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SPECTRAL REFLECTANCE AND EMITTANCE AND ASSOCIATED PHOTOGRAPHIC AND NON-PHOTOGRAPHIC IMAGERY IN RELATION TO SOILS OF THE EDMONTON-VEGREVILLE REGION, ALBERTA

by

Ⓒ PETER HERBERT CROWN, B.S.A., M.Sc.

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF SOIL SCIENCE

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Spectral Reflectance and Emittance and Associated Photographic and Non-Photographic Imagery in Relation to Soils of the Edmonton-Vegreville Region, Alberta" submitted by Peter Herbert Crown in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

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ABSTRACT

This study was designed to relate spectral reflectance and emittance to soils in the Edmonton-Vegreville region of Alberta and is presented in three chapters.

The results of a field study of soil reflectance are discussed in Chapter I. Soil reflectance in the visible region of the electromagnetic spectrum is primarily influenced by surface soil color. In the reflective infrared spectral region, surface soil color is a dominant factor influencing soil reflectance but surface roughness or configuration and moisture content are also important. In most cases, infrared reflectance decreases as color darkens, moisture content increases, and surfaces become rougher. The exception is the increase in infrared reflectance as roughness increases for dry, very light colored surface soils.

Spectral emittance from soils is discussed in Chapter II. In the Edmonton-Vegreville region, topography and land use exert a strong influence on spectral emittance as recorded on thermal imagery of the 3.5 to 5.0 micrometer band. Once these are taken into account, variations in image tones for soils are related to soil moisture conditions that arise from differences in soil texture, drainage, and surface erosion.

The relationships between soil reflectance and emittance and the processes of soil formation operative in this region are dicussed in Chapter III. For bare soil surfaces, zonal soils can be discriminated on the basis of spectral reflectance, especially reflectance in the visible region of the spectrum. Reflectance is a surface phenomenon

and the processes of soil formation for the zonal soils of this region, the Black Chernozems and the Gray Luvisols, are strongly expressed by surface soil characteristics, especially color. When soils are covered by cultivated crops, patterns and variations in crop development, as observed on color aerial photographs, relate to the occurrence of zonal and intrazonal soils. These patterns and variations in crop development within fields of one crop type provide qualitative data on soil characteristics, such as the extent and relative degree of soil salinity, but quantitative assessments can not be accurately made.

Thermal imagery, in the 3.5 to 5.0 micrometer band, from spring provides tonal patterns that relate to the occurrence of zonal and intrazonal soils in this region. Halomorphic soils occur in areas of groundwater discharge and have mottled, light and dark image tones whereas zonal soils have more uniform thermal image tones. Halomorphic and hydromorphic soils, in areas of groundwater discharge, can be discriminated on the basis of diurnal and seasonal variations in associated thermal image tones. Greater diurnal variations in tone occur for hydromorphic soils. Hydromorphic soils of groundwater discharge and recharge areas are discriminated on the basis of seasonal variations in diurnal changes in thermal image tones. Hydromorphic soils in recharge areas are generally closer to ambient soil temperature conditions in the fall. Those of discharge areas have similar diurnal variations in image tones in the spring and fall with relatively dark tones (cooler surface temperatures) on midday imagery and relatively light tones (warmer surface temperatures) on predawn imagery.

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INTRODUCTION

INTRODUCTION

Basic Concepts of Remote Sensing

The term "Remote Sensing" describes the acquisition, recording and utilization of information about objects obtained through the use of various sensors placed at a distance from those objects. Through use, this term has come to describe studies of the earth's surface using sensors mounted in aircraft and satellites, with the data usually presented in the form of hard copy imagery although there are other forms of presentation as well, such as analogue or digital forms. Hard copy imagery is desired by those interested in earth resources since they are usually concerned not only with conditions at a given point location but also with the areal extent of particular features and spatial relationships between features. Also, many relatively inexpensive techniques for interpretation have been developed for hard copy imagery.

Aerial photography can be considered as the historical basis of remote sensing and continues to provide the most commonly used form of data. However remote sensing encompasses more than standard aerial photography in terms of both data collection and data handling. The development of various non-photographic sensor systems has provided the capability of acquiring and recording <u>multispectral</u> information about objects on the surface of the earth. Data can be obtained by recording reflected and emitted electromagnetic radiation in spectral regions beyond the capability of aerial film emulsions and in relatively narrow spectral bands from the ultraviolet to the microwave regions of the spectrum. Unfortunately not all types of sensors that have been developed are readily available for civilian use in Canada. Those systems that are available include photographic systems and thermal infrared line scanners mounted in conventional aircraft and the multispectral scanners mounted on the LANDSAT satellites. Aircraft for photographic missions at altitudes above 40,000 feet are not available, therefore, very small scale aerial photography is not possible. Aircraft mounted multispectral line scanners and microwave systems are not readily available. Therefore, for much of the work done in Canada the state-of-the-art technology in terms of multispectral sensors available has not advanced as rapidly as in the United States.

Particularly with sensor systems mounted in satellites providing repetitive coverage over a given location, the multidate concept of data acquisition is another way in which remote sensing expands the dimensions of standard aerial photography. Repetitive coverage provides the capability to monitor changes in objects and thereby aid in their discrimination and/or identification. This capability would be a most expensive proposition were it to be provided by aerial photography alone.

Conventional aerial photography has often been limited with respect to the variety of smaller scales of photography available and to the ability to provide coverage over a large area quickly and cost-effectively. Also, if extensive aerial coverage is required a great volume of conventional photography would be required and could prove to be costly if the object of interest occurs only in widely scattered locations. Remote sensing as now used emphasizes the concept of multistage or multiscale imaging. In this way large areas can be covered at extremely small scale, such as with satellite data, and only the most promising areas as seen on this small scale imagery can be reflown at successively larger scales in order to obtain the desired level of detail. In conjunction with the multiscale approach is the necessary distinction between "discrimination" and "identification". Discrimination involves the separation of different areas or objects as seen on an image. All that is required is that the areas be discriminated consistently. Identification can be delayed until the most detailed data are available followed by extrapolation to identify all those areas or objects previously discriminated.

Finally, many uses of remotely sensed data require some a priori knowledge of spectral signatures, the most likely objects to be found in an area and/or the condition of those objects if they possess some temporal aspects (i.e. changes that occur in a predictable fashion over the year, or year to year). In this regard the target calendar concept has proven to be most useful in deciding on imaging dates and in predicting tones or colors associated with different features. Target calendars are generally presented in the form of charts or tables that list the targets to be found in an area and the temporal changes in appearance or stage of development that are usually expected for each over a defined period of time.

Image Analysis

Image analysis or interpretation is defined by Estes and Simonett (1975) as "the act of examining images for the purpose of identifying objects and judging their significance". Techniques developed for the interpretation of aerial photographs can be applied to the analysis of the various types of imagery including black-and-white and color aerial photography, thermal infrared imagery and LANDSAT multispectral imagery, that are most readily available to Canadian pedologists. These techniques are described in detail in many texts, most notably publications of the American Society of Photogrammetry, including the Manual of Photographic Interpretation (1960), the Manual of Color Aerial Photography (1968), and the most recent Manual of Remote Sensing (1975).

For all types of imagery certain basic elements can be studied in order to identify and assess the significance of objects. These include consideration of size, shape, shadow, tone or color, texture and pattern (Estes and Simonett, 1975).

a) <u>size</u>: The size of an object, especially in relation to other objects around it, is most useful for identification although the apparent size of an object on a particular image will depend on the scale of that image as well as the resolving power of the system used.

b) <u>shape</u>: The shape or geometry of various objects can also be extremely useful in identification since certain objects have very distinct shapes. Shape or geometry is also important in relation to shadowing.

c) shadow: Shadows may be beneficial to the identification process if they provide details of shape by silhouettes especially if tonal contrasts are low but may also be a hindrance since detail within shadowed areas is often obscured.

d) tone or color: Tones or colors presented on images relate to scene reflectance, emittance or transmittance characteristics. With the partial emphasis of remote sensing being on the use of multispectral data for identification, tones or colors are the most significant element of image analysis. The successful use of tones or colors depends on a knowledge of the factors influencing tonal variations that arise from the sensor system used and of the manner in which various objects reflect, emit or transmit electro-magnetic radiation.

e) texture: Image texture refers to the perception of surface roughness or smoothness of objects due to the repitition of or lack of tonal changes. Textures may be useful in identification as in the case of the rough textures associated with forest stands or the smooth textures associated with agricultural crops.

f) pattern: Pattern refers to the spatial arrangement of objects and the use of patterns for identification depends upon the interpreter's knowledge of natural and cultural patterns in the terrain.

Although these elements are studied on any type of imagery, their meaning and significance vary with the type of imagery employed.

1. Photographic Imagery. Through the use of cameras, filters and film emulsions reflected energy in the spectral region between 0.36 and 0.9 microns wavelength or portions of it may be recorded (Table 1). All of

Table 1. Typical film-filter combinations for photographic imaging in various spectral bands (after Eastman Kodak Company, 1970, 1971).

Film Type	Kodak Filter	Spectral Band (nm)	Comments
Black & white panchromatic	--	360 - 720	unfiltered
	W12	500 - 720	for haze
	W58	500 - 590	green band
	W25	590 - 720	red band
Black & white infrared	W89B	700 - 900	extreme contrast infrared image
	W25	590 - 900	high contrast infrared image
	W12	500 - 900	modified infrared image
Normal color	--	360 - 720	unfiltered
	WHF3	400 - 720	for haze
Color infrared	W12	500 - 900	blue light elimination

the above mentioned elements are employed for the interpretation of photographic imagery. However when portions of this spectral region are utilized, tone or color becomes an even more important consideration since the tone associated with a given object may be quite different in one portion of this spectral region as compared to another.

One useful advantage of photographic imagery is the stereoscopic view of the terrain surface that is provided. By viewing overlapping photographs a three dimensional view of the photographed area allows for the delineation of topographic variations and height measurements.

Photographic imagery is best suited for a qualitative assessment of scene reflectance since many external factors other than the reflectance characteristics of targets affect the resulting tone on the image. These include physical environment factors such as the intensity and spectral quality of the illuminating sun and skylight, and the reflectance characteristics of terrain features. Other external factors are associated with the equipment used including exposure settings on the camera, and spectral sensitivity and other characteristics of the film emulsion. Finally, processing factors such as the length of time that the film is in the developing solutions will affect the final tone or color which represents a given scene reflectance value (Heller, 1970).

2. Thermal Infrared Imagery: Emitted energy in the spectral regions from 3.5 to 5.5 micrometers and 8.0 to 14.0 micrometers wavelength can be recorded using scanning devices. The black-and-white imagery produced is suited to both qualitative and quantitative evaluation (Estes and Simonett, 1975). Images may be studed qualitatively to

to identify objects based on considerations of the basic elements of image analyses. Tones in this case relate to surface temperatures and the imagery may also be studied quantitatively to assign specific temperatures to given tones on the imagery. One disadvantage of thermal infrared imagery is that it cannot generally be viewed in three dimensions since it is obtained as continuous strips.

Aerial Photography and Thermal Imagery for Soil Mapping

In very general terms the terrain can be viewed as being composed of three main components - vegetative material, mineral material and water. In most agricultural areas the dominant mineral component is soil and the amount of surface area exposed varies considerably with the time of the year. As with most other objects found in the terrain, soils are three dimensional, however their third dimension is down from rather than up from the terrain surface. Therefore, at the optimum time only the soil surface is imaged and once covered by cultivated crops even this is not the case. Some soil conditions, however, make their presence known by altering the growth of crops in such a way as to show differences between soils, at least in terms of areal extent.

The ability to discriminate between different soils and to identify these differences using various types of imagery is of great significance in soil mapping. A soil map shows the location and areal distribution of soil map units in relation to various physical and cultural features on the surface of the Earth (Soil Conservation Society of America, 1976). Although the term "soil mapping" generally connotes a soil resource inventory of a relatively large area, it can also be applied to the discrimination and identification of soils in a relatively small area of a few hectares.

The most common remote sensing system available to pedologists is aerial photography although thermal scanning is also becoming more readily available.

1. Aerial photography

Most pedologists are experienced in the use of standard black-and-white aerial photography and employ a combination of deductive and inductive reasoning during the interpretation of such photographs for soil mapping. In the former case, soil features are estimated by studying landform, topography and drainage, and vegetation patterns. In the latter case, tonal patterns found to be associated with specific soils in one area are recalled when studying soils in a different area. In both cases predictions based on the interpretation of photographs are verified by field checking. Much has been written on the value of aerial photography in terms of reducing the time, effort, and cost of soil mapping (Baldwin et al. 194[illegible] [illegible]ringh, 1960; Andronikov, 1967; Bie and Beckett, 1971). With the advent and availability of other types of photography, studies have been conducted in order to evaluate these for soil resource inventories.

Valentine (1970) found that in wildland areas, as opposed to agricultural areas, where access is limited and soil characteristics must be inferred from the occurrence of distinct vegetation communities and other terrain features, black-and-white infrared photography was generally better than black-and-white panchromatic photography. However, in agricultural areas most authors agree that panchromatic photography is better since with infrared photography shadow effects are severe (Carroll, 1973a), cultural features are less distinct especially on enlargements (Acton and Stonehouse, 1972) and the very dark tones associated with fields of bare soils make stereoscopic viewing of such fields difficult (Crown and Pawluk, 1972). However, if infrared photography is useful for mapping differences in vegetation in forested and agricultural areas and panchromatic photography is useful for mapping other features, the most accurate mapping should be accomplished by using both simultaneously. It is agreed that the use of both in the field would be cumbersome but many preliminary soil boundaries are drawn in the office prior to field checking. Unfortunately, in most instances both types of photography are not available for the same area.

The literature also contains much discussion comparing black-and-white and color photography for soil mapping. The color photography includes true or normal color as well as color infrared or "false" color photography. The properties and characteristics of each are discussed in detail by Slater (1975).

Dominguez (19[illegible]) compared true color and black-and-white photography at a scale of 1:5,000 for soil mapping in a forested region of the California Sierra Nevada mountains. He concluded that accurate mapping could be done based on surface soil colors as presented on the color photography and therefore color photography was better. Exact correspondence between field and photo colors, as measured using the Munsell system, were not obtained. Parry <u>et al</u>. (1969) reached the same conclusion after studying soils and color photography for an area in Quebec. Kuhl (1970) studied the accuracy of soil mapping done at a scale of 1:12,000 using black-and-white, true color and color infrared photography. Although a trend favouring true color for the interpretation of drainage and slope classes in upland New York state was detected, there was no statistical difference between the three types of photography. Anson (1968, 1970) reported that he preferred color infrared photography for the interpretation of soil drainage and the mapping of moist soils and vegetation in California and Arizona. Valentine et al. (1971) concluded that in their study area on the coast of British Columbia panchromatic photography was as good as any other type for obtaining soil information in the mountains while color photography was much better than panchromatic for specific soil information in the valleys, with true color better than color infrared.

Carroll (1973a) found few published accounts of the applications of multiband photography to soil mapping. This is not surprising since multiband photography provides at least three simultaneous images of the same scene and the time required for visual examination would be great if an entire survey area were to be covered. There are published reports, however, on the suitability of various bands of photography for the mapping of specific soil features. Carroll (1973b) reports that Evans of the soil survey of England and Wales found the blue waveband to be unsuitable due to haze effects, the green waveband to have subdued tones, the red waveband and panchromatic photography most clearly recorded ground detail, and the infrared waveband was not recommended. It is not stated how these results were obtained. Acton and Stonehouse (1972) reported that drainage patterns in vegetated fields are more clearly discernible on infrared photography while Beke (1972) concluded that red band photography provided the best data for delineating landscape and soil units.

Each band of black-and-white photography provides a different type of data. Infrared band photography provides information on soil conditions that affect plant growth but detail in fallow fields is often lacking whereas the red band photography provides more detail in fallow fields but less detail on soil conditions that affect plant growth.

There are, therefore, contradictory conclusions regarding the usefulness of various types of photography for soil mapping. While many believe color is superior to black-and-white photography, Carroll and Evans (1971) express reservations as to the value of color photography since in their opinion increases in the quality and speed of interpretations using color are not great enough to justify the extra costs involved. The apparent usefulness of various types of photography for soil mapping depends on the objectives of the survey and the type of terrain to be covered, the use to be made of vegetation as an indicator of soil conditions, and the kinds of soil units to be separated and identified. In most of the reported studies, one type of photography competes with another in doing the same work and few authors mention the need to select the type of photography best suited for a particular project. Gerbermann et al. (1971), however, concluded that gray or neutral colored soils are best distinguished by color infrared photography while strongly colored soils are best distinguished by true color photography. Valentine et al. (1971) also indicated that the type of photography should be selected to suit the terrain to be covered.

2. Thermal imagery.

Thermal imagery has not been used for general soil mapping.

This type of imagery provides only surface temperature data and the interpretation is more complex than the interpretation of reflectance data as recorded by aerial film emulsions. Thermal imagery does not provide a three dimensional view of the landscape nor does it provide a geometrically correct base for mapping purposes as does aerial photography. Thermal imagery has generally been used for soil studies in relatively small areas where a single factor, surface temperature, is related to specific soil properties (Myers and Heilman, 1969; Myers et al., 1970; Tarnocai, 1972; Michalyna and Eilers, 1973).

Nature and Scope of Study

In the early 1970's, prior to the launching of the first of the LANDSAT series of earth resource satellites, many Canadian pedologists took advantage of special airborne programs offered by the Canada Centre for Remote Sensing that were designed to acquaint potential users with multispectral data in the form of multiband and multi-emulsional photography and thermal infrared line scan imagery. Many investigations on the use of these forms of data for soil studies, particularly soil mapping, were undertaken and the results were presented at the First Canadian Symposium on Remote Sensing held in Ottawa in February, 1972 (Acton and Stonehouse, 1972; Beke, 1972; Mills, 1972; Tarnocai, 1972). In many cases the results of these investigations did not progress beyond the "one can see this or that" stage and many pedologists lost active interest in remote sensing research.

Pedologists engaged in soil resource inventories often become accustomed to viewing different soils only in terms of the kinds and arrangements of horizons within the soil body. Since the entire soil body is not imaged by any remote sensing means, the use of remote sensing for soil inventories is generally limited at present to the use of black-and-white, panchromatic photography which provides a three dimensional view of the terrain for mapping topography and a base map for plotting soil sampling sites and soil boundaries. Few Canadian pedologists have an awareness of or an appreciation for the broader aspects of remote sensing, particularly its multispectral concept.

This study was designed to relate spectral reflectance and emittance from soils to tones presented on photographic and non-photographic (thermal) imagery. The purpose was to investigate the use of such multispectral data to discriminate different kinds of soils. Empirical studies of soil reflectance, measured in the field, and soil emittance recorded by thermal imagery, were conducted in order to provide the _a priori_ knowledge necessary for the further interpretation of remotely sensed data. The results of these studies are presented in Chapters I and II respectively.

Based on these results a model was developed to relate spectral reflectance and emittance characteristics of soils to the processes of soil formation for the purpose of discriminating different kinds of soils. This model was tested using multiband photography to obtain airborne multispectral reflectance data from bare soil surfaces, color photography to obtain reflectance data from a cultivated crop pertaining to soil characteristics, and thermal imagery to obtain emittance data. The results are presented in Chapter III.

The data used to construct the various figures included in the text and a glossary of remote sensing terms are included in the appendices.

The Study Areas

The two areas selected are located in central Alberta with soils, landforms and land use patterns typical of the forest-grassland transition zone of Alberta. These areas were selected since relatively detailed soil mapping projects had been completed in each (Menon, 1971; Leskiw, 1971). One area is located northeast of Vegreville and the second is located immediately east of Edmonton (Figure 1). A study of soil genesis related to groundwater and soil moisture regimes was also being conducted in the Vegreville area (Maclean, 1974). These studies provide ground-truth data for the interpretation of remotely sensed data.

The Vegreville Area: This area, studied by Leskiw (1971), is northeast of Vegreville, east of the Vermilion River (Figure 2). Surficial deposits are dominantly glacial till, normally clay loam textured but with the occasional occurrence of sorted material on the surface. The western half of the area is undulating ground moraine while the eastern half is more hummocky, "dead-ice" moraine (Leskiw, 1971). Black Chernozem soils are dominant in the area with Solonetz soils frequently found at lower elevations. Leskiw (1971) discussed the relationships between groundwater flow and soil pedogenesis. In the groundwater recharge areas to the east the well drained soils are generally Eluviated Black Chernozems while the poorly drained soils are either Humic

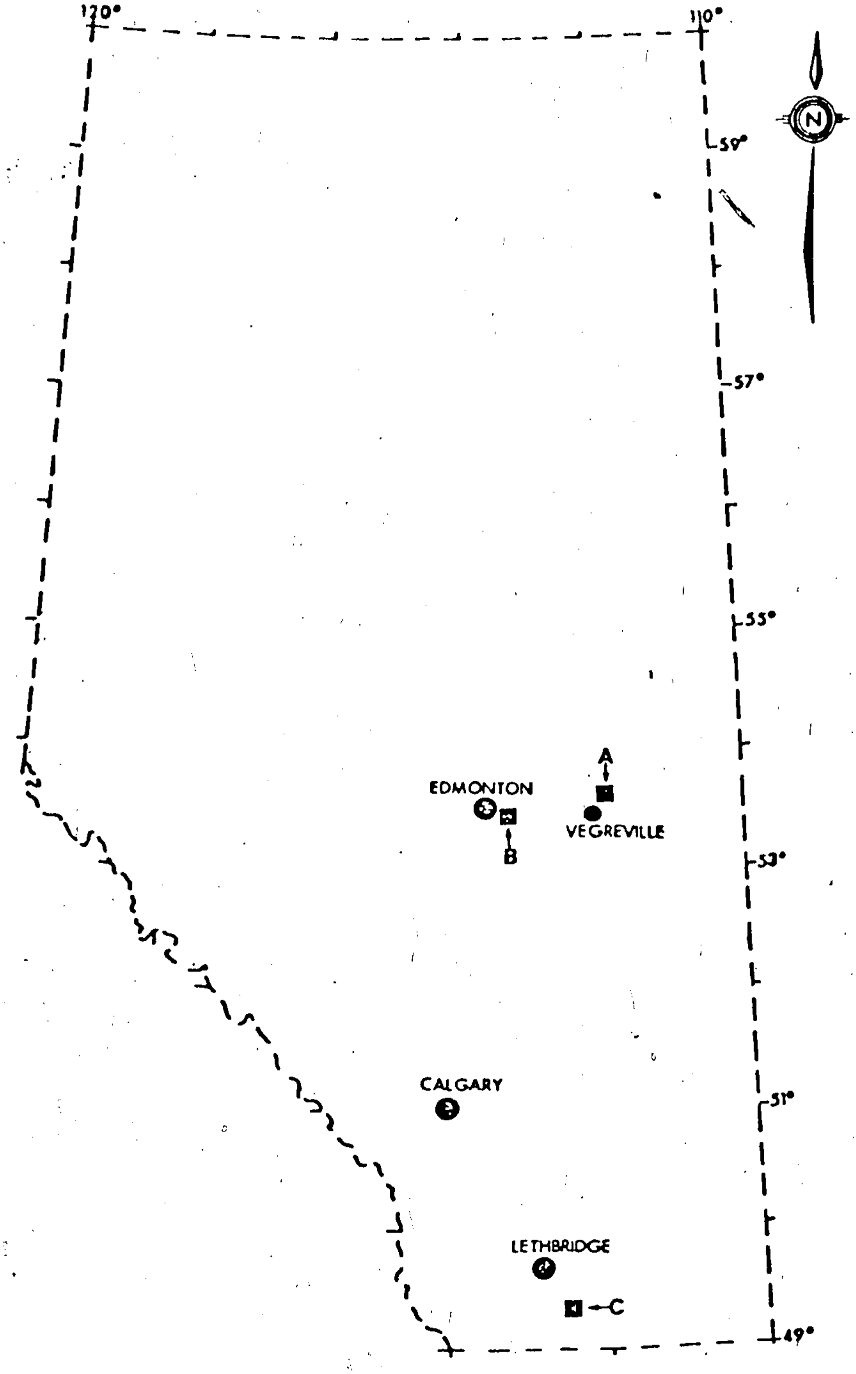

Figure 1. Sketch map of Alberta showing the locations of the Vegreville study area (A), Edmonton study area (B), and the Milk River Ridge Reservoir (C).

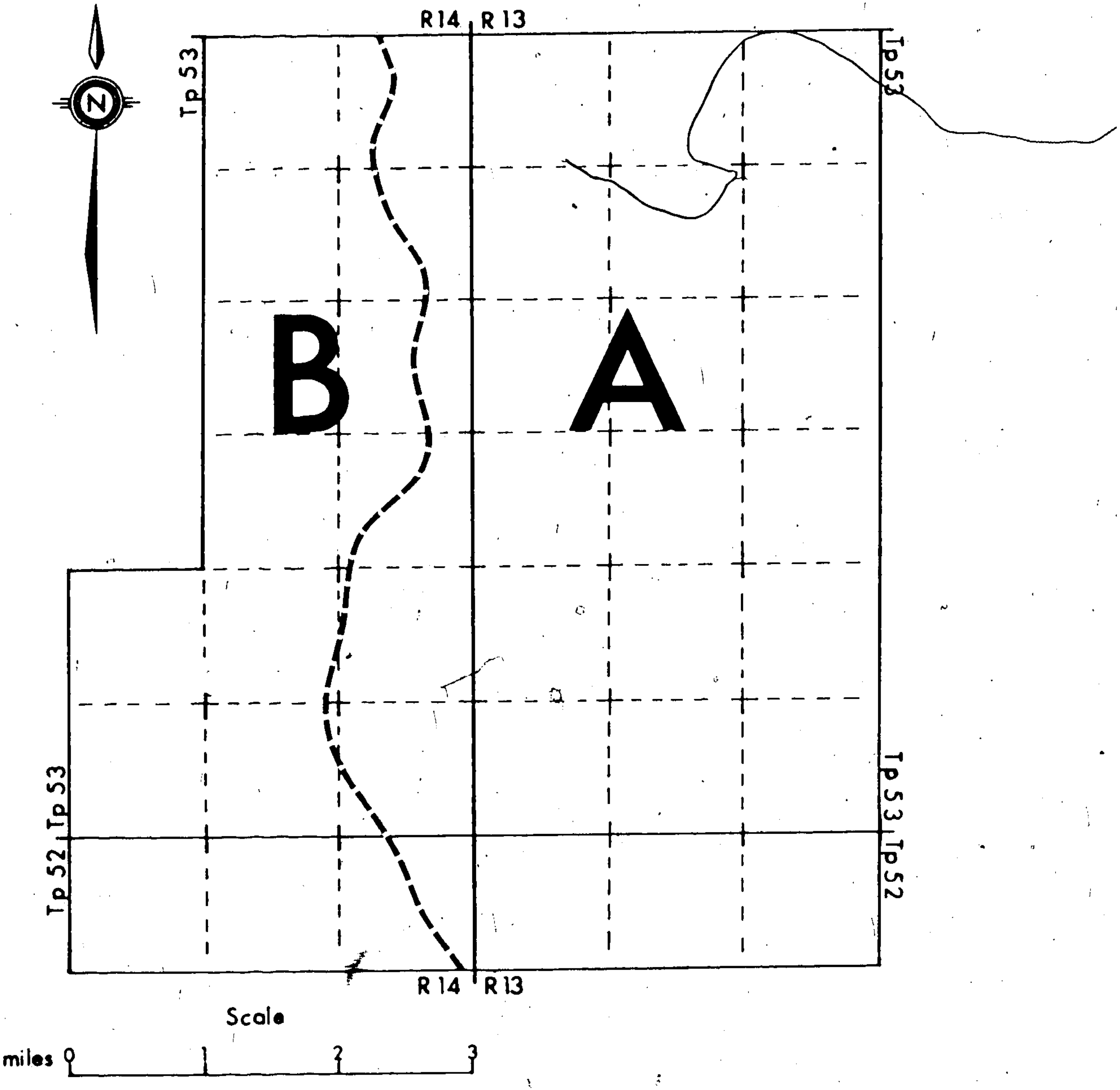

Figure 2. Map of the Vegreville study area showing the hummocky moraine area of groundwater recharge (A) and the ground moraine area of groundwater discharge (B) (modified after Leskiw, 1971).

Eluviated or Orthic Humic Gleysols. These poorly drained soils contain no layer of lime accumulation and no saline horizons. In the western portion of the area groundwater discharge occurs and the better drained soils are in the Solonetzic Order and the poorly drained Gleysolic soils contain saline horizons and lime accumulation layers. Maclean (1974) found similar relationships but with more data was able to relate soils to water table. In the eastern portion of the area the kind of poorly drained soil varies with the depth to the water table ranging from Humic Eluviated Gleysols to Orthic Humic Gleysols with decreasing depth to the water table from the ground surface. In the discharge area in the western portion of the area, the depth to water table greatly influences the kind of soil found. Where the water table is usually within 0.5 meters of the surface Alkaline Solonetz, Saline Carbonated Gleyed Regosol and Saline Black Solonetz soils occur whereas in the same discharge area where the water table is at least 0.5 meters from the surface Black Solonetz soils occur. In the recharge area, if the water table is 2 meters or more from the surface, soils of the Chernozemic Order can occur.

These relationships between depth to water table and the kind of soil developed are important in the interpretation of thermal imagery.

The Edmonton Area: Soils in the area immediately east of Edmonton (Figure 3) were mapped by Menon (1971). The western portion of this area is predominantly an undulating to gently rolling glaciolacustrine plain with Orthic Black, Eluviated Black and Solodic Black Chernozem soils. The central portion is dominantly ground moraine with Orthic

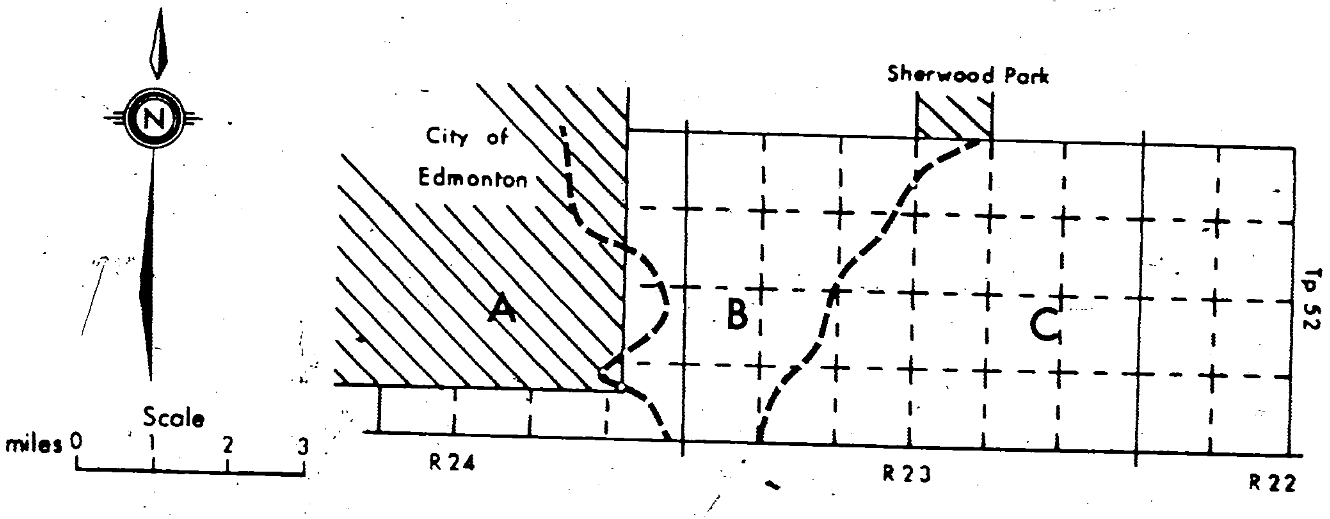

Figure 3. Map of the Edmonton study area showing the western portion comprised of undulating to gently rolling glaciolacustrine sediments (A), the ground moraine portion (B), and the hummocky moraine portion (C) (modified after Menon, 1971).

and Eluviated Black and Dark Gray Chernozem soils plus Dark Gray Luvisol soils developed on clay loam till. A few small areas of glaciofluvial sand are also found in this portion of the area. The eastern portion of the area is hummocky disintegration moraine with Orthic and Dark Gray Luvisol soils developed on clay loam till often with superglacial deposits of various textures.

The climate in both areas is characterized by cold winters and relatively warm summers. Mean annual precipitation varies from 40 to 46 cm with most of this falling as rain during the growing season (Menon, 1971; Maclean, 1974).

Grain and oilseed crops are the major land use in the Vegreville area with field sizes generally 28 hectares or more. The Edmonton area is used for mixed farming and field size is much more variable ranging from a low of 6 to 10 hectares up to 40 to 48 hectares. Extensive urbanization is occurring southeast of Edmonton and in the area around Sherwood Park.

CHAPTER I

SPECTRAL REFLECTANCE FROM SOILS

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INTRODUCTION

Interest in the spectral reflectance characteristics of terrain features results from the basic concept that these features reflect, absorb and emit electromagnetic radiation in unique and characteristic ways depending on their physical and chemical properties. Reflectance characteristics or spectral signatures influence image tones or colors as recorded by multiband or multiemulsion photography and assist in explaining the tones or colors that are presented on the final print or transparency. Also an understanding of spectral signatures is invaluable in planning remote sensing missions by providing _a priori_ knowledge necessary for the selection of spectral regions for sensing and optimum imaging dates.

Many studies of the spectral reflectance characteristics of soils have been conducted in the laboratory under controlled conditions and more recently in the field under natural conditions. Most of the reported work, however, has been conducted in areas of the United States where soil and other natural conditions are dissimilar to those in the Edmonton region. In order to obtain the _a priori_ knowledge necessary for further soil investigations using remote sensing techniques, a field study of soil reflectance was conducted using soils of the Edmonton and Vegreville areas of Central Alberta which had been previously mapped in detail by Menon (1971) and Leskiw (1971), respectively.

Factors Affecting Soil Reflectance

Studies reported in the literature have identified certain soil properties that influence soil reflectance in the ultraviolet, visible and reflected infrared regions of the electromagnetic spectrum.

a) moisture content. The visual darkening of soil on wetting is a commonly observed natural phenomenon. Planet (1969 - 1970) referenced the work done by Angstrom (1925) where the decrease in the visible reflectance from soils with wetting was explained on the basis of the total internal reflections in the water film that surrounded each soil particle. Some of the energy reflected from the surface of the soil particle does not return to space but is re-reflected by the water film to the soil surface. Planet (1969 - 1970) supported this explanation but also noted conditions where it may not be valid such as where changes in the physical nature of the soil occur by the wetting process and where changes in the index of refraction of the water occur due to dissolved soil constituents. It was also noted that soils with high reflectance in their dry state have a greater decrease in percent reflectance on wetting than soils with low reflectance in their dry state.

Bowers and Hanks (1965) showed that the percent reflectance at each wavelength from 400 to 2,200 nanometers decreases as soil moisture content increases, with the greatest changes occurring between dry soil and soil at relatively low moisture content. Shields et al. (1966) showed that as soil is wetted the greatest color changes occur at the lower moisture contents and once wetted past a limit of moisture content, further changes in soil color are not significant.

This limit is at a lower moisture content for Chernozemic soils than for Luvisolic soils. Hoffer and Johannsen)69) reported that for fine textured soil, percent reflectance curves maintain the same spectral shape as the soil is wetted although reduced in magnitude. Coarse textured soils exhibit a marked change in curve shape with an increase in moisture content, from relatively flat curves in the reflective infrared for dry soils to curves with pronounced water absorption bands at wavelenths of 1,440 to 1,900 nanometers for moist soils. With both soil textures the greatest changes in percent reflectance with wetting are in the reflective infrared. Cipra _et al._ (1971) reported a decrease in percent reflectance from wet soils when compared to the reflectance from the same soil when dry at all wavelengths, with the change in percent reflectance being greater as the wavelength increased. They also reported a greater change in reflectance on wetting from coarse textured soil than from fine textured soil.

The decrease in percent reflectance with increase in moisture content therefore appears to be most pronounced with lighter colored and coarser textured soils and at relatively lower moisture contents. Although reflectance in the visible portion of the spectrum is reduced by wetting, the most pronounced reductions in percent reflectance occur in the reflective infrared, specifically at wavelengths where the increase in absorption is related to the increase in the number of water molecules present. At these wavelengths (1,440 and 1,900 nanometers) the energy of the incident radiation equals the vibrational energy of the water molecules (Colwell _et al._, 1963).

The decrease in percent reflectance as soil moisture content increases also appears to be specific for each soil texture or soil type (Bowers and Hanks, 1965; Hoffer and Johannsen, 1969).

Since reflectance is a surface phenomenon of soils, the results of these reported studies are probably not directly applicable to the field. Soils in the field although moist often develop a thin, dry crust at the surface in which case reflectance data do not provide information as to the soil's subsurface moisture status.

b) soil organic matter. The relationships between soil organic matter and soil color and reflectance have been reported by many authors. Although the organic matter content of soil is only approximated by soil color (Buckman and Brady, 1969), Bowers and Hanks (1965) reported that as the amount of organic material decreases soil reflectance increases at all wavelengths but in particular in the 600 to 800 millimicron range. Shields *et al.* (1968) reported that the nature of the organic material is more important in influencing soil reflectance than the total amount of organic material present. Other workers (Al-Abbas *et al.*, 1973; Mathews *et al.*, 1973b) have investigated the relationship between soil reflectance and organic matter content and express difficulty in relating the two quantitatively but suggest that soil organic matter, even in relatively small quantities, may mask the contribution to soil reflectance from other soil constituents.

Various Soviet workers, however, have concluded that soil reflectance in the 620 - 720 nanometer or the 700 - 720 nanometer spectral region varies inversely with the amount of organic material present in the soil, provided soil parent materials are the same

(Orlov, 1966; Mikhaylova et al., 1967). These studies, however, were conducted using soil samples from all horizons whereas the former studies used samples from surface horizons only.

The literature indicates that soil organic matter most greatly affects soil reflectance in the visible portion of the spectrum, primarily through its influence on soil color and through its masking effect on other soil constituents particularly iron oxides. When the organic matter is removed reflectance increases, especially in the visible red spectral region. Organic materials themselves may be distinguishable and quantified by ultraviolet absorption spectra (Shields et al., 1968).

c) physical surface effects. Physical surface effects include roughness, aggregation, texture and surface crusting. Bowers and Hanks (1965) measured the reflectance characteristics of kaolinite and bentonite samples of various particle size and concluded that as particle size increases from diameters of 22 to 2,680 nanometers, percent reflectance decreases with the greatest decrease occurring in the reflective infrared region. Tanguay et al. (1969) reported that reflectance decreases as surface roughness increases but that reflectance from low plasticity soils (sands) was less affected by surface roughness. This is due to the naturally rough surfaces of sandy soils relative to the wavelength range employed and to the random orientation of particles. Surface roughness is a difficult parameter to measure and in most cases a general statement defining roughness relative to the wavelength of the sensor is all that can be said (Lee et al., 1975). Cipra et al. (1971) reported a decrease in reflectance as surface soil crusts were broken in the ield. Orlov (1966) and Zyrin and Kuliyev (1967) reported that reflectance decreases as particle size or size of aggregates increases.

Most of the studies cited above were conducted under conditions where the illumination and the recording of reflected energy both occurred perpendicular to the soil surface. Rougher surfaces produce more scattering of the incident energy thereby reducing that recorded from a vertical position.

d) _soil mineralogy_. Mathews _et al._ (1973b) reported that the spectral reflectance from standard clay mineral samples shows differences in overall reflectance as well as different absorption intensities for the iron (850 nanometers) and water 1,400, 1,900 and 2,200 nanometers) absorption bands. These are related to clay structure and chemical composition. Various Russian authors have correlated the spectral reflectance of soil samples to iron content especially in the visible portion of the spectrum (Orlov _et al._, 1966; Zyrin and Kuliyev, 1967).

Mineralogy exerts its influence on soil reflectance in the visible spectrum primarily through its contribution to soil color and although it may be exerting some influence in specific absorption frequencies this influence can be masked by organic matter or soil moisture.

e) _illumination_. Variations in the spectral intensity of incident light energy can produce variations in the spectral reflectance of soils. Such variations result from many factors including sun angle which varies with latitude, time of year and time of day;

proportion of cloud cover; and/or the amount of other matter in the atmosphere which may cause scattering or attenuation.

The incident energy falling on a particular point on the ground surface is a combination of direct sunlight, diffuse or scattered skylight, and cloud light each having a characteristic spectral signature as illustrated by Gates (1970) (Figure 4). On a cloud free day the direct sunlight and diffuse skylight components in combination produce a spectral signature that is different from those of the two taken separately. The resultant spectral intensity was illustrated by Yost and Wenderoth (1969) (Figure 5). The cloudlight component is the most variable due to the fact that the percentage of clouds and their position in the sky can change relatively quickly. The presence of clouds reduces the intensity of the incident near-infrared energy if the clouds block the direct sunlight. Since very little near-infrared energy comes from diffuse or scattered skylight (Figure 4) the presence of clouds in other positions in the sky has a less drastic affect on incident near-infrared energy but reduces the amount of visible band incident energy. Some researchers who have attempted to record the spectral intensity of incident energy conclude that measurements should be discontinued if any clouds appear in the sky regardless of their position (Mack, 1974). In the Edmonton - Vegreville area of Alberta, field experience has shown that absolutely cloud-free days are rare during the summer months. Clouds are usually observed somewhere in the sky by late morning and during the afternoon of any given day.

As variations in the spectral intensity of the incident

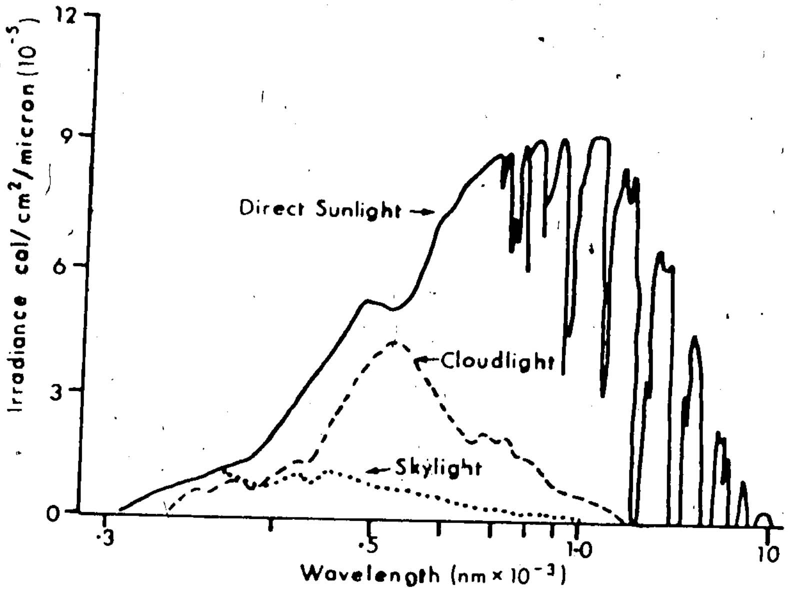

Figure 4. Spectral distribution of direct sunlight, cloudlight, and skylight (modified after Gates, 1970).

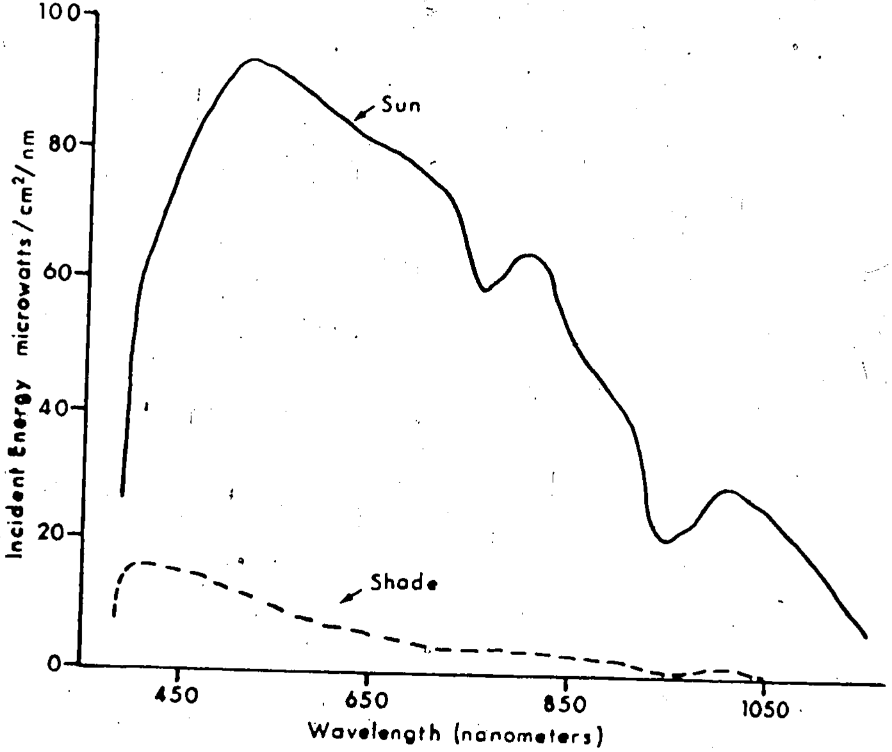

Figure 5. Spectral distribution of sun and shade measured at Davis, California. Sun includes direct sunlight and diffuse skylight (modified after Yost and Wenderoth, 1969).

energy occur, variations in the intensity of the reflected energy also occur. Gates (1970) reported on the reduction in reflected energy from vegetation when the illuminating source changed from direct sunlight to cloudlight and Crown and Pawluk (1973) studied the changes in reflected energy from gravel as the intensity of the incident energy varied. In both cases reflectance in the near-infrared is reduced to the greatest extent.

Variations in the angle of illumination also affect the recorded reflectance. Soils are not perfectly diffusing reflectors nor do they reflect isotropically but rather they reflect differentially in different directions in relation to their surface configuration and incident angle of illumination (Wagner, 1971). Coulson (1966) studied reflectance from short grass turf, soil and sand and noted that in the visible portion of the spectrum, reflectance from vegetation changes little with changes in angle of incidence but that reflectance from soils and sand is strongly dependent on angle of incidence, reflectance decreasing as angle of incidence increases from zenith. In the reflective infrared, however, reflectance from short grass turf was strongly dependent on the angle of incidence, dark soils less strongly and sand more strongly. As the angle of incidence increases from zenith, more of a given field of view is in shadow thereby reducing the effective reflecting surface area and simultaneously reducing reflectance. The reflective infrared wavelengths are more greatly affected than the visible wavelengths. Kondratiev et al., (1964) also noted the wavelength dependence of relative changes in soil reflectance with angle of incidence.

Measurement of Soil Reflectance

Numerous authors have reported the use of various makes and models of spectrophotometers with diffuse reflectance attachments to measure reflectance from soil surfaces in the laboratory (Bowers and Hanks, 1965; Shields _et al._, 1968; Tanguay _et al._, 1969; Planet, 1969 - 70; Mathews _et al._, 1973b). In all cases samples were disturbed by sieving and packing into small holders so that results are not directly applicable to the field situation. An advantage of laboratory methods is that illumination sources, being artificial, are relatively constant and the illuminating energy is usually monochromatic. In order to express results as percent reflectance some standard is employed, generally fresh magnesium oxide or barium sulphate.

Other authors (Krinov, 1974; Silva _et al._, 1971; Cipra _et al._, 1971; Kristof, 1971) have reported the use of various makes and models of spectroradiometers for measuring soil reflectance under field conditions. Such instruments allow for the measurement of the actual amount of energy being reflected from the soil surface at a given instant of time. However, because the field equipment is often cumbersome, measurements from many different kinds of soil cannot be made in a very short period of time. For comparisons between soils the results are usually expressed as a percentage of the incident energy at the time the measurements were made or as a percentage of the energy reflected from some standard surface.

Soil reflectance has also been measured using airborne techniques the most common being the multispectral scanner. Wagner

(1971), Al-Abbas et al. (1972) and Mathews et al. (1973a) reported on studies of soil reflectance as measured using the University of Michigan airborne optical-mechanical scanner. With such a system the reflectance from a variety of soils can be measured in a short period of time, depending on the areal distribution of the soils. Compared to laboratory and field instrumentation, airborne measurements are perhaps the most useful although the most costly. Laboratory and field measurements, however, provide much finer spatial and spectral resolution than airborne methods.

Summary

The spectral reflectance characteristics of soils are very complex resulting from many interacting factors. It is therefore difficult to isolate and study one factor influencing soil reflectance without altering some other factor in the process (i.e., studying effects of changes in organic matter content without considering color differences). However, a generalization may be made regarding soil reflectance in the light of what is known about plant reflectance. With plants, pigmentation (color) influences visible band reflectance, internal leaf structure influences near infrared reflectance (700 - 1,300 nanometer region) and moisture content influences reflectance in the 1,300 to 1,500 nanometer region of the infrared (Colwell et al., 1963). For soils, a similar model is possible. For instance, any factor affecting soil color, especially organic matter and moisture content, will most strongly influence visible reflectance. Infrared reflectance in the 700 to 1,300 nanometer region is influenced by surface characteristics such as roughness. In the 1,300 to 2,500 nanometer region moisture content is the main factor influencing soil reflectance especially at specific water absorption frequencies. Reflectance in all spectral regions is influenced by the intensity and angle of the illuminating energy.

Also, because of the many factors influencing soil reflectance, quantifying surface soil characteristics based on reflectance data is not considered to be possible although some of the Soviet research has been towards this end. At best, qualitative relationships can be established between reflectance data and soil characteristics.

MATERIALS AND METHODS

Field Study of Soil Reflectance

Spectral reflectance was measured in the field from selected cultivated surface soils representative of some of the more commonly occurring soils of the study areas (Table 2). All sites were located on level landscape positions and measurements were made using an Instrumentation Specialties Company Spectroradiometer powered by a 12 volt vehicle battery with a remote probe attachment and chart recorder (Plate 1, page 74). Spectral irradiance received by the detector was measured in microwatts per square centimeter per nanometer with integrated bandwidths of 25 nm in the region from 450 to 750 nm, and 50 nm in the region from 750 to 1,000 nm. The remote probe attachment head contained a diffusing screen with a hemispherical field of view that acted as a cosine filter so that the intensity of the radiance measured varied as the cosine of the angle of incidence upon the diffusing screen.

At each site measurements were made of the spectral reflectance from a 75 x 75 x 0.3 cm aluminum panel coated with Eastman White Reflectance Paint, this panel being used as a standard. Measurements of the spectral reflectance of the soil surface were then made. In both cases the remote probe head was suspended perpendicular to the surface at a height of 15 cm. The data are reported in terms of percent reflectance calculated by the ratio:

$$\frac{\text{spectral irradiance from the soil surface}}{\text{spectral irradiance from the standard panel}}$$

Table 2. Locations of soils used in the field study of reflectance and dates and times of measurements.

Soil	Sample No.	Location	Date and Time (hrs M.S.T.)	
Orthic Luvic Gleysol	L1	SE1-53-14-W4	June 20/72,	1200
	L2	SE1-53-14-W4	June 29/72,	1130
	L6	SW32-52-13-W4	June 20/72,	1300
	L7	SW32-52-13-W4	June 29/72,	1145
Orthic Gray Luvisol	L3	NW7-52-22-W4	June 16/72,	1015
	L4	NW7-52-22-W4	June 19/72,	1035
	L5	NW7-52-22-W4	June 28/72,	1100
Eluviated Black Chernozem	D1	NE11-52-24-W4	July 19/72,	1540
	D2	NE11-52-24-W4	June 28/72,	1400
	D3	NE11-52-24-W4	June 19/72,	1530
Orthic Black Chernozem	D4	NE7-52-23-W4	June 19/72,	1430
Black Solonetz	D5	SW14-52-24-W4	June 19/72,	1450
	D6	SW14-52-24-W4	July 14/72,	1150
	D7	SW14-52-24-W4	June 28/72,	1340
	D8	SE2-53-14-W4	June 20/72,	1340
	D9	SE2-53-14-W4	June 29/72,	1040
Dark Gray Luvisol	G1	SW11-52-23-W4	June 19/72,	1255
	G2	NE9-52-23-W4	June 28/72,	1120
	G3	NE9-52-23-W4	July 19/72,	1345
eroded Eluviated Black Chernozem	B1	SE1-53-14-W4	June 20/72,	1230
	B2	SE1-53-14-W4	June 29/72,	1330
	B3	SE19-53-13-W4	July 20/72,	1140
	B4	SE19-53-13-W4	June 20/72,	1140
	B5	SE19-53-13-W4	June 29/72,	1255
Terric Mesisol	F1	NW7-52-22-W4	June 28/72,	1230
	F2	NW7-52-22-W4	June 19/72,	1120
Salt crust	S1	NW25-53-14-W4	June 20/72,	1420
	S2	NW25-53-14-W4	June 29/72,	1400

Immediately after measurements had been made, surface soil color was recorded in Munsell color notation and samples collected for the gravimetric determination of moisture content, both from directly below the probe head. The date and time of measurement were recorded at each site and additional notes made on cloud conditions and surface roughness or configuration. With the date and time recorded, solar altitude and azimuth tables were consulted in order to determine the sun's position in the hemisphere.

One of the major limitations associated with the use of this instrumentation was that of the time required to move from site to site and to set-up in order to make measurements. Although measurements could be made at one site within 3 to 5 minutes, at least 30 minutes were required to move to and set-up at another site. In this time interval significant changes in illumination could occur especially in terms of cloud cover around midday. Sites were therefore visited in a random sequence on each day of field work in order that each would be visited in the morning on at least one occasion.

Data Analysis

The analysis of the data involved a characterization of the percent reflectance versus wavelength curves in terms of curve shape and slope changes. The technique employed follows that of Condit (1970) who studied the spectral reflectance of surface soils from across the United States and determined that the reflectance spectra could be classified in terms of three general curve types on the basis of curve shape and slope. The reflectance spectra for the soils of this study were classified according to this scheme in which each curve type has the following distinguishing features (Figure 6):

Type 1. Over any range of wavelengths the slope of the curve either remains constant or increases and is typical of soils with low reflectance.

Type 2. In the visible region of the spectrum, reflectance increases relatively rapidly while in the reflective infrared portion of the spectrum the increase is more gradual. The slope of the curve is greater in the visible than in the reflective infrared and is typical of lighter colored soils with more neutral hues.

Type 3. Reflectance increases gradually to approximately the 530 nm wavelength, increases sharply to 600 nm, increases less sharply to 800 nm and increases gradually to 1,000 nm. This type is typical of light colored soils with bright hues.

In order to compare differences in reflectance spectra for the various soils with different surface conditions, mean percent reflectance values were calculated for 100 nm wavelength intervals (500 - 600 nm, 600 - 700 nm, 700 - 800 nm, 800 - 900 nm, 900 - 1,000 nm),

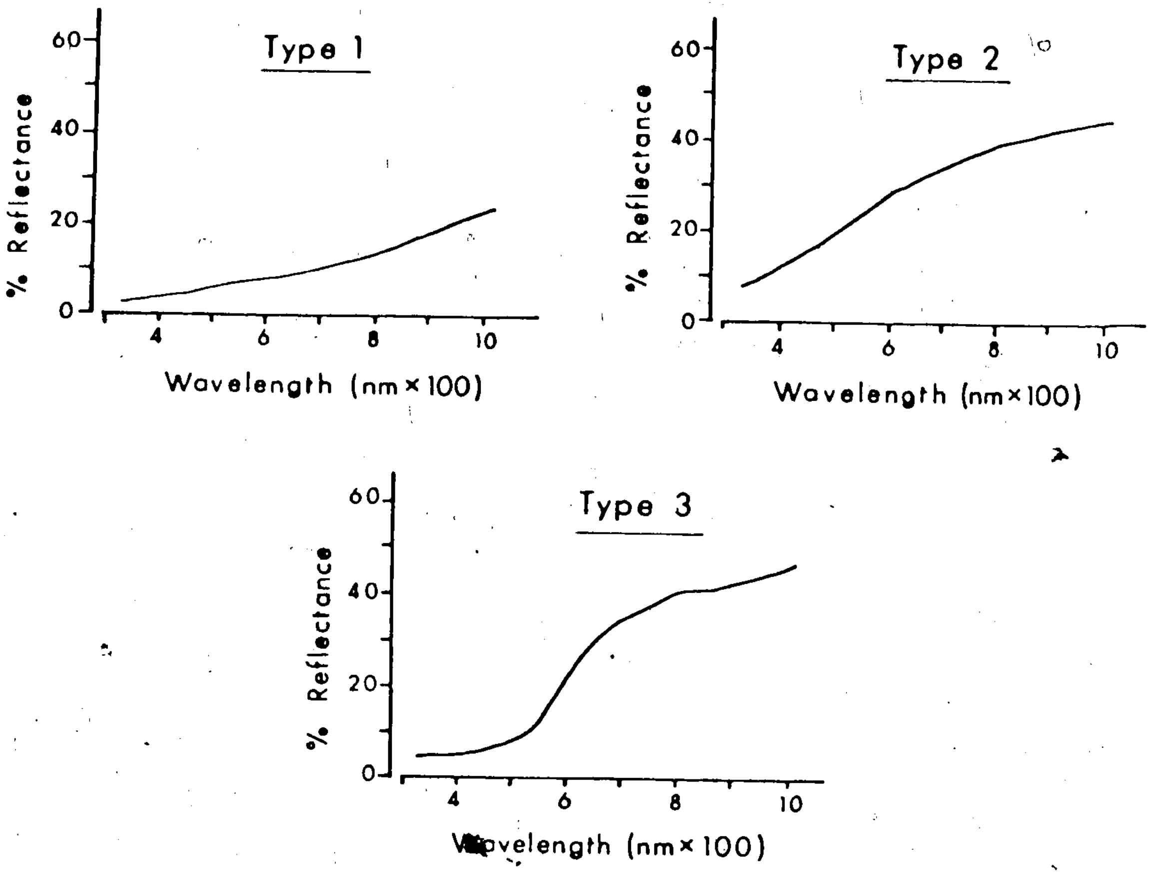

Figure 6. Examples of the three types of soil reflectance spectra of the classification of curve shape proposed by Condit (1970). All spectra are for dry soils (modified after Condit, 1970).

chosen to correspond to those spectral bands employed by the multispectral scanners of the LANDSAT vehicles, at least in the spectral region from 500 to 800 nm, and to the green (500 - 600 nm) and red (600 - 700 nm) bands of multiband photography. In the 500 - 600 and 600 - 700 nm bands the means are for 5 values at 25 nm intervals and in the 700 - 1,000 nm bands the means are for 3 values at 50 nm intervals. Differences in reflectance were analyzed in terms of soil surface conditions.

Results of field and laboratory studies of the spectral reflectance of soils are usually presented in the form of percent reflectance data. These data, however, may be misleading if attempts are made to use them to predict the tone associated with a given object on different bands of imagery. Sensor systems do not record data on a percentage basis but in terms of the actual or relative amount of energy reflected from various targets. A low percent reflectance in the red portion of the spectrum and a relatively higher percent reflectance in the near-infrared does not necessarily lead to the conclusion that less energy is being reflected in the red band. The intensity of illumination is generally greater in the red band than in the near-infrared (Figure 5) thus a slightly greater amount of energy reflected in the red band could calculate to a lower percent reflectance.

Reflectance data for soils expressed as a percentage of the reflectance from the standard panel were compared to the same data expressed in terms of the actual amount of energy reflected (microwatts/square centimeter/nanometer) in order to identify the spectral band or bands in which the greatest energy is reflected. These results were compared to digital reflectance data as recorded by the multispectral scanner of LANDSAT 1.

Digital data for fields of bare soil located immediately north of the Edmonton study area[1] were obtained as individual pixel values in each of four spectral bands, 500 - 600 nm, 600 - 700 nm, 700 - 800 nm and 800 - 1,100 nm. The data were from a July 9, 1975 satellite pass (Canada Centre for Remote Sensing frame no. E-11081 - 17390) and were used to construct frequency histograms showing for each field, the number of pixels having a given value in each band and to compute the mean pixel values for each field in each band.

Digital data for areas of salt crusting near the Milk River Reservoir (Figure 1) in southern Alberta[2] were obtained as frequency histograms [illegible]ing, for each salt crust area, the number of pixels in each spectral band having a given value plus mean pixel values in each band and correlation coefficients comparing the pixel values in one band to those in another. These data were from a June 11, 1973 satellite pass (Canada Centre for Remote Sensing frame no. E-1323 - 17515).

In both of the above cases fields and areas of interest were delineated on aerial photographs obtained within 4 days of the satellite pass and the digital data were requested for these specified fields and areas.

[1] Data courtesy Mr. C. L. Sibbald, The Sibbald Group, Calgary.

[2] Data courtesy Dr. F. Peet, Forest Management Institute, Environment Canada, Ottawa.

RESULTS AND DISCUSSION

Characterization of Reflectance Spectra

On the basis of surface soil characteristics, especially color, the reflectance spectra for the soils studied are separated into five groups (Table 3, Figure 7).

Group I. The soils included in this group are those characterized by light colored surfaces (high Munsell value, low Munsell chroma) which have resulted from the incorporation of thin, dark colored surface horizons (LH) with very light colored, eluviated horizons (Ae) through cultivation. This group includes Orthic Gray Luvisol and Orthic Luvic Gleysol soils developed on glacial till and having loam to silt loam surface textures.

A typical curve, as for sample L4 (Figure 7), shows a relatively high reflectance throughout the spectral region from 450 to 1,000 nm. Reflectance increases as wavelength increases with the slope of the curve increasing from 450 to 750 nm then remaining relatively constant to 1,000 nm. According to the scheme proposed by Condit (1970) this is an example of Type 2 curve (Figure 6). Reflectance spectra for the other samples in this group are shown in Figure 8. All spectra for Group I soils have a similar shape. The effect of an increase in moisture content is illustrated by the curve for L7. The slope of the curve is reduced in the regions from 450 to 650 nm and 750 to 900 nm with percent reflectance values reduced to a slightly greater degree in the reflective infrared.

Table 3. Surface characteristics of soils used in the field study of reflectance and solar altitude and azimuth at the time of measurement.

Group	Sample No.	Color	Moisture (%)	Surface Characteristics*	Solar Altitude (^{o})	Solar Azimuth (^{o} E from N)
I	L1	10YR 7/2	2.7	dry crust, medium clods	59	165
	L2	10YR 6/2	9.6	dry crust, fine clods	57	150
	L3	10YR 6/2	5.4	dry crust, smooth	49	124
	L4	10YR 5/2	12.4	dry crust, pebbled	53	133
	L5	10YR 5/2	10.5	dry crust, pebbled	55	140
	L6	10YR 5/1	5.2	dry crust, smooth	59	192
	L7	10YR 3/2	20.9	smooth, puddled	58	155
II	D1	10YR 2/1	26.0	freshly cultivated, large clods	42	244
	D2	10YR 4/1	10.1	smooth, puddled	56	216
	D3	10YR 4/1	10.9	fine clods	45	245
	D4	10YR 3/1	18.8	pebbled	53	228
	D5	10YR 4/2	17.1	smooth, puddled	51	232
	D6	10YR 3/1	23.8	smooth, puddled	57	163
	D7	10YR 2/1	42.6	medium granular	57	208
	D8	10YR 4/1	10.5	fine clods	58	209
	D9	10YR 2/1	36.5	smooth, pebbled	55	140
III	G1	10YR 3/1	29.9	smooth, puddled	60	192
	G2	10YR 4/1	9.6	smooth, puddled	57	147
	G3	10YR 5/1	3.6	dry crust, smooth	55	206
IV	B1	7.5YR 5/2	2.2	fine gravelly, pebbled	59	174
	B2	10YR 5/3	6.5	fine gravelly, pebbled	58	200
	B3	7.5YR 5/2	1.6	smooth, pebbled	55	155
	B4	7.5YR 4/3.5	2.4	dry crust, fine clods	58	156
	B5	10YR 3/2	18.7	smooth, pebbled	59	191
V	F1	5YR 3/2		spongy	51	182
	F2	5YR 3/2		spongy	57	148
Salt Crust	S1	dazzling white	-	smooth	54	224
	S2	10YR 6/2	-	smooth	56	216

* Surface characteristics terms are descriptive only as defined in Appendix 1.

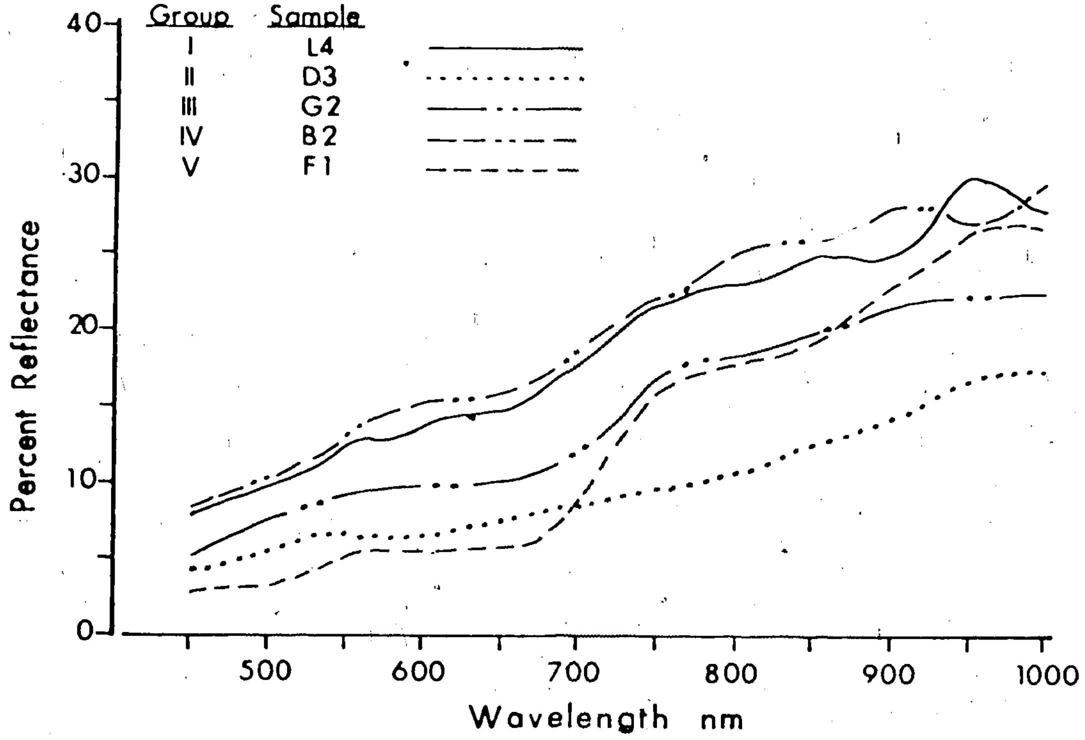

Figure 7. Typical percent reflectance spectra for soils in each of the five Groups.

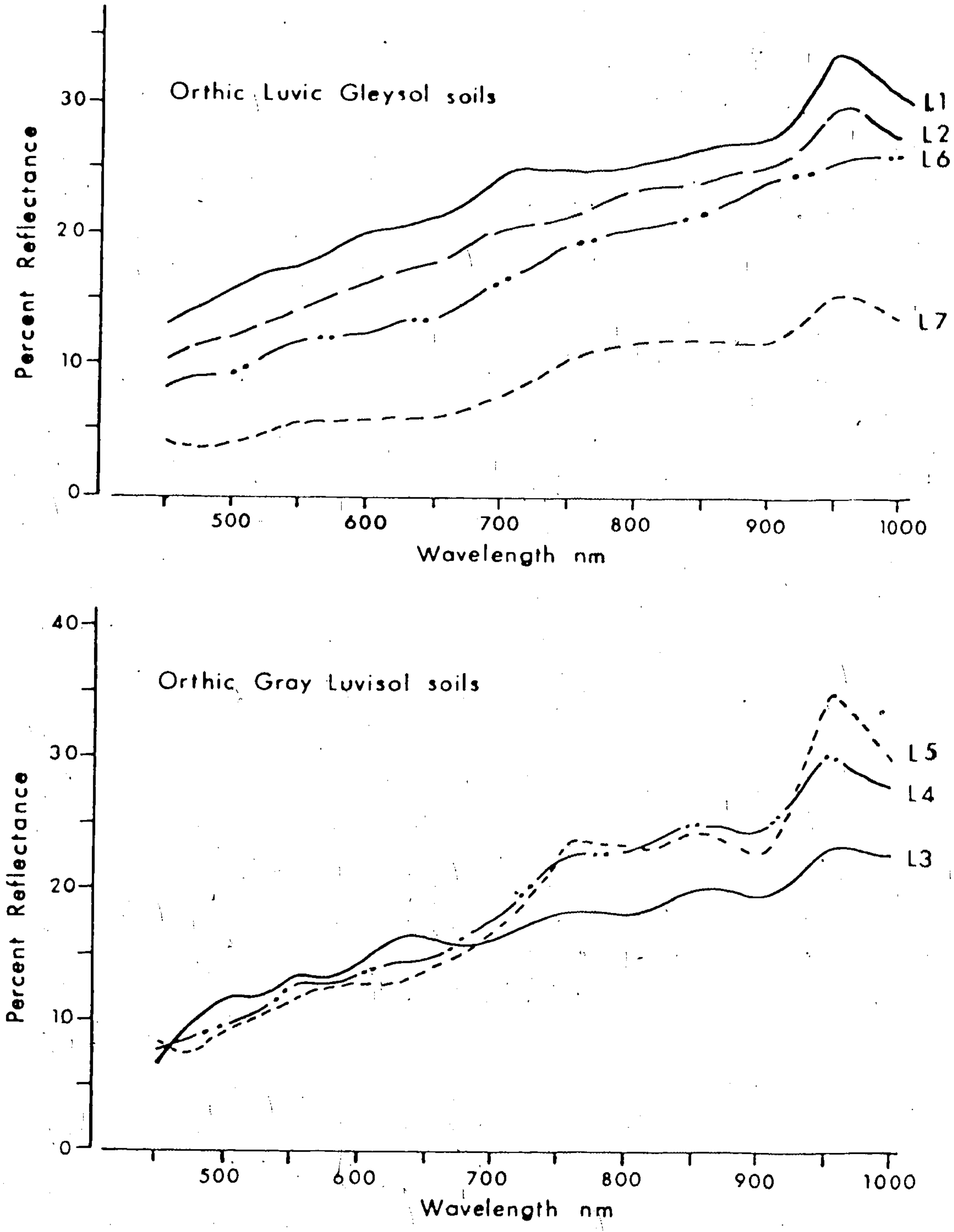

Figure 8. Percent reflectance spectra for the light colored surface soils of Group I.

The mean percent reflectance values in various spectral bands for the soils of this group are shown in Table 4. In the 500 to 600 nm and 600 to 700 nm bands, ranking the mean reflectance values in decreasing order also ranks the samples according to decreasing Munsell value (Tables 4 and 2). Although soil color, in particular Munsell value, appears to be the dominant characteristic influencing reflectance in the visible region, surface configuration and the angle of illumination are also important. Samples L2 and L3 were assigned the same color in the field and both possessed a dry surface crust. However, the mean percent reflectance values in the two visible bands are different (Table 4). Sample L2 possessed a rougher surface than sample L3 but produced a higher reflectance. The rougher surface produces a more random arrangement of reflecting surfaces within the field of view of the sensing head resulting in more surfaces inclined at an angle such that maximum reflectance is towards the sensing head. The smoother surface and lower solar altitude associated with sample L3 result in reflectance of a more specular nature.

In the reflective infrared region, in particular from 800 to 1,000 nm, ranking the mean percent reflectance values in decreasing order again ranks the soils in order of decreasing Munsell value. Although color remains a dominant characteristic influencing reflectance, the dominance of color is not as great as it is in the visible spectral region and other surface characteristics such as surface roughness and moisture content become more important. Correlation coefficients for mean reflectance in various spectral bands compared to Munsell value decrease from the visible to the infrared spectral region,

Table 4. Comparison of mean percent reflectance values among Group I soils in five spectral bands.

Spectral Band	Sample Numbers* with Mean Percent Reflectance Values (± standard deviation) in Decreasing Order of Magnitude						
500 - 600 nm	L1 18.0 (1.7)	L2 14.3 (1.6)	L3 12.5 (1.3)	L4 11.8 (1.6)	L5 11.5 (1.5)	L6 11.3 (1.3)	L7 5.1 (0.7)
600 - 700 nm	L1 22.0 (2.1)	L2 18.1 (1.6)	L3 15.7 (0.9)	L4 15.2 (1.8)	L5 14.3 (1.5)	L6 14.1 (1.6)	L7 6.3 (0.7)
700 - 800 nm	L1 25.1 (0.1)	L2 21.6 (1.8)	L4 21.4 (2.7)	L5 21.4 (4.0)	L6 18.9 (2.1)	L3 17.5 (1.0)	L7 9.7 (2.1)
800 - 900 nm	L1 26.3 (1.0)	L2 26.0 (4.0)	L4 24.2 (1.3)	L5 23.5 (1.3)	L6 22.2 (2.1)	L3 18.7 (1.2)	L7 11.4 (0.1)
900 - 1000 nm	L1 30.7 (4.0)	L2 29.6 (2.4)	L5 29.5 (6.9)	L4 27.8 (3.2)	L6 25.4 (0.9)	L3 21.5 (3.1)	L7 14.0 (2.4)

* Sample numbers as in Table 3.

while for mean reflectance compared to moisture content they increase from the visible to the infrared (Table 5). The effect of surface roughness of infrared reflectance is illustrated by the data for samples L2 and L3. Differences in reflectance between these two samples are relatively greater in the infrared than in the visible region (Table 4) and therefore, the combination of surface roughness and solar altitude is having a greater e[illegible] the infrared reflectance. Direct sunlight is the source of [illegible]ated illumination (Gates, 1970) and the infrared reflec[illegible] the smooth surface of L3 with low solar altitude is relatively less than the visible band reflectance from the same surface where the illumination is not only from direct sunlight but also partially from skylight and cloudlight (Gates, 1970).

Group II. The soils included in this group are those characterized by very dark colored surfaces (low Munsell value, low Munsell chroma). They include Orthic and Eluviated Black Chernozem soils developed in clay loam till and Black Solodized Solonetz soils developed on clay loam, glaciolacustrine sediments. All of these soils had clay loam surface textures.

A typical curve for this group as for sample D3 (Figure 7) is characterized by either a constant or a slightly increasing slope and generally low reflectance over the entire region from 450 to 1,000 nm. The spectra for Group II fit the definition of Type 1 curves (Figure 6) in the scheme proposed by Condit (1970). Reflectance spectra for all the soils included in this Group are shown in Figure 9. Reflectance spectra for two of the samples, D4 and D9, show rapid

Table 5. Correlation coefficients (r) for mean percent reflectance values in different spectral bands compared to surface color (Munsell value) and moisture content for Group I, II and IV soils.

	Spectral Band			
	500-600 nm	600-700 nm	800-900 nm	900-1000 nm
Group I				
Munsell value	r =+0.996	r =+0.996	r =+0.990	r =+0.989
moisture content	r =-0.773	r =-0.781	r =-0.838	r =-0.832
Group II				
Munsell value	r =+0.984	r =+0.979	r =+0.970	r =+0.972
moisture content	r =-0.807	r =-0.812	r =-0.840	r =-0.830
Group IV				
Munsell value	r =+0.996	r =+0.989	r =+0.975	r =+0.987
Munsell chroma	r =+0.968	r =+0.988	r =+0.996	r =+0.995
moisture content	r =-0.532	r =-0.574	r =-0.614	r =-0.619

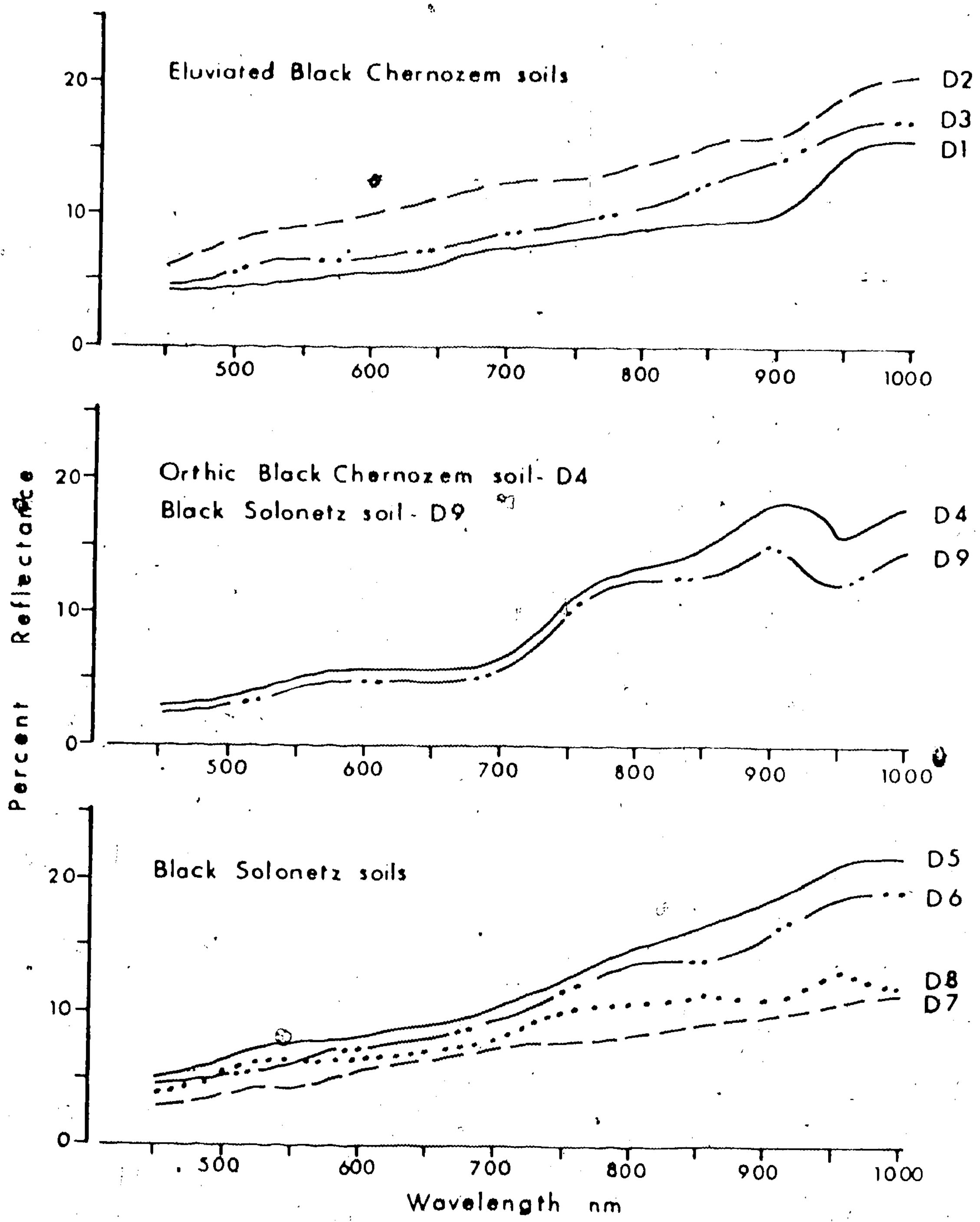

Figure 9. Percent reflectance spectra for the dark colored surface soils of Group II.

increases in slope between 700 and 750 nm dissimilar to other spectra for this group and similar to the spectra of soils included in Group III discussed later.

The mean percent reflectance values in various spectral bands for the soils in this group (Table 6) show that in the visible portion of the spectrum, 500 to 600 nm and 600 to 700 nm, differences occur between the lighter (samples D2, D3, D5 and D8 with Munsell value 4) and darker (samples D1, D7 and D9 with Munsell value 2) soils and therefore that color is a dominant factor influencing reflectance. Moisture content is also indicated as a major factor with those soils with relatively high moisture content (D1, D7 and D9) having lower reflectance than those with relatively low moisture content (D2, D3 and D8). Two of the soils, D4 and D6, have the same color (10YR 3/1) and similar moisture content; however, D6 has a higher mean percent reflectance in the visible bands than D4. This is attributed to a combination of surface roughness and solar altitude effects. Sample D6 has a smoother surface and greater solar altitude associated with it while D4 has a rougher surface and lower solar altitude. In the latter case, surface roughness produces more effective surface area for absorption by the dark colored soil and reflectance is decreased.

In the reflective infrared bands ranking the soils in order of decreasing mean percent reflectance does not rank the soils in order of darkening color to the same extent as in the visible bands (Table 6). The influence of color in determining reflectance in the infrared spectral region is modified by moisture content and roughness. Correlation coefficients for mean reflectance compared to Munsell value

Table 6. Comparison of mean percent reflectance values among Group II soils in five spectral bands

Spectral Band	Sample Numbers* with Mean Percent Reflectance Values (± standard deviation) in Decreasing Order of Magnitude								
500 - 600 nm	D2 9.2 (0.8)	D5 7.5 (0.6)	D6 [illegible] (1.0)	D3 6.4 (0.4)	D8 6.3 (0.5)	D7 5.1 (0.6)	D1 5.0 (0.4)	D4 4.8 (0.7)	D9 4.8 (0.7)
600 - 700 nm	D2 11.5 (1.1)	D5 9.2 (0.9)	D6 8.5 (0.8)	D3 7.6 (0.7)	D8 7.3 (0.6)	D7 6.6 (0.6)	D1 6.5 (0.8)	D4 5.6 (0.3)	D9 5.6 (0.7)
700 - 800 nm	D2 13.2 (0.8)	D5 12.9 (2.2)	D6 12.1 (2.3)	D4 10.7 (4.1)	D9 10.6 (3.3)	D8 10.1 (1.3)	D3 9.8 (1.2)	D7 8.2 (0.7)	D1 8.2 (1.1)
800 - 900 nm	D4 16.5 (3.6)	D5 16.5 (1.7)	D2 15.4 (1.0)	D6 14.8 (1.5)	D9 13.8 (1.5)	D3 12.8 (2.0)	D8 11.2 (0.5)	D1 9.6 (0.4)	D7 9.3 (0.5)
900 - 1000 nm	D5 20.7 (2.1)	D2 19.1 (2.6)	D4 18.4 (2.3)	D6 18.3 (1.7)	D3 16.7 (1.6)	D9 14.2 (2.0)	D1 13.8 (3.4)	D8 12.0 (1.2)	D7 10.9 (1.[illegible])

* Sample numbers as in Table 3.

decrease from the visible to the reflective infrared bands, and for mean reflectance compared to moisture content they increase from the visible to the infrared bands (Table 5). Also, in the infrared bands, samples with smoother surfaces and medium solar altitude (D2, D5 and D6) have higher mean reflectance values than samples with rougher surfaces (D1, D3 and D8), the results of rougher surfaces providing more effective surface area for absorption and more shadowing.

Group III: The soils included in this group are Dark Gray Luvisols developed on glacial till with silty clay loam to clay loam surface textures and surface colors intermediate between those of the Group I and II soils. A typical reflectance curve for this group, as shown in Figure 7 by sample G2, has relatively low reflectance in the visible portion of the spectrum with a relatively rapid increase in slope between 675 and 800 nm followed by a decreased slope from 800 to 1,000 nm. The reflectance spectra for samples G2 and G3 in this group (Figure 10) are similar in shape to those [illegible] Group II in the visible region and those for Group I in the reflective infrared region of the spectrum and are therefore transitional between the Type 1 and Type 2 curves as proposed by Condit (1970) (Figure 6). The reflectance spectra for the wet sample G1 (Figure 10) is similar in shape to the spectra for Group II soils (Figure 9).

In both the visible and reflective infrared spectral regions, ranking these soils in order of decreasing mean percent reflectance also ranks the soils in decreasing Munsell value and increasing moisture content (Table 7). In the visible bands, the greatest differences in mean percent reflectance occur between the lighter colored and

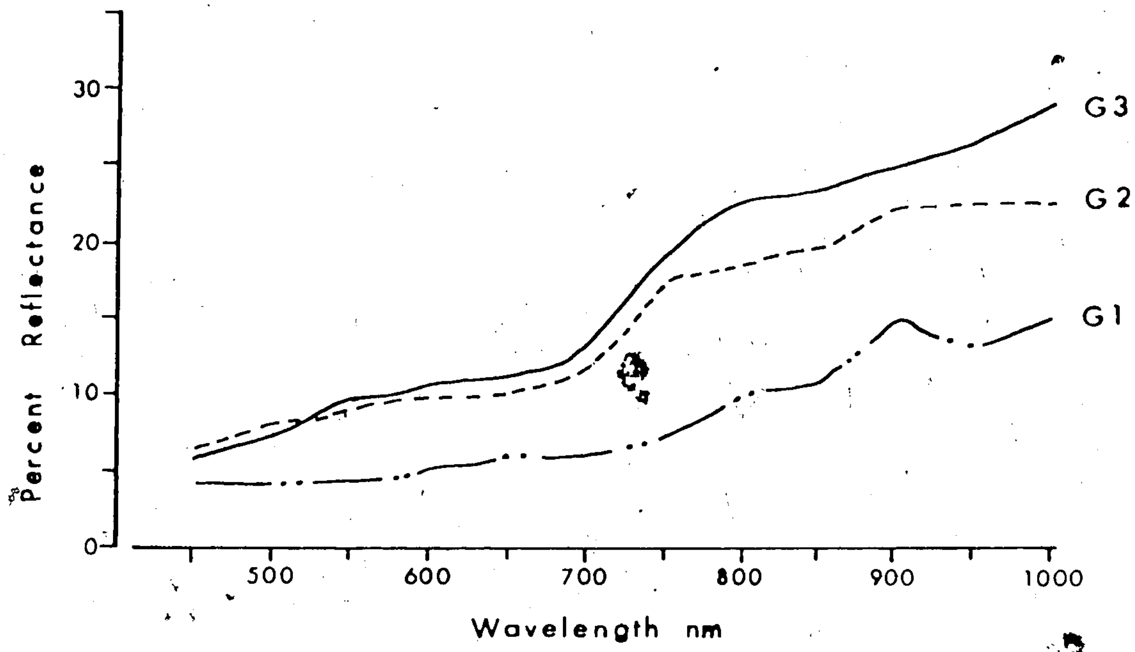

Figure 10. Percent reflectance spectra for the gray colored surface soils of Group III.

Table 7. Comparison of mean percent reflectance values among Group III soils in five spectral bands.

Spectral Band	Sample Numbers* with Mean Percent Reflectance Values (± standard deviation) in Decreasing Order of Magnitude		
500 - 600 nm	G3 9.3 (1.1)	G2 9.0 (0.6)	G1 4.6 (0.5)
600 - 700 nm	G3 11.6 (1.4)	G2 10.5 (1.0)	G1 5.8 (0.4)
700 - 800 nm	G3 18.7 (4.6)	G2 16.2 (3.7)	G1 8.2 (1.9)
800 - 900 nm	G3 24.1 (4.0)	G2 20.5 (2.0)	G1 12.2 (2.9)
900 - 1000 nm	G3 27.2 (2.2)	G2 22.8 (0.1)	G1 14.8 (1.2)

* Sample numbers as in Table 3.

relatively dry samples (G2 and G3) and the darker colored, moist sample (G1). In the infrared bands, the differences in mean percent reflectance between samples G2 and G3 are greater than they are in the visible bands.

Group IV. The soils included in this group are eroded Eluviated Black Chernozems that have light colored surfaces with loam to gravelly sandy loam textures. These surfaces have moderately high Munsell values (3 to 5) and moderate Munsell chroma (2 to 3) compared to the other soil surfaces studied. A typical curve for this group, sample B2 in Figure 7, shows relatively high percent reflectance throughout the spectral region from 450 to 1,000 nm and a unique peak, compared to the spectra from other soils in Figure 7, in the visible region between 575 and 625 nm wavelengths. The slope of the curve increases after 675 nm and percent reflectance continues to increase as wavelength increases. Reflectance spectra for the other soils in this group are shown in Figure 11 where surfaces with redder hues, 7.5YR for samples B1, B3 and B4 as opposed to 10YR for samples B2 and B5, exhibit a stronger peak in the visible reflectance between 575 and 625 nm wavelength. The spectra for this group are similar in shape to the Type 3 curves (Figure 6) of the scheme proposed by Condit (1970).

The mean percent reflectance values for this group (Table 8) show that the percent reflectance from the darkest colored, most moist soil (B5) is always the lowest. With the remaining drier and more brightly colored soils, mean reflectance values in the various spectral bands rank the soils in terms of decreasing values of Munsell value plus chroma combined. The exception in the 500 to 600 nm band is

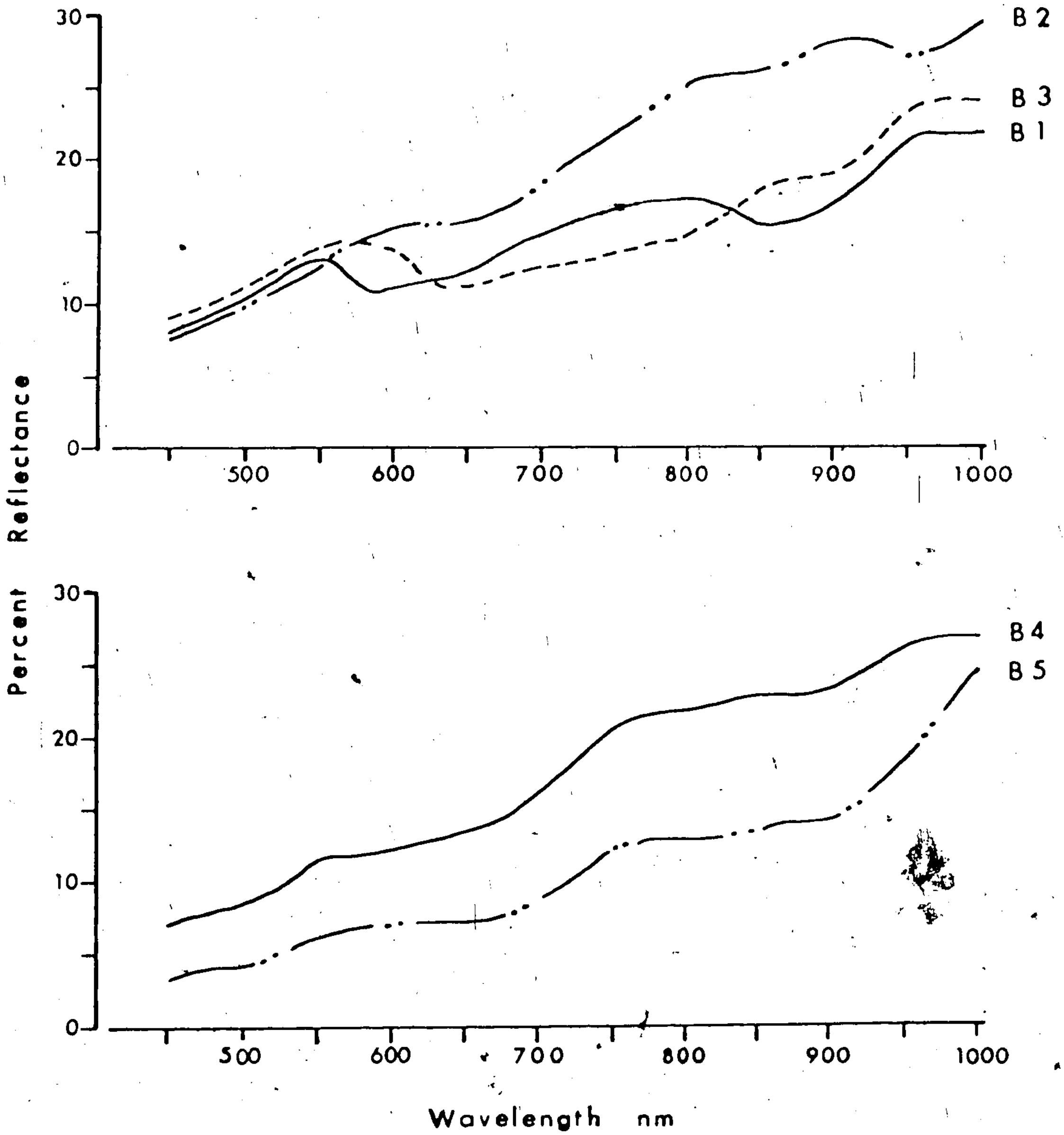

Figure 11. Percent reflectance spectra for the brownish colored surface soils of Group IV.

Table 8. Comparison of mean percent reflectance values among Group IV soils in five spectral bands.

Spectral Band	Sample Numbers* with Mean Percent Reflectance Values (± standard deviation) in Decreasing Order of Magnitude				
500 - 600 nm	B2 13.0 (2.2)	B3 13.0 (1.4)	B1 11.5 (1.3)	B4 10.8 (1.5)	B5 5.9 (1.1)
600 - 700 nm	B2 16.5 (1.5)	B4 13.8 (1.4)	B1 12.8 (1.7)	B3 12.2 (1.2)	B5 7.8 (0.7)
700 - 800 nm	B2 22.3 (3.5)	B4 19.7 (3.2)	B1 16.4 (1.0)	B3 13.8 (1.2)	B5 11.8 (2.4)
800 - 900 nm	B2 26.8 (1.8)	B4 22.6 (0.8)	B3 17.4 (2.1)	B1 16.5 (1.1)	B5 13.9 (0.7)
900 - 1000 nm	B2 28.5 (2.0)	B4 25.5 (2.0)	B3 22.5 (3.2)	B1 20.2 (2.7)	B5 16.9 (6.6)

* Sample numbers as in Table 3.

sample B4 which, with the highest chroma (3.5) and a 7.5YR hue, possessed a more distincly reddish color than the other soils resulting from stronger absorption in this band. With the above exception, samples B2 and B4 have consistently higher reflectance than samples B1 and B3, especially in the reflective infrared spectral region. This is attributed to surface soil characteristics of texture and structure. Samples B1 and B3 represent a soil with a surface having a fine gravelly to coarse sand texture and single grain structure, while samples B2 and B4 represent a soil with a surface having a loam to sandy loam texture and granular to subangular blocky structure. Samples B1 and B3 therefore presented a more open, porous surface with internal shadowing while samples B2 and B4 presented a more compact surface to the probe head.

In general, the reflectance from this group correlated poorly to surface soil moisture content but highly to soil color (Table 5) and surface texture and structure.

Group V. This group includes two sets of measurements for a cultivated Terric Mesisol soil, the surface of which retained a high moss fiber content and a sponge-like surface configuration. A typical curve as for sample F1 (Figure 7) is characterized by relatively low visible reflectance in the 450 to 700 nm region and a relatively high infrared reflectance. This is similar to the Type 3 curves (Figure 6) defined by Condit (1970), although his curves were for mineral soils and this is an organic soil. In the visible region the curves for this group (Figure 12) have low values and are relatively flat between 450 and 650 nm indicating the dark soil color. The high infrared reflectance

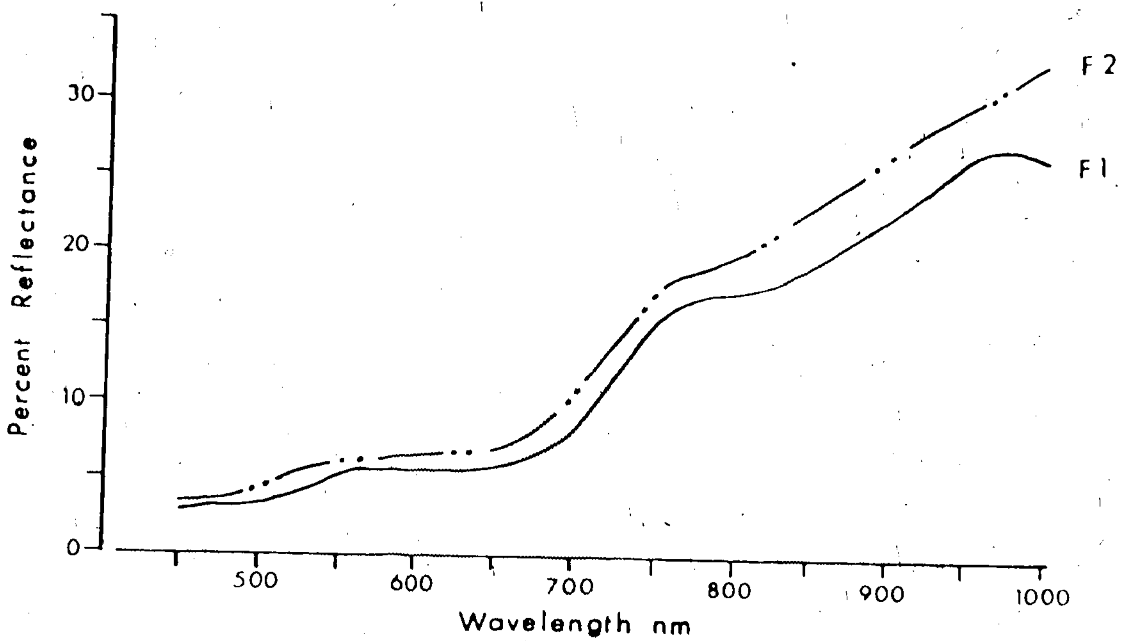

Figure 12. Percent reflectance spectra for the cultivated organic surface soils of Group V.

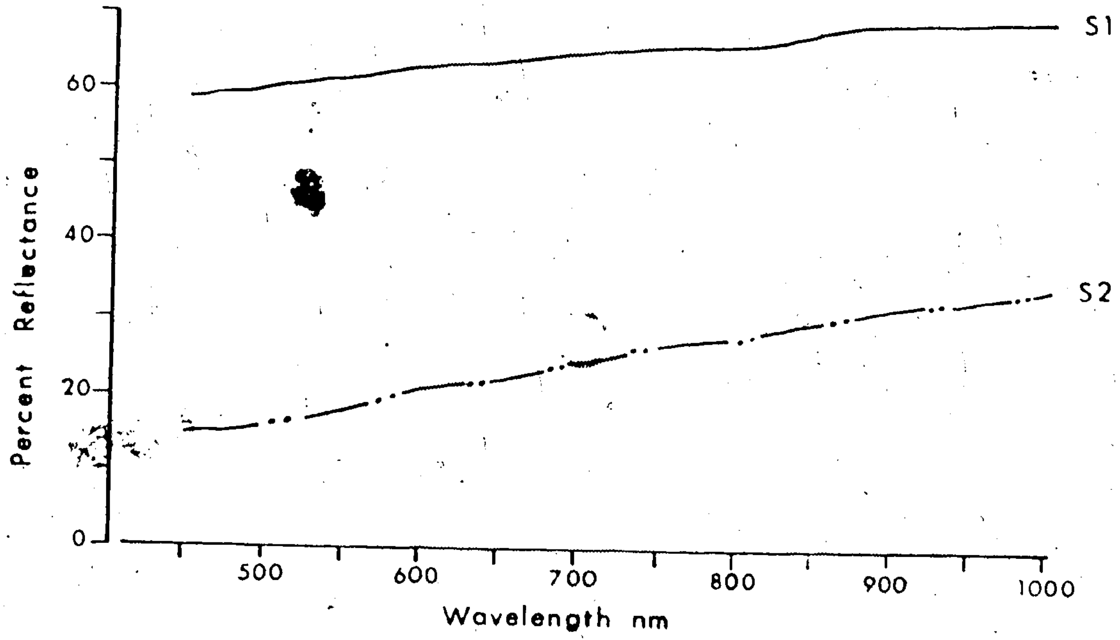

Figure 13. Percent reflectance spectra for surface salt crusts.

appears to be anomalous for such poorly drained and usually wet soils. However, the surface fibers were quite dry at the time the measurements were made and it is proposed that the high infrared reflectance is attributable to the spongy structure of this surface.

Salt Crusts. Surface salt crusts occur in the western portion of the Vegreville study area in association with saline soils (Leskiw, 1971). The spectral reflectance from surface salt crusts is characterized by extremely high percent reflectance over the spectral range from 450 to 1,000 nm (Figure 13). Sample S1 had a dazzling white color whereas sample S2 had a light gray color similar to that for the very light colored surface soils of Group I and its reflectance curve is similar in shape to those for Group I soils. This latter crust was more moist than the former.

Comparing the mean percent reflectance values from all the mineral soils in each band (Table 9) shows that the light colored Group I soils (L samples) are always greater than the dark colored Group II soils (D samples) with the exception of L7 which was relatively dark colored and moist. The Group IV and [illegible] soils (B and G samples, respectively) are intermixed with the other two groups with often little difference between the lighter colored and drier B and G samples and the L samples of Group I. Differences between the Group IV and Group III are greater in the visible bands (500 to 600 nm and 600 to 700 nm) than in the infrared bands.

Table 9. Comparison of mean percent reflectance among all mineral soils in five spectral bands. Mean values (underlined) are rounded off to the nearest whole number; sample numbers as in Tables 3, 4, 6, 7, and 8.

Spectral Band	Mean Percent Reflectance Values in Decreasing Order with Sample Numbers Having Each Value Shown																				
500-600 nm	18 L1	17	16	15	14 L2	13 B3 B2 L3	12 L4 L5 B1	11 L6 B4	10	9 D2 G3 G2	8 D5	7 D6	6 D3 D8 B5	5 L7 D7 D1 D4 D9 G1							
600-700 nm	22 L1	21	20	19	18 L2	17	16 B2 L3	15 L4	14 L5 L6 B4	13 B1	12 B3 G3 D2	11	10 G2	9 D5	8 D6 B5 D3	7 D8 D7	6 D1 L7 G1 D4 D9				
700-800 nm	25 L1	24	23	22 B2 L2	21 L4 L5	20 B4	19 L6 G3	18	17 L3	16 B1 G2	15	14 B3	13 D2 D5	12 D6 B5	11 D4 D9	10 D8 D3 L7	9	8 G1 D7 D1			
800-900 nm	27 B2	26 L1 L2	25	24 L4 G3 L5	23 B4	22 L6	21	20 G2	19 L3	18	17 B3	16 D4 D5 B1	15 D2 D6	14 B5 D9	13 D3	12 G1	11 L7 D8	10 D1	9 D7		
900-1000 nm	31 L1	30 L2 L5	29	28 B2 L4	27 G3	26 B4	25 L6	24	23 G2	22 B3 L3	21 D5	20 B1	19 D2	18 D4 D6	17 B5 D3	16	15 G1	14 D9 L7 D1	13	12 D8	11 D7

Percent reflectance spectra for the five representative samples shown in Figure 7 are compared to reflectance spectra for the same soils expressed in terms of the actual amount of energy reflected (microwatts/cm^2/nm) in each wavelength interval (Figure 14). Direct comparisons between soils are not possible due to differences in illumination at the various times of measurement. Mineral soils (Groups I to IV) show increasing percent reflectance as wavelength increases with the greatest percent reflectance occurring in the reflective infrared region of the spectrum. The actual amount of energy being reflected, however, is usually greatest in the red region of the spectrum. The organic soils included show the greatest percent reflectance and the greatest reflectance in terms of microwatts/square centimeter/nanometer in the reflective infrared.

Comparison Between Reflectance Spectra and LANDSAT Digital Data

The data above for Group II soils are compared to digital multispectral data obtained from the multispectral scanner of LANDSAT 1. The digital multispectral data are for portions of three fallow fields with Eluviated Black Chernozem soils similar to those included in Group II (Plate 2, page 75).

Field #1 had been recently cultivated and the surface of the soil was very dark colored and relatively moist. Field #2 had also been partially cultivated, the north half more recently than the south half so that the surface of the north half was darker in color and more moist. The surface of the south half also contained residue from the previous year's grain crop. Field #3 had the driest soil surface

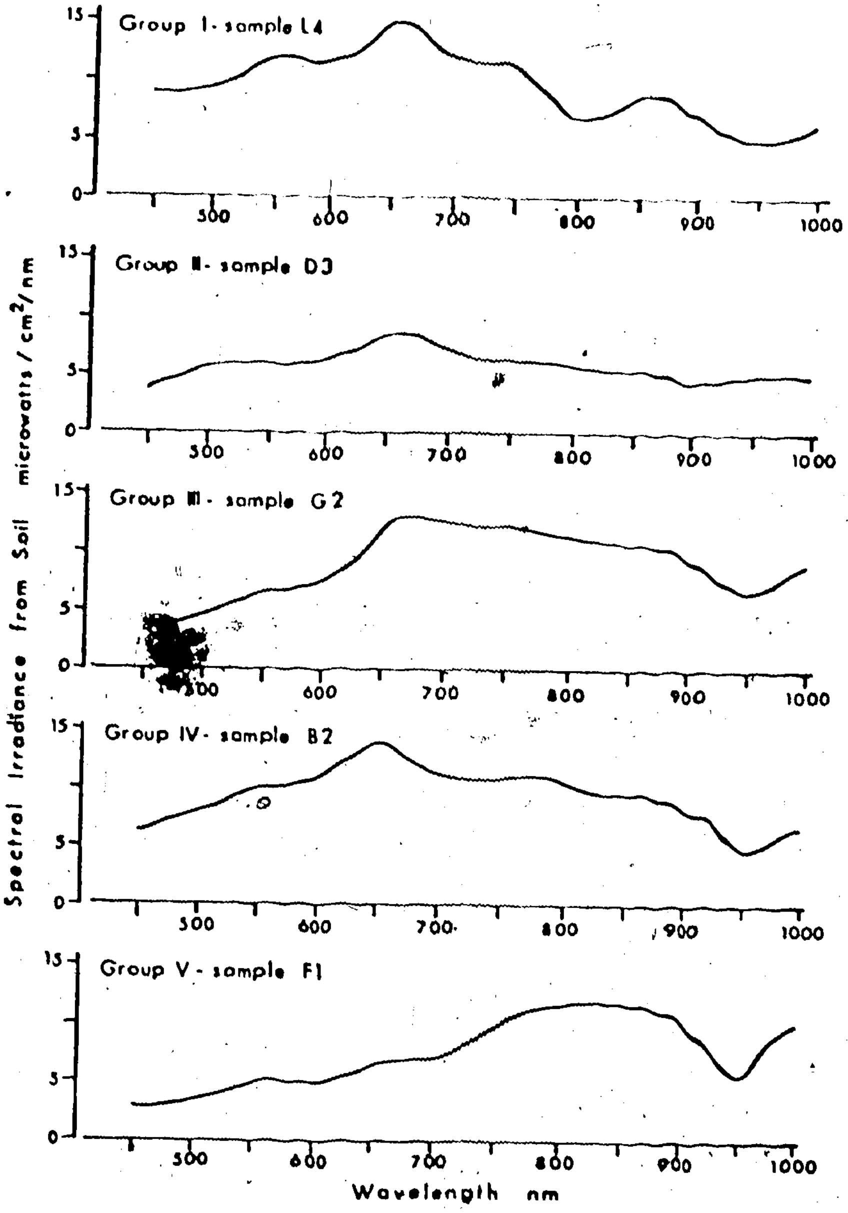

Figure 14. Reflectance spectra for the example soils from each of the five Groups with reflectance expressed in microwatts/ square centimeter/ nanometer.

and relatively greater amounts of crop residue.

The LANDSAT 1 data were for a satellite pass on July 9, 1975 and are presented in the form of frequency histograms (Figure 15) with the mean values for each band shown in Table 10. The frequency histograms show that as surfaces become relatively lighter in color and drier and as the amount of crop residue increases, pixel values in all bands become greater. Also, the spread in pixel values becomes greater in all bands from Fields #1 through #2 to #3 indicative of the increased variability in surface condition. Mean values for Field #1 are the lowest in each band, while those for Field #2 are intermediate and those for Field #3 are the highest. For each field, mean values for the red band (600 to 700 nm) are the lowest. This is an unexpected result when compared to the reflectance spectra for Group II soils (Figure 14) where reflectance in the red band is highest.

Similar digital data were obtained for large salt crusts found in the area around the Milk River Reservoir in southern Alberta. Salt crusts from this area were chosen because of their relatively large size, compared to those of the Vegreville area, which would provide a sufficient number of pixel values to show the variability in reflectance. The salt crusts for which digital data are available are shown in Plate 3 (page 76) and the satellite data are presented as frequency histograms (Figure 16) with mean values for each spectral band shown in Table 11.

Percent reflectance spectra for salt crusts (Figure 13) show high reflectance in all bands from well developed and white crusts (S1) and lower reflectance from more moist salt crusts (S2). In both cases

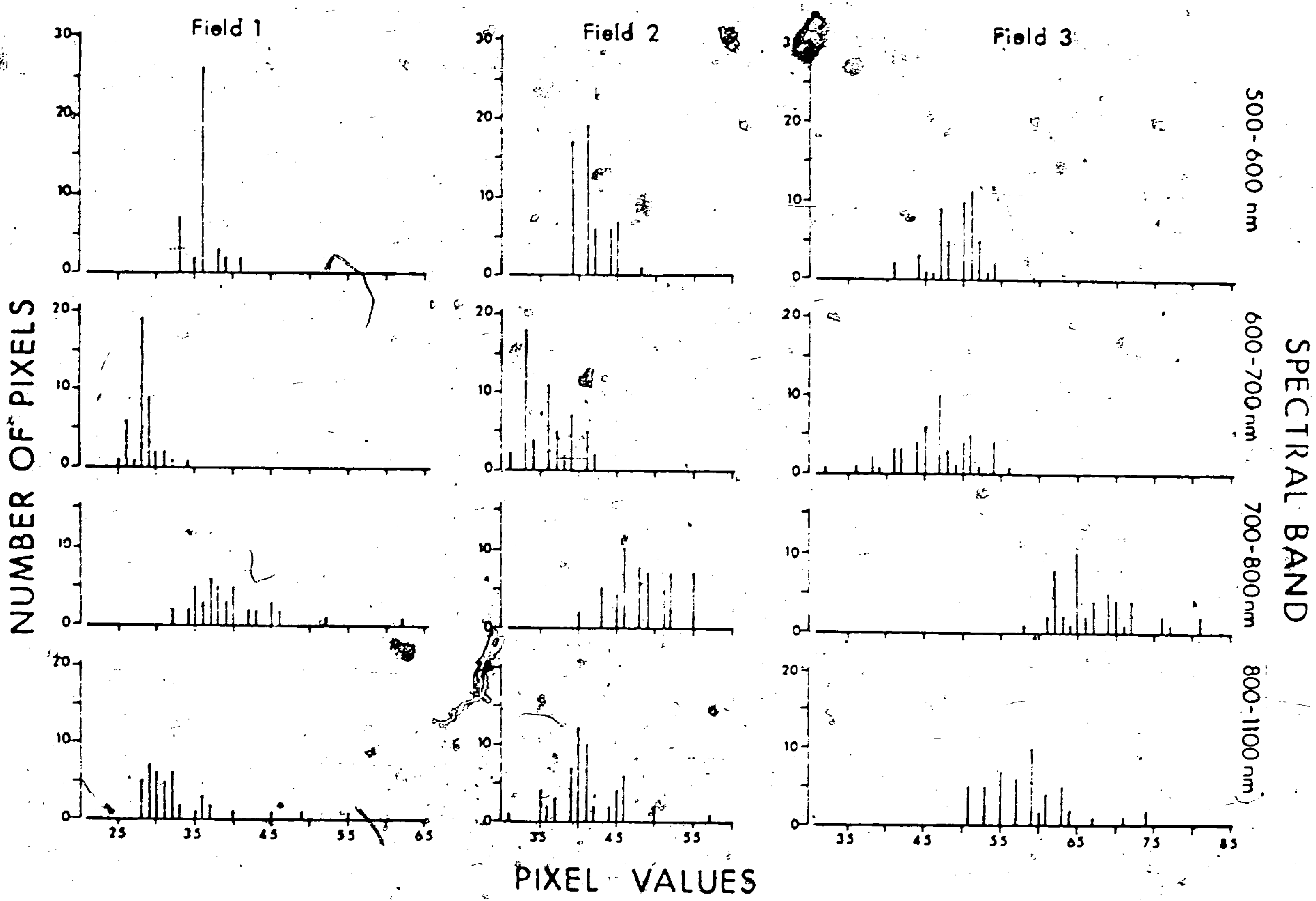

Figure 15. Histograms showing the number of pixels having a given value in each of the four spectral bands of the LANDSAT 1 multispectral scanner for [illegible]e fallow fields shown in Plate 2. Minimum/ maximum pixel values 0/ 256.

Table 10. Mean pixel values (± s[illegible]d deviation) for 3 fallow fields of Eluviated Bl[illegible]ernozem soils in four spectral bands [illegible] recorded by LANDSAT 1. Minimum/maximum pixel values 0/256.

Field No.	No. of pixels	Spectral band 500-600 nm	 600-700 nm	 700-800 nm	 800-1100 nm
1	42	36.0 (1.9)	28.3 (1.7)	39.5 (5.6)	32.8 (5.[illegible])
2	56	41.4 (2.2)	35.9 (3.0)	48.8 (4.5)	40.9 (4.4)
3	50	49.1 (2.9)	46.4 (5.0)	67.2 (5.1)	58.6 (5.4)

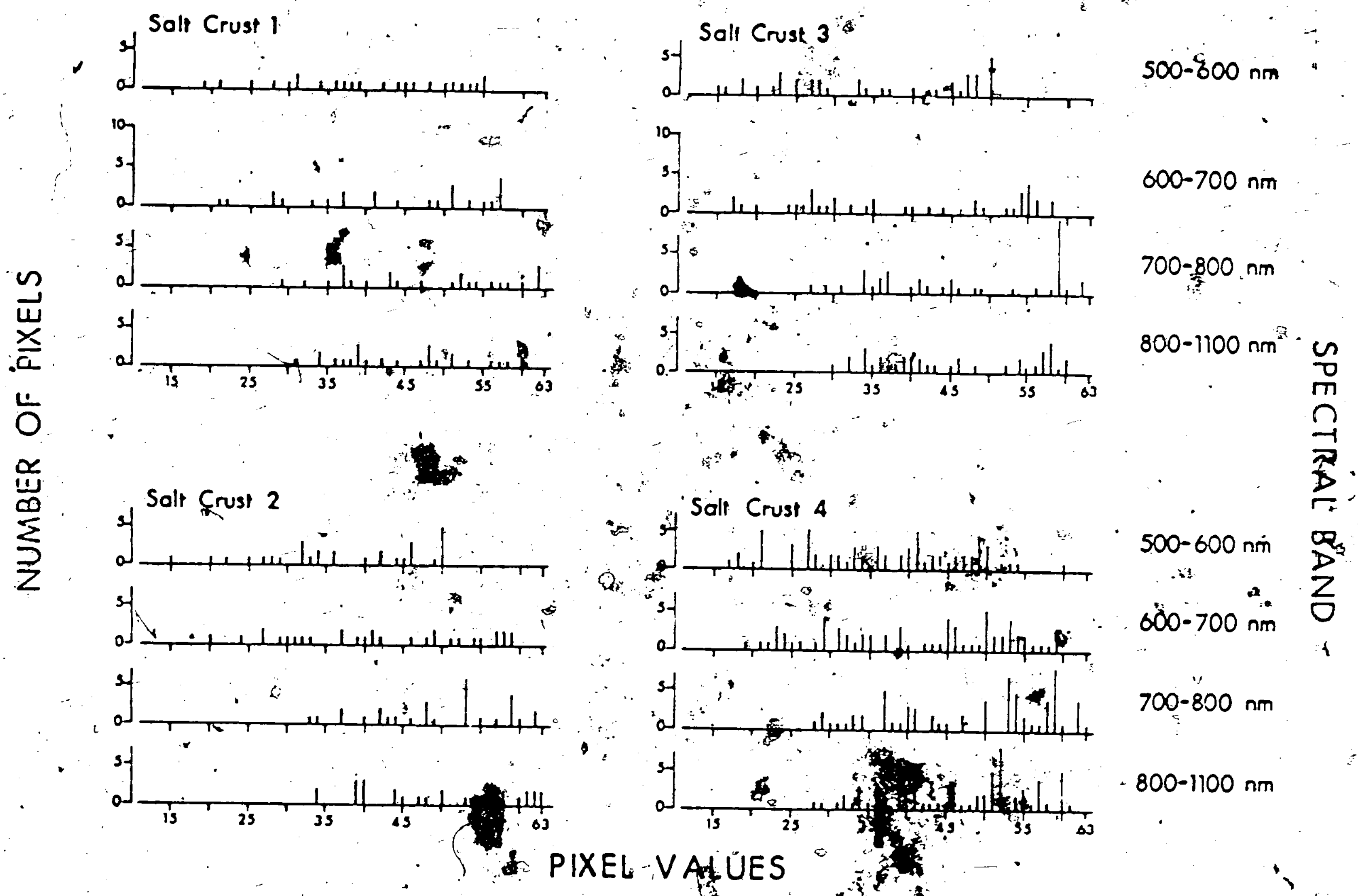

Figure 16. Histograms showing the number of pixels having a given value in each of the four spectral bands of the LANDSAT 1 multispectral scanner for the four salt crust areas shown in Plate 3. Minimum/ maximum pixel values 0/ 63.

Table 11. Mean pixel values (standard deviation) for [illegible] salt crust areas in four spectral bands as recorded by LANDSAT 1. Minimum/maximum pixel values 0/63.

Salt Crust	No. of Pixels	Spectral band 500-600 nm	600-700 nm	700-800 nm	800-1100 nm
1	24	40.2 (10.8)	43.3 (11.7)	48.5 (10.1)	45.0 (8.2)
2	29	37.5 (9.8)	43.3 (11.5)	49.7 (8.4)	50.2 (9.3
3	38	35.2 (11.7)	39.6 (13.5)	47.1 (11.1)	48.8 (9.8)
4	67	36.7 (10.5)	41.5 (11.5)	48.1 (10.3)	46.4 (9.1)

reflectance increases as wavelength increases. The frequency histograms for salt crusts (Figure 16) show a great variability in reflectance in each band as recorded by the satellite scanner. However, for each salt crust, the values in all four bands are highly correlated (Table 12). If the recorded scene reflectance for a given pixel is relatively low in one band, it is also relatively low in all other bands. These results indicate that within the various salt crust areas there is a mixture of bare soil and salt crust targets, the bare soils having relatively low reflectance in all bands and the salt crusts having relatively high reflectance in all bands.

Table 12. Correlation (r) between pixel values in paired spectral bands for each salt crust area.

Salt Crust	4 vs 5	4 vs 6	4 vs 7	5 vs 6	5 vs 7	6 vs 7
			Spectral bands*			
1	1.0**	1.0	1.0	1.0	0.9	1.0
2	1.0	0.9	1.0	0.9	1.0	0.9
3	1.0	1.0	0.9	1.0	1.0	1.0
4	1.0	9.0	0.9	1.0	1.0	1.0

* Band 4 = 500-600 nm
Band 5 = 600-700 nm
Band 6 = 700-800 nm
Band 7 = 800-1100 nm

** All values of r positive

CONCLUSIONS

General agreement is found between percent reflectance versus wavelength curves for surface soils in the Edmonton and Vegreville study areas and each of the curve types proposed by Condit (1970).

For the light colored surface soils of Group I reflectance in the visible portion of the spectrum is dominantly influenced by surface color. Reflectance in the near infrared portion of the spectrum is strongly influenced by surface color with surface moisture content and roughness [illegible]ng important. These results follow those obtained by o[illegible] (Bowers and Hanks, 1965; Tanguay et al., 1969; Mathews et al. [illegible]3a, 1973b) with one notable exception. Most of these authors state that reflectance from rougher surfaces when surface crusts are broken or aggregate size increases, is lower than reflectance from smooth surfaces. Within the soils of Group I, however, reflectance from the rougher surfaces was greater than that from smoother surfaces.

Reflectance in both the visible and infrared spectral regions from the dark colored soils of Group II, the gray colored soils of Group III and the brownish colored soils of Group IV is influenced by surface color, moisture content and roughness in much the same manner as the results reported by Bowers and Hanks (1965), Tanguay et al. (1969), Mathews et al. (1973a, 1973b) especially with respect to decreasing reflectance as roughness increases.

Reflectance from the fibric surfaces of the organic soils studied in Group V is dominated by color in the visible portion of the spectrum and by surface structure in the near infrared portion of the spectrum.

Reflectance from mineral soil surfaces is not analogous to that from vegetation although in both cases reflectance in the visible region is dominated by color. Soil reflectance in the near infrared region (700 to 1,000 nm) is greatly influenced by color with moisture content and roughness also being contributing factors. Plant reflectance in this spectral region is dominated by structure with color or pigmentation being of little consequence. Soil reflectance is also much more complex due to the interactions among various factors influencing reflectance.

Within Groups I and II are soils that are classified in different Orders of the Canadian system of soil classification. Reflectance data do not discriminate the poorly drained Gleysolic soils from the well drained Luvisolic soils in Group I, nor the Solonetzic soils from the Chernozemic soils in Group II. However, the Group I soils are discriminated from the Group II soils by reflectance data particularly in the visible region of the spectrum. Reflectance differences between Group III and Group IV soils are most significant in the visible region of the spectrum.

Digital satellite data may be useful in discriminating and identifying areas of salt crusts providing these are relatively large in terms of areal extent. Digital satellite data do not correspond exactly to the field measurements of reflectance due to atmospheric effects of scattering and attenuation.

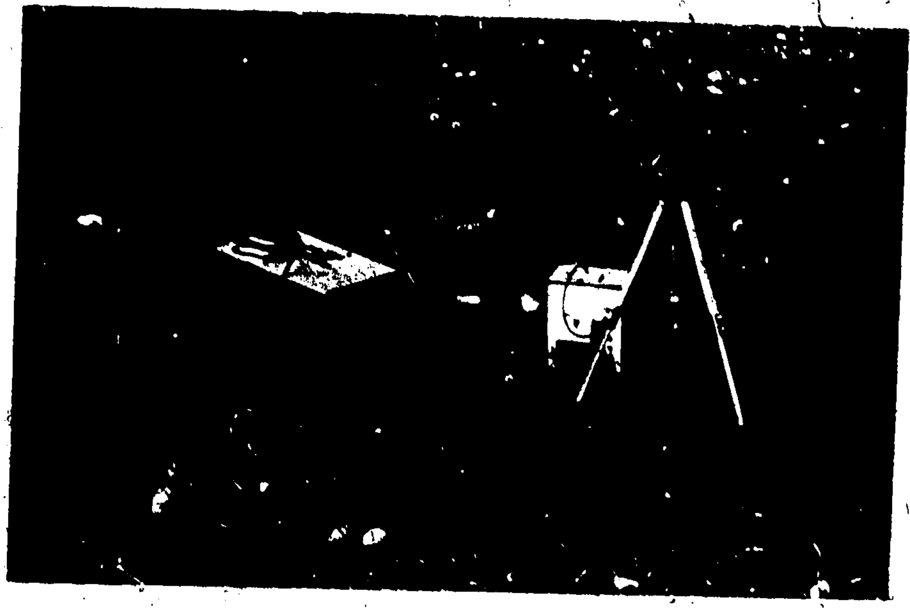

Plate 1. Instrumentation Specialties Company Spectroradiometer with remote probe attachment (A) and strip chart recorder (B) used in the field study of soil reflectance. Remote probe head is shown suspended from a tripod.

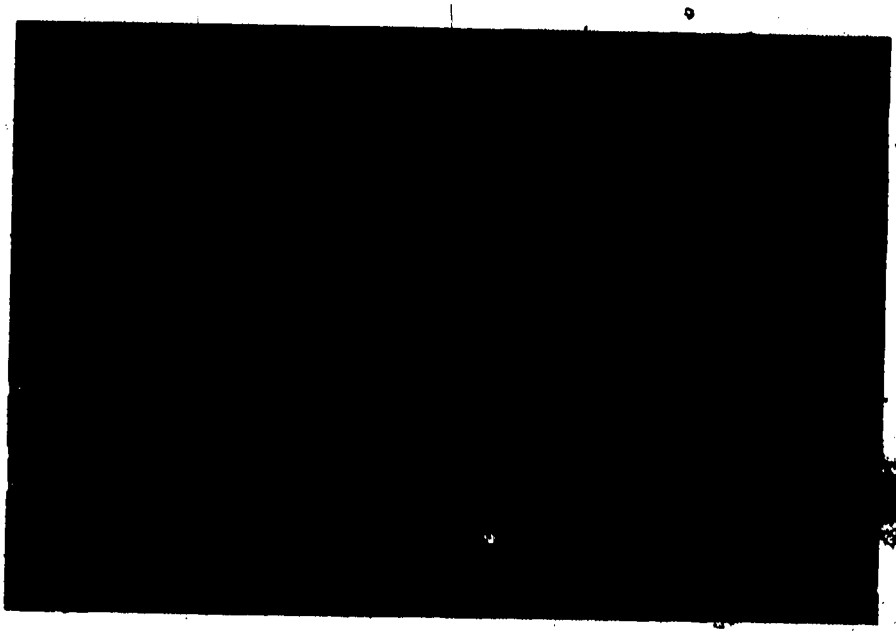

Plate 2. Color infrared aerial photograph showing surface characteristics of the three fallow fields for which digital LANDSAT 1 multispectral data were obtained (July 7, 1975; approximate scale 1:92,000).

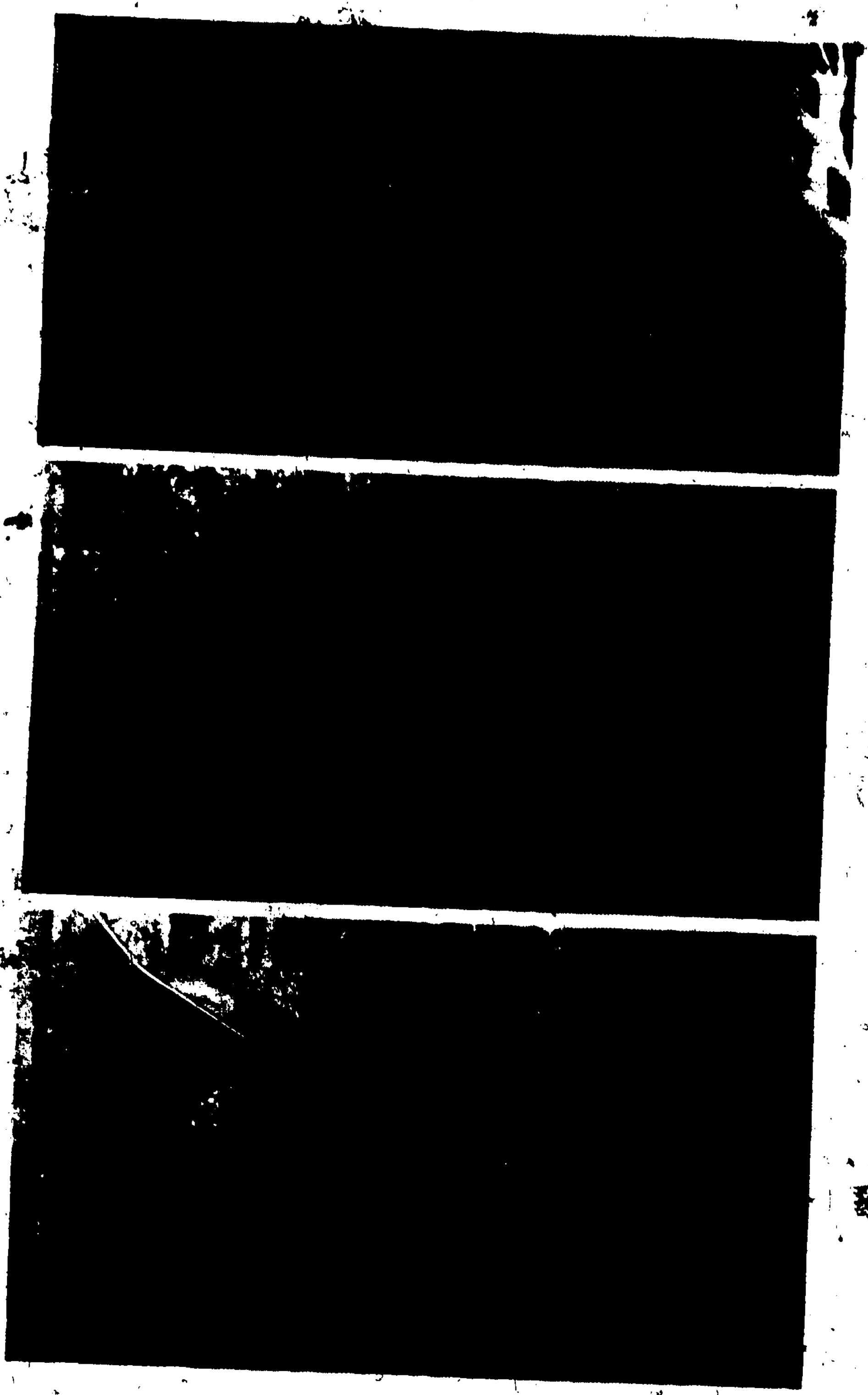

Plate 3. Color infrared aerial photographs showing surface characteristics of the four salt crust areas for which digital LANDSAT 1 multispectral data were obtained (June 11, 1973; approximate scale 1:49,000).

CHAPTER II

EMITTANCE FROM SOILS

CHAPTER II

EMITTANCE FROM SOILS

INTRODUCTION

Spectral reflectance data provide some information on soil surface conditions. However information about subsurface conditions is only provided if these have a definite surface expression such as salt crusting indicating soil salinity or anomalous vegetation patterns indicating salinity or textural differences. Thermal emissions from soils may provide additional information on soil surface or subsurface conditions providing these have some influence on surface temperatures.

Energy [illegible]get for Soils

All objects at temperatures above absolute zero (0 degrees K or -273 degrees C) radiate electromagnetic energy. As surface temperatures increase the amount of energy emitted increases proportional to the fo[illegible]f the surface temperature in degrees Kelvin and the wavele[illegible]h peak emissions occur decreases (Colwell et al., 1963). Thermal infrared line scanners provide a means whereby this emitted energy may be detected and recorded.

Various factors which influence surface soil temperature may be expressed in terms of an energy budget for the soil surface (Gates, 1970) as follows:

$$Q\ abs. = E\sigma T^4 \pm Q\ cond. \pm Q\ conv. \pm L E$$

where Q abs = the total energy absorbed

$E \sigma T^4$ = graybody radiation with E the emittance, σ the Stephan-Boltzman constant, and T the surface temperature in degrees K. Emittance is the ratio of energy emitted to that absorbed, and for a perfect blackbody this ratio is unity but for objects in nature it is less than unity. Thus most naturally occurring objects are "graybodies" as opposed to "blackbodies".

Q cond. = energy exchange by conduction between the surface and the soil body.

Q conv. = energy exchange by convection between the surface and the air.

LE = energy lost or gained by evaporation or condensation respectively.

a) The total energy absorbed (Q abs.) depends on a number of factors. Gieger (1971) estimated that of the solar radiation reaching the earth's outer atmosphere, 45 percent reaches the earth's surface (19 percent as direct beam and 26 percent as diffuse skylight). Of the remaining 55 percent, 11 percent is scattered back to space, 28 percent is reflected by clouds, and 16 percent is absorbed by the atmosphere. The intensity of the solar radiation falling on the earth's surface perpendicular to the sun's rays and for a mean earth-sun distance is, estimated as 2.00 calories per square centimeter per minute. This value is referred to as the "solar constant" and according to Geiger (1971) it may vary by approximately 7 percent with the changing distance of the earth from the sun over the year. Baver et al. (1972) stated that this amount of energy incident on a unit area also varies with the cosine of the angle between a perpendicular to the surface and the direction of the sun's rays. Therefore for level surfaces, as the latitude increases the incident energy per unit area decreases. For sloping surfaces the situation is further complicated by the degree of slope and aspect. The more closely the degree of slope approaches a perpendicular with the sun's rays the greater is the energy incident upon it. Therefore in northern latitudes, south facing slopes receive more incident energy than north facing slopes.

The amount and type of vegetative cover also influences the amount of energy absorbed by the soil. Vegetation reflects and absorbs incident energy and the layer of air between the vegetation and soil provides insulation to the soil surface.

Finally the energy absorbed by the soil surface varies inversely with the amount reflected. Factors which reduce reflectance as discussed in Chapter I will therefore increase absorption.

b) Energy exchange between the soil surface and the soil body may be either away from or towards the surface (positive or negative sign, respectively). Conduction is the process by which heat flows through the soil solids while conduction, convection and radiation act together for the flow of heat across pores (Taylor and Jackson, 1965). These processes depend on the soil's thermal conductivity, volumetric heat capacity and temperature gradient (Baver et al.1972).

The volumetric heat capacity, (number of calories required to raise the temperature of 1 cubic centimeter by 1 degree C) of water is much greater than that of soil solids which themselves can be ranked in decreasing order as quartz - feldspar - clay minerals - humus. The thermal conductivity (quantity of heat that in 1 second passes through a 1 centimeter thickness of homogeneous material with an area of 1 square centimeter where the temperature difference is 1 degree C per centimeter) for different soil minerals is approximately the same and soil differences therefore arise from the degree of compaction and porosity since heat flow in dry soil is through particle to particle contact and air has a low conductivity. As soils are wetted however, water which is a good conductor replaces the insulating air and the thermal conductivity of the soil increases, rapidly at first and then at a reduced rate. Lastly, the greater the temperature gradient between two points the greater the heat flow between them from the warmer to the cooler area.

c) Energy exchange between the soil surface and the air may be from the soil to the air (positive sign) if the air is cooler than the soil, or from the air to the soil (negative sign) if the air is warmer. The rate of convective transfer is related to surface roughness and wind speed (Geiger, 1971) with convective transfer being greater from rougher surfaces and when wind speed increases

d) Energy may be lost (positive sign) from the soil surface by evaporation of moisture or may be given up to the surface (negative sign) by condensation.

Soil temperatures are also subject to temporal variations due mainly to the temporal aspects of the incident energy which occur diurnally and seasonally. In both cases the greatest variations occur at the soil surface with the amplitude of these variations decreasing with depth into the soil. Also in both cases a time lag occurs between changes at the surface and corresponding increases or decreases at depth due to the time required for heat transfer through the soil. Gates (1970) illustrated the diurnal temperature variations in the air near the ground and in the soil for a typical clear midsummer day and night at temperate latitudes.

Maximum surface temperatures occur in the early afternoon while minimum values occur shortly before sunrise. On a seasonal basis maximum surface temperatures occur in early summer, while minimum values occur in winter. In both instances the specific temperature values, their rate of change with depth and the amplitude of these changes vary with different soils due to differences in texture, moisture content, landscape position and vegetative cover.

Because of these diurnal and seasonal variations in soil temperature, consideration should be given to the time of day and time of year which would be considered optimum for detecting soil differences based on thermal emissions. Considering the diurnal variations, midday to early afternoon and predawn imaging may be the optimum times for thermal sensing. At these times surface soil temperatures should be at their maximum and minimum respectively and thus indicate soil conditions by their actual and relative values as well as by the maximum-minimum differences. Perhaps a more important consideration is that during the morning or afternoon but especially the former, surface temperatures are changing rapidly. If relatively large areas are to be covered, there may be some question, once the imagery was obtained, as to whether or not a temperature difference between a given location at the beginning of the mission and one at the end of the mission, resulted from any real terrain difference or simply resulted from the time difference in imaging and associated exposure to less or more incident radiation. In a study of the use of thermal infrared scanning for soil temperature studies Myers and Heilman (1969) concluded that thermal sensing of soils was best at night when differential thermal conductivity and heat storage characteristics cause surface temperature contrasts. These were indicative of profile conditions in their study of an alluvial floodplain in Texas. Gates (1970) predicted that on a seasonal basis late spring and fall are the most productive times of the year for thermal sensing. The greatest positive heat exchange occurs in the spring while the greatest negative heat exchange occurs in the fall.

Thermal Scanners and Imagery

The technical operation of thermal scanners has been well documented with reviews by Holter _et_ _al_. (1970), Carroll (1973b) and Lowe _et_ _al_. (1975). Thermal scanners provide data relating to the surface temperatures of target features. This is accomplished by collecting the energy emitted from a given area on the ground, the instantaneous ground patch or instantaneous field of view, by means of an optical system and focusing this energy onto a sensor element. The data are collected by a physical sweeping motion of a rotating mirror across the te[illegible]ain perpendicular to the line of flight and certain distortions may be apparent on the final imagery. These were discussed by Derenyi and Konecny (1964) and include:

a) ground resolution distortion: The collecting optics of scanners have constant angular fields of view. As the scanning motion occurs the size of the instantaneous field of view increases as the scan angle changes from a vertical to an oblique view due to an increase in the distance from the optics to the ground. On the resultant imagery spatial resolution would be poorer towards the edges.

b) scale compression at the edges: As the scan angle from vertical becomes successively larger during scanning the size of the instantaneous field of view increases. On the final imagery however each instantaneous field of view is assigned the same size of area. Therefore on the imagery from the centre to the edges the same distance on the image represents successively larger distances on the ground.

c) scale expansion or compression along the direction of flight: Scale expansion or compression along the line of flight may result from the increasing or decreasing of the platform's velocity. These changes in scale may be evident on imagery obtained using light aircraft on windy days when one flight line is with the wind and the next is into the wind.

d) S - shaped distortion: Due to the scanning motion of the optics coupled with the forward movement of the platform, S-shaped distortion often becomes evident on the imagery especially for what should be straight features across the imagery (roads, etc.). As the scanner accomplishes one scan line the platform moves a given distance forward so that the final "view" of the ground is not straight across from the first.

Although the thermal infrared region of the electromagnetic spectrum includes a relatively wide range of wavelengths, atmospheric attenuation is great over most of this region and only two atmospheric windows, or spectral regions where the atmosphere is relatively transparent, are available for use in remote sensing (Colwell _et al._ 1963). These windows occur in the wavelength regions from 3.5 to 5.0 microns and from 8.0 to 14.0 microns. In each of these regions a different detector is employed; generally indium antimonide (InSb) in the 3.5 to 5.0 micron region and mercury-doped germanium (Ge:Hg) in the 8 to 14 micron region. Bastuscheck (1970) discussed the differences between the two detectors and suggested instances where each should be considered for use. If for instance minor thermal detail is desired in an area generally cooler than its surroundings the Ge:Hg detector would be required. This detector should also be used for thermal resolution stability since the minimum resolvable temperature difference does not change as target temperatures change to the same extent as for the In:Sb detector. With the In:Sb detector the minimum resolvable temperature difference increases as terrain temperatures increase above a range from 283 to 293 degrees K (10 to 20 degrees C). It was also noted that the In:Sb detector should provide better imagery if it is desired to detect warmer spots in a cooler background.

Thermal Sensing for Soil Studies

Much of the work relating soil characteristics to thermal image tones has been presented by Myers and others from the Remote Sensing Institute of South Dakota State University. Perhaps the most widely referenced work related tones on imagery obtained at different times of the day and year to the soils of an alluvial floodplain in Texas (Myers and Heilman, 1969). Image tones were quantified by microdensitometer tracings and used to give a qualitative indication of moisture in the upper 50 cm of soil, providing the surface was bare. Other studies reported by Myers et al. (1970) attempted to relate plant temperatures to soil conditions, particularly salinity. Stressed plants had higher temperatures than normal plants and a significant correlation was established between cotton leaf temperatures and soil salinity expressed as electrical conductivity of saturated soil extracts. In the field however, the response from a particular area on the ground corresponding to the instantaneous field of view is an integrated response from all targets within that area. Since stressed plants compared to those not under stress are usually shorter and not as numerous per unit area, higher leaf surface temperatures would be integrated with soil surface temperatures since there would not be one hundred percent crop cover. The addition of a response from the soil itself could mask slight differences in plant leaf temperatures. In studies such as this the size of the instantaneous field of view is a most important factor.

Rather than study single factors in small areas as mentioned above, some Canadian pedologists have attempted to use thermal imagery as a mapping tool. Beke (1972) reported that midday thermal imagery in the 3.5 to 5.0 micron band did not prove satisfactory for the delineation of the boundaries of landscape or soil units or of natural vegetative types. It was reported however that the imagery did provide a qualitative assessment of the occurrence of landforms and soil members within a given landscape or soil unit. Although the particular soil members were not mentioned it is assumed that they were generally drainage members. It was also not specified whether or not this assessment was possible using photographic data.

Tarnocai (1972) studied the use of thermal imagery in the 3 to 5 micron band for permafrost surveys. From imagery obtained at midday in the summer and late fall he concluded that patterns generally resembled those of panchromatic black-and-white photographs but that late fall imaging, possibly at night, may allow for the discrimination of frozen and unfrozen peats.

Mills (1972) studied the use of thermal data for mapping soil erosion. The results of this study were inconclusive although it was concluded that some indication of the areal extent and degree of erosion was provided by the thermal imagery. It was also concluded that anomalous thermal patterns occur where the removal of dark surface soil would result in less absorption and therefore lower surface temperatures than surrounding non-eroded areas or where the ablation of fine textured surface material would reduce the moisture holding capacity of the surface soil producing higher daytime surface temperatures. However because of a lack of ground truth data these relationships were not tested.

Michalyna and Eilers (1973) attempted to relate tones on thermal imagery to soils but apart from being able to identify some drainage differences concluded that management practices had the greatest influence on image tones. In particular tones related more to time and depth of cultivation and to the amount of plant debris in the field than to actual soil body characteristics.

Summary

Based on the energy budget for soils, consideration of soil properties affecting thermal imagery tones should be prefaced by a consideration of the amount of energy available for and absorbed by the terrain surface. Therefore latitude, topography and land use must be considered as a first step in image analysis. Their influence on image tones is so great that most subtle differences in soil surface temperature resulting from internal soil differences could be masked. One important feature that should be recognizable however is soil moisture. Water is an anomalous terrain feature in terms of its thermal characteristics of high heat capacity and high thermal conductivity and the presence of moisture in the soil has a pronounced effect on soil temperatures.

In this study thermal imagery was analyzed in terms of the effects of latitude, topography and agricultural land use on image tones followed by an analysis for some of the soil factors which affect soil moisture conditions including the time of cultivation relative to imaging dates, variations in soil texture, internal soil drainage and soil erosion.

MATERIALS AND METHODS

Acquisition of Thermal Imagery

Thermal imagery in the 3.5 to 5.0 micrometer range was obtained for the Edmonton and Vegreville study areas on two dates in 1971 (Table 13). The In:Sb detector was used as it was the only detector available at the time of the May flights and was selected for use in October for consistency. The flying was contracted to INTERA (formerly ERA) Environmental Consultants of Calgary, Alberta by the Canada Centre for Remote Sensing to whom the original request for thermal imagery was made.

The scanner used for the May flights was an older model Daedalus scanner that did not have equivalent blackbody temperature references. Prior to each flight in May, the scanner was adjusted to record the range of emissions between the maximum and minimum values obtained from the scanning of random portions of the terrain. The scanner used for the October flights was a Daedalus model that did have equivalent blackbody temperature references. Calibration was achieved by relating maximum and minimum levels of terrain emissions to their equivalent blackbody temperatures, the data being recorded on the flight logs. For all flights a small Cessna aircraft was flown at an altitude of 2000 feet (600 meters) above mean terrain. The spatial resolution of the systems used was 2.5 milliradians which from 2000 feet produced an instantaneous field of view of 5 feet (1.5 meters). The theoretical thermal resolution or minimum detectable temperature difference was 0.3° C.

Table 13. Thermal imaging dates and times for the Edmonton and Vegreville study areas.

Study Area	Date	Time (hrs MST)	Sunrise (hrs MST)
Edmonton	May 26, 1971	0400 (predawn) 1200 (midday)	0515*
	October 5, 1971	0600 (predawn) 1300 (midday)	0700*
Vegreville	May 26, 1971	0500 (predawn) 1300 (midday)	0515*
	October 6, 1971	0600 (predawn) 1200 (midday)	0700*

* Imaging before sunrise, therefore, no solar effect.

Data were recorded in analogue form on magnetic tapes during each flight run. The tapes were later processed using a Daedalus Field Printer Camera (#DEI 602) and accessories to produce hard copy imagery. This processing was carried out by INTERA Environmental Consultants in Calgary. The final imagery was in the form of black-and-white, 70 mm roll negatives cut into strips that corresponded to each flight run. Each set of imagery as strips, one set for each scanning mission, was supplied with a 16-step gray scale as an integral part of the imagery. During the processing of the analogue data adjustments were made to the Daedalus Field Printer Camera to ensure that on the negative transparencies the warmest terrain objects had a density as dark as the darkest gray scale tone and the coolest terrain objects had a density as light as the lightest gray scale tone. On positive prints the warmest terrain objects have the lightest tone and the coolest terrain objects have the darkest tone. The surface temperature corresponding to a given film gray scale level varied from one flight to the next, and, the range in surface temperature represented by the 16 steps of the gray scale varied from flight run to flight run.

Ground Truthing

Prior to each flight, maps of present land use were prepared for each study area. Soil maps prepared by Menon (1971) and Leskiw (1971) for the Edmonton and Vegreville study areas, respectively, provided most of the soils information whereas selected small areas were studied in more detail and additional notes made during the mapping of present land use. Flight logs provided data on aircraft speed and direction, strength and direction of wind, and scanner settings during each flight run.

During each flight run soil temperatures to a depth of 2 cm were recorded in the field using temperature probes since radiometers for measuring surface temperatures were not available for use. Surface samples were collected for the gravimetric determination of moisture content. The recording of soil temperatures and sample collection was carried out at preselected sites representing the various soils and materials, slope classes, aspect and land use found in each area (Appendix 6). The number of sites preselected was relatively small (12 to 15) due to the time restriction that all sites be visited during the actual flying period which extended for approximately 45 minutes.

Analyses

1. Seasonal and diurnal variations in soil temperature.

Published soil temperature data (Environment Canada, 1971 - 1972) were used to study variations in soil temperature with soil depth for 1971. The data were recorded at Ellerslie, Alberta, approximately 2 miles west of the Edmonton study area. Soils and parent materials at Ellerslie are similar to those of the western half of the Edmonton study area (Bowser et al., 1962). Mean maximum soil temperatures for each month of the year were used to assess the seasonal shifts from a positive to a negative energy exchange in the soil in relation to the dates of thermal imaging. Daily maximum and minimum soil temperatures for the day of and for 4 days prior to the actual imaging dates were used to assess the energy exchange in the soil at the times of the thermal sensing. Daily maximum and minimum temperatures and precipitation data were also obtained (Environment Canada, 1971 - 1972) to show ambient conditions at the times of the thermal missions.

2. Potential latitude and topography effects.

The amount of solar energy incident per unit area of the terrain surface is greatest when that surface is perpendicular to the direction of the sun's rays and thereafter varies with the cosine of the angle between a normal to that surface and the direction of the sun's rays (Baver *et al.*, 1972). Using solar altitude tables (Winzer, 1976) and trigonometric functions, and assuming a solar constant of 2.00 calaries per square centimeter per minute, the potential incident energy was calculated for a level surface and for surfaces with a 15 percent slope towards and away from the direction of the sun's rays in the Edmonton area. These calculations were made to demonstrate the effects of latitude and topography on the thermal imagery for this area.

3. Relationships between image tones and soil surface temperatures and moisture content.

Myers *et al.* (1970) reported a high correlation between thermal imagery tones and surface soil temperatures and between image tones and soil moisture content in the upper 50 cm of soil. The thermal imagery was analyzed to determine the correlation between tone and soil surface temperatures and moisture content for the Edmonton study area.

Since the scanner used for the May flights did not have internal blackbody temperature references, image tones can only be related to surface temperatures using the ground truth soil temperature data. The ground truth sites were located on the thermal imagery and their tones recorded in terms of the corresponding gray scale step number, 1 equalling the darkest possible tone and 16 the lightest possible tone. These were tabulated along with the recorded soil temperatures and the correlation coefficient calculated (Steel and Torrie, 1960). Similarly, the correlation between image tone and moisture content was calculated. Image tones were related to the 16 step gray scale using the density level determination capabilities of a Spatial Data Systems Inc. Datacolor 703-32 color density slicer available at the Alberta Remote Sensing Centre, Edmonton.

The scanner used for the October flights did have internal blackbody temperature references which provided temperature values for maximum and minimum levels of terrain emissions. Therefore the temperature range represented by the 16 step gray scale is known and since a near-linear relationship exists between changes in surface temperature and changes in image tone, the surface temperature of any given location can be determined by relating its tone to the gray scale. For the October imagery correlation coefficients were calculated between image tone and surface temperature and moisture content as obtained from the ground truth data.

4. Examples of thermal imagery.

Example imagery was selected for visual study to evaluate the effects of landscape and soil characteristics on image tones. The imagery was selected on the basis of repetitive coverage for areas that represented variations in landform and topography, soil drainage, soil texture and land use in the Edmonton study area.

RESULTS AND DISCUSSION

Soil Temperature

a) Seasonal and diurnal variations in soil temperature.

Based on monthly mean maximum soil temperature values, the energy flow in the soils of the Edmonton study area shifted from a negative flow, upwards from "warmer" to "cooler" portions of the soil, [illegible] ositive flow, downwards, in the month of April, 1971 (Figure 17). [illegible] May 26 imaging date a strongly positive energy exchange had developed. The shift back to a negative energy exchange occurred in the period between September and October (Figure 17). By the October 5 imaging date there was a very slight negative energy exchange in the soil. Based on these data a slightly later imaging date in October would have been preferred in order to guarantee a more strongly developed negative energy balance.

Daily soil temperature values for the day of and for 4 days prior to each imaging date are shown in Figure 18. These values were recorded at 0800 and 1700 hours local time (M.S.T.) and do not represent true minimum and maximum values, respectively. These will occur just before dawn and in the early afternoon, respectively. However, the data indicate a strong positive energy exchange at 1700 hrs. on May 26 while at 0800 hrs. a negative exchange occurred in the upper 20 cm and a positive exchange below (Figure 18). On October 5 a slightly positive energy exchange occurred in the upper 10 cm at 1700 hrs. while at 0800 hrs. a negative energy exchange occurred (Figure 18). At all

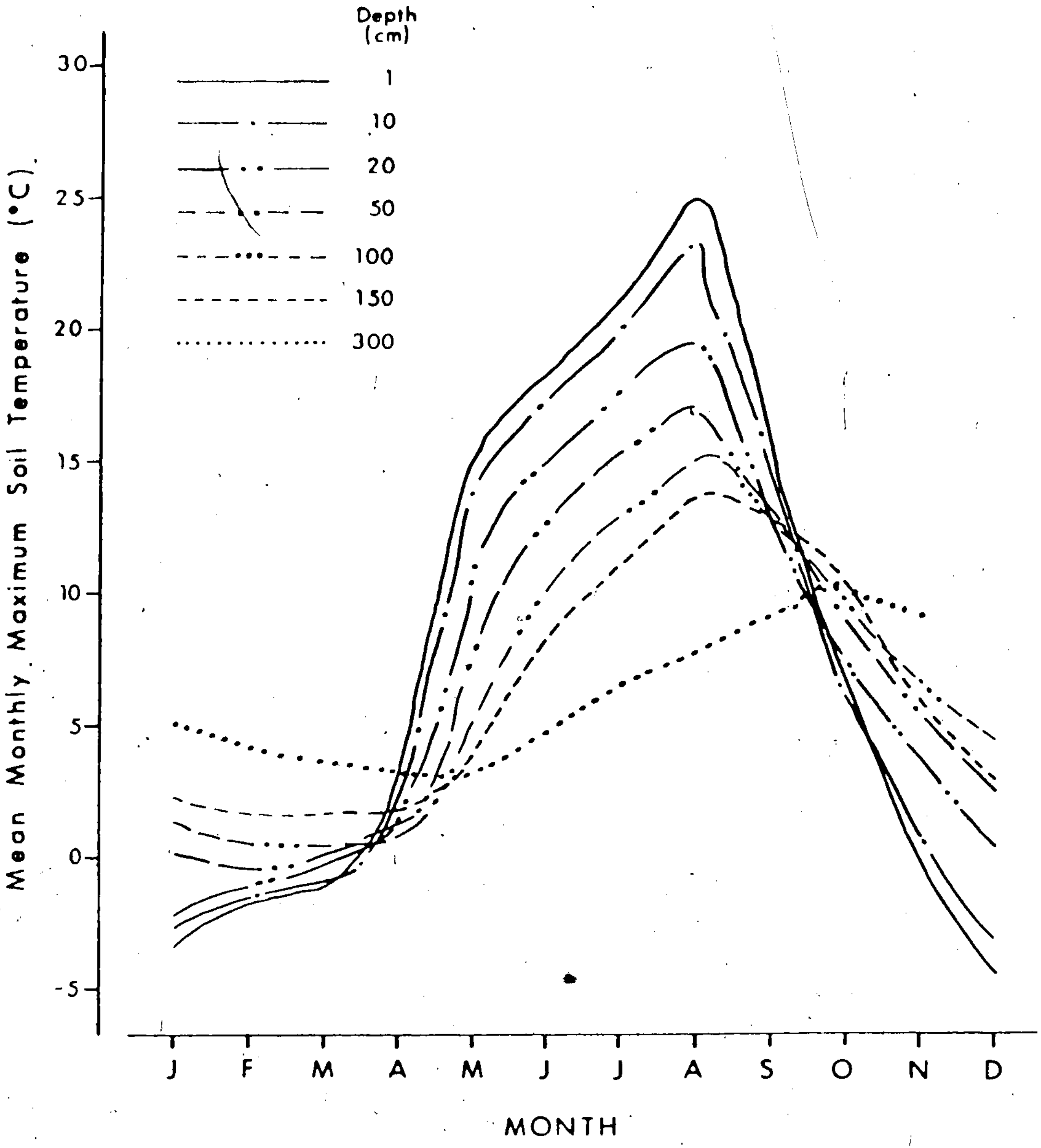

Figure 17. Variations in monthly mean maximum soil temperatures with soil depth as recorded at Ellerslie, Alberta in 1971 (modified after Environment Canada, 1971-1972).

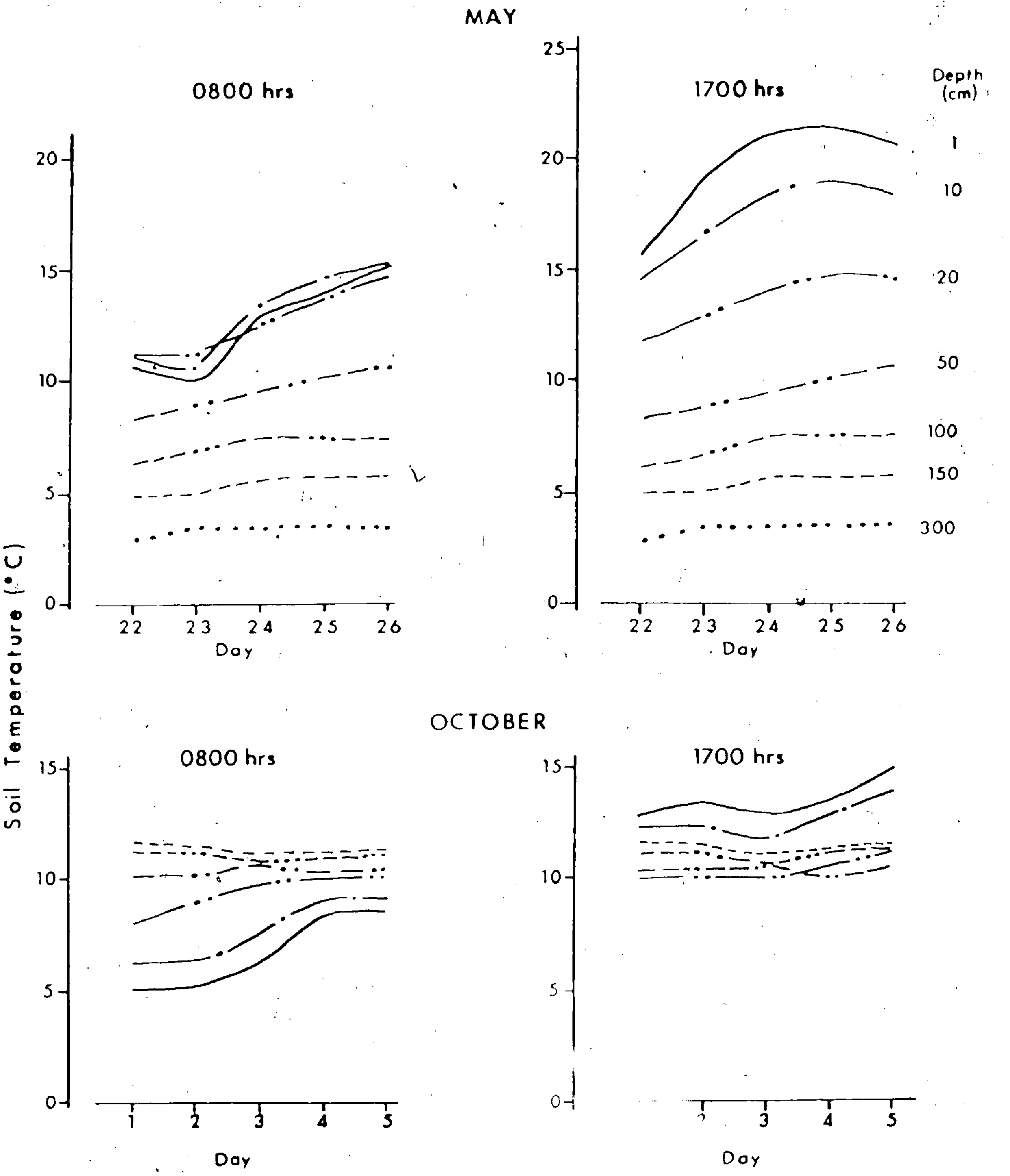

Figure 18. Variations in daily minimum (0800 hrs) [illegible] ximum (1700 hrs) soil temperatures with depth on the day of and for four days prior to thermal imaging of the Edmonton study a[illegible]. Data recorded at Ellerslie, Alberta (modified after Environment Canada, 1971-1972).

depths greater than 50 cm soil temperatures were the same at both times that measurements were made.

Therefore, on the May imaging date, especially at predawn, soil characteristics at depth will have a greater influence on surface temperatures than in October when a subsurface temperature gradient is essentially non-existent.

Daily minimum and maximum air temperatures and precipitation data (Table 14) show ambient conditions on the dates of thermal scanning. Of interest is the fact that by both imaging dates precipitation for the preceeding month was well below the average. Although soil moisture reserves were probably not too low in May due to spring runoff, soils in October were much drier than normal.

b) Potential latitude and topography effects on soil temperature.

The Edmonton study area is situated at approximately 53° 30' North latitude and 113° 45' West longitude. At this latitude and longitude seasonal variations in solar altitude from the horizon are great (Table 15) and therefore so are variations in the amount of incident solar energy falling on the terrain surface. Daily maximum solar altitudes occur between 1200 and 1300 hrs. M.S.T. with a seasonal maximum of 60° on June 21. By middav on May 26 the solar altitude was approximately 59°, close to the seasonal maximum. By midday on the October 5 imaging date the solar altitude was approximately 31°, almost half of that in May.

The potential incident energy on a level surface at 1300 hrs. on May 26 is 66 percent greater than that on a level surface at 1300 hrs.

Table 14. Daily minimum and maximum air temperature (° C) and precipitation (mm) for the date of and for four days prior to thermal imaging of the Edmonton study area in 1971. Data recorded at Ellerslie, Alberta (modified after Environment Canada, 1971-1972).

	May, 1971					May
	22	23	24	25	26	1-26 inclusive
Precipitation	--	--	T	0.2	--	7.6 (36 below average)
Air temperature						
max. (1700 hrs)	20	22	27	26	21	
min. (0800 hrs)	9	5	12	11	11	

	October, 1971					September
	1	2	3	4	5	1-30 inclusive
Precipitation	-	-	-	T	-	17.9 (20 below average)
Air temperature						
max. (1700 hrs)	16	19	19	19	24	
min. (0800 hrs)	3	3	8	[illegible]	6	

Table 15. Solar altitude in degrees at various times of the day and year for 53° 30' N latitude and 113° 45' W longitude (modified after Winzer, 1976)

Date	Time (hrs MST)				
	0800	1000	1200	1400	1600
May 7	27	44	53	49	35
May 26	30	47	57	53	39
June 21	31	48	59	56	41
July 21	28	45	56	53	39
August 20	22	38	48	46	32
September 20	14	29	37	34	22
October 5	10	24	31	28	16

on October 5 (Table 16) while for a 15 percent slope away from and towards the sun the percent difference decreases to 52 and 49 percent, respectively. Therefore the effect of latitude and season on potential incident energy is greatest for level surfaces and less for surfaces sloping towards the sun.

Solar azimuth at any particular time on a given day dictates which slope aspect is facing away from or towards the sun's rays. Values for solar azimuth are found in Table 17. In northern latitudes solar azimuth is measured in degrees east from north. On May 26 the sun is approximately due east from north by 0800 hrs. whereas on October 5 the sun is further south at this same time of day. By 1600 hrs. the sun is further north on May 26. Therefore on May 26 a greater range of slope aspects will be illuminated by direct sunlight and a greater proportion of sloping terrain receives the maximum possible amount of potential incident energy than on October 5.

The term "potential incident energy" is used since atmospheric conditions can alter the actual amount of incident energy reaching the terrain surface. Also, the incident energy falling on a surface is not entirely absorbed. Varying amounts of energy are reflected depending on the amount and type of surface cover as well as those factors discussed in Chapter I for bare soil surfaces. That energy which is absorbed increases surface soil temperatures to a degree and at a rate which depend on the thermal conductivity and heat capacity of the soil and soil temperature gradient.

Table 16. Potential incident energy (calories / cm^2 / min.) on a level surface and on slopes of 15 percent at 1300 hrs on May 26 and October 5 for the Edmonton study area.

	May 26	October 5	% Difference
Level surface	1.71	1.03	66%
15 percent slope away from the sun	1.23	0.81	52%
15 percent slope towards the sun	1.83	1.23	49%

Table 17. Solar azimuth in degrees East from North at various times of the day and year for 53° 30' N latitude and 113° 45' W longitude (modified after Winzer, 1976).

Date	Time (hrs MST)				
	0800	1000	1200	1400	1600
May 7	98	128	169	215	249
May 26	94	124	168	217	252
June 21	92	121	165	217	253
July 21	94	122	164	213	249
August 20	100	128	168	210	244
September 20	109	137	172	208	240
October 5	113	140	174	208	238

Image Tones Related to Surface Soil Temperature and Moisture Content

1. Predawn and midday imagery from May 26.

On the imagery obtained in May, sites with the same ground truth surface temperature were often represented by different image tones and sites with dissimilar surface temperatures were often represented by the same image tone (Table 18). Therefore, the relationship between image tone and surface temperature or moisture content cannot be established and correlation coefficients are low (Table 18). During the flight runs the gain setting on the scanner was adjusted continuously by the scanner operator and these adjustments were noted only briefly and in many cases not at all on the flight logs.[1] Therefore, during the conversion from analogue data to hard copy imagery not all of these adjustments could be applied to the Daedalus Field Printer Camera. The result is that along each strip of imagery changes in gray scale may not necessarily be related to changes in surface temperature. The May imagery can be considered only in a qualitative manner.

A second problem relates to the method of scanner calibration prior to the actual flight runs. By adjusting the scanner to record maximum and minimum terrain emissions over random portions of the terrain, emissions from anomalous "hot" and "cold" spots could be encountered. Since the range in soil surface temperatures was relatively small compared to the total range in terrain surface temperatures, all

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[1] Noted by Mr. B. McKibbon, Canada Centre for Remote Sensing, Ottawa, during a study of the analogue data.

Table 18. Predawn and midday surface temperatures (°C) and surface moisture content (% by wt.) from ground truth sites compared to tones on the May 26, 1971 thermal imagery of the Edmonton study area. For image tones: 1= light tone and higher relative surface temperature; 16= dark tone and lower relative surface temperature.

Site	Predawn			Midday		
	Temp.	Moisture	Tone	Temp.	Moisture	Tone
1	11.0	25.4	11	22.5	10.2	11
2	11.5	13.6	12	23.2	12.5	13
3	10.5	19.1	10	27.5	8.9	7
4	11.0	14.9	10	30.0	3.4	6
5	11.2	13.8	13	26.0	10.4	8
6	12.0	15.8	11	32.0	5.2	7
7	11.8	16.2	10	32.0	8.2	5
8	11.8	14.6	11	36.0	9.2	4
9	12.5	17.1	10	26.0	9.7	9
10	13.0	18.0	10	30.0	16.3	6
11	13.5	12.4	10	27.5	10.7	9
12	13.5	7.4	8	–	–	–
13	16.0	11.6	7	–	–	–
14	16.0	12.0	8	33.0	9.4	4

Temperature-tone r=+0.78**
[illegible]ure-tone r=-0.41

Temperature-tone r=+0.92**
% Moisture-tone r=-0.28

** Ind[illegible] significant correlation (P=0.01) bare soil surfaces have relatively similar image tones, especially on the predawn imagery which accounts for the higher correlation between tone and temperature (Table 18).

2. <u>Predawn and midday imagery from October 5.</u>

For the October imagery, maximum and minimum equivalent blackbody surface temperatures were provided on the flight logs. Therefore the range in surface temperature represented by the gray scale is known and relating image tone to gray scale step provides a value for surface temperature. On the October predawn imagery each gray scale step represents a temperature difference of approximately 0.6° C since the 16 steps represent a temperature range of from 4 to 13° C. On the midday imagery the temperature range, according to the internal references of the scanner, was from 8 to 30° C so that each step of the gray scale represents a temperature difference of approximately 1.4° C.

On the October imagery ground truth temperatures were more highly correlated with image tone than on the May imagery (Table 19). The correlation between image tone and moisture content is significant only for the October midday imagery.

Examples of Thermal Imagery

Thermal imagery from the May 26 and October 5 imaging dates are included for discussion (Plates 4 and 6, pages 124 and 127, respectively).

Table 19. Predawn and midday surface temperatures (^{o}C) and surface moisture content (% by wt.) from ground truth sites compared to tones on the October 5, 1971 thermal imagery of the Edmonton study area. For image tones: 1= light tone and higher relative surface temperature; 16= dark tone and lower relative surface temperature.

Site	Predawn			Midday		
	Temp.	Moisture	Tone	Temp.	Moisture	Tone
1	5.0	24.5	14	22.0	11.8	7
2	4.5	21.7	13	22.0	14.5	6
3	6.5	18.6	11	28.0	7.9	3
4	4.5	22.0	14	23.0	13.7	5
5	5.5	8.9	13	25.0	7.8	4
6	6.0	21.9	12	14.0	23.9	12
7	4.0	-	15	18.0	-	9
8	7.0	20.8	10	30.0	8.0	2
9	6.0	18.7	12	21.0	5.1	7
10	6.5	17.4	12	17.0	13.9	9
11	5.0	-	13	13.0	-	12
12	5.0	8.2	14	23.0	3.8	5
13	4.5	31.7	14	16.0	27.2	10

	Predawn	Midday
Temperature-tone	r=+0.93**	r=+0.99**
% Moisture-tone	r=-0.08	r=-0.76**

** Indicates significant correlation (P=0.01)

a) Distortions.

The predawn imagery from May 26 (Plates 4A and 6A, pages 124 and 127) show S-shaped distortions most evident for the north-south roads on either side of the areas shown. The flight logs from the May flight runs record a southwest wind at 0400 hrs. With east-west flight lines this wind was sufficient to cause some crab in the light aircraft used and thus produced this type of distortion. In Plate 6A the distortion is in the opposite direction to that in Plate 4A. This is due to the fact that the two areas were covered by adjacent flight runs with the aircraft heading west during the predawn flight shown in Plate 4A and east during that shown in Plate 6A. The direction of crab is reversed between the two flight lines.

Also evident in the imagery in Plate 4 is scale compression at the edges. This type of distortion is particularly evident for the field labelled A on the midday imagery of May 26 (Plate 4A) and the predawn imagery of October 5 (Plate 4B, page 125). In both cases the dimensions of this field have been foreshortened in the Y direction when this field occurs towards the very edge of the imagery.

Although the scale in the X direction is similar for most of the imagery shown in Plates 4 and 6, the predawn imagery from October 5 (Plate 4B) has an expanded scale in the X direction, along the line of flight which was east to west. This scale expansion is the result of some factor involved in the processing of the analogue data to negative transparencies, probably the rate of film advance and operation of the Daedalus Field Printer Camera.

The May imagery of Plates 4A and 6A show missing scan lines the result of improper synchronization between the rate of scan and the speed of the aircraft.

b) Land use and topography effects.

According to Menon (1971), the area shown in the imagery of Plates 4A and 4B includes Orthic Black, Eluviated Black and Gleyed Orthic Black Chernozem soils developed on glacial till, and Gleyed Black and Solonetzic Black Chernozem and Orthic Humic Gleysol soils developed on glaciolacustrine sediments. Both parent materials have a clay loam texture to the subsoil although soils developed on the glacial till generally have loam textured surfaces compared to silty clay loam surfaces on the glaciolacustrine soils. Slopes range from 2 to 5 percent.

On the May predawn imagery (Plate 4A) there is generally little tonal difference between fields of bare soil with 20 percent stubble (C and D), the field with 90 percent stubble cover (E), and the hay field (B). The field of bare soil without stubble (A) has a slightly lighter tone indicating a slightly higher surface temperature. On the May midday imagery (Plate 4A), the field of bare soil (A) has a very light tone, fields with 20 percent stubble (C and D) moderately light tones, the field with 90 percent stubble cover (E) a darker tone and the hay field (B) an even darker tone.

On the October predawn imagery (Plate 4B) all fields have a similar dark tone regardless of land use whereas on the October midday imagery (Plate 4B), as with the midday imagery from May, surface temperatures are the greatest and the tones the lightest for fields of bare soil and tones darken as the amount of cover on the surface increases. As the amount of cover increases, reflectance increases and surface temperatures do not attain the same high maximum values as fields without cover. At night, with no insulating cover, bare soil surfaces generally emit energy readily so that by one hour before dawn their surface temperatures are generally similar to those of fields with cover.

For the undulating terrain shown in Plates 4A and 4B no slope detail is evident at these times and on these dates of imaging, even in October when sun angles are relatively low. However, features with some anomalous height associated with them present interesting tones. In the hay field (B) on the October imagery (Plate 4B), hay stacks are observed having relatively warm south facing surfaces on the midday imagery and relatively warm total surfaces on the predawn imagery. These are inanimate objects as they occupy the same positions in the field on both predawn and midday imagery. Their relief is evident by the warm south facing surfaces and cooler north facing surfaces on the midday imagery. The dark tone associated with the north facing surfaces may also include some shadow area on the ground. One may speculate that the relatively high predawn temperatures possibly result from the moisture content and dense, compact nature of the hay stacks; or since incident energy raises the surface temperature of the south facing sides of the stacks, sufficient heat energy is "stored" so that nighttime temperatures remain relatively high.

Another feature relating to relatively low sun angles in October is shadow. On the midday October imagery (Plate 4B) with solar altitude and azimuth of 31° and 174° (east from north), respectively, strong shadow effects on surface temperature are observed on the north side of treed fencelines and other isolated clumps of trees (Location 1). On the October predawn imagery a much larger area of relatively lower surface temperatures is observed to the northeast of the trees at Location 1 due to shadow effects and higher soil moisture conditions. During the afternoon at this time of year at this latitude and longitude, solar altitude decreases rapidly from a maximum of approximately 31° at noon producing successively longer shadows. Kaiser (1960) reported that trees may affect soil temperatures at considerable distance from the tree cover itself.

The area shown on the imagery in Plate 6 is part of a large hummocky disintegration moraine with till ridges and prairie mounds providing the surficial expression. Menon (1971) mapped the area as having Orthic Gray Luvisol soils developed on the glacial till on the ridges and prairie mounds with poorly drained mineral and organic soils in depressions and interridge areas. Slopes were mapped as being between 9 and 15 percent with erosion of the surface soil common on the steeper slopes. Land use in this portion of the study area is primarily pasture and hay lands with smaller areas seeded to coarse grains. In cultivated fields depressional areas are generally too wet to be cultivated in the spring and thus are usually left with grass cover all year.

As with the imagery for the undulating area in Plate 4, on the imagery for the hummocky area shown in Plate 6, fields with bare soil surfaces (A) have the lightest relative tones corresponding to the highest relative surface temperatures, and fields of hay (B) have darker tones and lower relative surface temperatures on the midday imagery from May (Plate 6A). On the predawn imagery from May (Plate 6A) bare soil surfaces (A) maintain higher relative surface temperatures than surfaces with vegetative cover (B). This differs from the situation found on level terrain (Plate 4A) where predawn tones for bare soil and vegetated surfaces were generally similar. The relative temperature differences between bare soil surfaces and vegetated surfaces in the hummocky terrain may not be as great as the predawn image tones (Plate 6A) suggest. The gain setting of the scanner may have been adjusted during the flight run over this area which could result in an exaggeration of very slight temperature differences. On the October predawn imagery for this same area (Plate 6B, page 128) bare soil surfaces and vegetated surfaces have similar image tones, field C having a bare soil surface and field D a vegetated surface.

The October imagery for this hummocky area (Plate 6B) also illustrates the significant effects on surface temperature of percent slope and slope aspect in relation to solar altitude and azimuth. On the midday imagery southeast facing slopes (Location 1) have very light tones while northwest facing slopes (Location 2) being almost in shadow have very dark image tones. The predawn imagery shows a carry-over effect of slope and aspect. The southeast facing slopes (1) maintain relatively high surface temperatures the the northwest facing slopes (2) have a similar tone. This latter slope has had little illumination by direct sunlight by midday but is illuminated in the afternoon causing its surface temperature to increase. By predawn both slopes are at approximately the same relative surface temperature.

Also the effect of tree shadows in reducing both midday and predawn soil temperatures may be noted (Location 3, Plate 6B).

c) Soil moisture effects through cultivation.

In the previous discussion of the tones on May and October imagery attention was given to topography and land use effects, where differences in land use were generally considered to be differences in the amount and type of surface cover. Myers *et al.* (1970) suggested that predawn imagery may provide more soils information than midday imagery since differences in tone associated with differences in agricultural land use are a minimum at this time of imaging. Therefore, the example imagery of Plate 4 is discussed further.

On the May midday imagery (Plate 4A) the field with a bare soil surface (A) has a slightly lighter tone than fields with 20 percent stubble (C and D). On the predawn imagery from the same date, Field A retains a slightly lighter tone than Fields C and D except at its eastern end. This slightly lighter predawn tone is the result of the cultivation of most of this field just prior to the imaging date which would bring more moist soil from depth to the surface. Aerial photography obtained that day (Plate 5, page 126) shows the cultivation pattern for this field. The reduced red band reflectance from Field A compared to Fields C and D is due to darker surface color, higher soil moisture in the surface and the absence of surface crop residue. It would be expected, however, that if the slightly lighter tone on the May predawn imagery were due to surface moisture content alone, the midday imagery should show a darker tone for Field A but it does not.

Even moist soils tend to dry at the surface forming a thin dry crust (Michalyna and Eilers, 1972). The presence of such a dry crust by midday plus a less dense surface with more pore space due to cultivation, could sufficiently reduce the thermal conductivity of the surface to produce midday surface temperatures slightly higher than those for drier, uncultivated fields. By predawn the effects of this surface crust have been eliminated and the higher soil moisture conditions directly below the surface crust prevail in maintaining slightly greater soil surface temperatures.

On the October midday imagery (Plate 4B) Field A is again in the process of being cultivated but from east to west. The pattern of cultivation is only evident on the midday imagery unlike in May (Plate 4A) where the cultivation pattern is evident on both predawn and midday imagery. In the fall, a negative total energy budget occurs in the soil and energy absorbed during the day is not retained at night. Also, the soil moisture content in October of this year was below normal due to the below normal amounts of precipitation.

d) Soil moisture variations due to variations in soil drainage and soil texture.

Another example of an anomalous tone occurs on the May imagery (Plate 4A) at Location 2 in Field C. The predawn imagery shows a lighter tone at this location than for the rest of the field while the midday imagery shows a slightly darker tone. This diurnal pattern of tones is typical of moisture effects. The black-and-white aerial photography (Plate 5) shows little tonal variation for this field. According to Menon (1971) this corner of Field C labelled Location 2 is an area of Black Solonetz soils developed on glaciolacustrine sediments with the map unit used having inclusions of imperfectly and poorly drained soils. The rest of Field C includes Black Chernozem soils developed on glacial till. The thermal imagery particularly the predawn imagery in Plate 4A shows this drainage detail at Location 2 with the tone being lighter as the soil moisture content increases. The October imagery (Plate 4B) shows no tonal difference for Location 2 compared to the surrounding area on the midday imagery, attributed to the generally low soil moisture conditions at this time of year as well as to the presence of a crop residue on the surface. The October predawn imagery shows a slightly darker tone at Location 2 indicating relatively lower soil surface temperatures. This is due to slightly higher soil moisture conditions that instead of producing relatively higher temperatures as in May, produce relatively lower temperatures. The high amount of surface cover maintains a relatively low surface temperature to Field C during the day. The more moist soils, requiring a greater amount of energy to raise their temperature due to the high heat capacity of water, do not heat sufficiently during the day to be relatively warm by the time of the predawn flight.

Comparing the imagery in Plates 4A and 4B it is noted that differences in soil drainage are more evident in May than in October. Also on the May imagery, drainage differences in fields of bare soil are more evident on the predawn imagery while drainage differences in vegetated fields (B) are more evident on the midday imagery.

In most instances, variations in surface soil texture in the portions of the Edmonton area covered by thermal imagery are not great and this, plus the fact that management practices and agricultural land use vary from field to field, make it difficult to assess the influence of soil textural changes on image tones. However, in one field in the Edmonton area, Menon (1971) mapped Black Chernozem soils developed in fine textured glaciolacustrine sediments, moderately fine textured glacial till and coarse textured glaciofluvial sediments. Since all three materials occur in one management unit (one field) the effects of soil texture on thermal image tones should be readily apparent. Thermal imagery from May 26 and October 5 for this field are found in Plates 8A and 8B (pages 130 and 131, respectively). Multiband photography is found in Plate 9 (page 132).

Based on the literature review of the effects of soil texture on soil surface temperatures, it is expected that the surfaces of coarser textured soils will be relatively warmer than the surfaces of finer textured soils during the day but relatively cooler by predawn. The predawn May imagery (Plate 8A) shows a slightly darker tone for the sandy area (A) but the tonal difference between coarse and fine textured material is not great. The midday imagery from May is poor in that some drastic distortions occur. However, the sandy area (A) has a slightly lighter tone than the fine textured areas of glaciolacustrine sediments (B) or glacial till (C). These tones representing various surface temperatures are in agreement with the predicted tones. Although the sandier area reflects more energy (lighter toned on the multiband photography Plate 9) than surrounding finer textured areas, it is still slightly warmer during the day. The temperature difference could be greater at predawn except that the pattern on the photography suggests that the field is being cultivated.

The thermal imagery obtained in October is shown in Plate 8B. Since a crop of wheat was grown on this field during the year of the imagery, a cover of stubble was present on the field in October. The stubble cover masks the reflectance differences between the coarser and finer textured materials although the red band photography does show a slightly darker tone in the sandy area (Plate 9). This is the result of poorer crop growth and therefore less stubble on the surface of the sandy portion of the field. The midday thermal imagery shows little tonal difference that can be attributable to the textural difference (Plate 8B), the stubble being as warm as the sandy soil. The predawn imagery, however, shows a marked tonal contrast between the area of sand and the rest of the field (Plate 8B) with the sandy area having a lighter tone indicating a higher predawn surface temperature. In this instance the surface cover is having a significant effect. Soil temperature data show the change from a positive to a negative heat balance in the soil generally occurs in late summer to early fall. By the end of the first week in October sufficient energy has been lost by the soil that coupled with the insulating effect of the ground cover the soils are very cool. If the ground cover is sparse as on the sandy soils, energy is still being absorbed during the day and must be of sufficient quantity to raise soil temperatures at depth enough so that predawn temperatures are still high. Another explanation is possible, based on soil moisture conditions at this time of year. With precipitation well below normal for the month of September and with essentially no precipitation for the 5 days preceding the imaging, soils would be very dry regardless of texture. Theoretically dry sand has a greater thermal conductivity than dry clay since without moisture, heat transfer is by particle to particle contact and there are more such contacts in granular sand than with platy clay particles. Also, the heat capacity of quartz and feldspars is greater than that of clay minerals (Baver _et al._, 1972). Therefore, the dry sand absorbs and transfers to depth more heat energy than the dry clay. At night there is a greater thermal reserve in the sand which is dissipated slowly enough so that by predawn surface temperatures of the sand are higher than those of the dry clay. It is most likely that in this instance both explanations apply.

e) Erosion.

The thermal detection of soil erosion is a possibility since as pointed out by Mills (1972) eroded slopes would have a different thermal energy balance than ~~adjacent~~ non-eroded slopes. Menon (1971) stated in his map unit descriptions that erosion was a notable feature in the hummocky moraine that comprises the eastern portion of the Edmonton study area. The soils in this area were mapped as dominantly Orthic Gray Luvisols developed on glacial till. In cultivated fields these soils have relatively light colored surfaces and relatively high reflectance in the visible and reflected infrared spectral regions (Chapter I). Eroded surfaces are also very light in color and it may be difficult to discriminate between eroded and non-eroded bare soil surfaces using reflectance data only. However, if erosion has removed the finer particle size fraction thereby altering the surface soil texture or has removed sufficient surface to expose the underlying B horizons, the thermal regime of the surface may be sufficiently altered to allow for thermal detection. Many of these slopes are vegetated (hay and pasture crops). Vegetative growth is generally poorer in eroded areas and with the percentage cover reduced, reflectance should be altered since more bare soil would be exposed. Also, thermal difference should be apparent with the eroded areas having greater surface temperatures during the day since they resemble bare soils surfaces more than vegetated surfaces.

A major problem in using thermal imagery to detect erosion relates to the fact that erosion occurs in the more steeply sloping areas. It is in these areas where topographic effects on surface temperatures are prominent so that only thermal imagery from midday in early summer when solar altitudes are a maximum and corresponding nighttime imagery should be considered.

Examples of erosion are labelled E on the thermal imagery of Plate 6A and on the corresponding black-and-white red band and infrared photography of Plate 7 (page 129). Erosion (E1) in the fields of bare soil (A and C) is difficult to detect on the black-and-white red band photography. Relative to vegetation, the light colored surface soils of this area reflect more strongly in the red band and thus have very light tones of the black-and-white red band photography. However, erosion (E1) in the fields of bare soil is easier to detect on the black-and-white infrared photography since soils generally have dark tones while the coarser textured surfaces of eroded slopes have slightly higher infrared reflectance and slightly lighter tones. In the pasture field (D), erosion (E2) is noticeable on the red band photography as lighter tones where vegetative cover is reduced and more soil surface is exposed. On the black-and-white infrared photography the same areas of erosion are represented by darker tones since bare soil reflects less than vegetation in this spectral region.

On the thermal imagery (Plate 6A) erosion in the fields of soil (A and C) is shown by darker tones on both the midday and predawn imagery, indicating lower surface temperature. This darkening in tone is more evident on the predawn imagery. The darker tone for eroded areas shown on the midday imagery is due to the increased reflection and lower absorption of the eroded surface. The relatively darker tone and therefore relatively lower surface temperature associated with erosion on the predawn imagery results from less absorption of energy during the day.

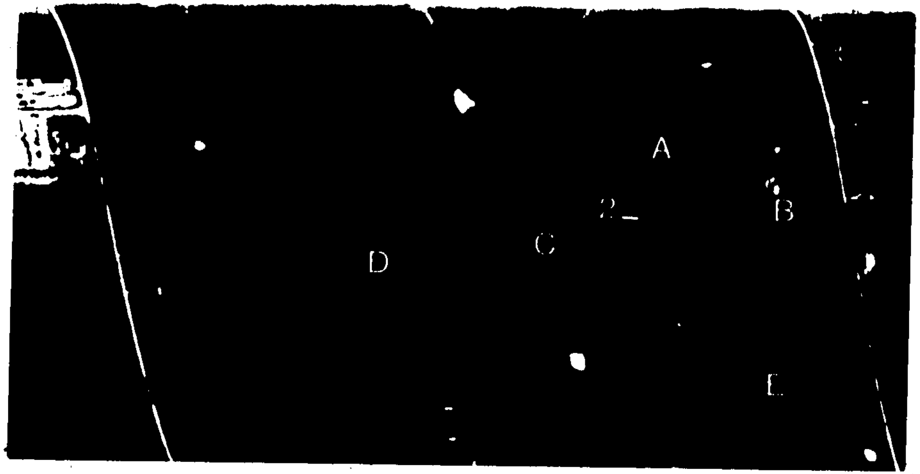
In the pasture field (D) eroded slopes (E2), having less vegetative cover and therefore more bare soil exposed, are represented by relatively lighter tones on the thermal imagery when compared to non-eroded portions of the field. In this case, the eroded areas are more evident on the midday imagery. By one hour before dawn surfaces with relatively more and those with relatively less vegetation have more similar surface temperatures than at midday.

CONCLUSIONS

Thermal imagery is most useful for studying soil conditions related to moisture content. However, land use patterns and topography influences may mask the thermal response related to some soil feature. Predawn imagery provides more information related to soil differences than midday imagery when the soil surface is devoid of vegetation. This is in agreement with the conclusion stated by Myers et al. (1970). In fields with vegetative cover, midday imagery provides more information on soil differences than predawn imagery.

Certain soil differences were not discriminated using reflectance data especially those related to subsurface characteristics. Thermal data discriminates between these soils providing the subsurface characteristics affect soil moisture conditions.

PREDAWN (0400 hrs)



MIDDAY (1200 hrs)

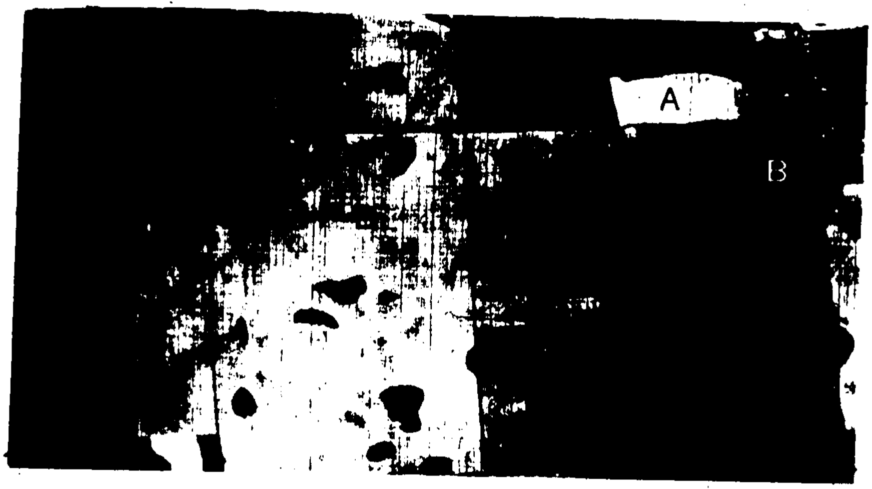
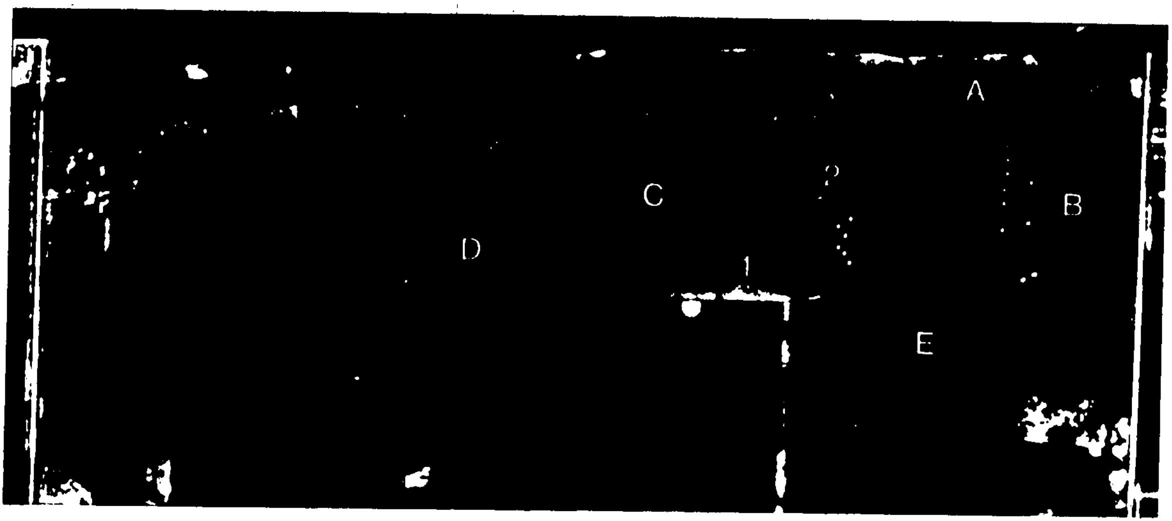


Plate 4A. Predawn and midday thermal imagery (In:Sb detector) from May 26, 1971 of undulating to gently rolling terrain in the Edmonton study area. Location of Fields B and C: NE Sec.13-Tp.52-R.24-W 4th meridian.

PREDAWN (0600 hrs)



MIDDAY (1300 hrs)

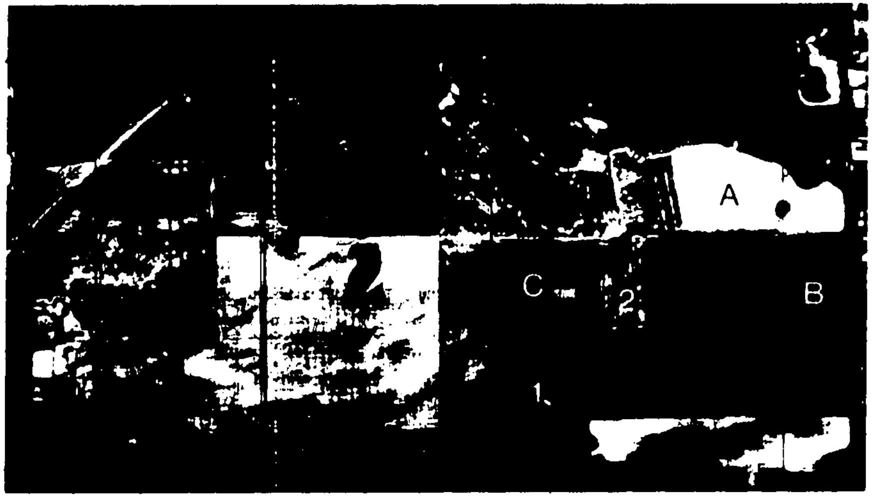


Plate 4B. Predawn and midday thermal imagery (In:Sb detector) from October 5, 1971 of undulating to gently rolling terrain in the Edmonton study area. Location of Fields B and C: NE Sec.13-Tp.52-R.24-W 4th meridian.

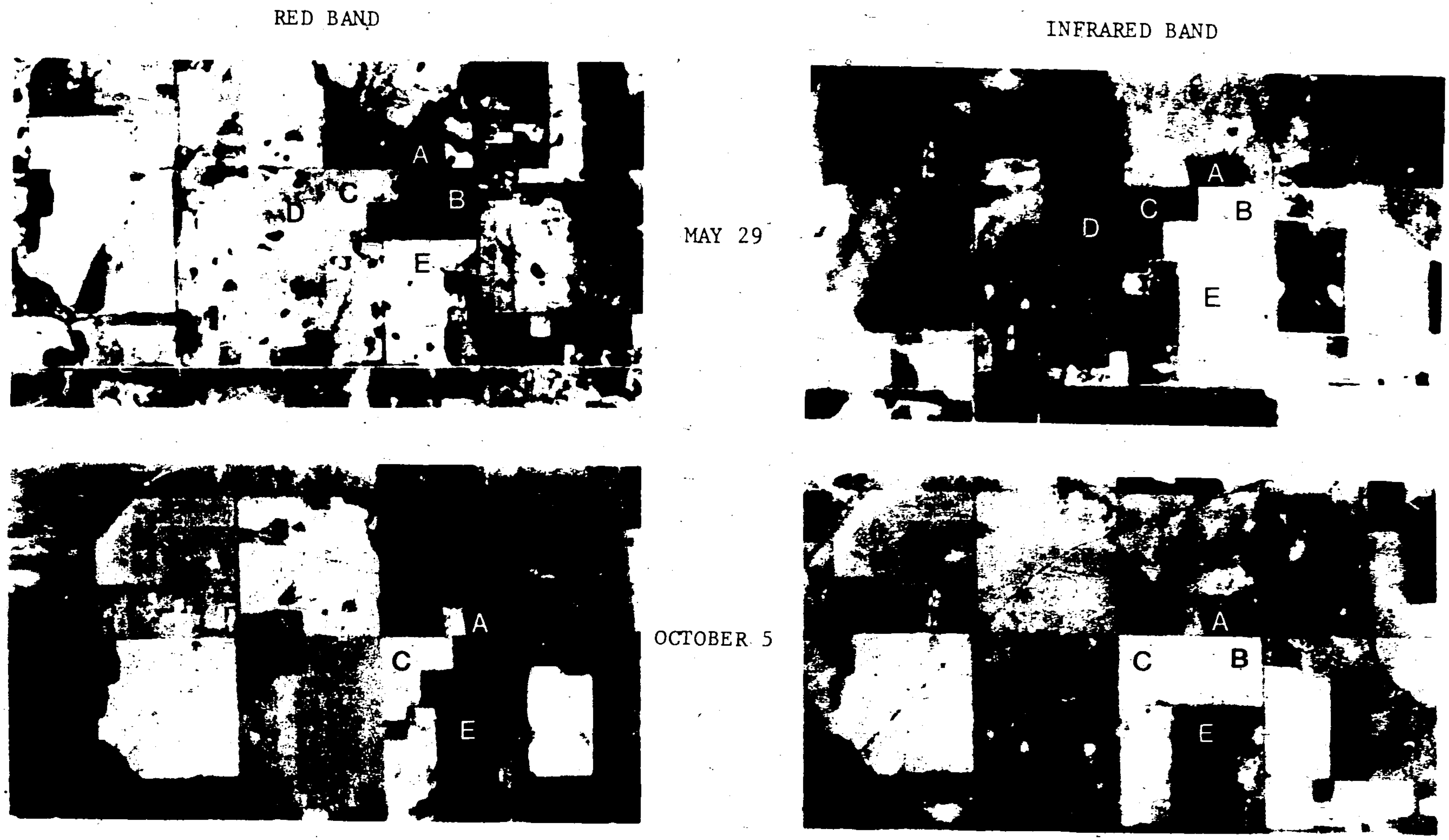


Plate 5. Black and white red and infrared band photography from May 29 and October 5, 1971 taken in support of the thermal imagery shown in Plates 4A and 4B. Approximate scale 1:34,000.

PREDAWN (0400 hrs)

MIDDAY (1200 hrs)

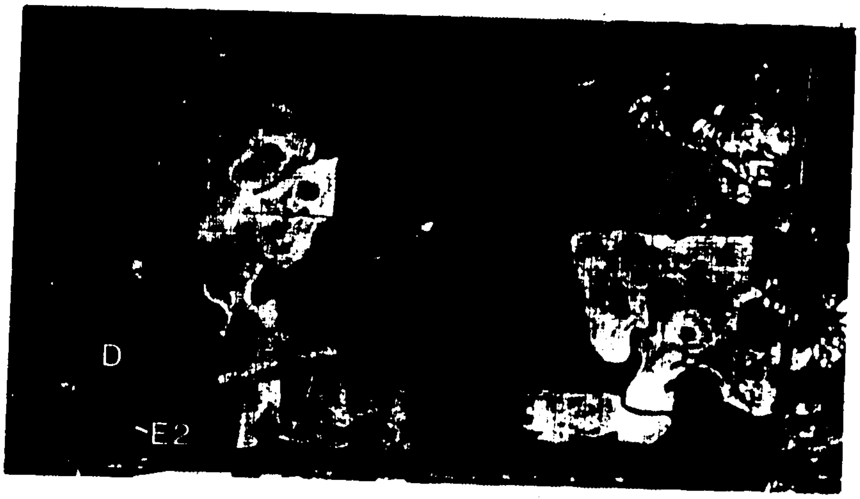


Plate 6A. Predawn and midday thermal imagery (In:Sb detector) from May 26, 1971 of hummocky terrain in the Edmonton study area. Location of Fields A and B: SE Sec.18-Tp.52-R.22-W 4th meridian.

PREDAWN (0600 hrs)

MIDDAY (1300 hrs)

Plate 6B. Predawn and midday thermal imagery (In:Sb detector) from October 5, 1971 of hummocky terrain in the Edmonton study area. Location of Fields A and B: SE Sec.18-Tp.52-R.22-W 4th meridian.

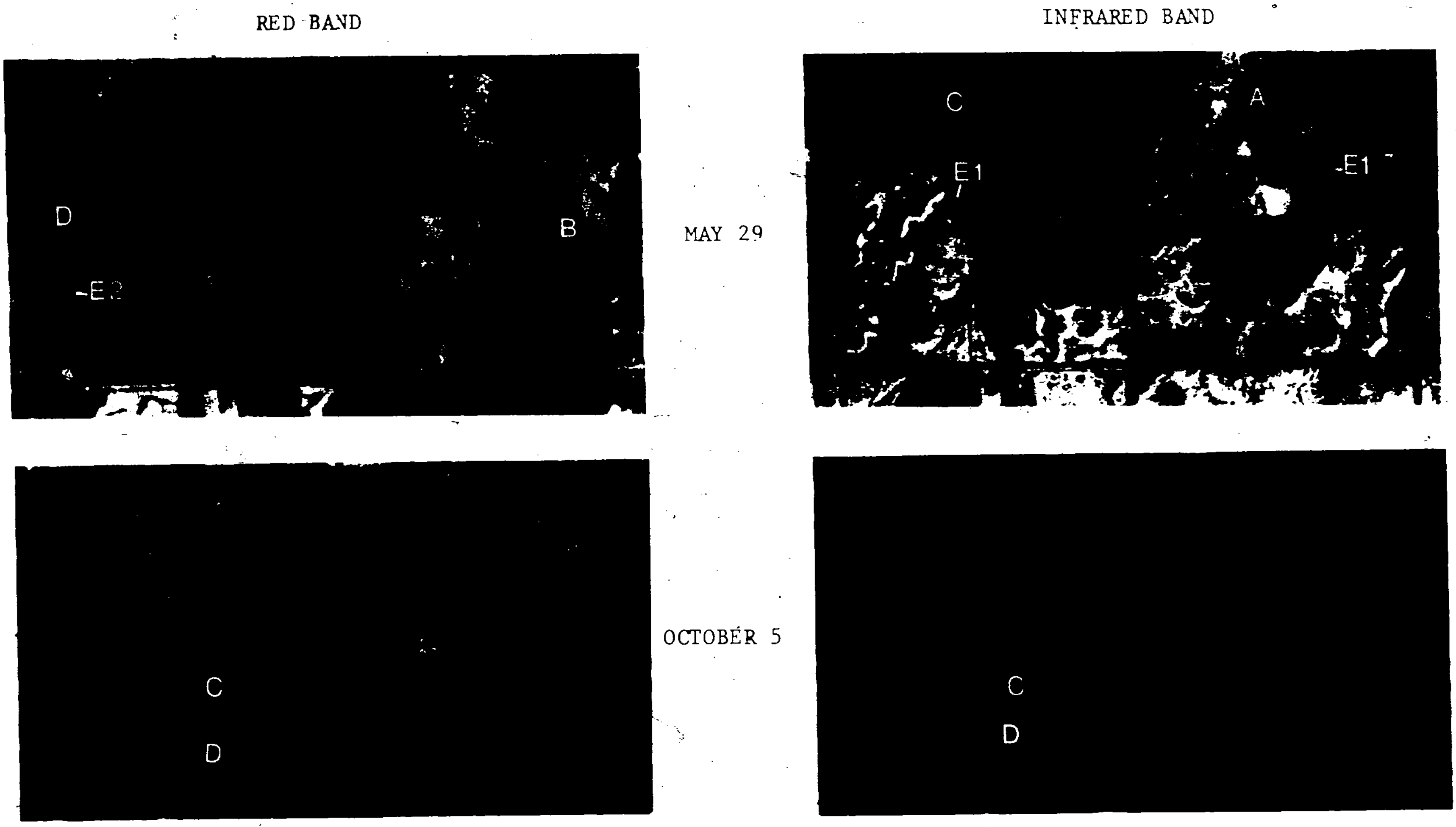


Plate 7. Black and white red and infrared band photography from May 29 and October 5, 1971 taken in support of the thermal imagery shown in Plates 6A and 6B. Approximate scale of photography 1:17,500.

PREDAWN (0400 hrs)

MIDDAY (1200 hrs)

Plate 8A. Predawn and midday thermal imagery (In:Sb detector) from May 26, 1971 of an undulating area of glaciofluvial, glaciolacustrine, and till deposits in the Edmonton study area. Location of the field labelled with A, B, and C: SE Sec.12-Tp.52-R.24-W 4th meridian.

PREDAWN (0600 hrs)

MIDDAY (1300 hrs)

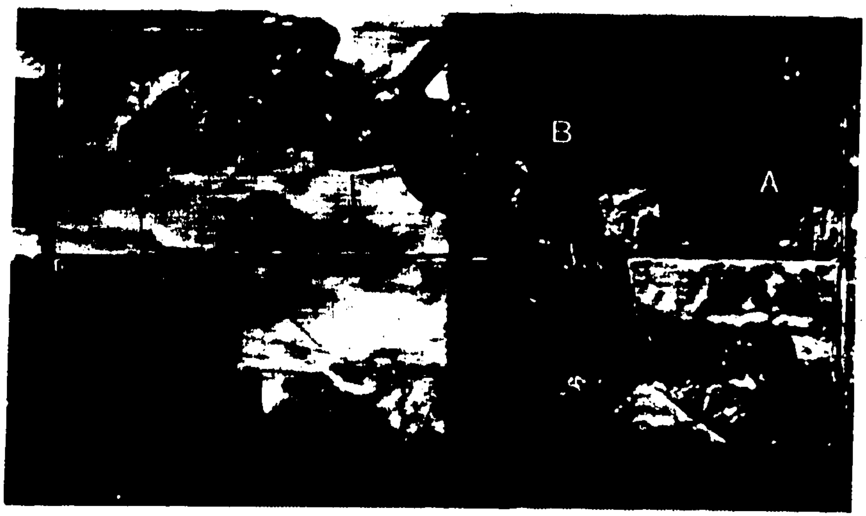


Plate 8B. Predawn and midday thermal imagery (In:Sb detector) from October [illegible] 1971 of an undulating area of glaciofluvial, glaciolacustrine, and till deposits in the Edmonton study area. Location of the field labelled with A, B, and C: SE Sec.12-Tp.52-R.24-W 4th meridian.

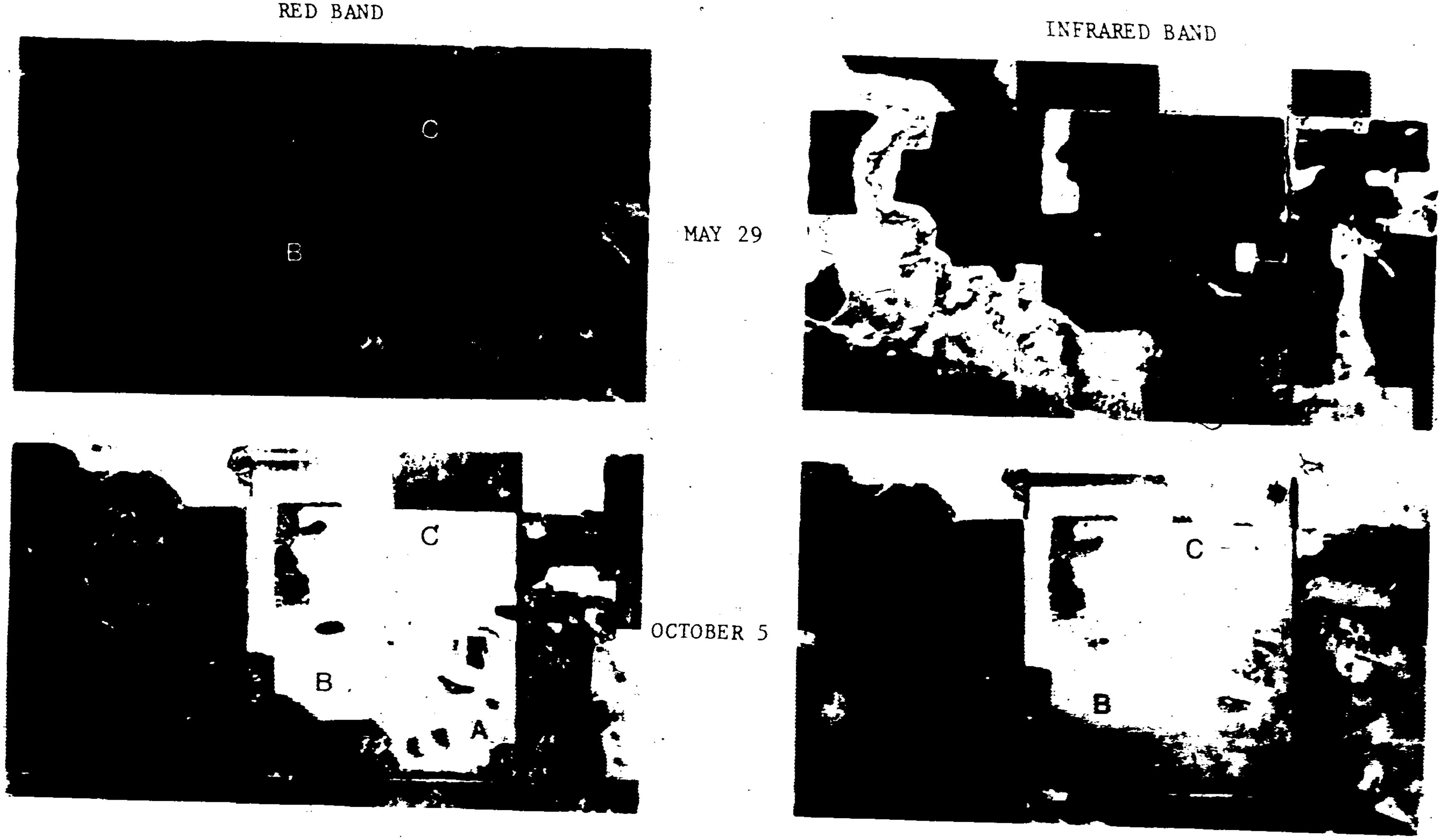


Plate 9. Black and white red and infrared band photography from May 29 and October 5, 1971 taken in support of the thermal imagery shown in Plates 8A and 8B. Approximate scale of photography 1:18,800.

CHAPTER III

SOIL REFLECTANCE AND EMITTANCE RELATED TO SOIL FORMATION

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INTRODUCTION

The concept of the zonality of soils provides a point of view from which soil reflectance and emittance characteristics can be discussed in relation to soil formation. Zonal soils are those whose characteristics are determined primarily by regional climate and vegetation influences (Buckman and Brady, 1969). In the Edmonton - Vegreville region of Alberta the zonal soils are the Black and Dark Gray Chernozems and Gray Luvisols. The processes of soil formation and salient features of these soils are discussed by Pettapiece (1969).

The Black Chernozem soils have developed under grass vegetation, dominantly Fescue grasses (Pawluk and Dumanski, 1969), with the dominant process being the accumulation and decomposition of organic materials at the soil surface. Through this decomposition, cations, dominantly calcium, are recycled replacing those lost through leaching and maintaining a near neutral pH in the surface soil (Pawluk and Dumanski, 1969; Pettapiece, 1969). The result is a well humified, organic rich, dark colored surface Ah horizon that is underlain by a mellow, lime-free Bm horizon and a horizon of lime accumulation, a Cca horizon. Soil descriptions presented by Menon (1971) and Leskiw (1971) indicate that in the Edmonton and Vegreville areas removal of matter from the surface often occurs, not only the leaching of carbonates and other soluble salts but also the eluviation of organic and finer inorganic constituents with the development of eluviated Ae and illuviated Bt horizons. These indicate the probable invasion of grasslands by forests in the past (Pettapiece, 1969).

The Luvisolic soils have developed under forest vegetation with the dominant processes being the removal and translocation of organic and inorganic materials from the surface. The result is the development of soils with thin, organic, surface mats underlain by thick, light colored, eluviated horizons and dense, dark colored, illuviated horizons (Pettapiece, 1969). The surfaces of the Luvisolic soils can therefore be considered as being more dynamic than the surfaces of the Chernozemic soils in that organic material added to the surface in the form of forest litter is rapidly mineralized.

With the progression from grassland to forest vegetation, the changes in surface soil characteristics, especially color, reflect the changes in processes of soil formation. Orthic Black and Eluviated Black Chernozem soils are found in the western portion of the Edmonton study area and to the east, as elevation increases, climate becomes cooler and more moist, and vegetation changes from grassland to forest communities, Dark Gray Chernozem, Dark Gray Luvisol and Orthic Gray Luvisol soils are found. Therefore, from west to east, surface horizons contain less organic matter and become thinner and lighter in color. Menon (1971) suggested that some Chernozemic soils in the Edmonton area may also have developed under hydromorphic conditions that no longer exist. The presence [illegible] Orthic Dark Gray Chernozem soils on level to undulating topography in an area where Orthic Gray Luvisol soils are dominant, indicates that these Chernozems probably developed under meadow conditions that were altered when the area was settled and cultivated and drainage improved.

The processes of soil formation influence the spectral reflectance from zonal soils. Reflectance is a surface phenomenon and these processes are strongly expressed by surface soil characteristics, especially soil color. As discussed in Chapter I data from the field study of soil reflectance indicated significant differences in reflectance between the Black Chernozems and the Gray Luvisols. These differences were most strongly expressed in the reflectance in the visible portion of the spectrum where surface soil color is the dominant factor influencing reflectance.

Intrazonal soils are those that exhibit the influence of some local conditions on soil development, such as drainage or salinity and because of this often cross zonal boundaries (Buckman and Brady, 1969). In the Edmonton - Vegreville region of Alberta the intrazonal soils include those affected by poor soil drainage (hydromorphic) and those affected by high concentrations of salts in the upper solum (halomorphic).

The hydromorphic soils of this region include the Gleysolic and Organic soils. [illegible] soils occupy lowlying and depressional landscape positions an [illegible] urated with water and are under reducing conditions continuously or during some period of the year" (Canada Soil Survey Committee, 1973). The high soil moisture content and reducing conditions separate these soils from their zonal associates. The reduced condition may result from the accumulation of runoff water which saturates the soil for part of the year but which, in groundwater recharge areas, eventually leaches the soil producing Humic Luvic Gleysols. Where the accumulated waters do not leach the soils as readily due to impeded internal soil drainage or near surface recharge of waters low in soluble salts, Orthic Humic Gleysols may develop. In groundwater discharge areas where depressional or lowlying areas accumulated surface runoff from soil areas with high concentrations of surface salts, or where the water table is maintained at a high level by the discharge of groundwaters with high salt concentrations, saline Gleysols may develop (Maclean, 1974).

Organic soils in the Edmonton study area occupy very poorly drained bottomlands of creeks and streams and depressional areas. Those of the western portion of the area, the Chernozemic zone, have surfaces comprised of moderately to well decomposed mixed peat while those of the eastern portion of the area, the Luvisolic zone, have surfaces comprised of fibric moss peat (Menon, 1971).

In most instances the hydromorphic soils have surfaces with physical characteristics, especially color, similar to the surfaces of the associated better drained soils. One exception would be the saline Gleysols where drying of the very surface of the soil may produce a white salt crust. In general, however, reflectance data for bare soil surfaces would only allow for the spectral discrimination of the

Gleysols from their associated zonal soils if surface moisture conditions between the two are sufficiently different. Either surface colors would have to be sufficiently different to alter reflectance or significant differences in reflectance at specific water absorption bands of the spectrum would have to occur. Reflectance data from vegetated soil surfaces often show detail on internal soil drainage due to variations in the reflectance of vegetation in response to variations in soil moisture conditions (Acton and Stonehouse, 1972). The data presented in Chapter II illustrate that emittance characteristics of soils are influenced by variations in soil moisture conditions and that the discrimination of hydromorphic soils from their associated zonal soils may be accomplished using thermal infrared line scanning.

Halomorphic soils are common in the Edmonton and Vegreville study areas an [illegible] lude soils of the Solonetzic Order as well as salt affected soils of the Chernozemic and Gleysolic Orders (Leskiw, 1971; Menon, 1971). Solonetzic soils have developed in salinized parent materials (Canada Soil Survey Committee, 1973) with the accumulation of salts originating from groundwater discharge (Pawluk and Bayrock, 1969). Once this process of salinization is disrupted by a reduction in the amount of groundwater discharge, solonization begins and alkali soils with dense, massive B horizons develop (Pawluk and Dumanski, 1969). The next process of solodization ameliorates the soil conditions for plant growth through progressive stages from Solonetz to Solod to Solodic Chernozem as leaching continues (Joffe, 1949). However, studies by Leskiw (1971) and Maclean (1974) show the importance of groundwater discharge in maintaining soils at various stages within this progression. In discharge areas in the Vegreville study area a typical sequence is from Carbonated Saline Gleysol at the foot of a slope to thin Black Solonetz to Black Solonetz on upper slopes. Up a similar slope in recharge areas a typical sequence is from Orthic Humic Gleysol to Humic Luvic Gleysol to Gleyed Eluviated Black Chernozem to Eluviated Black Chernozem.

The occurrence of halomorphic soils in the study areas is related to the occurrence of groundwater discharge and therefore the halomorphic soils should be more moist than their associated zonal soils. Also, Maclean (1974) concluded that the kind of halomorphic soil is related to the depth to water table. Alkaline Solonetz, Saline Carbonated Gleyed Regosol and Saline Black Solonetz soil occur where the water table is within 0.5 meters of the surface while Black Solonetz soils occur where the depth to the water table is greater than 0.5 meters.

Reconnaissance soil surveys in Alberta have mapped many soil units which include soils affected by salts. Because the map scale is often in the order of 1:125,000, detailed information on the exact location and extent of soils affected by salts is often lacking. In the field the pattern of salinity is usually erratic with soils affected by salts and soils not affected often intimately associated within the landscape. Often the change from one to the other occurs within a distance of a few meters (Myers <u>et al.</u>, 1970, Acton and Stonehouse, 1972).

Salt affected soils occupy a significant proportion of the settled land area in western Canada to the extent that from 15 to 20 million acres may be involved (Cairns and Bowser, 1969). Greenlee (1966) concluded that in his study area southeast of Calgary, the extent of soil salinity is increasing. There is concern that this is due in part to higher groundwater levels from irrigation and to the removal of native vegetation and crop residue in fallowing to develop dryland areas for cultivated crops.

Greenlee (1966) and Leskiw (1971) used the presence of surface salt crusts as indicators of saline soils. Surface salt crusts form as groundwater containing high amounts of dissolved salts evaporate at the soil surface thereby concentrating salts as they precipitate (Qayyum and Kemper, 1962). If such salts contain an abundance of sodium ions, solonetzic soils are likely to occur (Leskiw, 1971).

The presence of "burnt crops" or poor crop growth due to the adverse effects of soil salts has also been used to delineate salt affected soils (Greenlee, 1966; Greenlee _et al._, 1968; Leskiw, 1971). The effect of soil salts on plant pigmentation and internal leaf structure and therefore on the spectral signatures of plants has been well documented. As salinity increases leaves become thicker as the pallisade parenchyma increases, there are fewer chloroplasts and less chlorophyl, intercellular spaces become smaller and there are fewer stomatal openings per unit area (Myers _et al._, 1975). Different crops, however, possess different levels of tolerance to soil salinity, tolerance as measured by the electrical conductivity of the soil that is associated with a 50 percent decrease in yield (United States

Salinity Laboratory Staff, 1954). Of the commonly grown field crops of the Edmonton - Vegreville region, barley and rape possess a relatively high tolerance (electrical conductivity from 10 to 16 millimhos per cm) while wheat, oats and most forage crops possess a medium tolerance (electrical conductivity from 6 to 10 millimhos per cm). Tolerance to soil salinity is not necessarily constant for each species or variety but may vary with local environmental conditions especially temperature and precipitation. Tolerance is often increased by cooler more humid weather but decreased by hot and dry conditions (Black, 1968).

Because of the changes in plant morphology caused by high concentrations of salts in the soil, photographic imagery should provide detail not only on the location and extent of soil salts but also on the degree of soil salinity (Myers _et al._, 1975). With some general _a priori_ knowledge of the soils and topography of an area, emittance data should provide a means to discriminate halomorphic from zonal soils based on soil temperature differences that arise from differences in soil moisture content.

Summary

The potential use of remote sensing for any purpose depends upon the relationships that can be established between spectral reflectance and emittance as presented as image tones or colors and target characteristics. Reflectance data obtained in the field study of soil reflectance (Chapter I) relates to the dominant processes of soil formation for the zonal soils of the study areas while emittance data (Chapter II) relates to the processes of soil formation of the intrazonal soils. One purpose of this portion of the study is therefore to relate reflectance from bare soil surfaces, as recorded by black-and-white multiband photography, to the major zonal and intrazonal soils of the study areas in order to investigate whether or not the differences in reflectance from bare soil surfaces found in the field study are found on airborne multispectral imagery. Since soil surfaces are usually covered by cultivated crops during the summer months, the reflectance from a barley crop, as recorded by color and color infrared photography, is related to soil characteristics to investigate the qualitative and quantitative relationships between image color and the occurrence of zonal and intrazonal, in this case halomorphic, soils. Thirdly, the empirical data presented in Chapter II and the theory of halomorphic and hydromorphic soil formation in the study areas indicate that intrazonal soils may be discriminated from their associated zonal soils using thermal imagery. The use of thermal imagery to discriminate zonal and intrazonal soils, as well as hydromorphic from halomorphic soils, is investigated.

MATERIALS AND METHODS

Photographic Determination of Soil Reflectance

Multiband photography provides the only readily available means in Canada of acquiring airborne multispectral reflectance data apart from the LANDSAT satellites. Multiband photography was acquired for the Edmonton and Vegreville study areas on May 29, July 13 and October 5, 1971 with the various spectral bands specified by the film-filter combinations listed in Table 20. The photography was obtained as rolls of 70 mm, black-and-white, contact paper prints at a scale of 1:16,000. Examples of the type of photography obtained are shown in Plates 5, 7 and 9.

Assuming a scatter-free atmosphere, the film exposure should be directly proportional to the scene reflectance at a given instant of time. Therefore, on positive prints, lighter tones indicate greater reflectance. A twelve step photographed gray scale was used to qualitatively assess the response from selected zonal and intrazonal soils of the study areas in the three spectral bands. Visual comparisons were made between the gray scale and photographic tones for fields known to be bare soil from present land use maps compiled just prior to each flight. The soils in each bare field were identified using the soil maps prepared by Leskiw (1971) and Menon (1971). Only those fields or portions of fields found within the central one-half of each frame were considered in order to minimize tonal variations that may have been due to nonuniform filtering. Each step of the gray

Table 20. Film-filter combinations employed for the multiband photography of the study areas acquired on May 29, July 13, and October 5, 1971.

Kodak Film Number	Kodak Filter	Spectral Band
2424 (B+W Infrared)	W 89B	700 - 900 nm
5063 (B+W Pan.)	W 25A	600 - 700 nm
5063 (B+W Pan.)	W 12+44	500 - 580 nm

scale was assigned a number from 1 to 12 in order from the darkest to the lightest tone. Response levels for each kind of soil were recorded by their corresponding gray scale step numbers.

It is considered impracticable to quantitatively compare tones from one band of photography with those of another, or to compare tones from one date of photography with those from another since for each band on each date a separate roll of [illegible] used. Variations in the film itself or in the processing of [illegible] rolls of film could produce tonal variations that [illegible] controlled. However, assuming that any single roll of film would [illegible] processed uniformly, it is possible to make statistical comparisons between the tones associated with different soils on one particular date and spectral band. A Duncan's New Multiple Range Test (Steel and Torrie, 1960) was used to compare the tones for all soils in each band of photography on each date. Differences in tone associated with different zonal and intrazonal soils were compared.

Determination of the Relationships Between Crop Color and the Pattern of Crop Development as Observed on Color Aerial Photography and the Occurrence of Intrazonal Soils

One field located in the southwest quarter of Sec. 3 - Tp. 52 - R. 24 - W 4th meridian, in the western portion of the Edmonton study area, was selected for study. The selection of one field was based on the assumption that within a single field management practices such as crop type, date of seeding, and rate and time of fertilization would be uniform and not contribute significantly to crop color and pattern variations. The soil map prepared by Menon (1971) showed that the soils of this field have developed on similar glaciolacustrine sediments so that crop color and pattern variations due to differences in parent materials are minimized. This particular field was selected in that it is part of a larger area for which the soils were mapped at a scale of 1:8,160 and sampled on a 250 x 500 ft (76 x 152 m) grid basis in 1970 (Lindsay and Scheelar, 1972).

Simultaneous normal color (Kodak Film #2445) and color infrared (Kodak Film #2443) photography was obtained for the area including this field on August 16, 1970. The photography was at a scale of 1:20,000 and was obtained under contract by Grumman Aerospace Corporation through J. C. Sproule and Associates, Calgary. From an initial examination of the photography, it was concluded that four different soil-vegetation patterns or classes were evident within the selected field. Menon (1971) showed that the soils in this field were predominantly Black Solonetz with inclusions of Solonetzic Black Chernozem and it was therefore assumed that the soil-vegetation patterns observed on the photography was related to the distribution and degree of soil salinity.

The grid pattern used for soil sampling during the field survey by Lindsay and Scheelar (1972) was reconstructed on transparent material to fit the scale of the photography. With this grid in place the coordinates of each grid point falling within the field were tabulated along with an interpretation of the photography as to which salinity class occurred beneath each point. These classes were numbered 1 to 4 in decreasing order of salinity effects on the barley crop which at the time of photography was maturing in the field. The classes are defined as follows (Plate 10, page 170):

Class 1. Areas appear whitish on color photography and bluish-white on color infrared photography indicating relatively high reflectance in the visible and near-infrared spectral regions. The high reflectance results from the exposure of bare soil due to the absence of vegetation. The soil surface is very light in color, probably due to surface salt crusts. This class is assumed to represent the highest level of soil salinity with the most severe salt effects on plant growth and intrazonal halomorphic soils.

Class 2. Areas appear dark greenish-brown on color photography and dark purplish-red on color infrared photography indicating sparse ground cover. This class is assumed to represent a moderately high level of soil salinity and intrazonal halomorphic soils.

Class 3. Areas appear dark golden greenish-brown on color photography and white on color infrared photography indicating prematurely maturing, slightly stressed grain. This class is assumed to represent a moderate to low level of soil salinity and gradations between zonal and intrazonal halomorphic soils.

Class 4. Areas appear light yellowish-green on color photography and whitish-pink on color infrared photography indicating grain that is slowly maturing without osmotic stress. This class is assumed to represent a slight to none level of soil salinity and zonal soils.

For each sampling point, within the boundaries of the field under study, data were obtained on the thickness, soluble cations, and electrical conductivity of the surface horizon from J. D. Lindsay, Head of the Soils Division, Research Council of Alberta. These variables were chosen in that electrical conductivity relates, in a linear fashion, to the total soluble salt content of the soil (United States Salinity Laboratory Staff, 1954) and to the degree to which vegetation may suffer osmotic stress. High sodium content may lead to sodium toxicity (Buckman and Brady, 1969) or cause adverse soil structure whereby the soil becomes dispersed resulting in poor aeration and moisture movement (United States Salinity Laboratory Staff, 1954). Surface horizon thickness relates to the amount of rooting zone above any impermeable subsurface B horizon that may impede the growth of roots or the movement of water. An analysis of variance was conducted in order to test for significant differences, based on calculated least significant differences, between mean values of these three variables for the four classes. The statistical procedure followed is outlined by Steel and Torrie (1960).

Determination of the Relationships Between Tones on Thermal Imagery and the Occurrence of Intrazonal Soils

In a study of the relationships between soil genesis and groundwater and soil moisture regimes near Vegreville, Maclean (1974), dealt in detail with two small study areas. One of these represents an area of groundwater recharge and the other an area where groundwater discharge predominates. This latter area was selected for this study in that halomorphic and hydromorphic soils occur within a relatively small area located in the NE quarter of Sec. 11 - Tp. 53 - R. 14 - W 4th meridian.

Predawn and midday thermal imagery (In: Sb detector) was acquired over this study area on May 26 and October 6, 1971. The scanners used and other flight parameters are similar to those discussed under "Acquisition of Thermal Imagery" in Chapter II.

Maclean (1974) studied the relationships between the type of soil and soil temperature, soil moisture and groundwater flow data at 6 sites in this his "Lower Study Area." The sites were numbered 4 through 9 and the soils and groundwater flow data were discussed for each. These sites were located on the predawn and midday thermal imagery for each date and the image tones discussed in relation to the discussion presented by Maclean. The numbering of the sites on the thermal imagery is consistent with the site numbers used by Maclean.

RESULTS AND DISCUSSION

Reflectance from Bare Soil Surfaces as Recorded by Multiband Photography Related to Soil Formation

The various kinds of soil included in this study and mean values for their photographic response in the different spectral bands are shown in Table 21. On the multiband photography obtained significant differences in tone occur on all bands of photography and on all dates between the light colored surface horizons of soils developed under forest vegetation, the Orthic Gray Luvisols, and all other soils (Table 22). In all cases the Orthic Gray Luvisol soils are represented by lighter photographic tones. Significant differences in photographic tone between the Black Chernozem soils and the intergrade Dark Gray Chernozem and Dark Gray Luvisol soils occur on the red band photography from July and on each band of photography from October (Table 22). The lack of significant tonal differences between Black and Dark Gray Chernozem soils in May is probably due to the relatively recent cultivation of most fields prior to the date of photography. Cultivation would result in a darkening of soil surface color and an increase in the surface roughness which reduce reflectance from each soil as well as reduce the relative differences in reflectance between soils. A significant difference in tone between Dark Gray Chernozem and Dark Gray Luvisol soils occurs only on the green band photography from May. If soil color differences are sufficient in May to produce a significantly different photographic response in the green band, a similar significant difference would be expected on the red band

Table 21. Soils studied for the photographic determination of reflectance and their mean gray scale values in each spectral band (higher numerical value indicates lighter tone and higher relative reflectance). Missing data due to poor photography and cloud cover.

Soil	Date							
	May 29, 1971			July 13, 1971		October 5, 1971		
	G	R	IR	R	IR	G	R	IR
1. Orthic Humic Gleysol	2.9	2.9	1.8	3.2	1.6	3.7	3.0	2.7
2. Orthic Black Chernozem	3.3	3.8	2.3	4.1	1.9	2.9	2.3	1.9
3. Eluviated Black Chernozem	3.6	3.8	2.2	3.7	1.8	3.2	2.8	2.0
4. Black Solonetz	3.0	3.3	2.4	4.1	1.8	3.0	2.6	[illegible].4
5. Dark Gray Chernozem	3.6	4.1	2.4	4.6	2.0	3.8	3.7	2.8
6. Dark Gray Luvisol	4.4	4.2	2.7	5.0	2.1	3.8	3.3	2.5
7. Orthic Gray Luvisol	6.0	5.0	3.5	-	-	6.0	4.5	4.0

Table 22. Results of Duncan's New Multiple Range Test comparing mean tone values for different soils in each spectral band. Soils are indicated by numbers assigned in Table 21. Mean values for soil numbers not underlined by the same line are significantly different (P = 0.05).

Date	Band	Soil numbers according to mean values in decreasing order						
May 29	Green	7	6	5	3	2	4	1
	Red	7	6	5	3	2	4	1
	Infrared	7	6	5	4	2	3	1
July 13	Red	6	5	4	2	3	1	
	Infrared	6	5	2	4	3	1	
October 5	Green	7	6	5	1	3	4	2
	Red	7	5	6	1	3	4	2
	Infrared	7	5	1	6	4	3	2

7 - Orthic Gray Luvisol
6 - Dark Gray Luvisol
5 - Dark Gray Chernozem
4 - Black Solonetz
3 - Eluviated Black Chernozem
2 - Orthic Black Chernozem
1 - Orthic Humic Gleysol

photography from the same date. Since this does not occur it is possible that the tonal difference between these soils in the green band results from some factor other than soil surface color, such as variable degrees of haze on the photography caused by atmospheric scattering of the shorter wavelengths. The tones associated with Black Chernozem and Black Solonetz soils are not significantly different on any band of photography on any date (Table 22).

Statistically significant differences between the photographic response for Orthic Humic Gleysol soils and the other better drained soils with which they occur, Black Chernozem and Black Solonetz in particular, are sporadic (Table 22). In May, the Orthic Humic Gleysol soils have statistically significantly darker tones relative to the other soils. At this time of year the Gleysol soils are very moist which accounts for their low reflectance. In October, the Orthic Humic Gleysol soils often have significantly lighter tones relative to the Black Chernozem and Solonetz soils with which they occur. As discussed in Chapter II, the surface soils in the area were very dry in October with precipitation well below normal for the month preceeding the date of photography. Surfaces of cultivated Gleysolic soils had either dried to a lighter color than surfaces of the better drained soils and/or were smoother than surfaces of surrounding better drained and cultivated soils.

In general, the photographic response from all bare soil surfaces is low and some significant differences in soil reflectance may be lost due to the exposure settings used for the photography. Exposure is usually set to provide detail of all terrain features which may reflect more or less energy than soils. If general terrain reflectance is high and exposure settings made to record it, all bare soil surfaces may be underexposed and produce generally dark tones of the photography. A case in point is the infrared band photography from July. At this time of year much of the terrain is covered with green vegetation. Infrared reflectance from healthy vegetation is much greater than that from bare soils. The proper exposure to provide photographic detail of the general terrain provides little detail on soil reflectance differences based on the lack of tonal differences among soils as shown in Table 22. Thus, on the infrared band photography from July, there are no significant differences in response between any of the soils studied (Table 22).

The consistency with which spectral discrimination between soils can be made using multiband photography is strongly influenced by external effects relating to the operation of the aerial cameras. Temporal changes in the soil surface derived from management practices such as frequency and time of cultivation prior to the time of photography affect the recorded reflectance by altering surface soil color, moisture content and roughness. Surface soil color and moisture content and hence the relative reflectance from different soils are also affected by the frequency and times of precipitation relative to the time of imaging. Nevertheless, the results of this study concur with the results discussed in Chapter I, that the zonal soils of the Edmonton - Vegreville region may be discriminated on the basis of reflectance data, especially the prairie, Chernozem soils from the forest, Orthic Gray Luvisol soils.

Relationships Between Crop Color and Pattern as Observed on Color Aerial Photography and the Occurrence of Intrazonal Soils

The identification of the various classes of salinity, as defined, was easier using the normal color photography (Plate 10). Color infrared photography is generally considered to be the most useful type for determining the degree and extent of plant stress (Myers et al., 1975). However, this is probably only true when plants are in an actively vegetative stage of growth. Once a crop begins to mature, reflectance in the visible region of the spectrum increases. This is due to the loss of chlorophyl which normally absorbs energy in this spectral region (Colwell et al., 1963). The relatively high visible and infrared reflectance produces a whitish color rendition as seen on color infrared photography. In the field under study, a similar color rendition is observed on the color infrared photography for surface salt crust areas (Plate 10). On the normal color photography, the whitish color rendition for salt crust areas is not confused with the yellowish color rendition for mature grain (Plate 10).

The Individual's ability to visually discriminate various hues must also be considered. An individual with good color discrimination between red and blue hues will have little difficulty discriminating areas on the basis of color using color infrared photography. The same individual may have difficulty in discriminating areas on the basis of color using normal color photography on which green and neutral hues are dominant.

According to the report on the detailed soil survey of this area (Lindsay and Scheelar, 1972) and data obtained from J. D. Lindsay, the soils in Class 1 areas are dominantly Alkaline and Black Solonetz with inclusions of Black Solod soils. Areas of Class 1 occupy low-lying landscape positions where groundwater discharge occurs (Plate 10). G. M. Coen of the Alberta Institute of Pedology, Edmonton, suggested in a personal communication that many of the soils in areas identified as Class 1 resemble gleyed Saline Regosols.

Compared to the other soils in the field, the surfaces of soils in Class 1 areas have the highest electrical conductivities and least thickness. Electrical conductivities of the surface soils in Class 1 areas have a mean value of 1.48 mmhos/cm (Table 23). This is a much lower value than expected from the study of the aerial photography where Class 1 areas have no vegetative cover. If an electrical conductivity from 10 to 16 reduces barley yields by 50 percent (United States Salinity Laboratory Staff, 1954), a much higher electrical conductivity would be expected if the barley is absent entirely. It is possible that an electrical conductivity below 10 mmhos/cm indicates sufficient salt content to have a strong adverse effect on germination and/or early growth of barley. It is assumed that the entire field was seeded since there is no pattern on the photography of Plate 10 that indicates that the areas of Class 1 were not seeded. It is therefore possible that excessively wet conditions prevailed in these lowlying areas after seeding due to precipitation or groundwater discharge and that young plants did not survive. Therefore, the lack of crop growth in areas classified as

Table 23. Analytical data for the surfaces of representative soils within each class of salinity effects on crop development observed on the aerial photography (data supplied by J.D. Lindsay, Research Council of Alberta, Edmonton).

	Class 1	Class 2	Class 3	Class 4
No. of sampling locations in class	12	14	6	5
Soil Subgroups	Black Solonetz Alkaline Solonetz Black Solod	Black Solod Black Solonetz	Solodic Black Black Solod Black Solonetz	Solodic Black
Surface thickness (cm)				
mean(std. dev.)	8.5 (4.1)	11.8 (4.5)	11.7 (2.6)	19.8 (3.4)
range	5-20	5-20	10-15	15-23
Electrical conduct. (mmhos./cm)				
mean (std. dev.)	1.48 (0.75)	0.74 (0.32)	0.57 (0.17)	0.40 (0.07)
range	0.5-2.8	0.3-1.4	0.3-0.8	0.3-0.5
$\frac{\text{Soluble Na}}{\text{Sol. Na+Mg+Ca}} \times 100$				
mean (std. dev.)	76.1 (13.1)	51.4 (21.0)	19.8 (10.9)	24.2 (5.1)
range	52-90	17-81	1-29	19-30

Class 1 as observed on photography from August 16 may be due in part to the residual effects of conditions that prevailed earlier in the year but not at the time of sampling, which was in September and October after the crop had been harvested. The development of surface salt crusts in Class 1 areas has also had an effect on crop growth. Sodium is the predominant cation in the surface soils of Class 1 areas (Table 23) and the most probably detrimental effect on crop growth in Class 1 areas is sodium toxicity.

The soils in Class 2 areas are dominantly Black Solod with inclusions of Black Solonetz (Table 23). This class is found upslope from Class 1 areas where lateral groundwater flow or groundwater recharge occurs. The surface soils in Class 2 areas have a mean electrical conductivity significantly lower than that for Class 1 and higher than the mean electrical conductivity for Class 3 and 4 (Table 24). The surface soils in this class have a wide range in thickness (Table 23). The stressed condition of the crop in Class 2 areas is partially due to sodium toxicity. Sodium is the dominant cation in most of the surface soils in areas of this class. The dense Bnt horizon of the soils in this class also has a detrimental effect on the crop by restricting root development.

The soils included in Class 3 areas are dominantly Solodic Black Chernozem with inclusions of Black Solonetz, Black Solod and Orthic Humic Gleysol (Table 23). These soils are found further upslope from areas of Class 2. The Solonetz and Solod soils of this class have lower surface electrical conductivities than those of Class 1 and 2. The Solodic Black Chernozem soils of this class have thinner

Table 24. Results of the analysis of variance to test for significant differences in mean values of surface electrical conductivity, surface horizon thickness, and % soluble Na in relation to Na + Mg + Ca in surface horizons between the 4 classes of salinity effects on crop development observed on aerial photography.

Classes Compared	Surface Thickness			Electrical Conductivity			$\frac{Na}{Na+Mg+Ca}$ x 100		
	lsd.#		diff.#	lsd.		diff.	lsd.		diff.
	.05	.01		.05	.01		.05	.01	
1 and 2	3.35		3.30	0.41	0.55	0.73**	12.66	17.05	24.7**
1 and 3	4.24		3.18	0.52	0.70	0.91**	17.38	23.40	56.3**
1 and 4	4.62	6.22	11.13**	0.55	0.75	1.08**	17.38	23.40	51.9**
2 and 3	4.17		0.12	0.51		0.18	17.01	22.91	31.6**
2 and 4	4.47	5.99	7.84**	0.54		0.34	17.01	22.91	27.2**
3 and 4	5.13	6.91	7.96**	0.63		0.17	20.64		4.4

- lsd.= least significant difference; diff.= difference between means

** indicates that the difference between means compared is significant (P=0.01) surface horizons with slightly higher electrical conductivities than the Solodic Black Chernozem soils of Class 4. Class 4 is comprised of Solodic Black Chernozem soils with thick surface horizons that have low electrical conductivities (Table 23). The mean thickness of the surface horizon for this class is significantly different from those of all other classes (Table 24). Both Class 3 and Class 4 areas occupy upslope, groundwater recharge positions in the landscape. Calcium and magnesium are the dominant cations in the soil surface.

The pattern of crop vigour and photographic color in this field relates to the sequence of soils from upslope recharge areas to downslope areas of groundwater discharge. Similar soil toposequences in predominantly groundwater discharge areas but with local areas of groundwater recharge are described by Leskiw (1971) and Maclean (1974) in their studies in the Vegreville area. The pattern and color of vegetation for this field as observed on color aerial photography relates to the toposequence from "near" zonal soils in Class 4 areas where crop development is not adversely affected by soil characteristics and landscape position to the downslope intrazonal soils in Class 1 where crop development is severely restricted by soil characteristics and landscape position.

Although the distinction between Classes 1, 2, 3 and 4 appears real and valid from the photographic tones and patterns, the data on electrical conductivity and cultivated surface thickness does not support this distinction statistically. According to the results of the analysis of variance (Table 24), the mean electrical conductivity for Class 1 is significantly different (P = 0.01) from the mean electrical conductivity for each other class, and the mean thickness of cultivated surface for Class 4 is significantly different (P = 0.01) from the mean thickness of cultivated surface horizon for each other class (Table 24). The lack of other significant differences is attributable to the variability in electrical conductivity and surface horizon thickness within each class, especially Class 2. The mean percent soluble sodium content (soluble sodium as a percentage of soluble sodium + magnesium + calcium) of surface soils in each class provides statistically significant differences (P = 0.01) between Class 1 and Classes 2, 3 and 4, and between Class 2 and Classes 3 and 4 (Table 24).

Emittance from Soils as Recorded by Thermal Imagery Related to Soil Formation

The thermal imagery acquired for the "Lower Study Area" referenced by Maclean (1974) and located northeast of Vegreville is presented in Plate 11 (page 171). Although the image scales are variable, the ground distance from Site 8 to the road on the right (east) side of the images is one-quarter mile. Effects of land use differences on thermal image tones at the site locations are minimal since all sites are located in similar hay fields. The soils and groundwater flow conditions at each site are discussed by Maclean (1974) and tabulated in capsule form in Table 25.

Noticeable on the imagery of the hay fields containing the sampling sites are the erratic and plentiful tonal variations on the May imagery and the lack of such tonal variations on the October

Table 25. Soils and groundwater regimes at each of the 6 sites in the "Lower Study Area" included in the study by Maclean (1975) (data after Maclean, 1975).

Site No.	Ave. Depth to Water Table (cm)	Soil Subgroup	Comments
[illegible]	250 - 260	Orthic Black Chernozem	midline position in the landscape where the water table is relatively deep but discharge of groundwater low in soluble salts occurs
[illegible]	100 - 110	Black Solonetz	discharge of groundwater high in soluble salts
6	50 - 60	Alkaline Solonetz	groundwater discharge in drainageway with shallow depth to water table
[illegible]	180	Black Solonetz	site on slightly higher landscape position where lateral flow or groundwater recharge occurs
8	290	Black Solonetz	discharge of groundwater with high ion content although water table is relatively deep
9	70 - 90	Saline Black Solonetz	discharge of groundwater with high sodium content

imagery. On the May imagery the diurnal pattern to these variations, of relatively cool areas (dark tone) on the midday imagery shifting to being relatively warm areas (light tone) on the predawn imagery, is similar to that for water. Maclean (1974) states that superimposed on the deep groundwater discharge nature of this area "is a complex pattern of shallow flow systems which are greatly influenced by permeability contrasts both within the bedrock and surficial materials." This complex pattern of shallow flow systems is responsible for the complex pattern of tones for relatively moist and [illegible]y soils in this area as observed on the May imagery. Maclean (1974) further states that "the main source of water for infiltration and recharge is melting snow in spring." Therefore, by late May the shallow flow systems are relatively active whereas by early October the influence of shallow flow systems has been reduced. This would account for the lack of tonal variations related to soil moisture content in the hay fields on the October 6 imagery (Plate 11). The midday imagery from October does show some slight topography influence on tones resulting from relatively low solar altitude with north facing slopes slightly cooler (darker in tone) than other slope aspects. In this way the midday October imagery shows slightly depressional areas where active groundwater discharge occurs in the spring.

Site 4 located on the east side of the study area adjacent to trees along the road represents the Zonal Black Chernozem soils of the region. On the basis of thermal image tones alone, it is difficult to discriminate the zonal soils at this site from the Black Solonetz soils at Sites 5, 7 and 8, although Site 4 appears to be situated in an area of slightly darker predawn tone and slightly lighter midday tone on the May imagery. Since this site is situated at the midline position between groundwater discharge to the west and recharge to the southeast (Maclean, [illegible]), it is noted that the erratic pattern of tones associated with groundwater discharge begins immediately west of the site. To the southeast this pattern is not evident.

Image tones and patterns for Sites 5, 7, and 8 are similar. Black Solonetz soils occur at all three sites although discharge occurs at Sites 5 and 8 while localized recharge occurs at Site 7 (Maclean, 1974).

Areas of greater groundwater discharge and therefore greater relative diurnal fluctuation in soil surface temperature are represented by Site 6. In these areas, represented by anomalous dark tones [illegible] the midday imagery and light tones on the predawn imagery from May, Alkaline Solonetz and Saline Carbonated Gleyed Regosol soils occur (Maclean, 1974). The thermal patterns differentiate these soils from the Black Solonetz soils at Sites 5, 7 and 8.

In this area both recharge and discharge sloughs are found. The recharge slough (R) has Humic Eluviated Gleysol soils (Maclean, 1974) while the discharge slough (A) has carbonated and saline gleysols (Leskiw, 1974) and Orthic Humic Gleysols (Maclean, 1974). On the May midday imagery both have relatively cooler surface temperatures (darker tone) while on the May predawn imagery the discharge slough (A) has a lighter tone. On the October imagery the recharge slough (R) is difficult to detect by image tone alone while the discharge slough (A) is easily discernible. In the spring when soil moisture content is relatively high, both types of sloughs show the diurnal changes in tone associated with open water and wet areas. In the fall, however, recharge sloughs are generally dry since the source of water is spring runoff. Discharge sloughs on the other hand remain relatively moist especially if the discharge is from a relatively deep groundwater source. It is interesting to note that on the October imagery the zone of groundwater discharge immediately west of Site 9 (A1) is clearly discernible as an anomalous tone running north-south. The amount of water in this discharge slough has decreased by October from levels in May and variations in tone within the slough relate to the depth of the water present, the deeper water acting as "heat sink" and therefore is relatively cooler during the day and relatively warmer at night than shallower water.

In this area of dominantly groundwater discharge, the thermal imagery acquired indicates certain soil differences based on diurnal and seasonal image patterns and tones. Zonal and halomorphic soils are separated on the basis of pattern of groundwater discharge which is most evident on the May imagery. Halomorphic and hydromorphic soils are separated on the basis of diurnal variations in relative tones that relate to moisture content. Hydromorphic soils that occur in groundwater discharge sloughs and which may be saline, depending on the salt content of the groundwater, are separated from hydromorphic soils that occur in groundwater recharge sloughs on the basis of seasonal changes in the diurnal variations in image tone.

CONCLUSIONS

Reflectance from bare soil surfaces as recorded on multi-band photography allows for the spectral discrimination between the dominant zonal soils of the Edmonton - Vegreville region, the Orthic Gray Luvisols and the Black Chernozems. This is most evident on the red band photography since surface soil color influences visible reflectance and the differences in the processes of soil formation for these zonal soils are strongly expressed by surface color. Sensor and soil management effects, however, greatly influence the consistency with which this discrimination can be made. Also, this study was based on the reflectance from bare soil surfaces. Vegetative cover will mask the soil surface and thereby make it difficult to discriminate zonal soils using reflectance data.

Crop color and patterns of ground cover, however, provide evidence on the occurrence of intrazonal soils. Reflectance from a barley crop, as recorded by color aerial films, provides data on the location, extent, and possibly type of intrazonal soil (halomorphic or hydromorphic) depending on the degree and type of stress to which the crop is subjected. Crop color and patterns of crop development can be related to soil characteristics. In the case of soil salinity, these patterns and colors relate to more than one soil characteristic. In this regard it is imperative that sampling coincide with the acquisition of the imagery. This presents a problem in that land owners often request that sampling be conducted after the crop is harvested while imaging is accomplished much earlier during the growing season.

Thermal imaging provides by the pattern of tones possible distinctions between zonal and halomorphic soils in the Edmonton - Vegreville study area. Diurnal imagery in the spring provides a means to discriminate halomorphic from hydromorphic soils while diurnal imaging in the spring and fall provides a means of discriminating hydromorphic soils of groundwater recharge areas from those of groundwater discharge areas.

The optimum use of multispectral data to discriminate various soils or soil conditions requires the use of sensor systems whereby reflectance and emittance data can be obtained from the same small area on the ground simultaneously, and the data provided in a common form with a common format. Attempts to use aerial photography and thermal imagery from the same season for the same area are often frustrated by scale differences, lack of spectral resolution and possibly slightly different imaging dates. The multispectral information should also be acquired on a multidate basis and, in the case of thermal imaging, on a diurnal basis on each date.

Finally, the use of multispectral data to "map" soils requires that certain assumptions be made as to the kind of zonal and intrazonal soils that will be found in a given area. Based on these assumptions, specific spectral bands can be studied singly or in combination with predictions made as to possible results beforehand.

Potentials For The Use Of Remote Sensing For Soil Studies

The multispectral, multidate, and multiscale concepts of remote sensing and current capabilities in terms of sensors and platforms to provide these types of data, are potentially useful for many soil related studies. Further research is required in order to fully assess their use for general soil resource inventories, especially the multiscale approach in which generalizations are made using satellite data with further, more detailed examinations made using aerial photography at various scales. In agricultural areas where the pattern of crop development or stress may be used to assess soil characteristics, more emphasis on soil-plant relationships would be required in the mapping of soils with less emphasis placed on soil taxonomy. There are many instances where this kind of mapping may be useful, as in the selection of sampling locations for fertilizer trials, or to study the effects of soil amelioration practices, such as deep plowing of Solonetzic soils.

Further research is required to fully assess the application of remote sensing for reclamation studies. Sequential imaging may be useful to assess vegetation response to various soil treatments or reclamation practices. Similarily, vegetative response to soil pollution could be studied.

Investigations on the uses of thermal imagery for soil studies should include studies of the changes in soil climate brought about by specific management practices, such as the use of windbreaks. This type of imagery would also be useful in soil engineering studies, especially of slope stability in relation to groundwater seepage.

In most instances the question is not whether or not a specific study can be conducted using remote sensing techniques but rather, whether or not it is cost-effective to do so. This economic question must be considered when the results of mission-oriented remote sensing projects are presented.

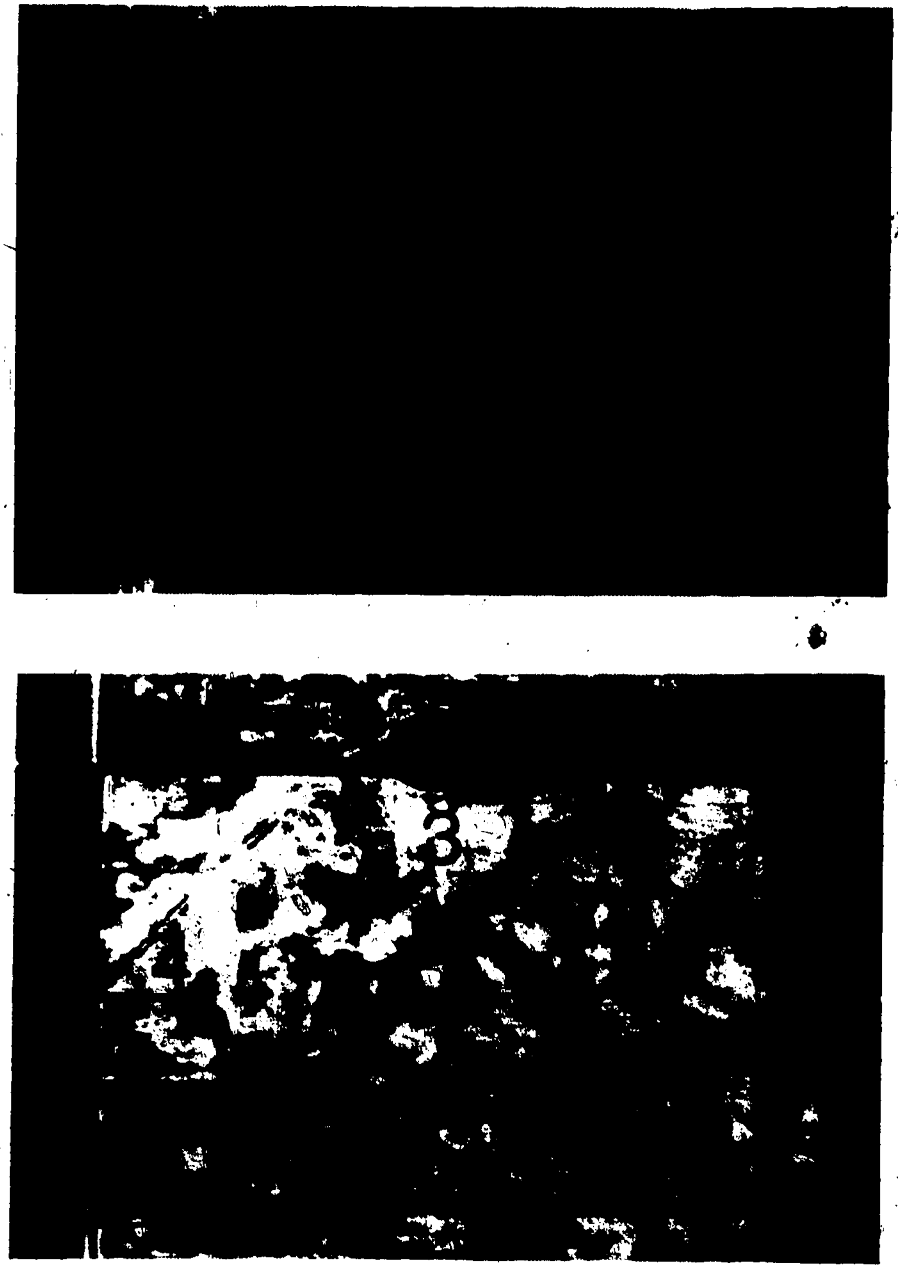

Plate 10. Normal color (upper) and color infrared (lower) simultaneous aerial photographs acquired on August 16, 1970 of a field of barley (NW Sec.3-Tp.52-R.24-W 4th. meridian) illustrating four classes of crop stress due to soil salinity. Approximate scale of photographs 1:8,000.

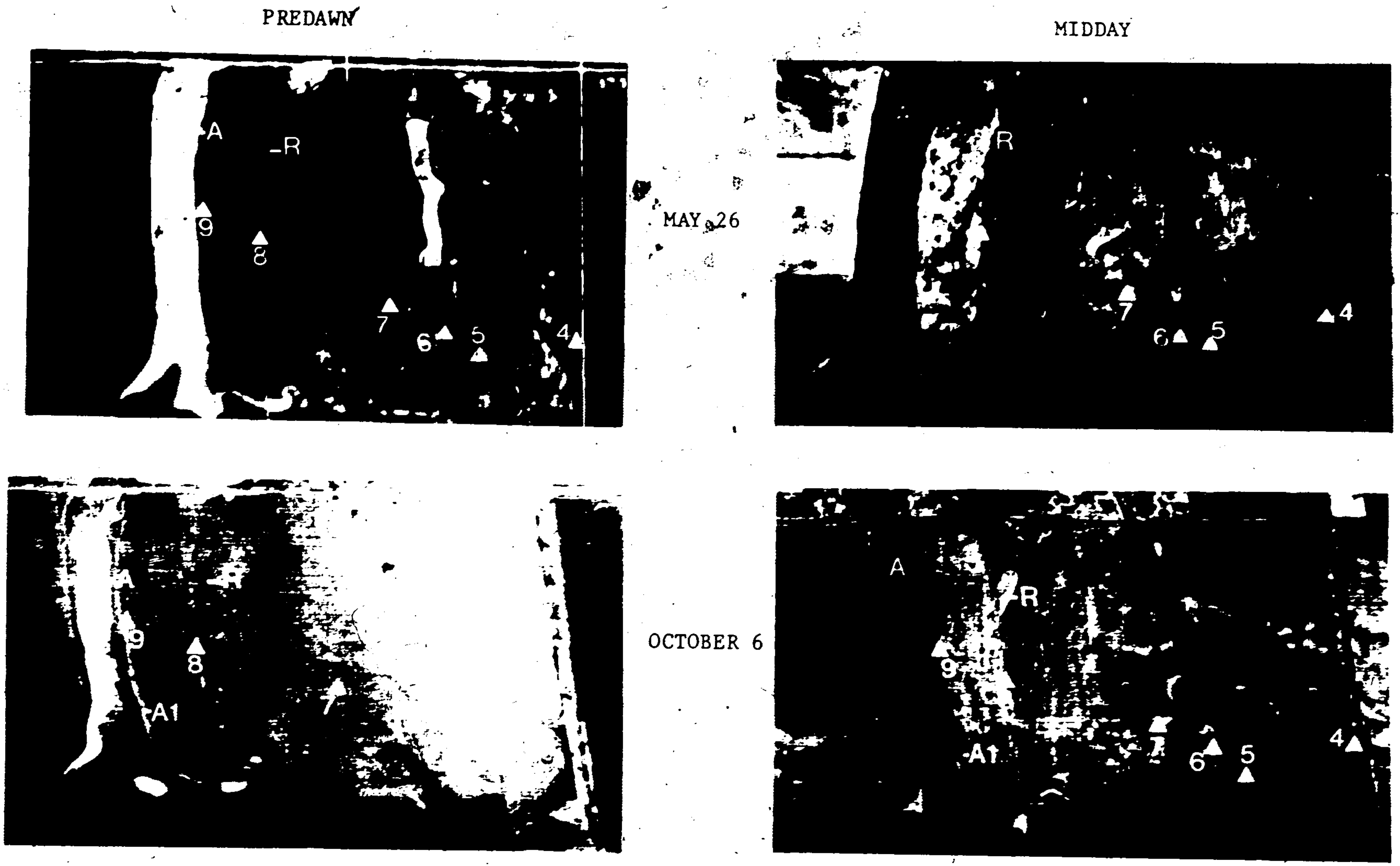

Plate 11. Predawn and midday thermal imagery (In:Sb detector) for an area of groundwater discharge near Vegreville, Alberta acquired on May 26 and October 6, 1971. Area imaged is the "Lower Study Area" in which Maclean (1974) studied the relationships between soils and groundwater flow conditions.

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APPENDICES

Appendix 1. Definition of terms used to qualitatively describe the configuration and roughness of bare soil surfaces at the time of field measurements of reflectance.

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clods: compact and coherent masses of soil produced through cultivation that are irregular in shape, variable in size, and occur as individual units.
fine - generally less than 2 cm in diameter
medium - generally 2 to 10 cm in diameter
large - generally greater than 10 cm in diameter.

granular: individual surface soil aggregates, rounded in shape, that result from the breakdown of clods and peds.
fine - less than 2 mm in diameter
medium - 2 to 5 mm in diameter
large - 5 to 10 mm in diameter

pebbled: individual aggregates are not discernible on the soil surface having coalesced due to effects of rain but the outline of individual aggregates remains visible. Used with gravelly indicates individual particles of coarse sand and very fine on the surface; used with smooth indicates a smooth surface with some protruding pebbles.

puddled: surface has been wetted and dried and neither individual aggregates nor their outlines are discernible; the surface is uniform and even with no protruding pebbles.

spongy: surface is very porous, rebounds quickly from pressure, and retains high amounts of moisture.

dry crust: indicates a very dry outer shell of soil on aggregates or clods, or a very dry surface layer on pebbled, puddled, or smooth soil surfaces.

Appendix 2. Percent reflectance for bare soil surfaces used in the field study of reflectance.

Sample No.	Wavelength (nm)																
	450	475	500	525	550	575	600	625	650	675	700	750	800	850	900	950	1000
L1	13.2	14.7	15.8	17.2	17.6	19.2	20.2	20.6	21.1	23.2	25.1	25.0	25.2	26.8	26.9	34.8	30.4
L2	10.3	11.8	12.1	13.4	14.3	15.2	16.2	17.2	17.5	19.2	20.3	21.3	23.8	23.7	30.6	26.9	31.3
L3	6.8	9.5	11.4	11.2	13.1	12.4	14.4	16.2	16.5	15.0	16.4	18.2	18.0	20.2	18.0	23.8	22.6
L4	7.7	8.2	9.7	10.8	13.1	12.4	13.3	14.2	14.6	16.0	17.9	22.4	22.8	25.3	24.6	31.0	27.7
L5	8.3	7.3	9.8	10.3	11.2	12.8	13.2	12.8	14.0	15.0	16.4	23.6	23.0	24.9	22.5	36.2	29.9
L6	8.2	9.0	9.2	10.8	11.7	12.1	12.6	13.1	13.4	15.0	16.4	19.2	20.5	21.7	24.5	25.3	26.3
L7	4.3	3.8	4.0	4.9	5.4	5.4	5.7	6.0	6.0	6.4	7.4	10.3	11.4	11.4	11.3	15.7	15.0
D1	4.2	4.3	4.7	4.6	5.0	5.1	5.7	5.9	6.3	7.5	7.1	8.2	9.2	9.8	9.9	15.7	15.9
D2	6.3	7.2	8.2	8.8	9.0	9.6	10.2	10.7	11.4	12.3	12.8	13.0	14.2	15.9	16.1	20.4	20.8
D3	4.4	4.9	5.8	6.5	6.6	6.3	6.8	7.2	7.5	8.1	8.6	9.8	10.9	12.8	14.8	17.6	17.6
D4	3.0	3.3	3.8	4.5	5.1	5.3	5.5	5.5	5.5	5.5	6.2	12.0	14.0	15.0	20.6	16.0	18.5
D5	5.3	5.8	6.6	7.4	7.9	7.4	8.2	8.7	8.9	9.8	10.5	13.3	14.8	16.5	18.2	21.9	21.9
D6	5.0	5.2	5.4	5.7	6.6	7.6	7.5	8.2	8.4	8.7	9.7	12.4	14.2	13.7	16.5	18.8	19.7
D7	3.2	3.8	4.3	4.8	4.8	5.5	5.9	6.2	6.6	7.1	7.4	8.3	8.8	9.4	9.8	11.1	11.8
D8	4.8	5.0	5.5	6.3	6.6	6.3	6.7	6.8	7.3	7.5	8.3	10.9	11.0	11.7	10.8	13.3	12.0
D9	3.2	3.4	3.7	4.6	5.2	5.2	5.2	5.2	5.2	5.5	6.8	12.0	13.0	12.9	15.6	11.9	15.2
G1	4.2	4.2	4.1	4.3	4.6	4.5	5.3	5.6	6.0	6.0	6.3	8.4	10.0	11.1	15.4	13.5	15.6
G2	1.8	7.3	8.3	8.4	9.2	9.4	9.7	9.8	10.1	10.8	12.0	17.7	18.8	20.0	22.7	22.9	22.8
G3	5.9	6.8	7.8	8.6	9.6	9.8	10.5	10.7	11.1	11.8	13.9	19.1	23.1	24.0	25.1	27.0	29.5
B1	8.2	9.5	10.1	12.0	13.5	10.6	11.2	11.6	12.2	13.8	15.2	16.7	17.2	15.2	17.0	21.8	21.7
B2	8.3	8.8	10.0	11.6	13.1	14.8	15.4	15.4	15.8	17.0	18.8	22.3	25.8	25.7	28.8	26.4	30.3
B3	9.5	9.6	10.9	12.2	13.4	14.1	14.2	11.1	11.4	11.8	12.6	14.0	14.9	18.4	18.8	24.3	24.3
B4	7.3	8.2	8.7	9.7	11.8	11.6	12.3	13.0	13.4	14.1	16.0	21.4	21.8	22.7	23.3	27.0	26.3
B5	3.4	4.2	4.2	5.5	6.2	6.7	7.1	7.3	7.6	7.8	9.0	13.2	13.1	14.2	14.5	18.7	27.4
F1	3.4	3.3	3.7	4.6	5.5	5.6	5.6	5.7	5.7	6.1	8.7	16.0	17.6	19.3	22.6	26.9	26.2
F2	3.9	3.8	4.4	5.4	6.1	6.4	6.7	6.8	7.0	7.8	10.7	17.9	19.7	23.7	27.0	29.2	33.0
S1	59.4	59.7	60.0	60.6	60.8	61.7	62.2	63.1	63.9	64.0	64.2	65.3	65.9	66.1	68.0	68.7	69.6
S2	15.1	15.8	16.0	17.0	18.1	19.3	21.1	21.8	22.2	23.1	24.3	26.8	28.1	30.1	31.9	32.8	34.6

Appendix 3. Aerial photography acquired through the Airborne Sensing Unit, Canada Centre for Remote Sensing, and available through the National Air Photo Library, Ottawa.

Plate 2.	July 7, 1975 Film 2443, filter W 12 RC 10, f=3.5 in., H=33,000 ft. AGL Roll A 37188 IR, Frame 127.
Plate 3.	June 11, 1973 Film 2443, filter W 12 RC 10, f=3.5 in., H=12,000 ft. AGL Roll A 30709 IR, Frames 7, 9, 11.
Plate 5.	May 29, 1971 Vinten 70 mm, f=3 in., H=38,650 ft. AGL B+W Red band: Roll BN1125, Frame 52 B+W Infrared band: Roll BN1124IR, Frame 52.
	October 5, 1971 Vinten 70 mm, f=3 in., H=38,600 ft. AGL B+W Red band: Roll BN1300, Frame 97 B+W Infrared band: Roll BN1299IR, Frame 97.
Plate 7.	May 29, 1971 Vinten 70 mm, f=3 in., H=16,800 ft. AGL B+W Red band: Roll BN1125, Frame 307 B+W Infrared band: Roll BN1124IR, Frame 306.
	October 5, 1971 Vinten 70 mm, f=3 in., H=16,800 ft. AGL B+W Red band: Roll BN1300, Frame 354 B+W Infrared band: Roll BN1299IR, Frame 354.
Plate 9.	May 29, 1971 Vinten 70 mm, f=3 in., H=16,800 ft. AGL B+W Red band: Roll BN1125, Frame 313 B+W Infrared band: Roll BN1124IR, Frame 312.
	October 5, 1971 Vinten 70 mm, f=3 in., H=16,800 ft. AGL B+W Red band: Roll BN1300, Frame 348 B+W Infrared band: Roll BN1124IR, Frame 348.

Appendix 4. Monthly mean maximum soil temperatures (^{o}C) at various depths from data recorded at Ellerslie, Alberta during 1971 (modified after Environment Canada, 1971-1972).

Month	Depth (cm)						
	1	10	20	50	100	150	300
January	-3	-3	-2	0	1	2	5
February	-2	-2	-1	-1	1	2	4
March	-1	-1	-1	0	1	2	4
April	3	3	2	1	1	2	3
May	16	14	11	8	6	4	3
June	18	17	15	13	11	8	5
July	21	20	18	15	13	11	7
August	25	23	19	17	15	14	8
September	16	15	13	13	13	13	-
October	8	8	7	9	9	10	10
November	0	1	4	6	7	6	-
December	-4	-3	1	3	4	3	-

Appendix 5. Minimum (0800 hrs) and maximum (1700 hrs) soil temperatures (°C) at various depths recorded at Ellerslie, Alberta, for the period May 22-26 and October 1-5, 1971 (modified after Environment Canada 1971-1972).

Date		Depth (cm)						
		1	10	20	50	100	150	300
May 22	min.	11	11	11	8	6	5	1
	max.	16	14	12				
23		10	11	11	9	7	5	3
		19	17	13				
24		13	13	13	9	7	6	3
		21	18	14				
25		14	14	14	10	7	6	3
		21	19	14				
26		15	15	14	11	7	6	3
		21	18	14				
October 1	min.	5	6	8	10	11	12	11
	max.	13	12	10				
2		5	6	9	10	11	11	12
		13	12	10				
3		6	7	9	11	11	11	11
		13	12	10				
4		8	9	10	10	11	11	11
		13	13	11				
5		8	9	10	11	11	11	11
		15	14	11				

Appendix 6. Location, slope, aspect and land use for the ground truth sites for thermal imagery of the Edmonton study area.

Site	Location (W 4th)	Slope	Aspect	Land Use	
				May	October
1	SE Sec.15-Tp.52-R.24	5%	NW	stubble	fallow*
2	SE Sec.15-Tp.52-R.24	1%	NW	stubble	fallow
3	NE Sec.11-Tp.52-R.24	2%	N	fallow	fallow
4	SW Sec.13-Tp.52-R.24	5%	SW	fallow	stubble
5	NW Sec.7-Tp.52-R.23	1%	W	fallow	fallow
6	NE Sec.7-Tp.52-R.23	2%	E	pasture	pasture
7	NW Sec.8-Tp.52-R.23	2%	E	fallow	fallow
8	NW Sec.8-Tp.52-R.23	5%	SE	fallow	fallow
9	NW Sec.9-Tp.52-R.23	5%	W	fallow	fallow
10	NE Sec.10-Tp.52-R.23	7%	S	pasture	pasture
11	NW Sec.11-Tp.52-R.23	1%	W	hay	hay
12	NW Sec.7-Tp.52-R.22	8%	E	fallow	fallow
13	NW Sec.7-Tp.52-R.22	1%	SE	hay	hay
14	NW Sec.9-Tp.52-R.22	8%	S	fallow	fallow

* fallow = bare soil surface

Appendix 7. Gray scale values from multiband photography indicating relative reflectance from different soils in 3 spectral bands on three dates in 1971; May 29, July 13, and October 5. Lower gray scale number indicates darker tone and lower relative reflectance (range: 1 = darkest tone, 12 = lightest tone).

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1. Orthic Humic Gleysol

May	G	4.0	3.0	2.5	2.0	2.5	2.0	2.5	3.0	3.5	3.5	3.0	3.0	2.0	4.0	3.5
	R	5.0	4.0	3.0	2.5	2.5	3.0	3.0	3.0	2.5	3.0	2.5	3.0	3.0	2.0	2.0
	IR	2.5	2.0	2.0	2.0	1.5	1.5	1.5	2.0	1.5	2.0	2.0	2.0	1.5	2.0	1.5
July	R	3.0	3.5	4.0	2.5	3.0										
	IR	0.5	2.5	1.5	2.0	2.0										
October	G	3.5	4.0	3.0	3.5											
	R	3.0	3.0	2.5	3.5											
	IR	2.5	3.0	2.5	3.0											

2. Orthic Black Chernozem

May	G	3.0	3.0	3.5	[illegible]	3.0	3.5	4.0	3.5		
	R	3.5	3.5	4.0	4.0	3.5	4.0	4.0	3.5		
	IR	2.5	2.0	2.5	2.0	1.5	2.5	3.0	2.5		
July	R	3.0	3.5	4.5	5.0	4.5	4.0				
	IR	2.0	2.0	1.5	2.5	2.0	1.5				
October	G	3.0	2.0	3.0	3.5	3.0	3.0	3.5	3.0	2.0	3.0
	R	2.0	2.0	3.0	3.5	3.0	1.0	2.5	2.0	1.5	1.0
	IR	2.0	2.5	2.5	2.0	2.5	1.5	2.0	1.0	1.0	2.0

3. Eluviated Black Chernozem

May	G	2.5	2.0	3.5	3.5	3.5	3.5	5.0	4.0	3.5	4.0	4.5	4.0
	R	3.0	3.0	4.0	4.0	4.5	3.5	4.0	4.0	4.0	3.5	4.5	4.0
	IR	1.5	1.0	2.5	2.5	3.0	2.5	1.5	2.5	2.5	2.5	2.5	2.5
July	R	4.0	3.5	3.5	4.0								
	IR	2.0	1.5	1.5	2.0								
October	G	3.0	2.5	4.0	3.5								
	R	3.0	2.5	3.0	3.0								
	IR	2.0	1.5	2.5	2.0								

4. Black Solonetz

May	G	3.5	3.0	3.0	2.5	3.0	2.5	3.0	3.5
	R	3.0	2.5	3.5	2.5	4.0	3.0	3.0	3.5
	IR	3.0	2.0	2.0	2.0	2.0	2.5	2.5	3.0

Appendix 7. continued:

July	R	4.5	4.0	3.5	5.0	3.5	4.5	3.5
	IR	2.0	2.0	1.0	2.5	1.5	2.5	1.0
October	G	3.0	3.0	3.5	3.0	3.0		
	R	2.5	2.5	2.0	3.0	3.0		
	IR	2.0	2.0	2.0	2.5	2.5		

5. Dark Gray Chernozem

May	G	4.0	3.0	3.0	4.0	3.0
	R	4.0	4.0	3.0	3.5	3.0
	IR	3.0	2.0	2.0	2.5	2.5
July	R	4.5	5.0	4.0	4.5	4.5
	IR	1.5	2.5	2.0	2.0	2.0
October	G	4.0	4.0	3.5	3.5	4.0
	R	4.0	4.0	3.0	2.5	3.5
	IR	3.0	3.0	2.0	1.5	2.5

6. Dark Gray Luvisol

May	G	3.0	3.5	4.0	4.5	4.0	5.0	4.5	5.5	5.5
	R	3.0	4.0	4.0	4.5	4.0	5.0	4.5	4.5	5.0
	IR	2.0	2.5	2.5	2.5	2.5	3.0	3.0	3.0	3.5
July	R	3.5	4.5	6.0	6.0					
	IR	1.5	2.5	2.0	2.5					
October	G	4.5	4.0	3.0	3.5					
	R	4.5	3.5	2.0	3.5					
	IR	3.0	2.5	2.0	2.5					

7. Orthic Gray Luvisol

May	G	6.0	6.0	5.5	6.0
	R	5.0	5.0	5.0	5.5
	IR	3.5	3.0	3.5	4.0
October	G	5.0	4.5	5.5	5.0
	R	4.5	4.5	5.0	4.5
	IR	4.0	3.5	4.5	4.0

Appendix 8. Thickness (cm), electrical conductivity (mmhos/cm) and soluble Na, Mg, and Ca (me./litre) of surface soils within each class of salinity effects on crop development as observed on color aerial photographs. Site numbers refer to coordinates within the sampling grid used.

Class	Site	Thickness	Electrical Conductivity	Soluble Na	Soluble Mg	Soluble Ca
1	12 J	7.5	1.9	19.1	1.6	1.4
	13 B	7.5	2.1	20.0	2.3	1.6
	13 F	7.5	1.2	9.0	1.1	1.3
	14 J	10.0	1.3	10.2	1.1	1.4
	15 D	7.5	2.1	27.1	2.1	1.4
	16 B	10.0	2.8	31.5	3.4	2.3
	16 D	5.0	1.0	6.5	1.4	0.9
	16 H	10.0	2.3	38.2	2.3	2.1
	17 F	5.0	0.5	3.2	1.4	1.6
	17 H	5.0	1.5	12.4	1.6	1.8
	17 J	20.0	0.5	3.5	0.9	1.4
	18 H	7.5	0,7	2.7	1.0	1.1
2	12 H	15.0	0.3	1.2	1.0	1.8
	13 D	15.0	1.1	5.0	2.7	2.8
	13 J	10.0	0.9	4.9	1.3	1.9
	14 H	15.0	0.6	4.4	0.8	1.6
	14 L	7.5	0.5	0.9	1.4	2.4
	15 F	7.5	0.6	2.5	0.9	1.3
	15 J	7.5	0.7	3.0	1.3	1.5
	15 L	18.0	0.5	1.0	1.6	3.3
	16 F	10.0	1.4	9.8	1.5	1.3
	16 J	15.0	0.6	3.0	0.6	1.0
	16 L	5.0	1.3	10.9	1.2	1.4
	17 B	10.0	0.5	2.5	2.0	2.1
	17 D	20.0	[illegible]	5.3	0.7	1.0
	17 L	10.0	0.7	2.6	1.8	2.6
3	12 B	10.0	[illegible]	0.5	1.5	31.9
	12 D	10.0	[illegible]	1.9	2.2	3.4
	12 F	10.0	[illegible]	–	–	–
	12 L	10.0	0.5	1.2	1.2	3.2
	14 D	15.0	0.7	2.1	1.8	3.3
	18 J	15.0	0.6	1.7	1.9	3.8
4	13 L	23.0	0.5	1.2	1.5	3.5
	15 B	20.0	0.4	1.4	1.5	1.7
	15 H	18.0	0.3	1.1	1.0	1.7
	18 D	23.0	0.4	0.9	1.3	2.4
	18 L	15.0	0.4	1.2	1.4	2.6

Appendix 9. Glossary of terms (after American Society of Photogrammetry, 1975).

analogue: A physical variable which remains similar to another with proportional relationships the same over some specified range; a temperature may be represented by a voltage which is its analogue.

blackbody: An ideal emitter which radiates energy at the maximum possible rate per unit area at each wavelength for any given temperature; also absorbs all radiant energy incident upon it.

crab: Any turning of an aircraft which causes its longitudinal axis to vary from the track of the aircraft.

emittance: Radiant flux per unit area emitted by a body.

equivalent blackbody temperature: The temperature measured radiometrically corresponding to that which a blackbody would have.

gain: The amplification given a signal by the receiver.

gray scale: A monochrome strip of shades ranging from white to black with intermediate shades of gray.

ground truth: Supporting data collected on the ground as an aid to the interpretation of remotely-recorded data; synonymous with ground data or ground information.

isotropic radiation: Diffuse radiation that has exactly the same intensity in all directions; therefore an isotropic reflector reflects energy equally in all directions.

LANDSAT: An acronym for Land Satellite, formerly Earth Resource Technology Satellite (ERTS).

multiband photography: A system of cameras for simultaneously observing the same small target with several filtered bands through which data can be recorded; generally black and white photography in different spectral bands.

multiemulsional photography: Photography with color films that have two or more emulsion layers.

Appendix 9. continued:

multispectral: Used to describe remote sensing in two or more spectral bands.

panchromatic: Used to describe films that are sensitive to broad band electromagnetic energy, usually the entire visible light spectrum.

perfectly diffuse reflector: A body that reflects radiant energy in such a manner that the intensity of the reflected energy is directly proportional to the intensity of the incident energy times the cosine of the angle of incidence.

pixel: Acronym for picture element. When pictures are processed by a digital computer they can be regarded as discrete arrays of numbers (i.e. matrices). The elements of the matrix are called picture elements or pixels.

The instantaneous field of view which each sensor of the LANDSAT multispectral scanner has of the ground is a square approximately 80m by 80m. Each of the sensors measures the intensity of the energy it receives and produces an output signal. The region of the ground for which the intensity is measured and recorded is called a pixel. The output signals transformed into numbers are called pixel values. Therefore for the LANDSAT multispectral scanner, each pixel has four corresponding pixel values representing the intensity of the scene reflection in each of four spectral bands (after Peet, F.G. 1976. A Primer on the Use of Digital LANDSAT Data. Forest Management Institute, Environment Canada, Ottawa. 21pp.).

spectral band: An interval in the electromagnetic spectrum defined by two wavelengths.

spectral signature: A quantitative measurement of the properties of an object at one or several wavelength intervals.