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Design, Implementation, and Results of LACIE Field Research

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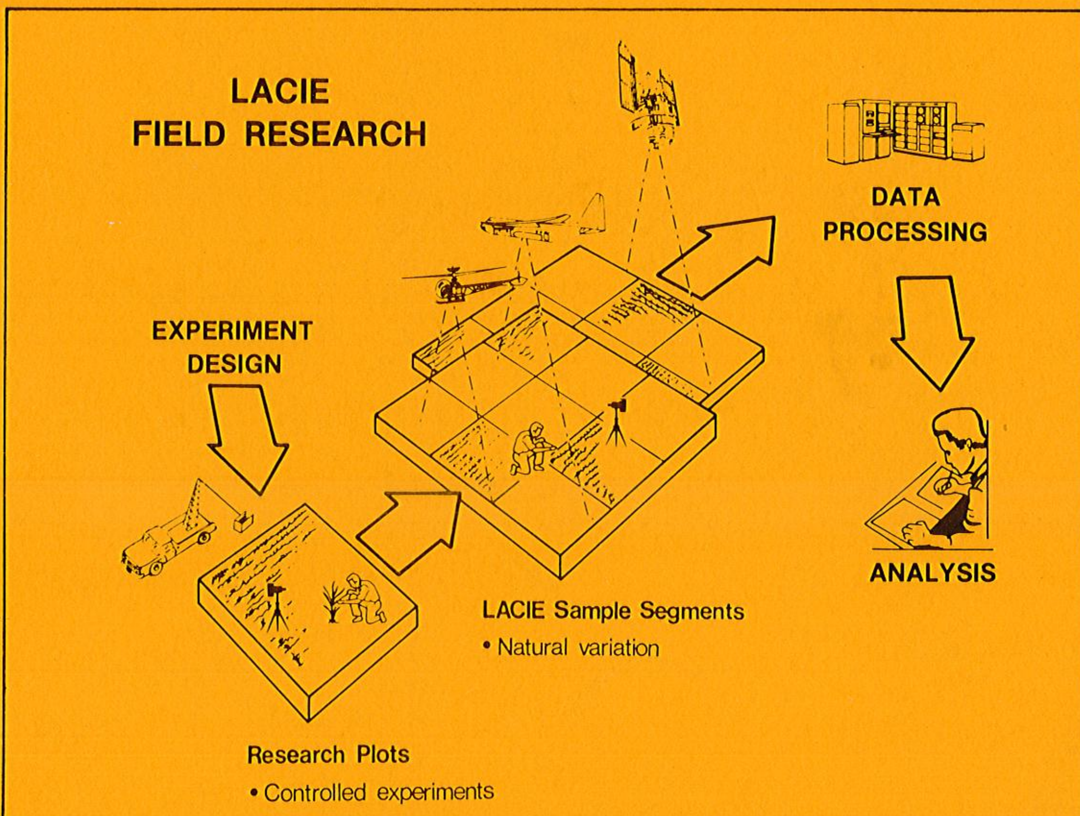

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ABSTRACT

The design, implementation, and results of a three year experiment at three sites in the Great Plains region of the United States are described. The overall objective of the project was to acquire, process, and analyze fully annotated and calibrated multitemporal sets of spectral measurements of crops and soils along with agronomic and meteorological data. The data serve as a data base for determining the spectral-temporal properties of wheat, soil and other crops; developing advanced spectral data analysis techniques; and defining sensor requirements.

The experiment involved the coordinated use of spectrometers mounted on mobile aerial towers, a helicopter-borne spectrometer, airborne multispectral scanners, and Landsat multispectral scanners. The approach included controlled experiments at agricultural experiment stations and measurements of commercial fields in large test sites.

Development and use of procedures for obtaining radiometrically calibrated spectral measurements permited valid comparisons to be made among data acquired at different dates and times, different sites, and by different sensors. The data sets acquired are comprehensive in terms of the number and kind of sensors, the number of sites and years included, the number of missions (8 to 12) for each site and year, and the amount of supporting agronomic and meteorological data acquired.

Analysis of the data is providing insight into the spectral properties, identification, and assessment of crops. The analyses described include development of predictive relationships between spectral variables and leaf area index, biomass, and percent soil cover; determination of the effects of cultural and environmental factors on the reflectance of wheat; investigations of the spectral separability of barley and spring wheat; determination of the early-season threshold for detection of wheat with Landsat data; and comparisons of Landsat MSS and thematic mapper spectral bands for crop identification and assessment.

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Design, Implementation, and Results of LACIE Field Research

M. E. Bauer,[a] M. C. McEwen,[b] W. A. Malila,[c] and J. C. Harland[d]

INTRODUCTION

Major advancements have been made in recent years in the capability to acquire, process, and interpret remotely sensed multispectral measurements of the energy reflected and emitted from crops, soils, and other Earth surface features. As a result of experiments such as LACIE, the technology is moving rapidly toward operational applications. There is, however, a continuing need for quantitative studies of the multispectral characteristics of crops and soils if further advancements in the technology are to be made. In the past, many such studies were made in the laboratory because of a lack of instrumentation suitable for field studies, but the applicability of laboratory studies is generally limited. The development of sensor systems capable of collecting high-quality spectral measurements under field conditions has made it possible to pursue investigations which would not have been possible a few years ago.

A major effort was initiated in the fall of 1974 by the NASA Johnson Space Center (JSC) with the cooperation of the U.S. Department of Agriculture (USDA) to acquire fully annotated and calibrated multitemporal sets of spectral measurements and supporting agronomic and meteorological data (ref. 1). The Purdue University Laboratory for Applications of Remote Sensing (LARS) was responsible for the technical design and coordination of the experiment, as well as for major portions of the data acquisition, processing, and analysis. Other organizations, particularly the Environmental Research Institute of Michigan (ERIM), Texas A & M Remote Sensing Center, and Colorado State University, contributed to the experiment planning and data analysis.

Spectral, agronomic, and meteorological measurements were made at LACIE test sites in Kansas and North Dakota for 3 years and in South Dakota for 2 years. The remote-sensing measurements include data acquired by truck-mounted spectrometers, a helicopter-borne spectrometer, an aircraft multispectral scanner (MSS), and the Landsat multispectral scanners. These data are supplemented by an extensive set of agronomic and meteorological data acquired during each mission.

The LACIE field measurements data form one of the most complete and best documented data sets acquired for agricultural remote-sensing research. Thus, they are well suited to serve as a data base for research to (1) determine quantitatively the relationship of spectral to agronomic characteristics of crops, (2) define future sensor systems, and (3) develop advanced data analysis techniques. The data base is unique in the comprehensiveness of sensors and missions over the same sites throughout the growing season and in the calibration of all multispectral data to a common standard.

Continuing analysis of the field data is providing insight into the spectral properties, spectral identification, and assessment of crops. The analyses include development of predictive relationships between spectral variables and leaf area index, biomass, plant water content, and percent soil cover; determination of the effects of cultural and environmental factors on the spectral reflectance of wheat; investigations of the spectral separability of barley and spring wheat; determination of the early-season Landsat threshold for detection of wheat; and comparisons of Landsat MSS and thematic mapper spectral bands for crop identification and assessment.

The remainder of this paper describes the project

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objectives, presents an overview of the experimental approach, describes the data acquisition program, and discusses selected results based on field data. The paper ends with a summary of the key accomplishments and results of the experiment and recommendations for future field research.

OBJECTIVES

The overall objective of the LACIE Field Measurements Project was to acquire, process, and distribute to researchers fully annotated and calibrated multitemporal sets of spectral measurements over the wavelength range of 0.4 to 15 micrometers, along with supporting agronomic and meteorological data. These data would serve as a data base for (1) determining quantitatively the temporal-spectral characteristics of spring and winter wheat, the soil background, and surrounding confusion crops; (2) defining future multispectral sensor systems; and (3) developing advanced data processing and analysis techniques.

Specific objectives are listed below for each of these categories. The objectives emphasize analyses to increase understanding of agricultural scenes; however, the data may also be used to pursue sensor design and data processing objectives.

1. Scene-related objectives
    a. Determination of the relation of crop canopy characteristics such as percent soil cover, leaf area index, biomass, and plant water content to multitemporal spectral response
    b. Determination of the effects of cultural and environmental variables on the spectral properties and spectral identification of wheat
    c. Determination of the spectral discriminability of wheat, small grains, and other crops as a function of growth stage
    d. Determination of the presence, severity, and extent of crop stresses such as drought, disease, and winterkill from spectral measurements
    e. Determination of the year-to-year variation in the condition and spectral response of wheat and other crops
    f. Determination of the relation of grain yield to the multitemporal spectral response of wheat
    g. Determination of the effects on spectral response of geometric factors such as Sun angle, view angle, and canopy structure of wheat and other selected crops
    h. Determination of the effect of the atmosphere on the measured spectral responses of wheat and other crops
    i. Determination of the characteristics and use of thermal measurements for discrimination of wheat from other crops
    j. Validation of canopy reflectance models
2. Sensor-system-related objectives
    a. Determination of optimum or required multispectral sensor system parameters including spectral bands, signal-to-noise ratio (S/N), noise-equivalent difference in reflectance (NE$\Delta\rho$), noise-equivalent difference in temperature (NEΔT),[1] and time and frequency of sensor overpasses
    b. Comparison and evaluation of Landsat MSS and thematic mapper wavelength bands for crop identification and assessment
3. Data-processing-system-related objective
    a. Development of advanced data processing and analysis techniques that use multitemporal, spatial, spectral, transformed spectral, and ancillary data characteristics

OVERVIEW OF EXPERIMENTAL APPROACH

An overview of the experimental approach is shown in figure 1. At the beginning of the project, the technical issues and specific objectives to be addressed with the field measurements data were defined. This led to the experimental design for data acquisition and processing and to the definition of initial data analysis plans and products.

A multistage approach to data acquisition was taken, including areal, vertical, and temporal staging. Areal sampling was accomplished with test sites in different parts of the U.S. Great Plains. Vertical staging, or collection of data by different sensor systems at different altitudes, ranged from mobile towers to Landsat. Temporally, data were collected at 7- to 21-day intervals to sample all important growth stages and during 3 years to obtain a measure of the year-to-year variation in growing conditions and their influence on spectral response.

Measurements were made at three LACIE test sites during 3 crop years, 1975 to 1977. The sites are

[1]NE$\Delta\rho$ and NEΔT are measures of minimum detectable differences in scene reflectance and temperature.

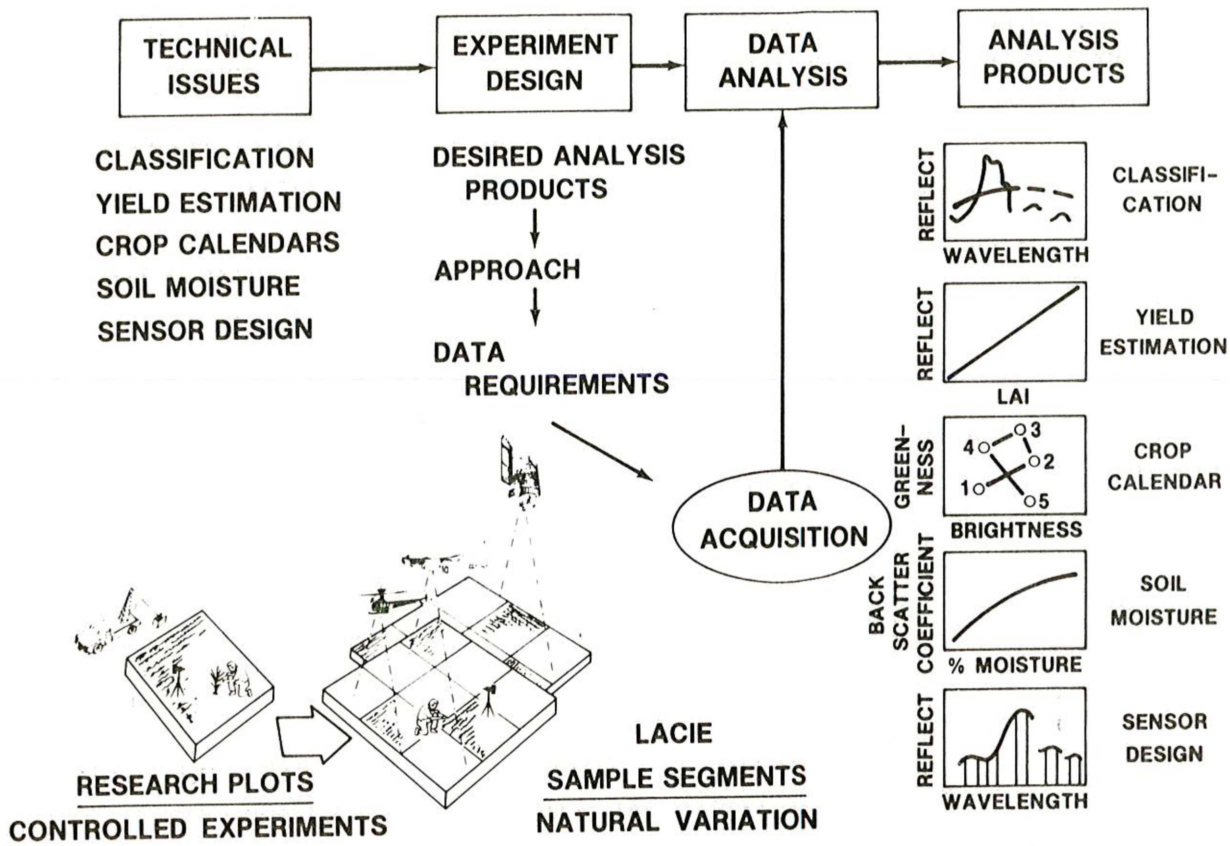


FIGURE 1.—Overview of experimental approach for LACIE field research.

in Finney County, Kansas; Williams County, North Dakota; and Hand County, South Dakota. Finney County and Williams County were chosen to represent winter and spring wheat growing areas, respectively. Hand County is typical of the transitional zone between winter and spring wheat growing areas.

The primary sensors for data collection were truck-mounted spectrometers, a helicopter-borne spectrometer, an aircraft multispectral scanner, and the Landsat-1 and -2 multispectral scanners. Each sensor system has unique capabilities for acquiring spectral data. The spectrometers produce the highest quality reflectance measurements but provide only limited measurements of spatial variability. On the other hand, an aircraft scanner provides spatial sampling of the scene and can obtain data at multiple altitudes, but its spectral coverage, although broader than that of a Landsat MSS, is limited to a fixed set of wavelength bands. The helicopter and aircraft data acquisition systems have the advantage of flexible scheduling and, therefore, provide greater opportunity to obtain cloud-free data at critical crop growth stages than the Landsat system provides. Landsat provides wide-area coverage but is limited in its spatial resolution and the placement and number of spectral bands.

The staging of data acquisition is summarized in figure 2. Helicopter-spectrometer and aircraft-scanner data were collected in a series of flightlines over commercial fields in the LACIE intensive test site in each of the three counties. Landsat MSS data were acquired and processed for the entire test site, as well as for surrounding areas. These data provide a measure of the natural variation in the temporal-spectral characteristics of wheat and surrounding cover types.

The truck-mounted spectrometers collected spectra of crops in controlled experimental plots at agricultural research stations near the test sites at Garden City, Kansas, and Williston, North Dakota. These data, combined with the more detailed and quantitative measurements of crop and soil conditions which were made at the experiment stations, enable more complete understanding and interpreta-

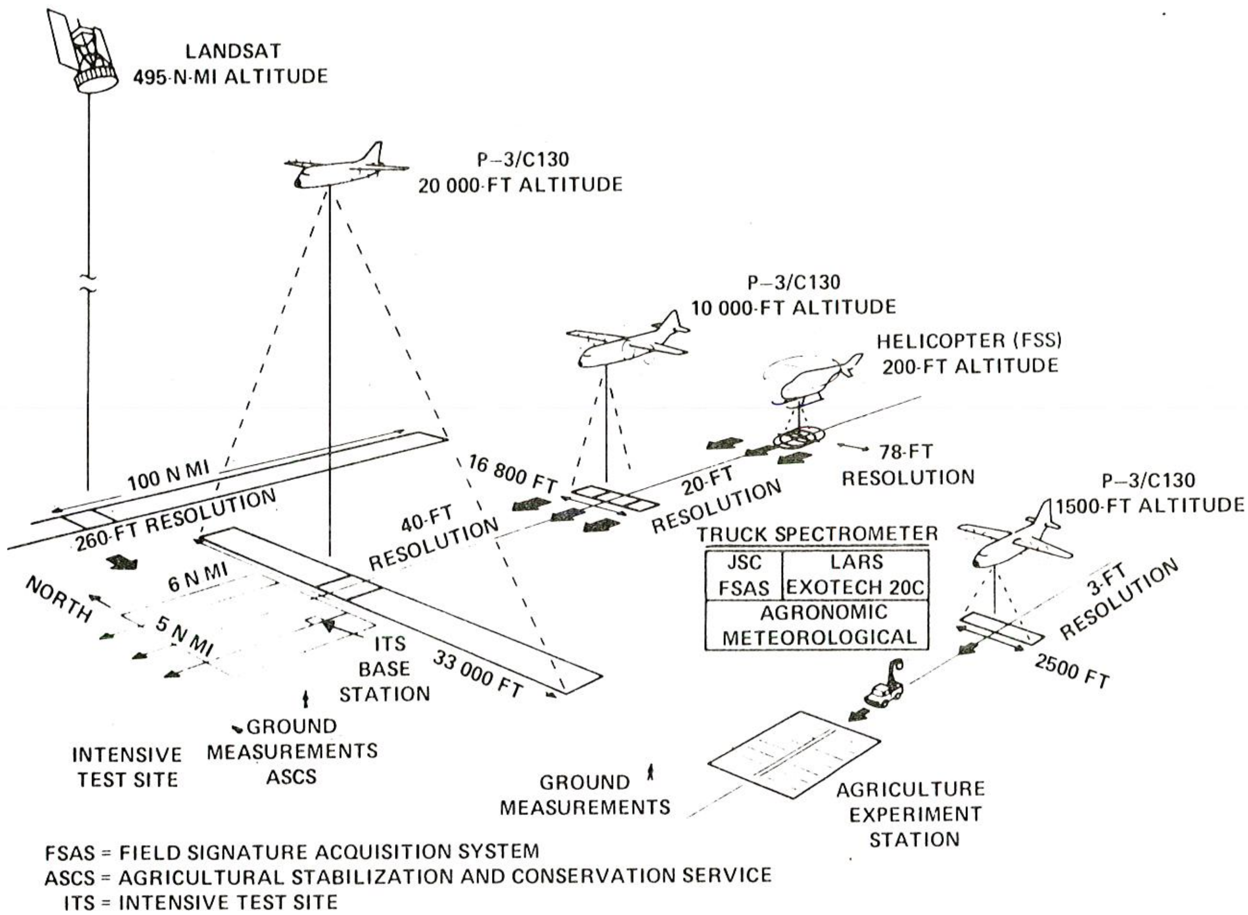


FIGURE 2.—Schematic illustration of LACIE field measurements data acquisition.

tion of the spectra collected from commercial fields. Past experience has shown that there are generally too many interacting variables in commercial fields to determine exact causes of observed differences in spectral response. With data from plots where only two to four factors are varied under controlled conditions, it is possible to determine more exactly and understand more fully the energy-matter interactions occurring in crops.

The spectral measurements were supported by descriptions of the targets and their conditions. The observations, counts, and measurements of the crop canopy include maturity stage, plant height, biomass, leaf area index, percent soil cover, and grain yield. Also included are measurement conditions such as sensor altitude and view angle, as well as measurements of the atmospheric and meteorological conditions. The data are supplemented by aerial photography and ground-level vertical and oblique photographs of the fields and test plots.

A data library of all spectral, agronomic, meteorological, and photographic data collected is maintained at LARS. The data have been processed in standard data formats and measurement units and made available to JSC-supported investigators and other interested researchers.

DESCRIPTION OF DATA ACQUISITION, PROCESSING, AND DISTRIBUTION

This section describes the acquisition, processing, and distribution of the LACIE field measurements data. It begins by describing the test sites and the experiments at the agriculture experiment stations, followed by descriptions of the sensors and sensor calibration. The procedures for acquiring the spectral, agronomic, and meteorological data are then described. The section ends with a description of the data processing, library, and analysis systems.

Test Site and Experiment Description

The test sites (fig. 3) were located in Finney County, Kansas; Williams County, North Dakota; and Hand County, South Dakota. Each site consists of a LACIE intensive test site and, in Kansas and North Dakota, an agricultural research station. Measurements were acquired for 3 years at the Kansas and North Dakota sites and for 2 years at the South Dakota site.

The test sites were chosen to include as wide a range of important wheat production areas as possible. In addition, the Finney County and Williams County sites were selected because of their proximity to agricultural research stations. Personnel from the USDA Agricultural Stabilization and Conservation Service (ASCS) were available in each county to collect the required intensive test site ground-truth data.

At the experiment station in Garden City, Kansas, experiments were conducted on dryland and irrigated winter wheat and small grains. At the Williston, North Dakota, experiment station, a small-grains experiment and a cultural practice experiment with spring wheat were conducted.

Intensive test sites.—The intensive test sites are 8.1 by 9.7 kilometers in size. Three flightlines, each 9.7 kilometers long, were located across each site. The number of fields of each major cover type in each site for 1976 is summarized in table I.

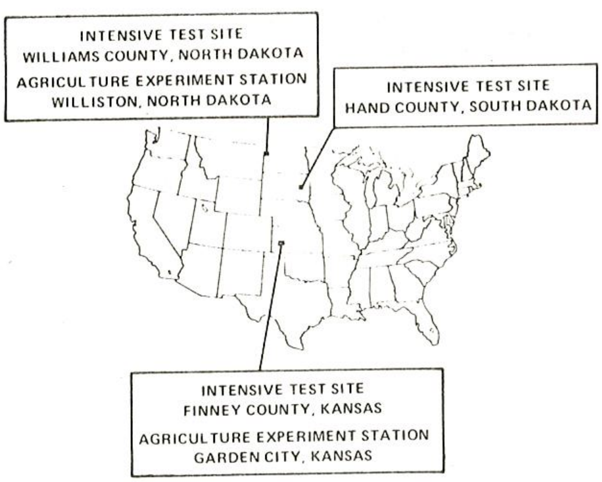


FIGURE 3.—Locations of LACIE field measurements test sites.

Finney County, Kansas: The test site is located in the High Plains Tableland physiographic area at latitude 38°10′ N and longitude 100°43′ W. The elevation of the site is 900 meters. The site is overlaid by 3 to 10 meters of loess from the early Wisconsin age.

The soils of the test site are in the Mollisol order, Ustoll suborder, and Argiustolls great group. Mollisols are soils that have nearly black, friable, organic-rich surface horizons high in bases. Ustolls are formed in semiarid regions; they are dry for long periods and have subsurface accumulations of carbonates. The major soil series in the area are Richfield and Ulysses, which are deep, fertile, well-drained, nearly level to gently sloping loamy soils of the upland that are well suited to cultivation.

The area has a distinct continental type of climate characterized by abundant sunshine and constant wind. Most of the precipitation falls during the early part of the year, with a rapid decline in the probability of receiving adequate rainfall during July and August. Thus, the growth cycle of winter wheat is well matched to the available moisture supply. Average annual precipitation for Finney County is 48.5 centimeters: 14.3 centimeters from March through May, 20.1 centimeters from June through August, 9.7 centimeters from September through November, and 4.4 centimeters from December through February.

TABLE I.—Number of Commercial Fields of Each Crop or Cover Type in the Field Measurements Test Sites, 1976

Cover type	*Test site*		
	Finney County, Kansas	*Hand County, South Dakota*	*Williams County, North Dakota*
Winter wheat	85	43	2
Spring wheat	—	38	222
Barley	—	9	—
Oats	—	15	4
Rye	—	1	1
Fallow	87	32	212
Corn	18	17	—
Grain sorghum	61	5	—
Alfalfa	1	26	1
Other hay crops	—	23	1
Pasture	9	48	61
Other	14	8	29

The major crops in Finney County are wheat and grain sorghum, which account for about 60 and 20 percent, respectively, of the total cropland. The majority of wheat is produced following summer fallow practices, although an increasing amount is being irrigated. Winter wheat is seeded in September or early October, then is dormant from December to February. Green-up occurs in March; the crop is fully headed by mid-May; and harvest is typically completed during the first week of July.

Williams County, North Dakota: This test site is located at latitude 48°19′ N and longitude 103°25′ W. It is representative of the cool semiarid areas of the northern Great Plains where annual precipitation averages 33 to 38 centimeters. The site is at an elevation of 650 meters and lies in the glaciated area with a drift mantle and an undulating to steep surface.

The soils in the site are of the Mollisol order, Boroll suborder, with Williams and Williams-Zahl being the major associations present. Both occur on undulating to rolling landscapes and are well to excessively drained. Much of the surface drainage is to depressions. The soils were developed from calcareous glacial till and are suitable for cropland and pasture. The soils of the Williams association are very productive.

The climate of the area is typically continental, with long cold winters, short warm summers, wide diurnal ranges in temperature, frequent strong winds, and limited (as well as uncertain and highly variable) precipitation. Average amounts of precipitation are 4.6, 15.5, 12.2, and 4.3 centimeters in the winter, spring, summer, and fall, respectively.

The major crop is wheat, which occupies about 70 percent of the grain crop acreage. Both hard red and durum spring wheats are grown. Most of the wheat is grown on summer fallow land. The major cover types in the site are wheat, summer fallow, and pasture; limited acreages of rye, barley, alfalfa, and flax are also grown. The cropping calendar for the spring wheats begins with seedbed preparation in late April to early May. Planting is generally in mid-May; heading occurs from late June to mid-July; and harvest is from mid- to late August.

Hand County, South Dakota: The test site is in the north-central Great Plains at latitude 44°34′ N and longitude 99°00′ W. It is a transition area with the Corn Belt to the east, spring wheat producing areas to the north, and winter wheat producing areas to the south. The boundary between the subhumid lowland of eastern South Dakota and the more arid Great Plains area of central and western South Dakota passes through Hand County. The area is nearly level to gently undulating. The principal soils of the test site are Houdek and Bonila, which are in the Mollisol order, Ustoll suborder. They are dark-colored permeable loams underlaid by slowly permeable glacial till.

Hand County has a continental climate. Winters are long and cold, and summers are warm. The average annual precipitation is 47 centimeters; typically, 33 to 36 centimeters fall between April and September. The county is subject to frequent weather changes, and airmasses that pass through the area bring a wide variety of temperature and moisture conditions.

The principal crops of Hand County are winter and spring wheat, pasture and hay, corn, barley, and oats. Most wheat is grown following summer fallow.

Agriculture experiment stations.—Agronomic experiments with wheat and other crops were available for study at the agriculture experiment stations at Garden City, Kansas, and Williston, North Dakota. The research farms are operated by Kansas State University and North Dakota State University. The advantages of using experimental plots at the stations were that (1) considerable amounts of agronomic data describing the treatments and their effects on the growth and development of the crop could be readily obtained, and (2) sources of difference in spectral response could be more readily determined since only the factors of interest were varied while other factors were held constant. The replicated experiments were designed to provide a range of growing conditions typical of those found in the intensive test sites. The crops were planted, grown, and harvested using conventional practices and equipment.

A small-grains and a wheat experiment were conducted at each location. The treatments and experimental designs for the 1977 crop year for each location are shown in figures 4 and 5.

Garden City, Kansas: The objective of the small-grains experiment was to determine whether various small grains can be discriminated from each other on the basis of their spectral reflectance. The experiment included four winter wheat varieties and one variety each of barley, rye, and triticale (fig. 4).

The principal objective of the dryland and irrigated winter wheat experiments was to characterize crop spectral response as a function of crop maturity and to relate the spectral response to crop variables

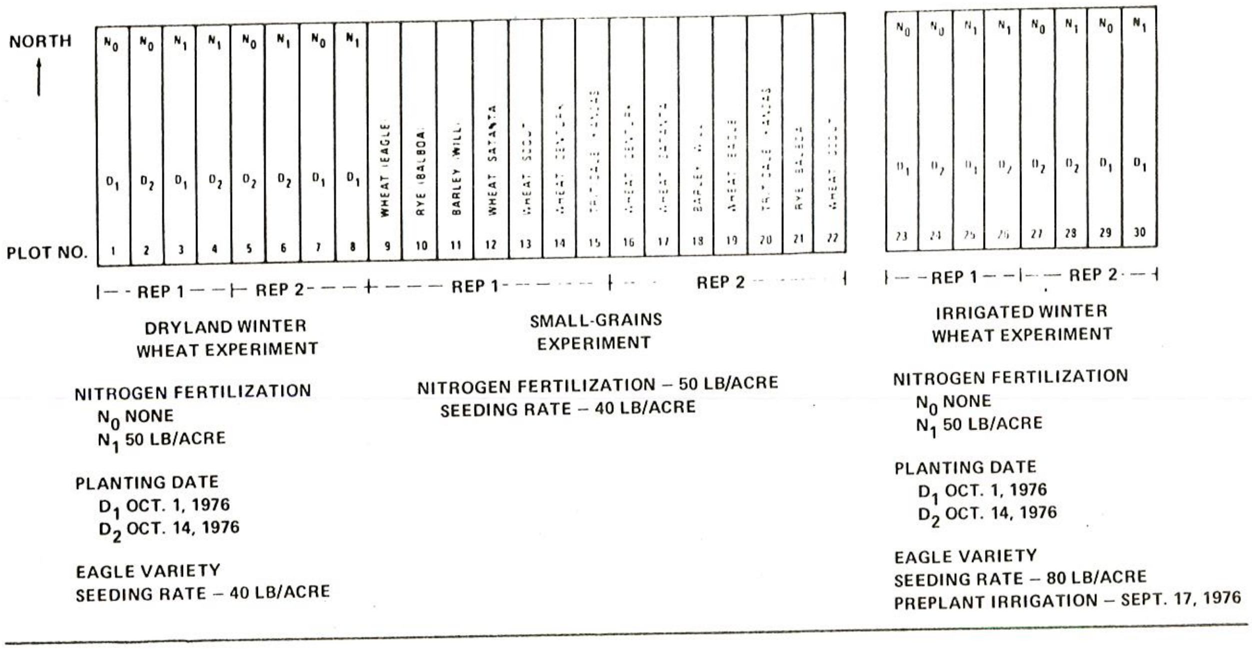


FIGURE 4.—Remote-sensing experiments at the Garden City, Kansas, agriculture experiment station.

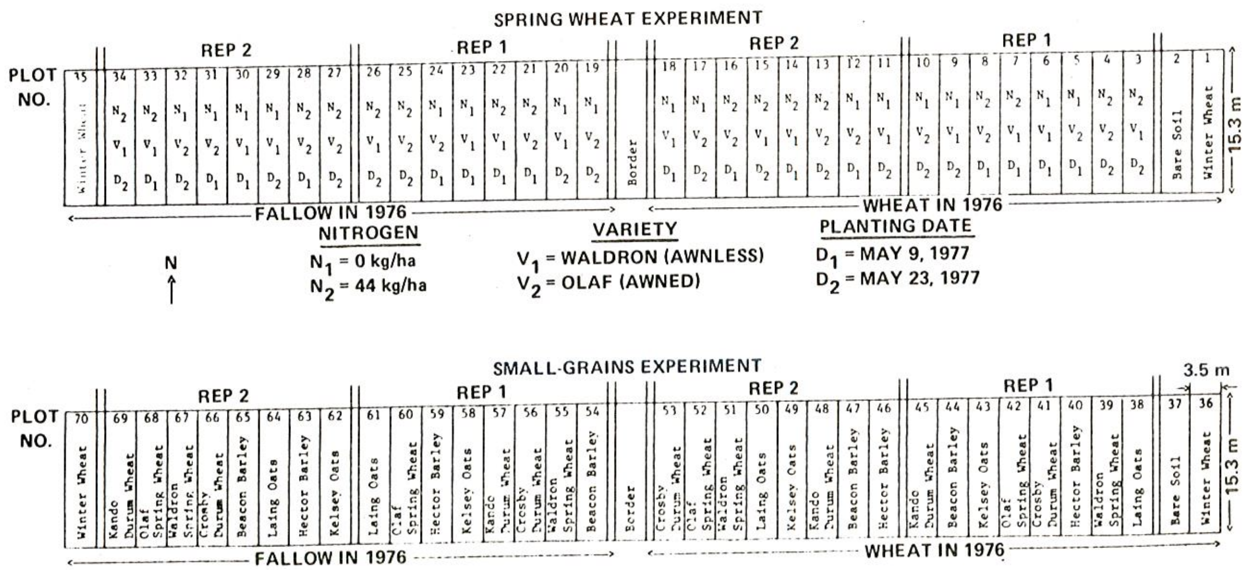


FIGURE 5.—Remote-sensing experiments at the Williston, North Dakota, agriculture experiment station.

such as leaf area index and biomass and to cultural variables such as planting date, irrigation, and nitrogen fertilization. The treatments were selected to give a range of leaf area indexes and biomass at any particular maturity stage or measurement time.

Williston, North Dakota: The objective of the small-grains experiment was the same as for the small-grains experiment at Garden City. This trial included two varieties each of hard red spring wheat, durum wheat, oats, and barley (fig. 5).

The objective of the spring wheat experiment was to quantify the effects on spectral response of the major variables affecting wheat growth, development, and yield. The factors and levels of each factor

TABLE II.—Characteristics of the Multispectral Scanner Systems

Characteristic	*Landsat-1 and -2 MSS*	*JSC MSS*	*JSC MMS*[a]
Spectral range, μm	0.5 to 1.1	0.4 to 13	0.4 to 1.1 10 to 12
Number of bands	4	24	11
Total field of view, deg	11.56	80	110
Normal operational altitude, km	944	0.5 to 6.1	0.5 to 6.1
Instantaneous field of view, m	79	1 to 12	1 to 15
Precision of data, bits	5 to 6	8	8

[a]Modular multiband scanner.

TABLE III.—Characteristics of the Spectrometer Systems

Characteristic	*JSC FSS*[a]	*LARS Exotech 20C*	*JSC FSAS*[b]
Spectral range, μm	0.4 to 2.5 8 to 14	0.4 to 2.4 3 to 14	0.4 to 2.5 3 to 14
Spectral resolution at 1.0 μm, μm	0.025	0.025	0.0064
Scan time, scan/sec	1	0.033 to 2.0	10
Field of view, deg	22	0.75, 15	11
Normal operational altitude, m	60	6	6
Data storage format	Digital tape	Analog tape	Digital tape
Camera			
Focal length, mm	76	55	50
Field of view, deg	36	43	46
Film type	70 mm color	35 mm color	35 mm color

[a]Field spectrometer system.
[b]Field signature acquisition system.

were (1) soil moisture—wheat in 1976 and fallow in 1976, (2) cultivar—standard height and semidwarf, (3) planting date—early and late, and (4) nitrogen fertilization—0 and 34 kg/ha.

Sensor Descriptions

The characteristics of the primary sensors used to acquire spectral data over the intensive test sites and agriculture experiment stations are described in this section. The sensors used in the intensive test sites included Landsat MSS, airborne MSS, helicopter-borne spectrometer, and tripod-mounted Landsat-band radiometers. The sensor systems acquiring spectral data at the agriculture experiment stations were the truck-mounted spectroradiometer and interferometer systems operated by LARS and JSC, respectively. General descriptions of the sensor systems are given in the following sections and summarized in tables II and III.

Landsat multispectral scanner.—Landsat 1 and 2 MSS data were acquired at 18-day intervals. The MSS data have four spectral bands from 0.5 to 1.1 micrometers. The sensor scans crosstrack swaths of 185 kilometers. Computer-compatible tape (CCT) data and imagery (both color and black and white) were requested for each cloud-free overpass of the intensive test sites.

Airborne multispectral scanners.—During 1975, the 24-channel scanner (ref. 2) operated by JSC was the primary scanner system; during 1976 and 1977, the 11-channel modular multiband scanner (MMS) was used.[2] Color and color-infrared photography was obtained during the scanner flights to be used as reference data by analysts.

Helicopter-borne field spectrometer system.—The helicopter-borne field spectrometer system (FSS) is a filter wheel spectrometer instrument that is a modification of the S-191 sensor used in the Skylab Earth Resources Experiment Package (EREP) (ref. 3). The FSS has been modified by NASA for mounting on a helicopter (fig. 6). The instrument produces data in 14-track digital format that are converted to CCT's for subsequent reformatting and analysis.

The spectral range of the spectrometer is 0.42 to 2.50 and 8.0 to 14.0 micrometers. The field of view is 22°, which gives a spot size of 24 meters diameter from a 60-meter altitude. The helicopter flies at 100 km/hr. The camera has a 76-millimeter focal length and a 36° field of view, giving 40 meters square ground coverage.

Truck-mounted spectrometer systems.—The Exotech Model 20C field spectrometer operated by LARS acquires spectral data over the visible, reflective infrared, and thermal infrared wavelength regions (ref. 4). The instrument consists of two inde-

[2]"Modular Multiband Scanner (MMS)," JSC Internal Note No. 74-FM-47, NASA Johnson Space Center, Houston, Tex., 1974.

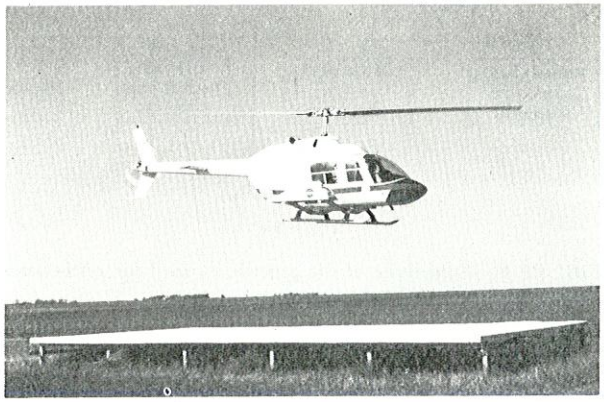


FIGURE 6.—Helicopter spectrometer system operated by the NASA Johnson Space Center acquiring measurements of the calibration standard. The spectrometer is located just below the window. The calibration standard is a specially coated canvas panel 6.5 by 13 meters in size mounted on a flat level platform.

pendently functioning units. The short-wavelength unit senses radiation from 0.38 to 2.4 micrometers and the long-wavelength unit senses radiation from 2.7 to 5.4 and 7.0 to 13.5 micrometers. The short-wavelength unit is equipped with a translucent diffusing plate, which is used to monitor incident spectral irradiance. Each optical head has a reflective fore-optic system that permits remote selection of the field of view (0.75° or 15°).

The instrument is mounted on a mobile aerial tower that operates with an instrumentation van containing the control electronics and data recorder for the system (fig. 7). The data produced by the instrument are recorded on an analog magnetic tape recorder and later converted into digital information by a laboratory analog-to-digital converter. Calibration sources designed for field use are used to calibrate the spectrometer onsite. Calibrated spectral data and field observations are combined on digital magnetic tapes during the data reformatting process.

The Block wideband interferometer (Field Signature Acquisition System or FSAS) operated by JSC acquires spectral data over the visible and infrared portions of the spectrum (ref. 5). The instrument scans the spectrum rapidly enough to account for environmental variables and is equipped with a self-contained computer system that yields spectral data from the interferograms produced by the instrument. The instrument control electronics and computer are mounted in an instrument van, and the optical head of the instrument is mounted on a mobile aerial tower. The spectral data (expressed as wave numbers) produced by the instrument were processed by JSC to provide CCT's of spectral reflectance factor calibrated with respect to wavelength.

Landsat-band radiometers.—Four-band radiometers (Exotech Model 100) with the same spectral bands as the Landsat MSS were operated by Purdue University and Texas A & M University to acquire measurements in selected fields at the Finney County and Williams County test sites to support canopy modeling studies. In addition, during 1977, measurements were made throughout the growing season of the plots at the Williston experiment station, using a radiometer mounted on a lightweight van. These measurements, made at hourly intervals, are being used to investigate the diurnal variation in reflectance of wheat.

Meteorological and atmospheric sensors.—Standard meteorological instrumentation was used to obtain measurements of temperature, humidity, windspeed and wind direction, barometric pressure, and total irradiance. Solar radiometers were used to obtain optical depth measurements in six visible and infrared bands during Landsat overpasses and during aircraft and helicopter missions.

Sensor Calibration and Correlation

A key objective of the LACIE Field Measurements Project was the acquisition of calibrated multispectral data. Calibrated data are required to (1) facilitate comparisons of data from different sensors and (2) compare and relate spectral measurements made at one time and location to those made at other times and locations.

FIGURE 7.—Field spectroradiometer system operated by LARS making spectral measurements of small-grains plots.

To have comparable data, scene reflectance was chosen as the measured property rather than scene radiance. Scene reflectance is a property only of the scene, whereas scene radiance is a property of the illumination also. Calibration largely removes the effects of varying illumination and measurement conditions because of changing Sun angle, atmospheric conditions, and sensor. The bidirectional reflectance distribution function gives the most complete description of the reflectance characteristics of a surface. However, because this property is difficult to measure, more common use is made of the reflectance factor.

Reflectance factor is defined as the ratio of incident radiant flux reflected by a sample surface to that which would be reflected into the same reflected beam geometry by a perfectly diffuse (Lambertian) standard surface identically irradiated and viewed (ref. 6). Because the principal component of the irradiance is direct solar irradiance and the measurement is made in a relatively small cone angle (15° to 20°), the term "bidirectional reflectance factor" is used to describe the measurement. One of the directions is specified by the solar zenith and azimuth angles; the other is specified by the zenith and azimuth viewing angles.

Because no perfectly reflecting diffuser is available, painted barium sulfate ($BaSO_4$) reference surfaces, which are highly diffuse, were used (ref. 7). The spectral bidirectional reflectance factor of these surfaces was measured in both the laboratory and the field by processes that are traceable to the reflectance of pressed barium sulfate (fig. 8). A correction using the published reflectance of the pressed barium sulfate enables the computation of an approximation of the bidirectional reflectance factor.

Because of the presence of skylight, the measurement is not strictly bidirectional. The process of eliminating skylight by subtracting the spectral response of the shadowed scene and shadowed standard has merit in that it could remove the effects of the skylight. However, the additional measurements and calculations add uncertainty to each computed reflectance. This uncertainty is greater than the effect itself (ref. 8). Furthermore, because the interest of the project was in producing data directly relatable to satellite data, which includes the effects of the skylight, the single comparison method was used. Because the dominant effects are due to the directional nature of the irradiance, the term "bidirectional reflectance factor" is appropriate to describe the measurements.

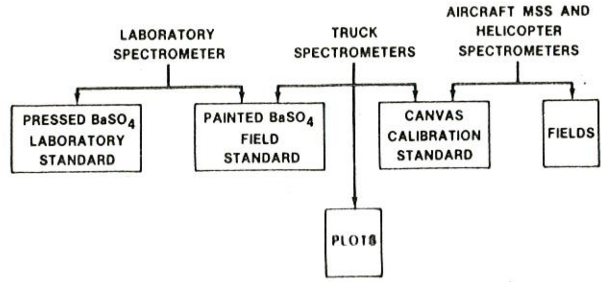


FIGURE 8.—Schematic of the procedures used for reflectance calibration of LACIE field measurements data.

Calibration of truck-mounted spectrometer systems.—Temperature variations, dust, vibration, and other adverse factors associated with field measurements require that calibration be performed at the field site. The procedures chosen reflect the availability of suitable standards and the principle that the calibration measurements be obtained under the same conditions as the target measurements.

The short-wavelength unit was calibrated for spectral reflectance factor. A standard based on the highly reflecting properties of barium sulfate was used as a basis for the reflectance factor calibration. The standards were prepared according to procedures described by Shai and Schutt (ref. 7).

The painted barium sulfate field standard was used to fill the field of view of the instrument under nearly the same conditions as for the measurement of plots. For the simplest calibration, the response to the standard, the response to the scene, the full-dark response (automatically provided during each spectral scan), and the spectral reflectance properties of the standard are used to compute the bidirectional reflectance factor. Since it is inconvenient to make this direct comparison for each measurement, the solar port is frequently used to transfer the reflectance standard for the LARS Exotech 20C system.

The calibration calculation consists of forming the ratio of the instrument response for the target to that for the reflectance standard and correcting for the known reflectance of the standard. This procedure produces a reflectance factor for the given Sun angle and normal viewing of the target.

During the calibration observations, the instrument was aimed straight down at the reflectance standard from a distance of 2.4 meters for the Exotech 20C system and 1 meter for the FSAS system. Care was taken to ensure that the standards were not shadowed and that the illumination conditions were as similar as possible to the conditions of the observation of the subject. Calibration observations were performed at approximately 15-minute intervals.

Wavelength calibration of the reflective wavelength unit was accomplished by irradiating the solar port with sources having known spectral lines (ref. 9). The primary sources are the General Electric A100.H4T mercury vapor lamp and the helium Pluecker tube. A field wavelength calibrator based on the helium tube was chosen for use because it has at least one strong line in the range of each section of the circular variable filters.

Calibration of the helicopter-borne FSS.—The helicopter-borne spectrometer was calibrated using a 60-percent reflectance canvas panel and the measurements made by the truck-mounted spectrometer of the canvas panel. These in turn were related to the measurements of the barium sulfate painted panels and the pressed barium sulfate standard.

The calibration procedure used deals with limitations imposed by the size and location of the standard by calibrating the instrument at a low altitude (6 meters) and collecting data over the flightlines at 60 meters. This procedure assumes that atmospheric absorption and path radiance are negligible for a 60-meter path.

The absence of an onboard solar sensor integrated into the instrument makes it desirable that calibrations be performed as frequently as possible. Therefore, the reflectance panels were centrally located and procedures were followed which allowed calibration within 15 minutes of any data acquisition (beginning of each flightline of data collection).

The data processing facility converts the FSS data to bidirectional reflectance factor based on the measurements made of the barium sulfate standard and the canvas panel. The calibration calculation consists of forming the ratio of the FSS response for the target to that for the canvas standard and correcting for the measured reflectance of the canvas standard. This procedure produces a reflectance factor for the given solar illumination angle and normal viewing of the subject.

Field calibration of the FSS with respect to emissive radiation was accomplished by recording spectral observations of a blackbody at a temperature below ambient and another blackbody at a temperature above ambient. The subsequent scans of subject scenes were converted to spectral radiance using linear interpolation.

Calibration of airborne MSS data.—The reflective data from the airborne MSS can be calibrated to reflectance using the five gray canvas panels located at the site and the spectral bidirectional reflectance factor measurements made by the truck-mounted spectrometers over the canvas panels. The nominal reflectances of the panels are 6, 12, 18, 30, and 60 percent.

The gray panel reflectance factor and MSS response data collected at low altitude (500 meters above the panels) can be related through linear regression. The regression equation can then be used to transform the low-altitude airborne MSS data to bidirectional reflectance factor. Fields overflown at the lower altitude can, in turn, be used as calibration targets to transform higher altitude data to bidirectional reflectance factor.

The emissive MSS data can be calibrated by means of the two blackbodies at known temperatures located in the scanner and viewed with each scan of the scene.

Sensor correlation procedures.—The three major sensor systems—the truck-mounted spectrometers, the helicopter-borne spectrometer, and the aircraft MSS—can be correlated using the spectral data collected by each system over common targets; i.e., five 6- by 12-meter gray canvas panels (fig. 9). The aircraft scanner collected data over the panels during each mission. The helicopter and truck spectrometer systems measured the reflectance of the four darker gray panels during correlation experiments performed during each crop year. The calibration measurements made of the brightest canvas calibration panel by the helicopter and truck spectrometer systems were also used in correlating the sensors.

All the spectrometers were brought together in 1977 for complete calibration and correlation. This included measurement of common targets and reflectance standards (fig. 10), comparison of data collection procedures, and evaluation of instrument performance.

Data Acquisition

The collection of multispectral remote-sensing, agronomic, and meteorological data for the intensive test sites and agriculture experiment stations is described in this section.

Intensive test sites.—This section discusses spectral data collection procedures and the measurements and observations of crop, soil, and meteorological parameters in the intensive test sites.

Spectral data collection: Helicopter-borne FSS, airborne MSS, and tripod-mounted radiometer data

FIGURE 9.—Canvas gray-level panels used for correlation of spectrometer systems and calibration of aircraft scanner data.

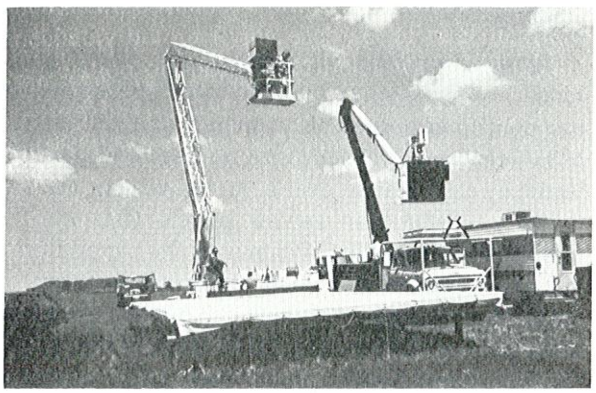


FIGURE 10.—Truck-mounted spectrometer systems operated by LARS and JSC preparing to measure the reflectance of the canvas calibration panel in a sensor correlation experiment. The common target was measured simultaneously by these systems, as well as by the helicopter spectrometer, to relate the instrument responsivities.

were collected within a 3- or 4-day mission window. Whenever possible, data were obtained on the same day and time as the Landsat overpasses.

The helicopter spectrometer data were obtained under stable atmospheric conditions with 20 percent or less cloud cover at solar elevation angles greater than 30°. At the test site, six 9.7-kilometer flightlines were flown by the helicopter in three sets of two lines. Flightlines were flown at an altitude of 60 meters, at 100 km/hr groundspeed, and in an east-west direction. Reference panel calibration measurements were made from a 6-meter altitude immediately before flying each set of two flightlines. Correlation of spectra and fields was accomplished using simultaneously acquired 70-millimeter color photography. A total incidence pyranometer was located at the helicopter calibration site to provide a strip-chart record of the irradiance conditions on the day of data acquisition (usually beginning 1 hour before and ending 1 hour after the data acquisition period). These strip charts provide the data analyst with a visual record of the irradiance conditions at the site during helicopter and MSS data acquisition.

The airborne scanner system acquired data over the intensive test sites and agriculture experiment stations concurrently with data collection by the helicopter spectrometer. The intensive test sites were overflown at 3300- and 7000-meter altitudes and the experiment stations and calibration panels at 500 meters. Collecting data at the two altitudes over the test site flightlines provided different spatial resolutions and different amounts of atmosphere between the scene and sensor. Data collection requirements specified that cloud cover be less than 30 percent and solar elevation greater than 30°. Color and color-infrared photography (23 centimeters) was obtained simultaneously with the scanner data.

A Landsat-band radiometer mounted on a 2-meter tripod was used to collect data from one to three fields in the Finney County and Williams County test sites. The measurements were made at four times during the day to provide four different Sun angles. A painted barium sulfate field standard was measured between the measurements of the canopy. The spectral measurements include wheat canopy reflectance, soil reflectance, the ratio of diffuse to total irradiance, and leaf transmittance. Canopy description data include leaf area index, biomass, number of tillers and leaves, and photographs. The photographs include vertical and 45° views and plant profile scenes. When possible, these data were acquired at five maturity stages (seedling, tillering, jointing, flowering, and ripe) at several locations in typical fields.

Agronomic data collection: Agronomic measurements and observations were acquired describing the condition of each of the fields for which spectral data were collected. These agronomic data describe the condition of each field as fully as possible and are used to account for differences in the spectral measurements. The data were recorded on standard forms, keypunched, and transmitted to LARS for inclusion in the data bank. Data describing all fields in the intensive test sites were collected by USDA ASCS (ref. 10). The following data were collected during the spring and fall inventories: field number, acreage, crop species and variety, irrigation, fertilization, planting date, and other descriptive information.

Periodic observations coinciding with Landsat overpasses and aircraft/helicopter missions were made to describe the condition of the fields. The variables observed were maturity stage, percent soil cover, plant height, surface moisture condition, stand quality, quality relative to other fields in the site, field operations, density of stand, weed infestation, and growth/yield detractants. Vertical 35-millimeter photographs were taken, and additional descriptive comments were added as appropriate. Grain yields of selected fields were measured at harvest time.

Meteorological data collection: The following atmospheric and meteorological measurements were made in conjunction with FSS and aircraft scanner data collection at the intensive test sites: percentage and type of cloud cover, wet and dry bulb temperature, barometric pressure, total irradiance, windspeed and wind direction, and optical depth at seven visible and near-infrared wavelengths. Daily measurement records of temperature, precipitation, relative humidity, soil temperature, and wind were obtained from the nearest weather station. In addition, rainfall was recorded at six to eight locations in each test site.

Agriculture experiment stations.—The collection of spectral, agronomic, and meteorological data at the agriculture experiment stations is described in this section.

Spectral data collection: The spectral data at the agriculture experiment stations were collected by JSC at Garden City, Kansas, and by LARS at Williston, North Dakota. The primary sensors were the Block wideband field interferometer and the Exotech Model 20C field spectroradiometer. During 1975, an Exotech Model 20D similar to the Model 20C was operated by the NASA Earth Resources Laboratory at Garden City. These were augmented by Barnes PRT-5 precision radiation thermometers boresighted with the spectrometers. To obtain data that could be readily compared, the interferometer and spectroradiometer were operated following similar procedures. The instruments were operated from their aerial towers at 6 meters above the target to minimize the shadowing of skylight and yet ensure that the field of view of the instrument contained only the subject of interest. Care was taken to avoid scene shadowing and to minimize the reflective interaction caused by personnel or vehicles. The routine data-taking mode of the instruments is straight down. Two measurements of each plot were made by moving the sensor so that a new scene within the plot filled the field of view.

To minimize the effect of solar elevation changes on the spectral response, measurements were made only when the Sun angle was greater than 45° above the horizon in the late spring and summer and greater than 30° in the late fall and early spring.

Data recorded at the time of each measurement included date, time, reference illumination, air temperature, barometric pressure, relative humidity, windspeed and wind direction, percentage and type of cloud cover, field of view, latitude, longitude, and zenith and azimuth view angles. Periodically during the day, spectral measurements of skylight were recorded by spectrometers with a solar port. A 35-millimeter color photograph of each observation was taken from the aerial tower, as were oblique ground-level photographs of each plot.

Agronomic data collection: Crop and soil information for the plots at the research stations were collected at Garden City by JSC with assistance from the agriculture experiment station personnel and at Williston by LARS. At the beginning of the season, information describing the species and cultivar, irrigation practices, fertilization history, soil type, and planting date was obtained for each plot.

Observations made at the time of each mission for each plot included maturity stage; plant height; percent soil cover; surface soil moisture and roughness; stand quality; field operations such as cultivation or harvesting; stress factors (insect damage, disease, nutrient deficiencies, moisture stress, weeds, or lodging); leaf area index; number of stems, leaves, and heads; fresh weight of plants; dry weights of stems, leaves, and heads; and soil moisture profile. Vertical and oblique 35-millimeter color photographs were taken, and grain yields were measured at harvest time.

Meteorological data collection: Percentage and type of cloud cover, wet and dry bulb temperature (or relative humidity), barometric pressure, total irradiance, and windspeed and wind direction were measured in conjunction with the truck-mounted spectrometer data collection. Daily measurement records of air temperature, humidity, radiation, wind, precipitation, and soil temperature were also obtained from the nearest weather station.

Summary of data acquisition missions.—Table IV summarizes the data acquisition for the 1976 crop year at Finney County, Kansas, and Williams County, North Dakota, for the major sensors involved in this information cannot be applied directly to the field situation because there are significant differences between the spectra of single leaves and the spectra of canopies. The reflectance characteristics of canopies are considerably more complex than those of single leaves because in canopies there are many more interacting variables. Some of the more important agronomic parameters influencing the reflectance of field-grown canopies are leaf area index, biomass, leaf angle distribution, leaf color, percent soil cover, and soil color. Differences in these parameters are caused by variations in many cultural and environmental factors, including planting date, cultivar, seeding rate, fertilization, soil moisture, and temperature.

The data analysis phase of the LACIE field research began in 1976 by addressing several of the LACIE critical issues, particularly the discrimination of wheat and small grains. More recently, the analyses have been extended to address objectives related to future crop inventory systems, such as the use of remote sensing to gather information about crop condition and yield. Because it would not be possible to describe adequately the results of all the investigations, several studies that are representative of the types of investigations that have used field measurements data have been selected for this report.

Several of the other studies that have used the LACIE field measurements data are briefly summarized here. Landgrebe et al. (ref. 17) used the spectrometer and MSS data to simulate and evaluate alternative combinations of scanner system parameters for the thematic mapper, such as the instantaneous field of view and signal-to-noise ratio. A comparison of the Landsat MSS and thematic mapper wavelength bands for crop identification has been made by Bauer et al. (ref. 8). The thermal measurements from the helicopter spectrometer have been examined by Harlan et al. (ref. 18), and Bauer et al. (ref. 8) developed a model describing the radiant temperature characteristics of spring wheat canopies in relation to the geometry of the canopy and environmental variables. As part of the LACIE field measurements research, Vanderbilt et al. (ref. 19) developed a method to obtain information on the geometrical properties of crop canopies needed for canopy reflectance and radiant temperature models. Berry and Smith (ref. 20) used LACIE field measurements data to test a canopy reflectance model to predict the spectral response in the Landsat MSS wavelength bands of winter wheat with varying amounts of leaf area and as a function of Sun angle. A nondestructive method to estimate leaf area index involving analysis of digitized aerial photographs was developed by Harlan et al. (ref. 18).

Objectives

Of the research objectives listed in the second section of this paper, the following are addressed as examples of current research results from LACIE field measurements.

1. To determine the relationship of agronomic variables such as biomass and leaf area index to multispectral reflectance of spring wheat
2. To determine the effects of cultural and environmental factors on the spectral response of wheat
3. To assess the spectral discriminability of spring wheat and other small grains
4. To determine the early-season threshold for detection of wheat
5. To compare and evaluate the Landsat MSS and thematic mapper bands for prediction of crop canopy variables

The results obtained to date for these objectives are presented in subsequent sections, following a summary of the approach used.

Experimental Approach

The data used for the analyses in this report were acquired during 1975 and 1976 in Kansas and North Dakota by the helicopter- and truck-mounted spectrometer systems at approximately 10- to 14-day intervals during the wheat growing seasons. Bidirectional reflectance factor and agronomic data were acquired in approximately 75 fields from each of the intensive test sites and 60 plots from the agriculture experiment stations.

Correlation and regression analyses were used to relate biological and physical variables describing the canopies to spectral response. To relate the reflectance measurements more directly to Landsat, the analyses were performed using reflectance data averaged into bands corresponding to the Landsat MSS and thematic mapper spectral bands. The "tasseled-cap" transformation (ref. 21) was also used to determine the greenness and brightness components of the Landsat MSS band reflectances for some of the analyses.

Relation of Landsat and Field Measurements of Spectral Response

Frequently the question is asked whether results from analyses of field measurements data can be related to and applied to Landsat MSS data. To help answer this question, analyses of the relationship between Landsat MSS data and helicopter spectrometer measurements of the spectral response were performed (ref. 22). Landsat data for 135 fields and 5 dates were correlated with the reflectances measured by the helicopter spectrometer. The Landsat data were first adjusted using the XSTAR algorithm (ref. 23) to minimize differences among the five dates in Sun angle and atmospheric conditions. As shown in figure 12, for MSS band 4 (0.5 to 0.6 micrometer), the two sets of measurements are highly correlated; similar relationships were found for the other spectral bands. Using empirical relationships such as these, or results of radiative transfer modeling (ref. 24), crop discriminability can be predicted by relating measured reflectance differences to corresponding differences in Landsat signals.

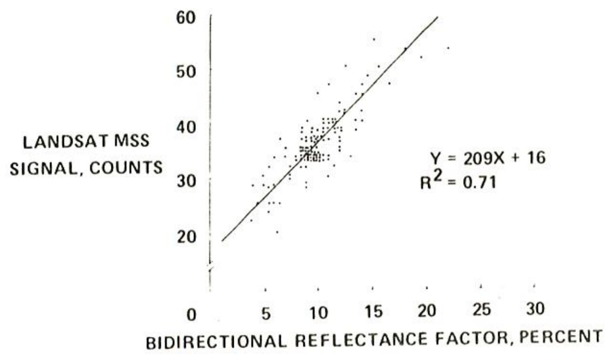


FIGURE 12.—The relation of Landsat MSS and helicopter spectrometer measurements of spectral response for five acquisition dates in Finney County, Kansas (MSS band 4, 0.5 to 0.6 micrometer).

Prediction of Crop Canopy Characteristics From Reflectance Measurements

One of the major long-term goals of agricultural remote sensing is to estimate from spectral measurements crop variables that can subsequently be used to assess crop vigor or be entered into a yield prediction model. To achieve this goal, the complex relationship between the spectral reflectance of crop canopies and their biological and physical characteristics must be understood.

One of the LACIE field research objectives (ref. 25) was to determine the relationship of canopy characteristics to reflectance and to assess the potential for estimating these characteristics from remotely sensed measurements of reflectance. The variables selected for analysis are indicators of crop vigor and growth, which could be used to augment agromet models of crop growth and yield.

This section treats the effect of varying amounts of vegetation and of maturity stage on the spectra of spring wheat canopies, the relation of canopy variables to reflectance in different regions of the spectrum, and the potential capability to predict canopy variables from reflectance measurements. As part of the analysis, the wavelength bands of current and proposed satellite MSS systems were compared. The measurements were made at the Williston, North Dakota, Agriculture Experiment Station on nine different dates during the summer of 1976.

The amount of vegetation present is one of the principal factors influencing the reflectance of crop canopies. Figure 13 illustrates the effect of the amount of vegetation (as measured by leaf area index, percent soil cover, biomass, and plant height) on the spectral response during the period between tillering and the beginning of heading, when the maximum green-leaf area is reached. As leaf area and biomass increase, there is a progressive and characteristic decrease in reflectance in the chlorophyll absorption region, increase in the near-infrared reflectance, and decrease in the middle-infrared reflectance.

Plant development and maturity (as opposed to growth or increase in size) cause many changes in canopy geometry, moisture content, and pigmentation of leaves. These changes are also manifested in the reflectance characteristics of crop canopies. Figure 14 shows the spectra of spring wheat at several different maturity stages (changes in the amount of vegetation are also occurring).

The linear correlations of five canopy variables with reflectances in the proposed thematic mapper (Landsat D) and Landsat MSS bands are listed in table V. The relationships of percent soil cover, leaf area index, fresh biomass, and plant water content with reflectance in selected wavelength bands are shown in figure 15. The correlations and plots include data from all treatments for the stages of maturity when the canopy is green, seedling through flowering.

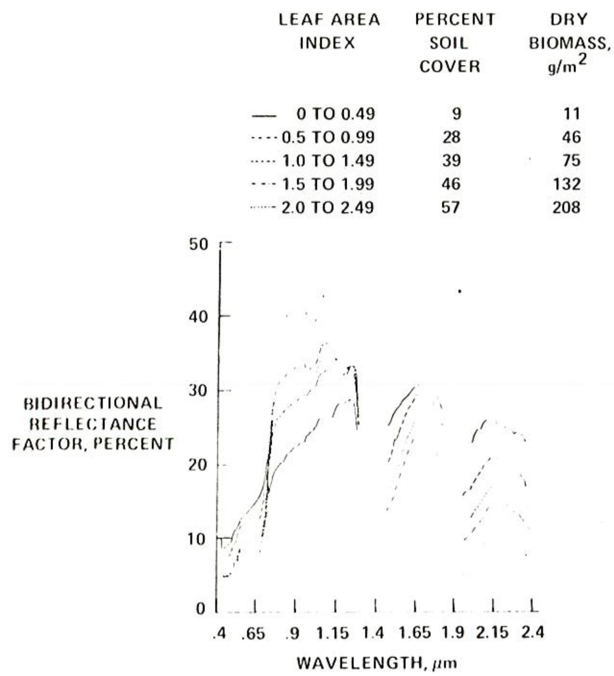


FIGURE 13.—Effect of leaf area index, percent soil cover, dry biomass, and plant height on the spectral reflectance of spring wheat during the period between tillering and the beginning of heading, when the maximum green-leaf area is reached. Data were acquired at Williston, North Dakota, from May 28 to June 18, 1976, and include plots with different soil moisture levels, planting dates, nitrogen fertilization, and cultivars.

TABLE V.—The Linear Correlations (r) of Reflectances in the Proposed Thematic Mapper and Landsat MSS Wavelength Bands With Percent Soil Cover, Leaf Area Index, Fresh and Dry Biomass, and Plant Water Content

Wavelength band, μm	Percent soil cover	Leaf area index	Fresh biomass	Dry biomass	Plant water content
			Thematic mapper		
0.45 to 0.52	−0.82	−0.79	−0.75	−0.69	−0.76
0.52 to 0.60	−.82	−.78	−.81	−.77	−.82
0.63 to 0.69	−.91	−.86	−.80	−.73	−.81
0.76 to 0.90	.93	.92	.76	.67	.79
1.55 to 1.75	−.85	−.80	−.83	−.79	−.84
2.08 to 2.35	−.91	−.85	−.86	−.81	−.86
			Landsat MSS		
0.5 to 0.6	−0.82	−0.79	−0.81	−0.76	−0.81
0.6 to 0.7	−.90	−.85	−.81	−.74	−.82
0.7 to 0.8	.84	.84	.57	.46	.60
0.8 to 1.1	.91	.90	.77	.68	.79

Fresh biomass, dry biomass, and plant water content correlate most highly (table V) with reflectance in the middle-infrared band, 2.08 to 2.35 micrometers. Percent soil cover and leaf area index correlate most highly with a near-infrared band, 0.76 to 0.90 micrometer. The visible wavelengths were less sensitive to leaf area and biomass; similar results have also been reported by Colwell (ref. 26) and Tucker (ref. 27). Other canopy variables analyzed that were not correlated with reflectance were plant height, percent green leaves, and percent plant moisture.

These and other analyses of the data indicate that the amount of photosynthetically active (green) vegetation has a dominant influence on the reflectance characteristics of crop canopies. This observation is substantiated by the decrease in the correlation of canopy variables and reflectance as the canopy begins to senesce or ripen (refs. 25 and 28).

Understanding the relation of the agronomic properties of crop canopies to reflectance in various regions of the spectrum is the first step in the development of models using spectral measurements. The remainder of this section describes the regression models developed for prediction of crop growth characteristics.

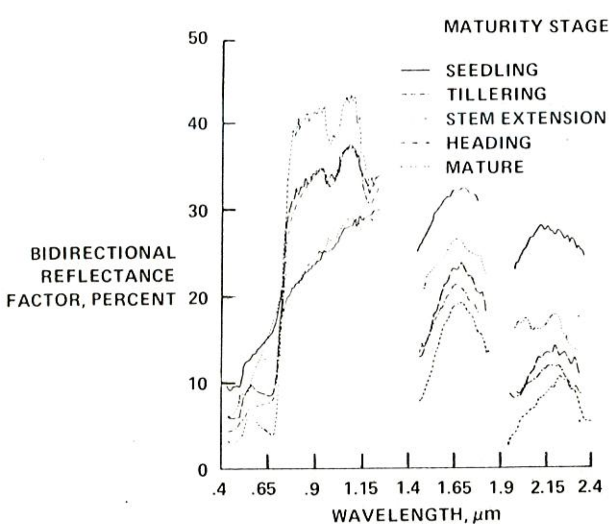


FIGURE 14.—Spectral reflectance of spring wheat canopies at several maturity stages. Measurements were made at Williston, North Dakota, from May to August, 1976, and include plots with different soil moisture levels, planting dates, nitrogen fertilization, and cultivars.

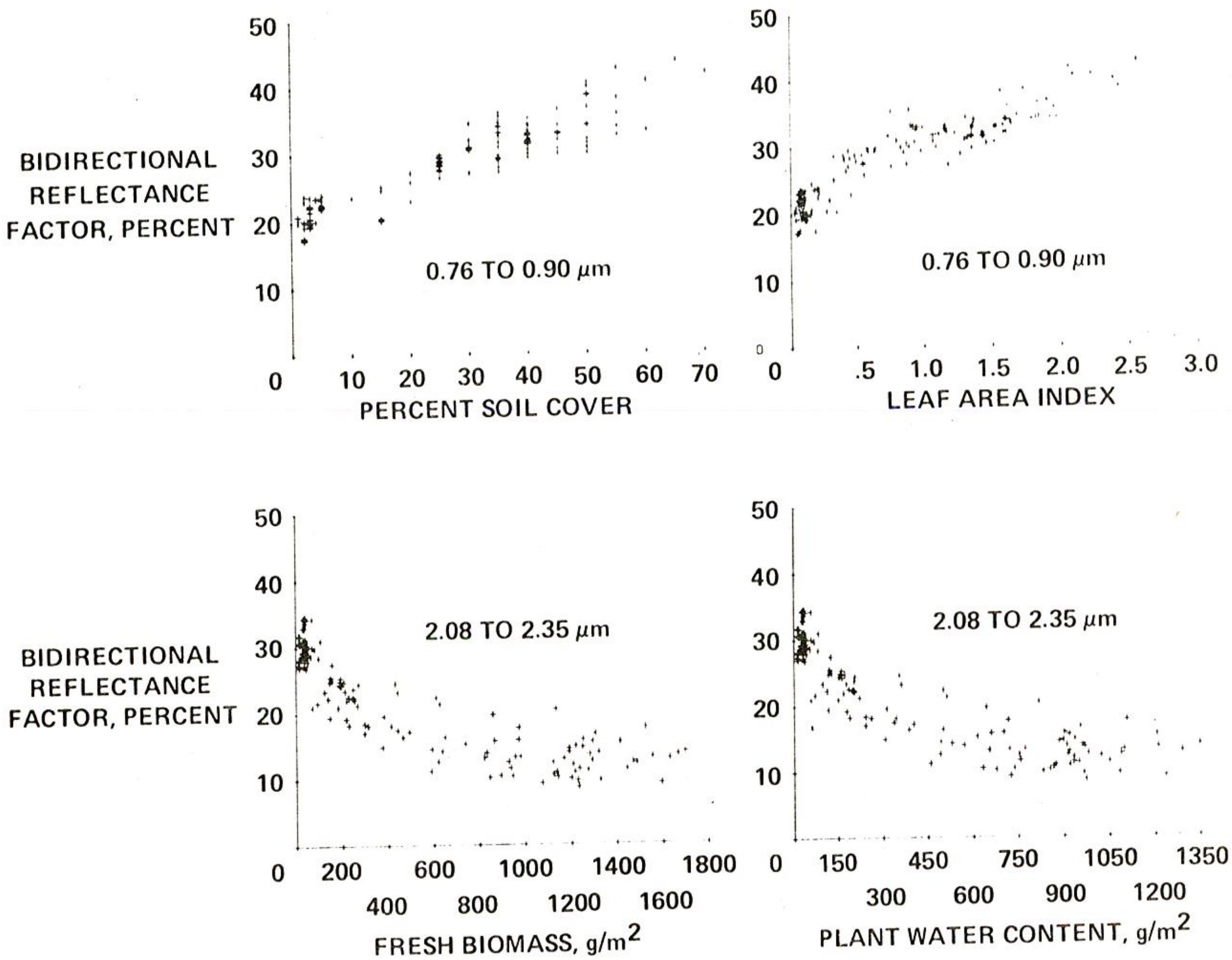


FIGURE 15.—Relationship of percent soil cover, leaf area index, fresh biomass, and plant water content to reflectance in selected wavelength bands.

Table VI shows results for selections of one to six wavelength bands to predict canopy variables. By computing all possible regressions, the best subset of one to six wavelength bands was selected, considering the amount of variability explained and the bias of the resulting regression equation. The near- and middle-infrared bands were found to be most strongly related to the canopy variables. For leaf area index and percent soil cover, the 0.76- to 0.90-micrometer wavelength band accounts for more of the variation than any other single band. The 2.08- to 2.35-micrometer wavelength band is the single most important band for predicting the variation in fresh biomass, dry biomass, and plant water. The 2.08- to 2.35-micrometer wavelength band is one of the two most important bands in explaining the variation in percent soil cover and one of the three most important bands in explaining the variation in leaf area index.

The relationships between the measured and predicted leaf area index and percent soil cover are shown in figure 16. Similar results were obtained for the other canopy variables. The results show that reflectance measurements in a small number of wavelength bands in important regions of the spectrum can explain much of the variation in canopy characteristics and can be used to estimate canopy variables such as leaf area index and biomass.

Table VII shows the maximum R^2 value obtained for predictions of each canopy variable using the Landsat MSS bands, the best four thematic mapper bands, and all six reflective thematic mapper bands. In every case, the best four thematic mapper bands explained more of the variation in a canopy variable

TABLE VI.—*Selection of Combinations of the Best 1, 2, . . . 6 Wavelength Bands for Estimating Percent Soil Cover, Leaf Area Index, Fresh Biomass, Dry Biomass, and Plant Water Content During the Seedling to Flowering Stages of Crop Development*

Canopy variable	*No. bands entered*	R^2	C_p (a)	*Bands entered, μm*					
				0.45 to 0.52	*0.52 to 0.60*	*0.63 to 0.69*	*0.76 to 0.90*	*1.55 to 1.75*	*2.08 to 2.35*
Percent soil cover	1	0.86	132				X		
	2	.92	16				X		X
	3	.92	15	X			X		X
	4	.93	4	X	X		X		X
	5	.93	5	X	X	X	X		X
	6	.93	7	X	X	X	X	X	X
Leaf area index	1	.84	37				X		
	2	.87	7				X	X	
	3	.88	2				X	X	X
	4	.88	4	X			X	X	X
	5	.88	5	X	X		X	X	X
	6	.88	7	X	X	X	X	X	X
Fresh biomass	1	.73	239						X
	2	.76	211		X				X
	3	.83	109		X	X			X
	4	.88	41		X	X	X		X
	5	.90	12	X	X	X	X		X
	6	.93	7	X	X	X	X	X	X
Dry biomass	1	.65	252						X
	2	.67	229	X	X				
	3	.81	78		X	X			X
	4	.84	44		X	X	X		X
	5	.87	20	X	X	X	X		X
	6	.88	7	X	X	X	X	X	X
Plant water content	1	.75	201						X
	2	.77	175		X				X
	3	.83	98	X	X		X		
	4	.88	34		X	X	X		X
	5	.90	9	X	X	X	X		X
	6	.90	7	X	X	X	X	X	X

[a]The regression equation is unbiased when the C_p value is less than or equal to the number of terms (wavelength bands) in the equation.

than the four Landsat bands. Addition of the other two thematic mapper bands resulted in small increases in the R^2 values.

The lower correlations (table V) and predictions (table VII) of the Landsat MSS bands compared to the thematic bands are attributed to the width and location of the bands with respect to the spectral characteristics of vegetation. For example, the data in table V demonstrate a disadvantage of collecting data in the 0.7- to 0.8-micrometer wavelength range. The inclusion in this band of the region (near 0.7 micrometer) of rapid transition from the chlorophyll absorption region of the spectrum to the highly reflecting near-infrared region (0.70 to 0.74 micrometer) results in a weaker relation between reflectance and crop canopy variables. Similar results were reported by Tucker and Maxwell (ref. 29). This low correlation reduces the usefulness of the data in the 0.7- to 0.8-micrometer wavelength band.

Effect of Agronomic and Environmental Factors on Spectral Reflectance

The crop canopy is a dynamic entity influenced by many agronomic and environmental factors. The

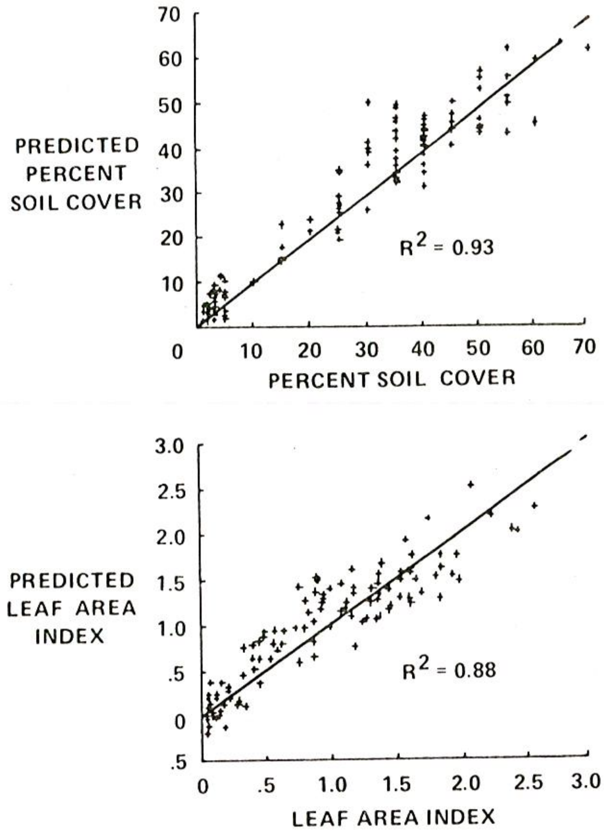


FIGURE 16.—Comparison of measured and predicted percent soil cover and leaf area index of spring wheat.

effects of several cultural and environmental factors on the reflectance of spring wheat were investigated using data acquired at the Williston, North Dakota, Agriculture Experiment Station. The examples of spring wheat spectra from selected measurement dates shown in figure 17 illustrate the effects of available soil moisture, planting date, nitrogen fertilization, and cultivar. Additional examples of crop spectra from the other test sites, crops, and years have been compiled by Hixson et al. (ref. 30).

The Waldron (standard height) cultivar planted early on fallow land with nitrogen fertilization was selected as a standard of comparison. One treatment at a time was varied from this standard, permitting comparisons of reflectance spectra measured on plots with different soil moisture levels, planting dates, fertilization, and cultivar. All treatment comparisons were made using spectra acquired on June 18, 1976, during the stem extension phase of development, except for the comparison of cultivars, which was on July 16, after heading.

In 1976, the effects of available soil moisture on plant growth and spectral response were quite significant. Wheat planted on fallow land had more tillers and, therefore, greater biomass, leaf area, and percent soil cover than the wheat crop grown on land that had been cropped the previous year. These differences account for the decreased visible reflectance, increased near-infrared reflectance, and decreased middle-infrared reflectance in the fallow treatment. The effect of planting date on spectral response is also illustrated in figure 17. The differences are attributed to differences in the amount of vegetation present, as well as differences in maturity stage.

Adding nitrogen fertilizer increased the amount of green vegetation early in the growing season. The fertilized treatment had the spectral characteristics of a greener, denser vegetative canopy—decreased red reflectance, slightly greater near-infrared reflectance, and reduced middle-infrared reflectance.

The two wheat cultivars, Olaf (semidwarf, awned) and Waldron (standard height, awnless), were similar in appearance before heading. After heading, some differences between the two cultivars were apparent but are probably not significant. The greatest spectral differences were in the middle infrared, indicating a difference in the moisture and biomass between the two cultivars at this growth stage.

In one analysis (ref. 22), one-way multivariate analyses of variance were performed on the Landsat MSS band reflectance data from individual plots of

TABLE VII.—The R^2 Values for Predictions of Percent Soil Cover, Leaf Area Index, Fresh and Dry Biomass, and Plant Water Content With Four Landsat MSS Bands, the Best Four Thematic Mapper Bands, and the Six Thematic Mapper Bands

Wavelength bands	*Percent soil cover*	*Leaf area index*	*Fresh biomass*	*Dry biomass*	*Plant water content*
Landsat MSS bands	0.91	0.86	0.86	0.84	0.85
Best four thematic mapper bands[a]	.93	.88	.88	.84	.88
Six thematic mapper bands	.93	.88	.91	.88	.90

[a]See table VI.

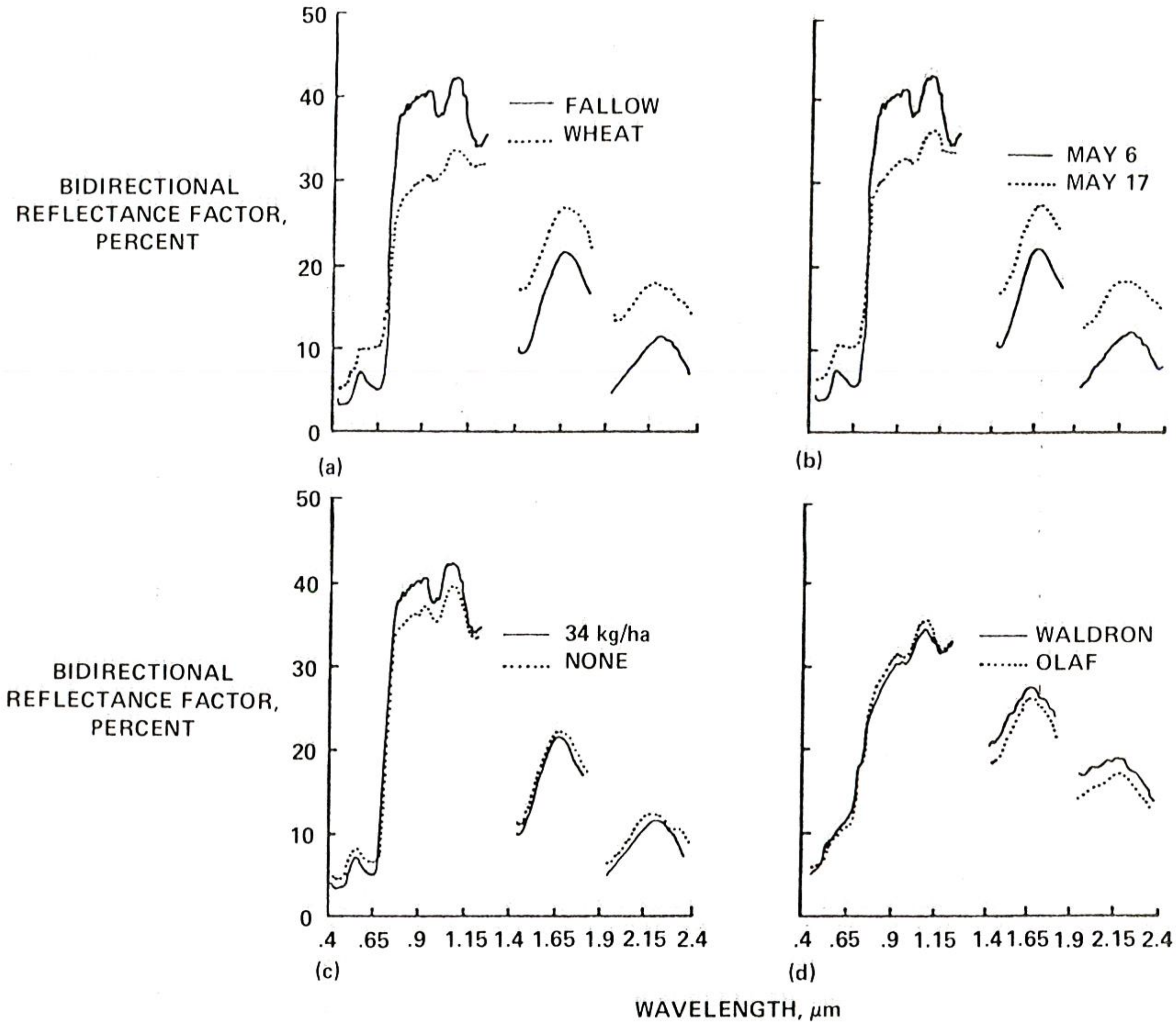


FIGURE 17.—Effects of agronomic treatments on the spectral reflectance of spring wheat. Spectra were measured on June 18 during the stem extension stage of development, except for the spectra of cultivars which were measured on July 16 after heading. (a) Previous crop. (b) Planting date. (c) Nitrogen fertilization. (d) Cultivar.

spring wheat using data from the entire season. Soil moisture availability was found to be the most significant factor. A decreased moisture supply, caused by planting wheat for a second year in succession on the same plot, both decreased the magnitude of green development from that of wheat planted on fallow ground and delayed the date of maximum greenness. A similar delay in maximum greenness was observed when the planting date was delayed by 10 days, but the difference in maximum greenness levels was not as pronounced as in the case where available soil moisture was reduced.

Figure 18 illustrates the effects of the soil moisture and nitrogen fertilization factors on the maximum values attained by the greenness and brightness components of reflectance for the small-grains test plots. Maximum greenness is most affected by soil moisture as plentiful soil moisture produces more vegetation, which covers the soil. Nitrogen fertilization was observed to affect the greenness component in a similar fashion, with the greening value of nitrogen fertilizer being very evident on those plots that were continuously cropped. Soil moisture also affected the brightness component.

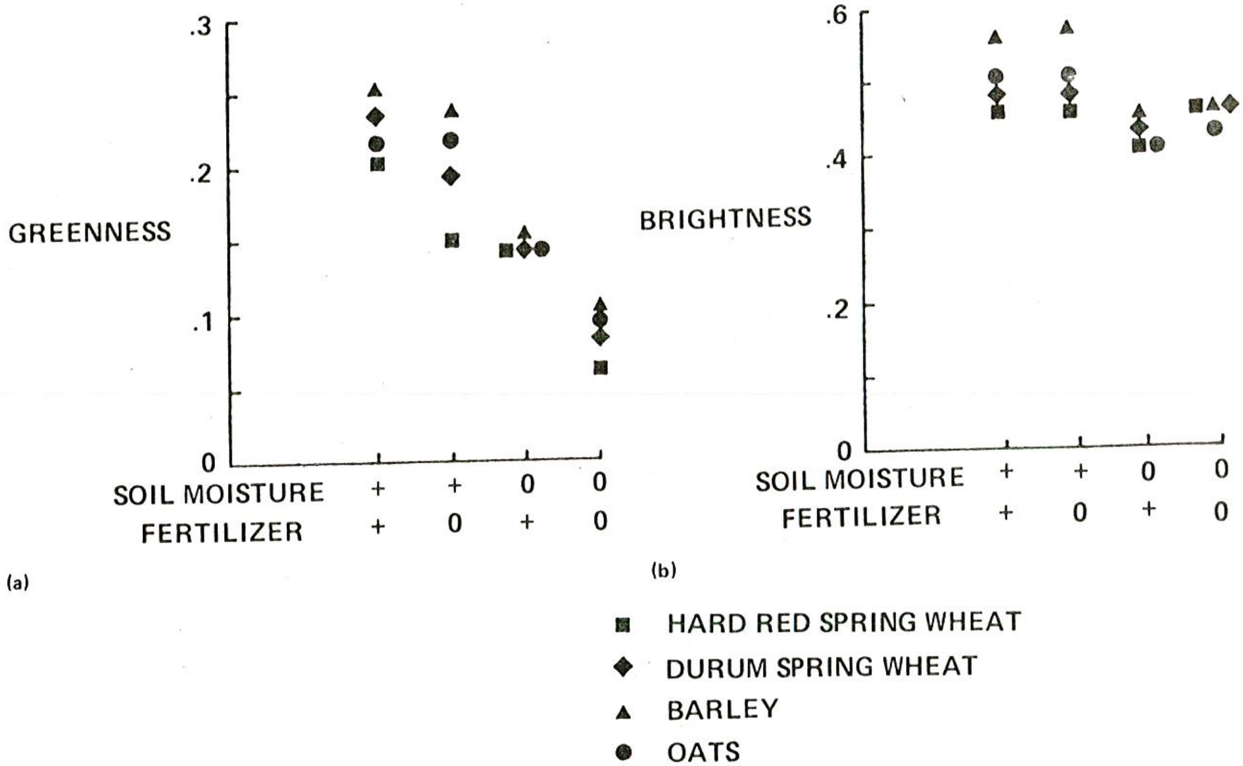


FIGURE 18.—Effects of soil moisture and nitrogen fertilization on the maximum greenness and brightness components of reflectance of small grains. (a) Maximum greenness, June 18. (b) Maximum brightness, July 29 to August 6.

These spectra and analyses illustrate the dynamic character of the canopy and the many factors that influence the spectral reflectance of the canopy. More quantitative analyses of the effect of agronomic treatments and environmental variables on reflectance of wheat are currently being conducted.

Spectral Discrimination of Spring Wheat From Other Small Grains

One of the critical issues that arose during LACIE was spectrally discriminating spring wheat from the other spring small grains. These crops have similar reflectance spectra and crop calendars; consequently, LACIE initially did not attempt to inventory them separately. Instead, a small-grains area estimate was obtained, and historical data on crop production were used to establish spring-wheat-to-small-grains ratios for producing a spring wheat estimate. It was found that these ratios could vary appreciably from year to year, introducing errors in the spring wheat estimates. Consequently, some supporting research effort was directed toward investigation of spectral techniques for achieving such discrimination (ref. 22). Although major emphasis was placed on analysis of Landsat data from LACIE blind sites, analysis of field measurement data played a strong supportive role, along with analysis of USDA crop statistics. Only data from the first 2 years were included in this analysis. An expanded small-grains experiment was conducted in 1977.

The objectives of the analyses of field measurements data on spectral reflectance of wheat and small grains were (1) to characterize the spectral reflectance of spring wheat and other small grains as a function of time throughout the growing season, (2) to characterize the sources and extent of variability to be expected, and (3) to develop discrimination techniques for distinguishing between spring wheat and other small grains through increased understanding of Landsat signals for these crops.

The change in spectral character of spring wheat reflectance at five maturity stages was illustrated in figure 14, while similarities and some differences of spring wheat, barley, and oats spectra on three dates are shown in figure 19. The spectral patterns throughout the growing season were determined for spring wheat and other small grains. One technique was to plot the time trajectories of transformed reflectance values for these crops and look for differences that might prove useful for discrimination. Linear combinations of values, analogous to the tasseled-cap transformation of Landsat data (see next section), were used to form greenness and brightness components of reflectance.

Figure 20 presents spectral trajectories for hard red spring wheat, barley, and oats; durum spring wheat is very similar to hard red spring wheat. Each trajectory is for a crop that had been planted on prior-year-fallowed soil (more available soil moisture than continuously cropped soil) and had been fertilized. Thus, they represent spectral patterns for the best growing conditions available at the experiment station. Although the general shapes of the spectral trajectories are similar, several differences can be seen among them; notably, barley attained greater values in both greenness and brightness before heading and its brightness upon ripening was greater than that of wheat. Less distinctiveness was observed in the spectral characteristics of other plots with crops that were grown under less favorable conditions (fig. 18).

An analysis of color photographs (fig. 21) and agronomic measurements (table VIII) made in conjunction with the spectral measurements helps to explain the physical causes of the observed spectral differences and variability. Grown under favorable conditions, the barley had greater biomass, leaf area index, and percent soil cover than spring wheat, resulting in higher maximum greenness values. The barley matured and ripened 1 week to 10 days before the spring wheat. Longer lighter colored awns, drooping heads, and greater soil cover all contributed to a greater maximum brightness for barley at maturity.

In summary, analyses of field measurements data provided insights into the causes of the spectral characteristics of spring wheat and barley that may prove useful for discrimination. For instance, differences in greenness and brightness at heading and brightness at ripening and the timing of these events appear key to their spectral discrimination. One preliminary operational technique for direct spectral classification of spring wheat was tested during LACIE Phase III and improved techniques are currently under development.

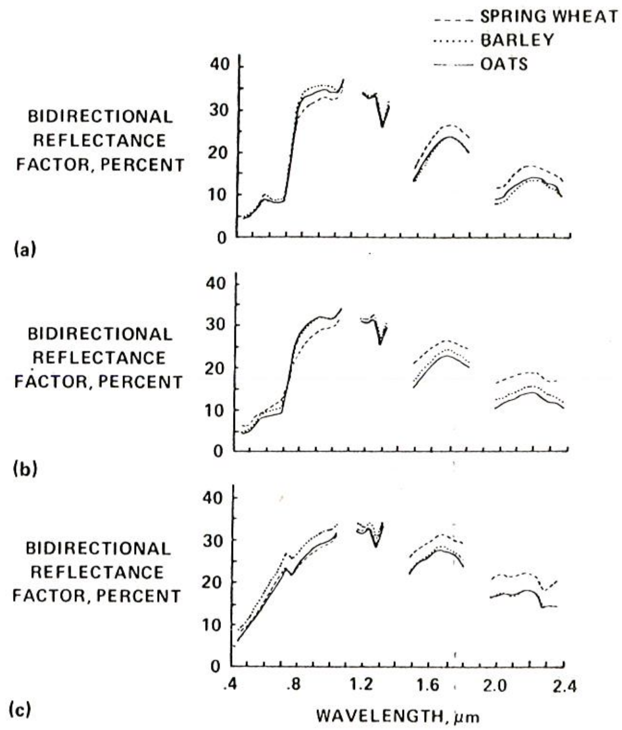


FIGURE 19.—Spectra of spring wheat, barley, and oats at stem extension, heading, and ripe stages of maturity. (a) Stem extension, June 18, 1976. (b) Heading, July 16, 1976. (c) Ripe, July 29, 1976.

Early-Season Detection of Wheat

In LACIE, it was found that early-season estimates of winter wheat area tended to be low and unreliable, because the emergence and development of green vegetative cover on the soil are variable because of differences in planting dates, crop rotation, irrigation and fertilization practices, and local weather.

A study was conducted using LACIE field measurement data to investigate the threshold of wheat detectability in Landsat data (ref. 22). Helicopter-spectrometer and agronomic data acquired for 10 dates during the 1975-76 growing season at the Finney County, Kansas, intensive test site were analyzed.

Figure 12 illustrated the reflectance spectra for fields with different amounts of vegetation. To relate these data to Landsat analysis, reflectance values for the Landsat MSS bands were computed. A useful technique for Landsat MSS data analysis has been to form linear combinations of the bands, defining a new coordinate system for describing the data. One such transformation, the tasseled-cap transforma-

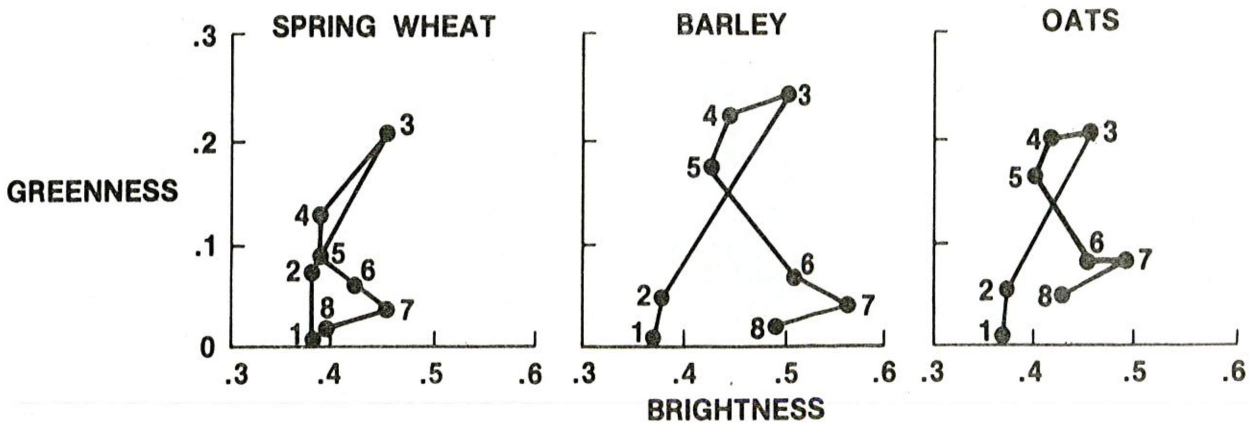


FIGURE 20.—Comparison of selected greenness-brightness trajectories of spring wheat, barley, and oats. The measurement dates and growth stages are as follows: (1) May 28, seedling; (2) June 3, tillering; (3) June 18, jointing; (4) July 8, heading; (5) July 15, milk; (6) July 29, dough; (7) August 1, ripe; (8) August 6, ripe. Note: Barley was in the milk stage on July 8 and was ripe by July 29.

tion, defines a brightness variable that alines closely with the direction followed by reflectances of varied soils. Orthogonal to brightness is the greenness variable, which is oriented toward the spectral response from healthy green vegetation. These two components describe most of the variability observed in Landsat scanner measurements of agricultural scenes (see the paper by Kauth et al. entitled "Feature Extraction Applied to Agricultural Crops as Seen by Landsat"). A principal components analysis of the reflectances revealed that 98 percent of the variability was in a plane analogous to the greenness and brightness plane for Landsat MSS data.

Four fields with different management practices were selected to illustrate the relationship of the greenness component of reflectance to measurement data (fig. 22). The absence of fall green development in the late-planted fields and the appreciable fall greening-up of the field that was irrigated and planted at the normal time are apparent.

The proportions of late- and early-planted fields and irrigated and nonirrigated fields will vary from site to site, as will other factors that determine development rates. Yet, it is of interest to determine both how the collection of wheat fields in the Finney County site developed in 1975-76 and how well they would have been detected by a decision rule that called them wheat if their greenness component of reflectance exceeded a given threshold by a given date.

To provide a quantification of the greening-up characteristics of this group of fields, histograms were computed to describe the percentage of fields exceeding a given greenness value as a function of acquisition date. Figure 23 displays these results in two ways: (1) with fixed threshold levels and varied dates and (2) with fixed dates and varied thresholds. With a threshold of 0.06, 95 percent of the wheat fields would have been detected on the eighth mission (May 6, 1976), 63 percent of them on the seventh mission (April 18), and 38 percent on the sixth mission (March 31). For a lower threshold of 0.04, the corresponding percentages would have been 100,

TABLE VIII.— Agronomic Characteristics of Small Grains on Three Measurement Dates at Williston, North Dakota, Agriculture Experiment Station[a]

Date	*Small grains*	*Percent soil cover*	*Leaf area index*	*Fresh biomass, g/m²*	*Maturity stage*[b]
June 18	Spring wheat	50	1.5	567	3.3
	Barley	90	2.9	1326	3.4
	Oats	80	2.0	1022	3.4
July 16	Spring wheat	30	.7	1162	5.1
	Barley	70	1.3	1686	5.2
	Oats	50	1.2	1388	5.1
July 29	Spring wheat	30	—	854	5.2
	Barley	60	—	961	5.4
	Oats	50	—	820	5.3

[a]The plots are the same ones shown in figures 19 to 21, were grown on fallow land, and received nitrogen fertilizer.

[b]Maturity stages: 3.3 to 3.4, stem extension; 5.1, milk; 5.2, soft dough; 5.3, hard dough; 5.4, ripe.

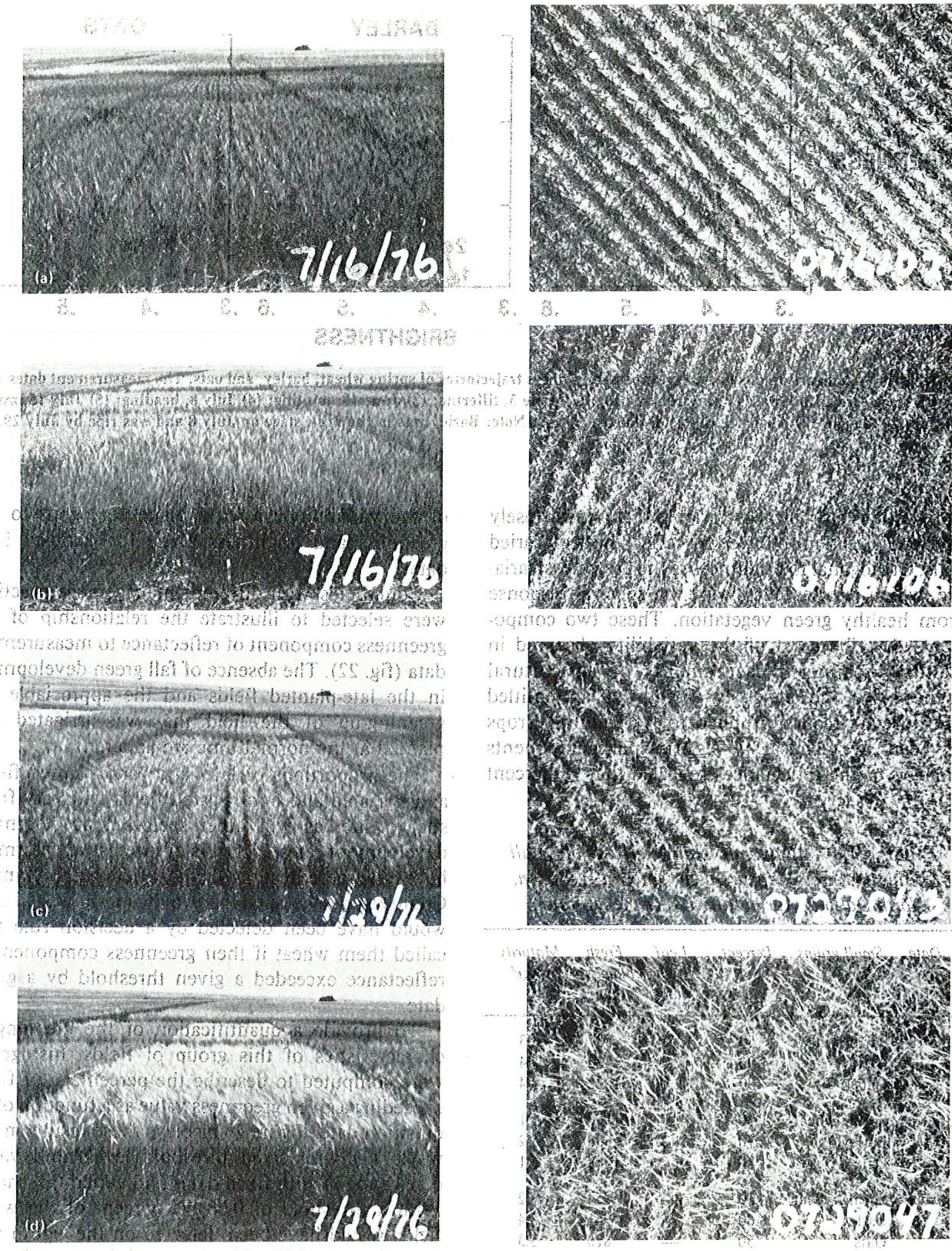


FIGURE 21.—Comparison of oblique and vertical views of spring wheat and barley canopies at two stages of maturity. (a) Spring wheat, July 16, 1976, day 198, milk. (b) Barley, July 16, 1976, day 198, milk. (c) Spring wheat, July 29, 1976, day 211, hard dough. (d) Barley, July 29, 1976, day 211, hard dough.

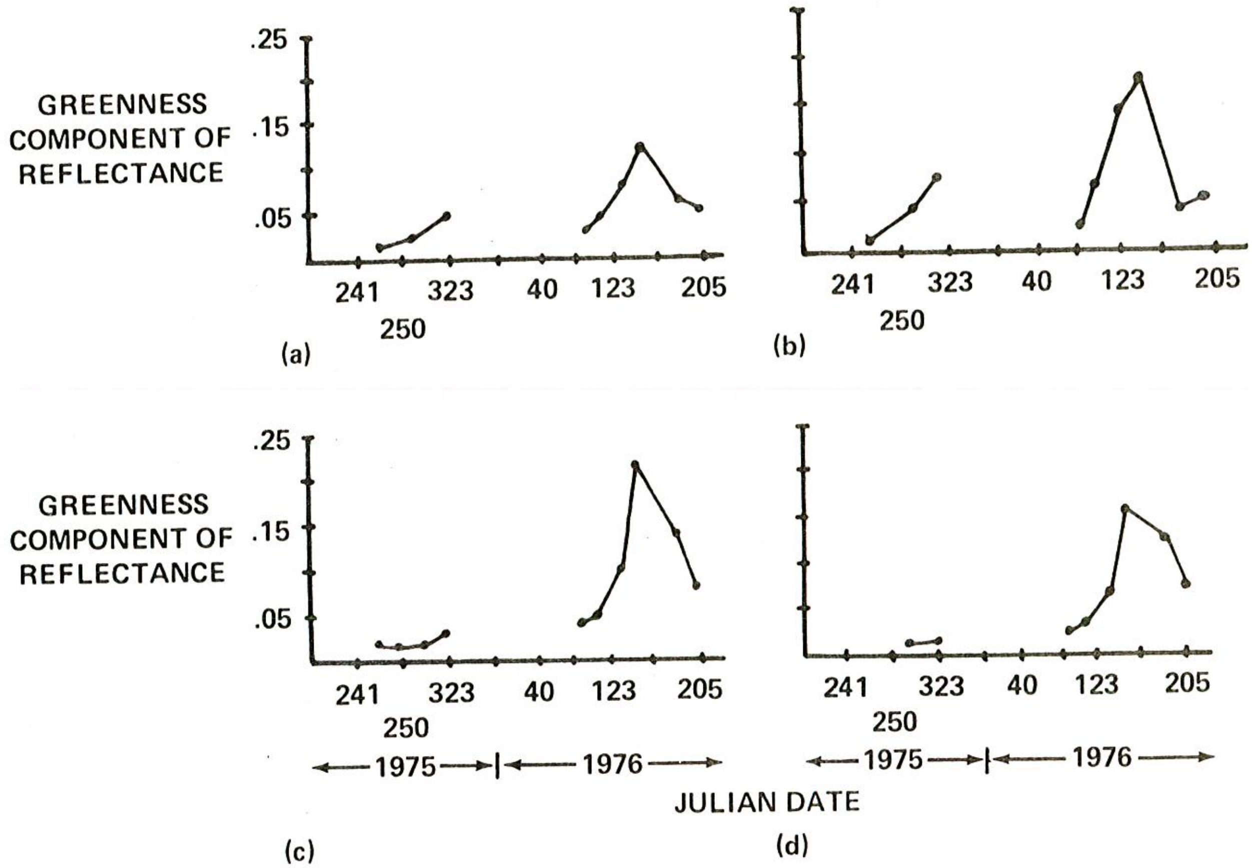


FIGURE 22.—Greenness component of reflectance of winter wheat fields as a function of date for different management practices. (a) Nonirrigated, normal planting date. (b) Irrigated, normal planting date. (c) Nonirrigated, late planting date. (d) Irrigated, late planting date.

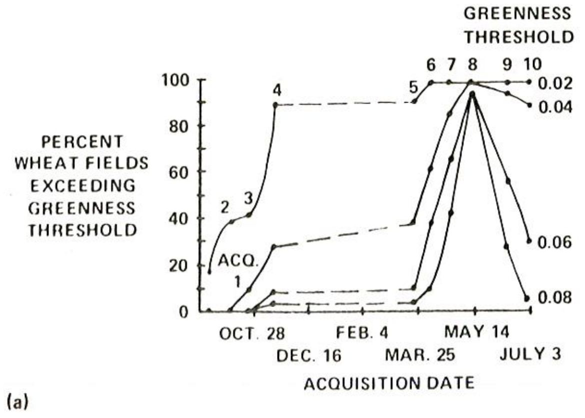
86, and 62 for the eighth, seventh, and sixth missions, respectively. On the two next earliest acquisitions, fourth (November 11) and fifth (March 18), 28 and 38 percent of the fields would have been detected, respectively. For a threshold of 0.02, 90 percent of fields would have been detected at acquisitions 4 and 5. The nonwheat fields in this data set were also tested for the greenness threshold crossing, with good exclusion of them by the 0.06 and 0.04 thresholds. For example, for the threshold of 0.06, only one field exceeded the threshold on the eighth acquisition and none on earlier missions. As a point of reference, a root mean square error (RMSE) of 0.018 in greenness would correspond to a two-count uncorrelated RMSE noise level in each Landsat band.

The relationship between the greenness component of measured reflectance and the observed percent soil cover for the wheat fields was also analyzed. A greenness reflectance threshold of 0.02 corresponded to 18 to 25 percent soil cover, one of 0.04 to 30 to 35 percent, and one of 0.06 to 40 to 45 percent soil cover. These values need refinement because only coarse (20 percent) increments of soil cover were recorded for the fields analyzed.

SUMMARY OF KEY ACCOMPLISHMENTS AND RESULTS

The LACIE Field Measurements Project successfully acquired a large amount of high-quality spectral measurements during 3 years at three test sites in Kansas, South Dakota, and North Dakota. Analyses of these data are providing new knowledge about the spectral properties of crops in relation to their agronomic characteristics.

Spectral measurements were made of controlled experimental plots of wheat and other small grains using truck-mounted spectrometers and of commer-



ACQ. NO.	DATE
1	SEPT. 16, 1975
2	OCT. 3, 1975
3	OCT. 21, 1975
4	NOV. 11, 1975
5	MAR. 18, 1976
6	MAR. 31, 1976
7	APR. 18, 1976
8	MAY 6, 1976
9	JUNE 12, 1976
10	JUNE 30, 1976

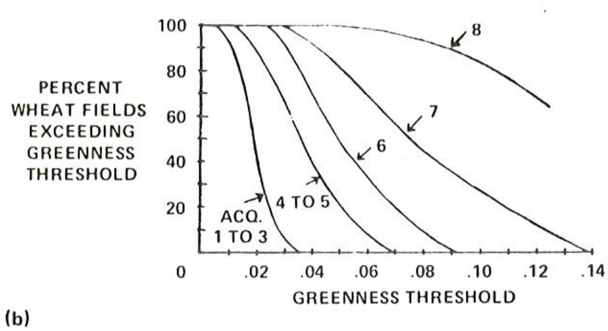


FIGURE 23.—Determination of the threshold of detection of winter wheat based on the greenness component of reflectance. (a) As a function of acquisition date. (b) As a function of greenness threshold.

cial fields of wheat and other crops by a helicopter-borne spectrometer, an airborne scanner, and the Landsat MSS. The spectral data are supported by extensive agronomic and meteorological measurements and observations. Together, the spectral, agronomic, and meteorological data form the most comprehensive data set now available for agricultural remote-sensing research. The data have been processed and provided to investigators who are now using them in research programs; they are available for use by other investigators.

The capability to acquire and analyze spectral measurements was significantly advanced during the LACIE Field Measurement Project. One of the important attributes of the LACIE field measurements spectral data is that they are radiometrically calibrated. Calibration enables valid comparisons of measurements from different dates, sensors, and/or locations. The procedures for field calibration of data have been defined and tested, and the knowledge gained will continue to be applied in future investigations.

The development of a computerized field research data base and an interactive graphics and statistics software system has significantly increased the capability to analyze and interpret interrelationships of the spectral and agronomic characteristics of crops and soils.

Another result of the LACIE field measurements experience is the definition of specifications of a standardized, flexible, and economical multispectral data acquisition system for field research. The instrument system would consist of a multiband radiometer, including the thematic mapper wavelength bands, and a data recording-handling-playback module. Development and use of these instrument systems will make it possible and economical to acquire and process calibrated spectral measurements from tripods, trucks, or helicopters over a wide variety of crops. This approach to spectral data collection was successfully tested by LARS in 1977.

Analysis of the LACIE field measurements data is providing new knowledge and understanding of the spectral characteristics of wheat and the biological-physical factors affecting spectral response. For example, strong relationships have been found between reflectance and percent soil cover, leaf area index, biomass, and plant water content. These are fundamental measures of crop vigor that can be used in crop growth and yield prediction models. In relating agronomic and spectral characteristics of wheat, it has been found that a middle-infrared wavelength band, 2.08 to 2.35 micrometers, is most important in explaining variation in biomass and plant water content, whereas a near-infrared band, 0.76 to 0.90 micrometer, accounts for the most variation in percent soil cover and leaf area index. In evaluating sensor characteristics, it has been determined that the reflective wavelength bands proposed for the thematic mapper are more strongly related to and better predictors of the canopy variables than the Landsat MSS bands. In other studies, insights for development of discrimination techniques have been gained through analysis of the spectral differences between spring wheat and barley and the spectral development of wheat fields early in the growing season.

RECOMMENDATIONS FOR FUTURE FIELD RESEARCH

Although the LACIE Field Measurements Project acquired a large quantity of data, the sample of crop, soil, and weather conditions was small, even for wheat. Each of the 3 years in each site was different in terms of the weather and the crop response to it; however, the crop cannot be treated as a constant even if the weather does not vary significantly from year to year. Changing economic conditions and advancements in agricultural technology will bring changes in crop and soil management (e.g., minimum tillage) and even the crop itself (e.g., introduction of semidwarf varieties of wheat). Measurements of wheat and its confusion crops should be continued over additional years if the full potential of the current effort is to be achieved.

As one looks ahead to the development of a global food and fiber information system using remote-sensing techniques, it is critical to begin to make the field measurements required to understand the spectral characteristics of crops other than wheat, such as corn, soybeans, rice, cotton, and rangeland. One of the lessons that should come from the LACIE Field Measurements Project is the importance of conducting field research before the results are needed to design a large-scale effort. Because of the year-to-year variations in weather, several years of data are required.

The primary sensors used for LACIE field measurements were spectrometers capable of producing high-resolution spectra. In the future, a new approach to the collection of field measurements data will be needed because it will not be feasible simply to multiply the current approach by the increased number of crops and regions that should be included in future experiments. Multiband radiometer systems can economically provide the necessary spectral measurements. With these instruments, it will be possible to acquire measurements at more sites than is possible with the currently available high-spectral-resolution spectrometer systems. And, it is more observations of crops and soils under a wide variety of conditions (not detailed spectral measurements of a limited number of locations and crop conditions) that are needed to increase our understanding of the spectral characteristics of agricultural scenes. There will be a continuing need for the high-resolution spectrometer systems to be used in field research, but less complex systems are also required that can be used to make large numbers of measurements at many sites economically and accurately.

The approach to data acquisition should include cooperative efforts with USDA, land-grant universities, and commercial test stations to make detailed crop, soil, and meteorological measurements in controlled plots, as well as less intensive observations of commercial fields in larger test sites.

In conclusion, field research is an essential component of the development of agricultural remote sensing. A sound field research program can provide the basis on which larger scale satellite experiments and operational systems are constructed. The overall objectives of future field research should be to obtain a quantitative understanding of the radiation characteristics of agricultural crops and their soil backgrounds and to assess the capability of current, planned, and future satellite sensor systems to capture available useful spectral information. Field research is a particularly important component of developing remote-sensing techniques for assessing crop condition and predicting crop yields.

ACKNOWLEDGMENTS

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