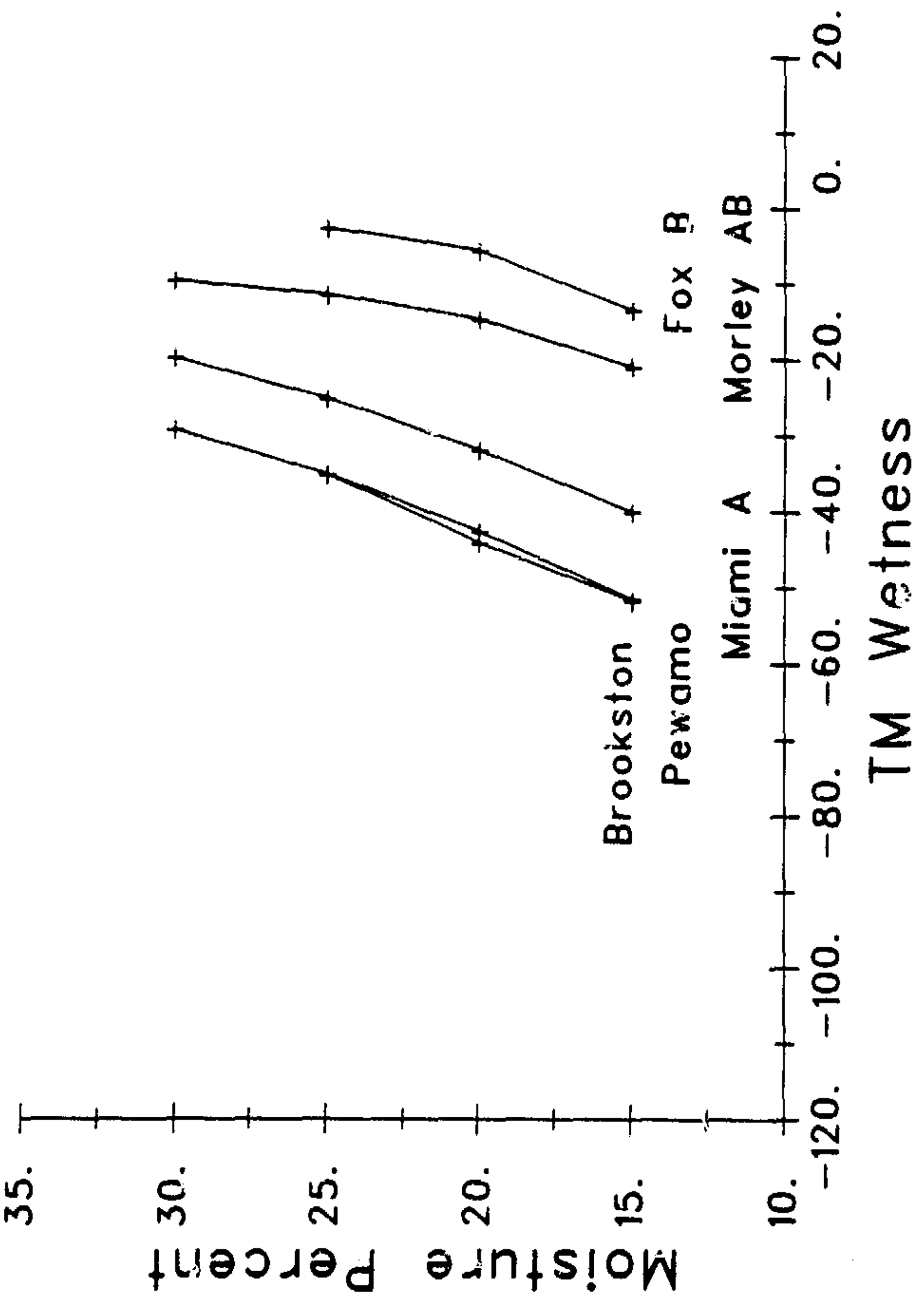

Figure 3.29b. Subgrouping comparison. Miami, Morley, Brookston, Fox, and Pewamo.

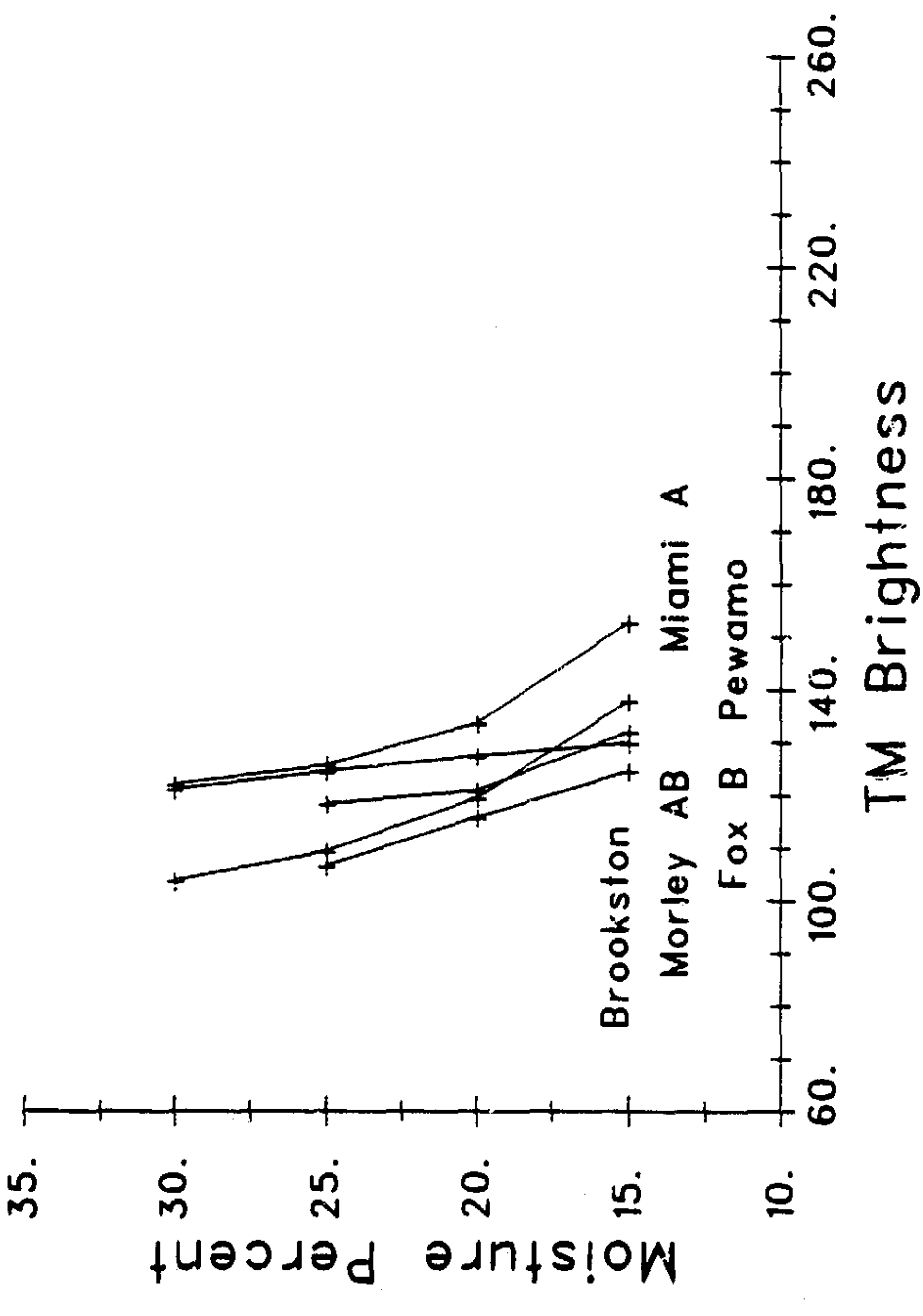

Figure 3.29c. Subgrouping comparison. Miami, Morley, Brookston, Fox, and Pewamo.

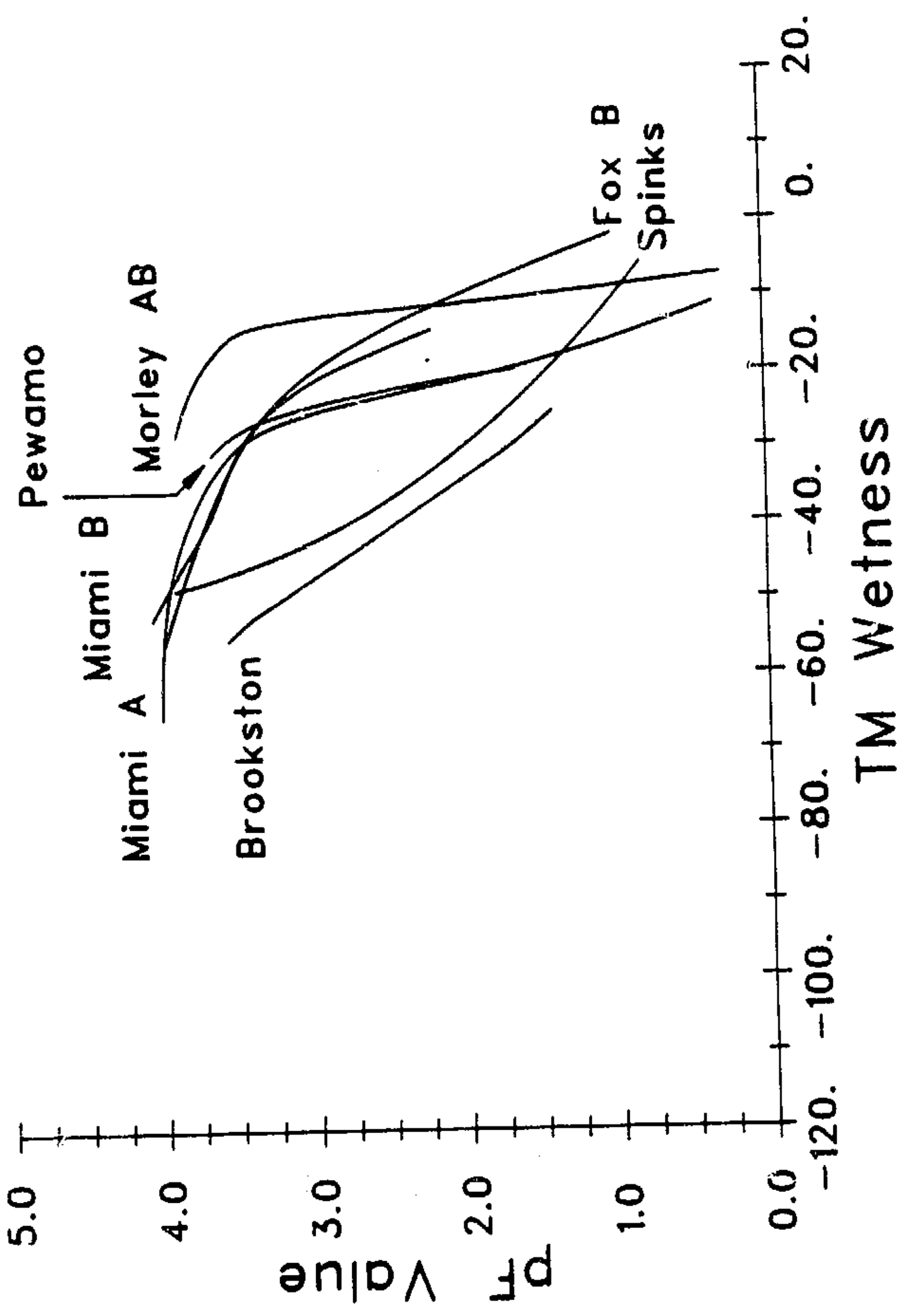

Figure 3.30. Wetness vs. pF value. Curves fit to available data.

Table 3.11 Soil groupings in Wetness vs. pF (Figure 3.30).

Group	Soil series	Texture category
1	Spinks, Brookston	coarse
2	Miami B, FoxB	medium-to-coarse
3	Miami, Pewamo	medium-to-fine
4	Morley AB	fine

Summary and Conclusions

The analyses presented here have primarily served to establish the complexity of the relationship between soil characteristics and TM Tasseled Cap response. The earlier hypothesis of a direct relationship between soil moisture content and TM Tasseled Cap Wetness response (Crist and Cicone, 1984a and 1984b) cannot be supported. However, the direction of moisture-related change in the TM Tasseled Cap Plane of Soils has been established to be consistent across a wide range of soil types.

While no particular soil characteristic or set of characteristics has been shown to be responsible for the varied response of soils in TM Tasseled Cap Wetness, organic matter content seems to exert a significant influence on both absolute Wetness values (at any given moisture level) and the Wetness response to changes in moisture content. When measuring moisture in terms of tension rather than percent by weight, textural class may be the primary cause for non-moisture-related Wetness variability. In general, it appears that Wetness response is more closely tied to moisture tension than to absolute moisture content.

As with Wetness, so the physical causes for soils variation in the TM Tasseled Cap Fourth Feature have not been fully determined. Earlier work suggested that organic matter content exerted an influence in a relative sense (Section 3.2), and this study has shown a clear delineation between red, especially African, soils and brown, mid-latitude soils in the Fourth Feature. Nevertheless, no definitive statements can yet be made with respect to the physical soil characteristics actually driving Fourth Feature response.

The studies described here are limited in the lack of detailed mechanical and chemical analysis of soil characteristics. In order to uncover the key physical drivers in the TM Tasseled Cap Plane of Soils and the Fourth Feature, the type of analysis described here should be expanded to include a wider range of soils, with precise mechanical and chemical descriptions of each. Soil pairs or groups should be selected to test specific hypotheses where possible. In addition, the influence of organic matter and iron oxide content could be determined through measurement of samples before and after extraction of these constituents. Though painstaking and complex, procedures do exist by which such extraction can be accomplished with no appreciable residual effect on the soil samples. Successful application of these techniques would allow analysis of the influence of these constituents in isolation from all other soil characteristics.

Finally, it may be the case that soil moisture determination can best be accomplished with other features derived from the TM bands. The TM Tasseled Cap transformation was not specifically designed to provide a soil moisture detection feature, but rather serves to characterize the underlying data structures and distributions in the TM data space which result from the interactions of sensor band placement and the physical properties of key scene classes (Crist and Cicone, 1984b, Crist and Kauth, 1985). Thus the TM Tasseled Cap features Brightness, Greenness, and Wetness first describe and define the two-plane structures noted in TM data for a range of vegetation and soil cover types (Crist and Cicone, 1984a and 1984b). Any band or multi-band feature can be described and understood in the context of the TM Tasseled Cap features, but need not be aligned with any of the axes of the transformed feature space. One example of such a feature is the ratio of TM bands 5 and 7, described in Section 3.3, which shows preliminary promise of providing actual soil moisture availability information independent of the textural makeup of the soil.

In any case, there is ample indication from this and other studies that information related to surface soil moisture does exist in TM data. While full understanding of the extent of that information. and the most efficient and effective means for its extraction, will only be gained through additional research, preliminary results seem to indicate that such additional effort is well warranted.

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3.5
SOIL EFFECTS ON CANOPY RESPONSE

Introduction

Recent evidence from field reflectance data suggests that soil response (brightness) may have a significant effect on vegetation indices (e.g. Huete, et al., in press). Further, the effect appears to be different depending on the vegetation index being considered. For ratio type indices (e.g. IR/red ratio or Normalized Difference, NVI) dark soil backgrounds tend to be associated with higher values of the index for intermediate levels of vegetation cover (20–60%), as compared to the same levels of cover with light soil backgrounds. For linear combination indices (e.g. Tasseled Cap Greenness), dark soil backgrounds tend to be associated with lower index values as compared to light soil backgrounds with the same intermediate level of vegetation cover. These effects have also been seen previously in field radiometric data (e.g. Colwell, 1973) and in simulated Landsat data (e.g. Malila, et al., 1977).

Since determination of the amount of vegetation in a scene is an important goal in many Landsat applications, and since the spatial extent of a Landsat scene is such that it is likely to include soils with a range of brightnesses, it is important to determine the exact nature and degree of the soil effect on vegetation indices. Although rigorous tests of the soil effect on actual Landsat data would require detailed field measurements of soil and vegetation properties within the Landsat scene, an initial examination of this issue can be based on available historical data.

One historical Landsat MSS scene that appears useful for obtaining some insight into this issue is a 6 May 1976 scene covering the area around Hays, Kansas (Scene ID 2470-16342; P32/R33). This scene appears to have had a recent rain in the southeast corner that has darkened the soil reflectance appreciably. The scene has fairly light toned, dry soils in the southwest corner. Previous ERIM experience in the study region (e.g. Nalepka, et al., 1977) indicates that the area is dominated by winter wheat of intermediate vegetation cover at the time of data collection. If the apparent soil variation were the only factor that varied, then one would expect the NVI to increase across the scene from southwest to southeast, while Tasseled Cap Greenness values should decrease over the same transect.

Scene Characteristics

Soils maps and precipitation history have been examined in order to assess the cause of the marked darkening of the southeast corner of the Landsat scene. A small scale soils map of the area from the National Atlas of the United States of America (U.S.G.S., 1970) shows that most of the soils in the scene are Mollisols, with some lighter toned Ustorthents on the west side of the image and some darker Argiudolls on the east side of the image. This soils distribution would probably result in soils on the west side of the scene being somewhat brighter than those on the east side of the scene, but is unlikely to entirely account for the darker tone of the southeast corner of the Landsat scene.

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Historical rainfall data were obtained from the National Weather Service. These data indicated that no rain had fallen in the previous three days north and west of the apparent rainfall line, whereas recent rainfall had occurred south and east of the apparent rainfall line. It is thus likely that the major cause of the observed darkening in the southeast corner of the May 6 Landsat scene was a recent rainfall.

Data Extraction

Samples were extracted from both the west (dry) and east (wet) sides of the Landsat scene. Tasseled Cap Greenness and the Normalized Vegetation Index were computed from the raw data, by the formulas:

$$\text{Greenness} = (-.28 * \text{MSS4} - .66 * \text{MSS5} + .58 * \text{MSS6} + .39 * \text{MSS7}) + 32.$$

$$\text{NVI} = [(\text{MSS7} - \text{MSS5})/(\text{MSS7} + \text{MSS5})] * 100. + 30.$$

To insure that differences in vegetation indices between the two samples were not due to differences in amount of cropped area, thresholds in Greenness and NVI were established based on histograms and training set values so as to separate cropped land from uncropped land. The thresholds chosen were 50. for Greenness and 10. for NVI. Data above these values were assumed to be from cropped land, while data below these values were assumed to be from non-cropped land (although some might have been rangeland).

Three blocks of data of approximately 15,000 pixels each were extracted from the west side of the image, and another three blocks of equal size were selected from the east side of the image. The number of pixels above the vegetation threshold was then examined for both sides of the image. The locations of some blocks of data were adjusted slightly until approximately the same total number of pixels in the three blocks were above the threshold for both sides of the scene. Average values of Greenness and NVI for all pixels in the blocks and for pixels above the threshold were then examined to assess the effects of soil brightness independent of cropping intensity (although perhaps not independent of crop condition).

Results

The results are shown in Table 3.12 for blocks of data on the west and east sides of the image. Total number of pixels in each group is 44984. The average Brightness on the west side is clearly higher than that on the east side, an indication of the dryer (brighter) soils on the west side of the image.

The average values from the blocks before thresholding might be affected by two parameters other than soil brightness. Light and dark bare soils might have different values, especially for NVI. In addition, some of the non-cropped pixels may be grassland that is not green enough to be called agricultural land, but has a higher Greenness than bare soil. As a result, variations in the percentage of bare land and prairie could affect the average Greenness value using all pixels. The vegetation index values of thresholded pixels

Table 3.12 Vegetation index values.

Block	Average -- All Pixels				Average – Above Threshold		
	Br	Gr	NVI	NVI/Gr	Gr	NVI	NVI/Gr
West	83.6	49.6	15.2	0.306	59.7	24.3	0.407
East	55.3	48.9	24.6	0.503	59.6	54.4	0.913

are considered to be a less ambiguous indication of the soil brightness effects on vegetation index values.

The Tasseled Cap Greenness data in Table 3.12 can be seen to be slightly higher on the west side of the image than on the east side, and the NVI is considerably higher on the east side than on the west side of the image, both for the thresholded and the unthresholded data. This is the pattern that would have been predicted by Huete, et al. (in press) if all other factors were equivalent on both sides of the image, although the differences in Greenness are so small they might not be considered significant.

All other factors are probably not equivalent, however, since growing conditions are expected to be slightly better as one moves from the west to the east in the Great Plains. Therefore, we hypothesize that the average actual green percent cover is slightly higher on the east side of the scene than on the west side. The increase in NVI which is observed may thus be more pronounced than it would have been if only soil brightness had varied from west to east, and the decrease in Greenness may be less pronounced than it would have been if only soil brightness had varied.

Given that a variety of factors could affect the absolute values of the vegetation indices studied, it may be more appropriate to examine the values of the vegetation indices relative to each other (i.e. the ratio of their values) as soil brightness varies. On the west side of the image (brighter soils) the ratio of NVI to Greenness for all pixels is 0.306, whereas on the east side (lower brightness) the ratio is 0.503. This represents a 64.6% increase in the ratio of the two indices from "dry" to "wet" conditions. A similar analysis for only the pixels above the vegetation index threshold shows that the ratio of NVI to Greenness is 0.407 on the west side and 0.913 on the right side, a 124.3% increase from "dry" to "wet."

Conclusion

As mentioned previously, a great many environmental factors may have affected the results presented here. Therefore, no definitive conclusions can be drawn. However, the results suggest that the two types of vegetation indices investigated do behave differently in response to environmental variation, and that these differences are consistent with modeled and field-measured differences associated with soil brightness. Thus, we believe that this issue deserves additional investigation, both theoretically and with actual Landsat data.

Decoupling the soil effects on vegetation indices is certainly a desirable goal. Not only would this capability enable us to monitor vegetation conditions more accurately, but it might also enable more accurate determination of soil conditions under partial vegetation cover (e.g. Colwell, 1981).

Recommendations

Without detailed ground truth, it will be difficult to ever carry out an analysis of Landsat data which can yield definitive answers to the issues discussed here. However, the basis of a good experiment probably occurs during most every summer overpass of the western Green Plains, where a significant amount of center pivot irrigation occurs. Any field which has been partially irrigated at the time of data acquisition is a candidate for assessing the effects of soil brightness (as affected by soil moisture) for a variety of vegetation indices, with other potential influences reduced to a substantial degree. Capitalizing on such targets of opportunity, or even making special irrigation arrangements with farm operators would allow for appropriate field data collection support, including measurements of soil brightness, field spectral response, and percent green cover in wet and dry parts of the test fields.

The above research should be done in conjunction with research on the effects of soil color, atmosphere, and viewing and illumination geometry, in order to determine the significance of any possible soil brightness effect relative to other possible effects on vegetation indices. In addition, potential ways of overcoming expected soil brightness effects should be explored.

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4.0 CONCLUSIONS AND RECOMMENDATIONS

The following represents a compilation of the significant results and conclusions discussed in the previous sections.

1. Reflectance factor data may be transformed, by means of the provided transformation matrix (Table 2.1), to a feature space analogous to the TM Tasseled Cap feature space for actual data. This analogous transformation allows more direct application of field-based results to actual satellite data.

2. Based on principle component analysis of soil spectra, it would appear that the TM bands capture most of the significant soils-related information in the 400 to 2500 nanometer spectral range, and in particular capture significant soil spectral variation (and presumably information) missed by the four MSS spectral bands. The first two principle components derived from the reflectance spectra are very similar in nature to TM Tasseled Cap Brightness and Wetness. There is, however, indication of soil spectral information in the 900 to 1300 nanometer spectral range which is outside the range of sensitivity of the TM bands. The nature of this variation, as captured in the principle components analysis, suggests that the MSS band placement may also result in the loss of the associated information.

3. Variation in the TM Tasseled Cap Fourth Feature is correlated to organic matter in the sense that a change in organic matter content seems to be accompanied by a spectral change in a predictable direction in the Greenness-Fourth Feature projection. However, a given Fourth Feature value cannot be used to predict the amount of organic matter in the soil sample. In addition, high iron, low organic matter African soils (red) were clearly delineated in this feature projection from brown, mid-latitude soils with a range of chemical and textural compositions. No direct association between any particular soil characteristic or condition and Fourth Feature response has been discovered which could be used to predict soil properties from Fourth Feature response.

4. Both the ratio of TM bands 5 and 7, and the TM Tasseled Cap Wetness feature, show promise of providing a means by which available moisture can be measured using TM data. The previously hypothesized relationship between Wetness and moisture content (percent-by-weight) independent of overall reflectance differences was not supported by the analyses reported here. Although the other factors primarily influencing Wetness response were not conclusively determined, both organic matter content and soil texture were found to influence the Wetness response to soil moisture in a consistent manner.

Recommendations

Because of the complexity and new range of spectral coverage which are characteristics of data from the Thematic Mapper, we should be cautious about too quickly assuming that we know all there is to be known with respect to the types of information which can be extracted from these data, or the best ways of extracting and analyzing that information. While the TM Tasseled Cap transformation has provided a means of viewing the key data structures in the TM data, the physical scene class characteristics which express themselves in the TM Tasseled Cap feature space are not, by any means, fully understood, particularly in the features most different from those derived from MSS data. Indications from Tasseled Cap analyses to date of improved potential for distinguishing between greening-up and senescing vegetation or cultivated and forest vegetation, deriving information about classes within the broad forest category, and of course, extraction of soils-related information, all suggest that a substantial number of basic research avenues are still in need of attention. In a very real sense, we do not yet know what the Thematic Mapper can do for us in monitoring vegetation resources.

The soils-related analyses described in this report have advanced our understanding of the TM's potential for providing soil moisture information, but as much as that, they point out the need for a more detailed and comprehensive soils-related research project. Using a broader range of soils, more detailed chemical and mechanical analysis of the soil samples, and more sophisticated laboratory techniques, the correlation between the TM5/TM7 ratio and moisture tension, and between TM Tasseled Cap Wetness and moisture tension, should be more fully explored. Such a data set should allow quantification of the errors associated with these approaches to spectral estimation of soil moisture status, as well as development of means by which the residual variation may be reduced or normalized. Accomplishing these goals could result in a truly operational, relatively low-cost method for soil moisture monitoring on a large scale, a capability which would be of significant value in managing the earth's resources.