

THE USE OF DENSITOMETRIC DATA FROM AERIAL PHOTOGRAPHS
FOR FIELD CROP CLASSIFICATION AND IDENTIFICATION
IN MANITOBA

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Harvey Leonard Glick

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ABSTRACT

Remotely acquired reflectance data from various crops were used to investigate the feasibility of crop identification and crop yield determination from the objective analysis of aerial photographs. A technique is described that may contribute to the development of a semi automatic crop information system.

Aerial photographs were obtained on nine dates and seven dates during the growing season in 1980 and 1981, respectively at a scale of 1:20,000. Imagery was obtained in the 0.6 to 0.7 μm spectral region as a result of a unique combination of filter and film. Densitometric analysis of the film was used to quantify the field images for analysis.

Two stages of crop development, heading and maturity, were well correlated with measurements of crop optical density. Successful discrimination of crops occurred when measurements of optical density from three or four dates were used in the classification. The accuracy of classification obtained was a function of the number of crops in the study, the number of variables used and the climatic conditions during the growing season. Classification accuracies were higher in 1980 as a result of uniformly dry conditions throughout the growing season.

Attempts to relate measurements of optical density with final grain yield were inconclusive.

INTRODUCTION

Remotely acquired reflectance data from crops has long been considered to hold potential for the classification and identification of agricultural crops. Analysis of conventional aerial photographs by trained interpreters facilitate the identification of crops in a small region. The cost benefit ratio of such techniques rise sharply as the size of the area to be classified increases. For an area the size of the prairies, estimates of crop acreage could quickly become cost inefficient using these subjective techniques.

In the last decade, crop reflectance measurements have been obtained from a wide range of non-photographic sensors mounted on sub-orbital and orbital platforms. In addition to subjective analysis of the data by trained interpreters, computer based pattern recognition algorithms have been used to analyse the data in an objective manner.

The use of remote reflectance measurements in the study of crops is limited by the type of attributes that can be measured by the sensor. In the separation and classification of different crop types, the attribute we are ultimately seeking - the genetic differences between crops - must be obtained through the measurement of crop

reflectance. Haralick et al. (1970) suggest that the surrogate measurement of crop reflectance may be imperfectly correlated, in a discriminatory sense, with the genetic attributes of the crops.

Results of research conducted during the past two decades however, have shown that a useful relationship exists between these two attributes. A variety of crops have been identified with varying degrees of accuracy using reflectance measurements obtained from a wide range of sensor/platform combinations. This relationship is not perfect and errors in classification occur because there are many factors that affect crop reflectance that are independent of the type of crop.

The results of these studies remain inconclusive since the optimum exploitation of the spectral and temporal variability of crop reflectance has yet to be realized. In particular the separation of small grain crops has also proved to be quite difficult due to the similarities in their reflectance properties. Results of several ground based spectroscopy studies have shown that the spectral regions near 0.48 μm and near 0.64 μm were useful in discriminating amongst cereal crops in the visible region (Mack et al., 1978; Glick et al., 1980, 1982).

The primary objective of this study was to investigate the feasibility of using medium scale photography in the

0.60 to 0.70 μm range to identify and classify economically important crops in Western Canada. The results may be useful in the development of semi automatic techniques for crop identification on a regional scale as well as providing information that may be useful in the development of large scale satellite based crop surveillance programs. The .6 to .7 μm range was specifically selected for this study since the absorption of radiant energy by chlorophyll is greatest in this region. Thus , the energy received by the sensor would provide indirect information on plant chlorophyll and potential yield.

REVIEW OF LITERATURE

Spectral Properties of Plants

The spectral properties of leaves have been studied extensively and reviews have been published by Gates et al. (1965); Myers and Allen (1968); Gates (1970); and Sinclair et al. (1973).

Willstatter and Stohl (1919) hypothesized that leaf reflectance occurred at interfaces in the mesophyll where large intercellular spaces and irregular cell wall orientations optimized the requirements for critical reflection. Gates (1970) suggested that the spectral properties of leaves in the visible wavelengths were largely related to the molecular absorption of radiation by chlorophyll. Sinclair et al. (1973) suggested a theory of diffusive reflectance which predicted that the magnitude of reflectance was proportional to the number of layers of cellular material the incident radiation encountered at right angles.

The spectral properties of single leaves however, cannot satisfactorily explain the reflectance from a plant canopy (Myers et al., 1966; Colwell, 1973). A plant canopy is a

composite of shaded and sunlit soil and leaf surfaces at various angular orientations (Richardson et al., 1975). Colwell (1973) concluded that the spectral properties of canopies were a function of 1) leaf transmission; 2) leaf area and geometry; 3) non-leaf canopy components; 4) background characteristics; 5) solar angle; and 6) look angle.

Aerial Photography

Early attempts at identifying farm crops on aerial photographs were based largely on the subjective skills of the interpreter. Standard techniques for manually interpreting large scale panchromatic aerial photography included the use of photographic tone, texture, size, shape and pattern (Manual of Photographic Interpretation, 1960). One of the earliest examples of land use studies using these techniques were experiments in land classification in Northern Rhodesia (Robbins, 1934). Powers and Kohn (1959) used farmstead features (barns, silos, cribs) to establish the type of farming and the types of crops on large scale black and white aerial photographs of dairy and spring wheat areas. It was recognized that the use of farmstead features may be unreliable as indicators of the types of farming

since farmers shift the basis of their operation from time to time without corresponding alterations in the outward appearance of the farm buildings.

Goodman (1964) expanded on those results and suggested three sets of criteria that could be obtained from large scale panchromatic photography to serve as indicators of the type of farming in agricultural regions of Illinois and Michigan. These were 1) farmstead features; 2) crop associations; and 3) the uses that were made of corn and hay. These manual techniques would not be directly applicable to other agricultural regions without modification.

Hoffer et al. (1966) analysed photographs of agricultural regions in California taken from Gemini 5. Conventional interpretive techniques such as the use of photographic texture, size, shape, pattern and association provided no indication of crop types on such small scale photography. The authors concluded that photographic tone was the primary factor for image interpretation, and that the development of a capability for differentiating various crop species under certain conditions of growth would be based on the characteristic multispectral signature for a given species.

The authors recognized that many variables could markedly affect the spectral response from a crop. Vegetation and soil variables of primary importance were 1) crop species

and variety, 2) relative size and maturity at the time of the flight, 3) soil type, moisture content and relative amounts of soil and vegetation observed, and 4) geometric configuration of the crop.

Stanhill et al. (1972) studied the effect of fertilizer application on solar reflectance from wheat. They reported that visible and infrared reflectivity were considerably but differently affected by fertilizer treatment. These effects however, were attributed to the amount of plant material present rather than to any change in the optical properties of the vegetation resulting from the fertilizer.

Doverspike et al. (1965) were one of the first to employ a scanning microdensitometer to identify land classes. Variations in film optical density on large scale (1:1000) aerial photography were attributed to aperture size and shape, and to wavelength.

Rib and Miles (1969) investigated the feasibility of quantizing the element of tone in aerial photographs and developing diagnostic patterns for various terrain features including vegetation. To simulate a scanning densitometer, the output from a point densitometer was connected to a variable speed chart recorder. Optical density 'scans' were obtained by manually pulling the film across the density head of the densitometer at a uniform rate.

Their results showed that the optical density scans were a function of 1) the type of film, 2) the time of year, 3) aperture size, and 4) the scale of the photography. They discovered that as the aperture decreased or the photoscale increased, more detail was recorded because of the finer tonal patterns of the imaged features. They concluded that one would not be able to develop suitable diagnostic patterns for terrain features since there was more variability within a terrain feature than between terrain features. Clearly some of the variability was a result of the method of obtaining density scans.

Steiner and Maurer (1968) found that the interpretability of crop types on aerial photography is highly dependent on the time of season and that no single date allows complete classification of individual crops with absolute certainty. The authors found that the accuracy of crop classification could be improved to 75% when both June and July photography were analysed as compared to 40% (June) and 29% (July) on single dates.

Efforts have been made to exploit this temporal variation for the development of semi-automatic crop classification techniques. Instead of comparing crop parameters for a given date, Steiner (1970) integrated crop observations taken at different times throughout the growing season. These observations were obtained from large scale

panchromatic photography of various agricultural regions in Switzerland. Photographs were obtained on 13 dates during the growing season at 10 day intervals and seasonal densitometric profiles were produced for 11 crop types. Using a discriminant function analysis (maximum likelihood) Steiner successfully classified natural and sown hay, winter and spring wheat, winter and spring barley, oats, potatoes, beets and canola.

The best single date for classifying these crops occurred on June 9 when the grain crops were near heading. Optical density was the only crop parameter used in the classification and no attempt was made to integrate environmental or agronomic parameters.

The ability to identify crops on aerial photography is related to the spectral range of the film/filter/camera system. Radziminisky and Kharin (1973) reported that the greatest contrast (maximum variability) in plant spectral reflectance using visible multiband photography occurred in two distinct wavebands, one at .480 μm to .520 μm and the other at .640 μm to .700 μm .

von Steen et al. (1969) studied the relationship between film optical density on colour infrared film and several yield determinants in cotton, sorghum, carrots, cabbage and onion. The primary difficulty encountered was that on the date of photography not all the fields of each crop were at

the same physiological stage of development. Their results did indicate however, the potential for relating the optical density of fields on aerial photographs to ground measured yield indicators such as number of plants, height of plants, size of head and percent cover.

Non Photographic Remote Sensing

Since early 1970, researchers have investigated the feasibility of using digital spectral data from ground and airborne platforms for surveying crop resources.

Spectral reflectance studies from ground based platforms are concerned with the relationship between crop reflectance and crop and environmental parameters. This information is useful in the development of larger airborne surveillance programs.

Absorption of light by chlorophyll pigment is the major factor affecting visible reflectance from crops (Gates, 1965; Verhoef and Bunnik, 1974). Other factors that affect crop reflectance include canopy geometry (Colwell, 1973), ground cover (Verhoef and Bunnik, 1973), stage of maturity (Thomas et al., 1966; Gausman et al., 1971; Leamer et al., 1978; Glick et al., 1980) and soil background

(Stoner and Baumgardner, 1980).

Leamer et al. (1978) compared the seasonal changes in reflectance of two wheat cultivars at three planting densities. Wheat reflectance at .550 μm and .650 μm were similar through the season and no discrimination between the cultivars was possible. At .650 μm fallow could be discriminated from wheat. At .750 μm the two cultivars differed in reflectance, although the results were difficult to interpret.

Brach et al. (1977) designed a mobile field spectrometer to measure the optical properties of crops. Results from the study were inconclusive although the data indicated that crops could be discriminated at the later stages of growth.

Mack et al. (1978) reported that the spectral regions near .480 μm and near .650 μm were useful in differentiating crop species from ground based spectral measurements.

Tinker et al. (1979) obtained visible and infrared spectra of sod, soil and various cereal and broadleaf crops from an oblique angle of view on several dates during the growing season. The purpose of the study was to determine if land use, crop type, crop maturity and disease status could be estimated by discriminant analysis of normalized plot reflectance data. While it was possible to discern general land use categories and crop maturity, the

classification of specific crop types, disease status and maturity were inconclusive.

Glick et al. (1980) measured visible reflectance from an oblique angle of view for wheat, barley and oats during the growing season. The oblique viewing angle was employed to minimize the effect of soil background reflectance and simplify analysis of the spectra. Discrimination was possible by statistically comparing the seasonal changes in the magnitude of reflectance for each crop type. The potential for discrimination was shown to be a function of the stage of maturity and optical wavelength. Discrimination between crops was greatest at the heading/anthesis stage in the .60 - .70 μm waveband.

Glick et al. (1982) compared the potential for discriminating sod, fallow and selected grain crops from both an oblique and vertical viewing angle. They reported that the viewing angle did affect the potential for discriminating crops. Obliquely measured crop spectra were generally more successfully discriminated, mainly because the differences between crop spectra occurred over a wide portion of the spectrum. It is not certain whether this is due to the soil background reflectance of vertically measured spectra or if other factors are involved. The percentage of crop comparisons however, in which differences were observed between spectra were similar for both the

oblique angle (67%) and for the vertical angle (64%).

In addition to classifying crop types, several studies have been conducted to develop techniques for estimating final grain yield from spectral data. Idso et al. (1977) reported that measurements of canopy reflectance could be related to grain yield. Daily measurements of shortwave albedo from irrigated wheat fields showed that final grain yield was a linear function of the minimum albedo value reached at head ripening. These results are limited by the data which is representative of only one crop/region/year. The model developed by the authors may not be applicable for other crops, other agricultural regions or other years where seasonal climate differs.

Tucker et al. (1980) used a hand held, two band radiometer to measure reflectance from a winter wheat field in the red and photographic infrared bands. They reported that the ratio of the infrared/red bands were linearly correlated with grain yield and accounted for 64% of the variability in grain yield that could not be explained by meteorological data. The authors concluded that although spectral data alone is useful, they are much more useful when combined with environmental or agronomic data.

MATERIALS AND METHODS

Test Area

Location The test area selected for this study was located 18 km west of Winnipeg, Manitoba near the town of Starbuck (Lat. 49.46N; Long. 97.37W). The area was 10 mi long and 2 mi wide and was one of the LANDSAT spring wheat test sites (Figure 1).

Land Use The land use of the test area was solely agricultural. Field size ranged from 16 ha to 130 ha with the average size being 65 ha. The predominant crops grown in this area were spring type wheat, barley and oats. In addition, canola, flax, sunflower, sweet clover, canary grass, buckwheat, lentils and peas were also grown in the area. Summer fallow was a significant component of the crop rotations in this area and each year several fields in the test area were left fallow.

Soil The soil in the test area included both Osborne Clay and Red River Clay soil types (Ehrlich et al., 1959). These soil types are quite similar and differ only in their drainage capabilities. The Osborne Clay is a poorly drained

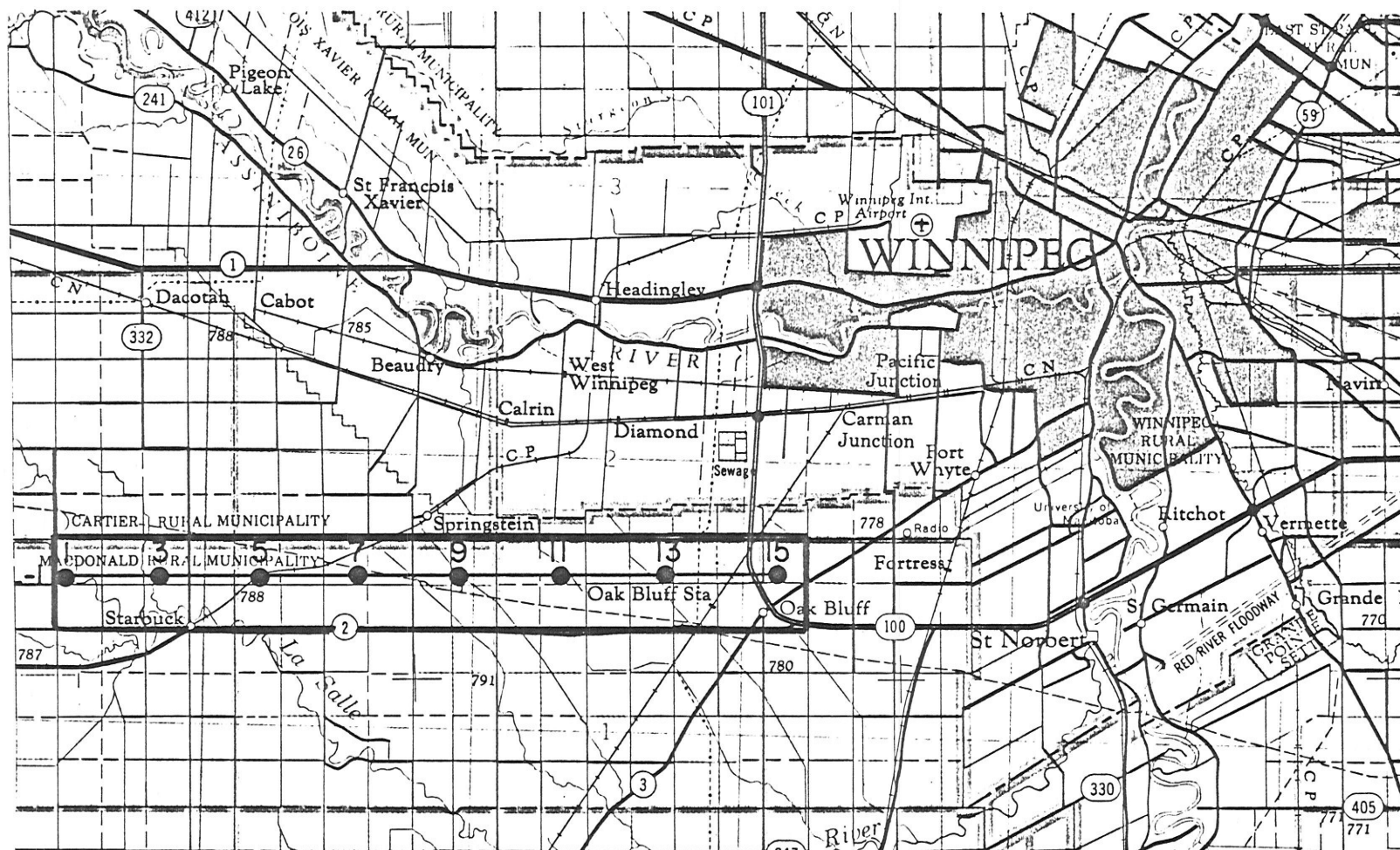


Figure 1. Location of test area and flight line.

soil while the Red River Clay has intermediate drainage. The mean summer soil temperature in the 0 to 10 cm profile was 18.4 C.

During the summer of 1980 a severe lack of precipitation created moderate drought conditions from seeding to anthesis. Rain began to fall in late August and in some regions the harvest was adversely affected by excess water.

In 1981 conditions for crop growth were ideal. Soil moisture levels were maintained at adequate levels due to timely rainfalls throughout the summer. Scattered patches of hail caused damage on two occasions to parts of some fields in the test area.

Aerial Photography

1980 Mission Prairie Agri-Photo (Carman, Manitoba) was contracted to provide black and white photography throughout June, July and August, 1980. Nine flights were requested at 10 day intervals (weather permitting) commencing June 6. The requested scale was 1:20,000.

Photography was obtained with a 70 mm Hassleblad camera mounted in a single engine Cessna 172 airplane. The altitude of the plane was 1340 m ASL. Complete coverage of the test area consisted of 80 frames of film. This required

four separate flight lines above the test area and took 20 to 30 min to complete. Whenever possible, photographs were taken at approximately 1000 hr to insure a sun elevation angle of 30 degrees and to minimize the cumulus cover.

Kodak Plus-X Aerographic Film 2402 was used in combination with a Wratten 25A glass filter to effectively limit the spectral sensitivity of the system to the red (.60 to .70 μm) wavelengths (Figure 2). This spectral sensitivity was obtained since the film is insensitive to radiation beyond .70 μm and the Wratten filter will not transmit any radiation below .60 μm . The exposed film was processed in Kodak D-19 developer.

1981 Mission Changes were incorporated into the 1981 photographic missions to improve the quality and the reliability of the data.

Airquest Surveys Limited (Winnipeg) was contracted to provide photographic coverage of the same test area. Seven flights were planned at 14 day intervals commencing June 2, 1981. The scale of the photography was 1:20,000

Photography was obtained with a Wild RC-8 camera with a 152 mm focal length wide angle lens. This enlarged format (23 x 23 cm) provided greater resolution of ground objects. A turbocharged Cessna 310 aircraft was flown at an altitude

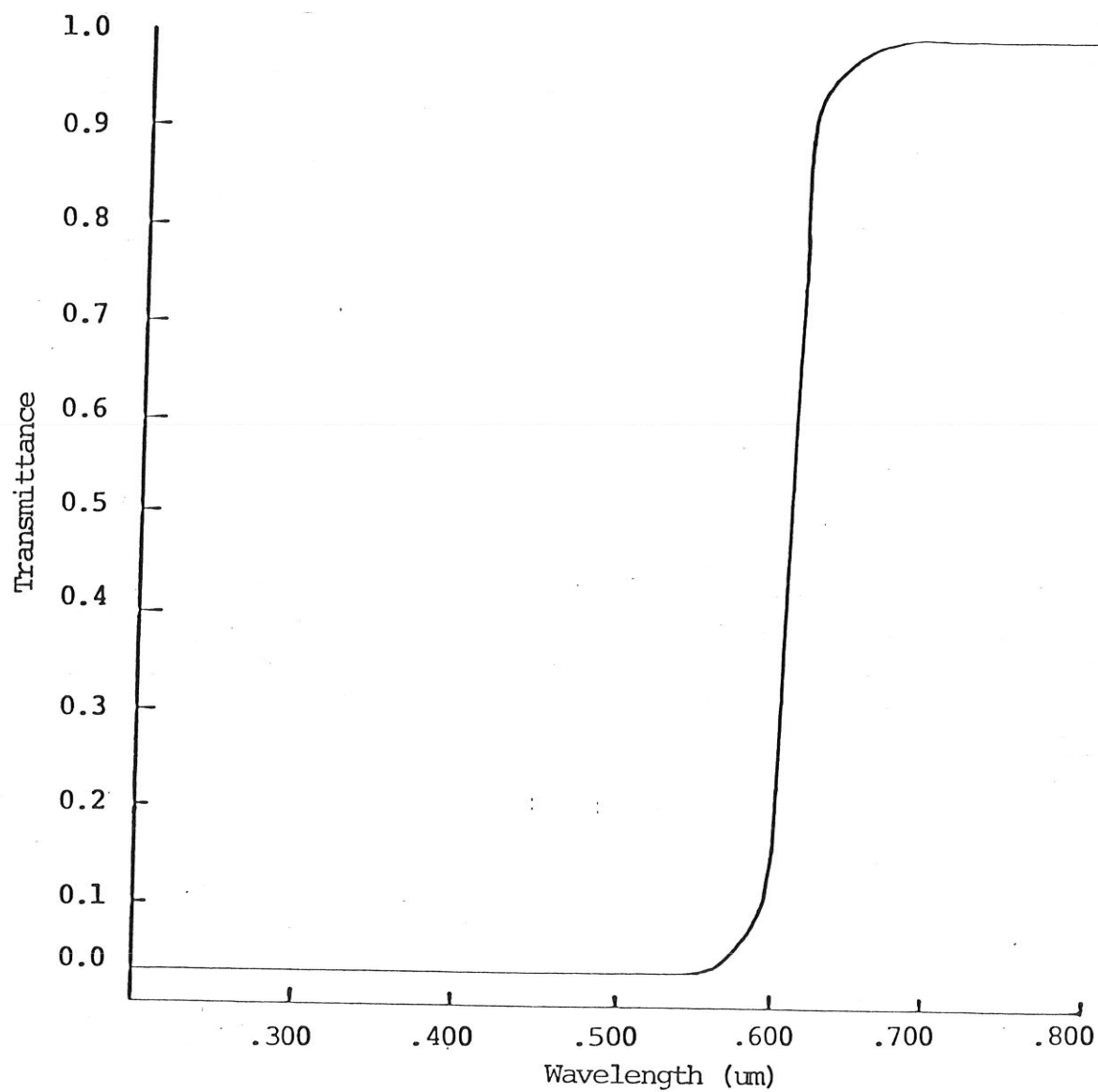


Figure 2a. Spectral transmission of Wratten 25A filter.

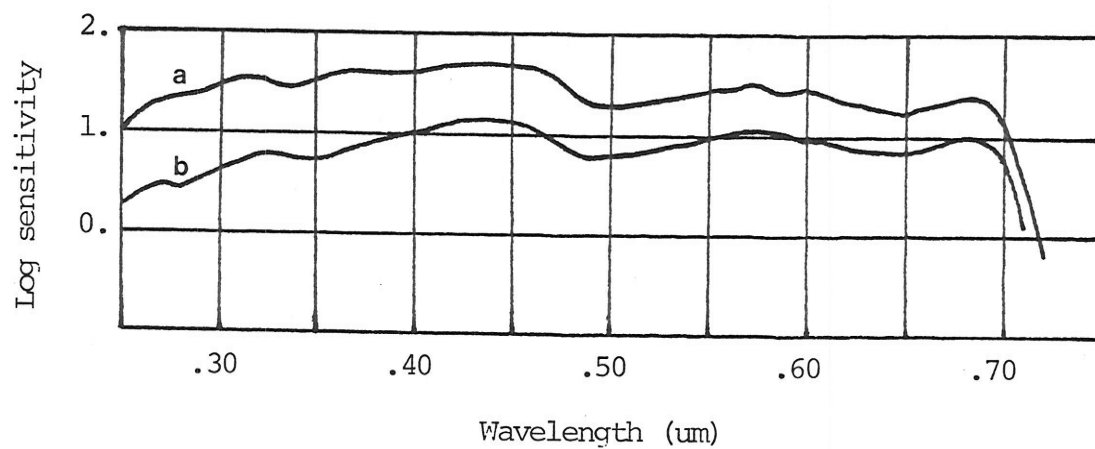


Figure 2b. Spectral sensitivity of Kodak 2402 film developed in Kodak D-19 for 8 min at 75 F. (a; D= .3 above fog, b; D=1.0 above fog)

of 3048 m above ground. Complete coverage of the test area required 2-3 min and only 12 frames of film. The Cessna 310 was extremely stable in flight and was able to fly at higher altitudes where the air is less turbulent. Since only 3 min were required to photograph the test area, variability between frames due to environmental effects were minimized.

The same film/filter combination was used as in 1980, although the glass filter was replaced by a gelatin filter for increased resolution. The effective sensitivity of the system remained at .60 - .70 μm .

The exposed film was processed under strict densitometric control. Maximum, minimum and average density values were documented and the film was developed to a uniform gamma of 1.0 ± 0.05 . A grey step wedge was exposed on each roll of film to reduce the variability in density due to non-uniform processing. These sensitometric control procedures reduced the variability between flights by minimizing some of the inherent variability in film processing.

Field Selection

Several fields were selected from within the test area for intensive ground truth sampling and analysis. Three

field selection criteria were employed.

1. Access - the fields had to be adjacent to an all weather road to permit reasonable access during the summer.

2. Producer - access to the producer who managed each field was desired since much information about cultural practices was obtained in direct communication with each producer.

3. Crop Type - the objective was to select several fields of each type of crop grown in the test area. The small grains and flax fields presented no problem as these were the predominant crops in the region. It was more difficult for some of the special crops such as lentils, sweet clover, peas, and buckwheat since often there was only one field of each present.

In 1980, a total of 32 fields were selected for study. They consisted of 9 wheat fields, 5 barley fields, 4 oats fields, 6 flax fields, 2 fields each of sunflowers, canarygrass and fallow and 1 field each of lentils and sweet clover. The grains and flax fields were of primary interest.

In 1981, 36 fields were selected. They consisted of 13 wheat fields, 6 barley fields, 5 fields each of oats and flax, 2 fields each of buckwheat, canola and fallow and 1 field of sunflowers. Again, grains and flax were the crops

of primary interest.

Data Collection

Prior to any aerial photographic missions, arrangements were made to meet with the appropriate producers to discuss the cultural practices used on their fields. The producers provided information on crop type, seeding date, seeding rate, the type and rate of herbicide applied and the amount of fertilizer applied. After the crop was harvested the producers were contacted again for information on crop yields in each of their fields. The collection of ground truth data in support of remote sensing studies is very often inadequate and can limit the scope of the project. In this study, emphasis was placed on the collection of accurate and timely ground truth information.

On the day of each photographic mission, each of the selected fields was inspected and the following five parameters were measured.

1. Growth Stage - the growth stage of each crop was measured according to the technique described by King and Mack (1972).

2. Height - for each crop, plant heights were measured from the soil surface to the upper boundary of the canopy. Thus a relative canopy height was measured rather than an actual per plant height.

3. Weeds - the type of weeds, the size of the population and their relative height in the canopy were measured.

4. Soil Moisture - gravimetric soil moisture was determined in the 0-5 cm and 5-10 cm profiles. These measurements were performed in 1980.

5. Reflectance Measurements - the amount of light reflected by the crop in .60 - .70 μm was measured using a hand held Licor Quantum/Radiometer/Photometer (LI-185B) with a quantum sensor (LI-190SB). The spectral sensitivity of the sensor is .40 - .70 μm . A Wratten 25A glass filter was placed over the sensor to provide an effective spectral sensitivity of .60 - .70 μm , similar to the sensitivity of the film in the aircraft.

The procedure was to measure the radiation reflected from the crop canopy (sensor pointed down) and to measure the incident solar irradiation (sensor pointed up). The ratio of these two readings was determined. This ratio has been

described by Duggin (1980) as the hemispherical directional reflectance factor. Three readings were made in each field under cloud free conditions and the mean value of the reflectance factor was used.

In addition, the relative uniformity, colour, density, vigour and crop cover for each field were recorded.

Densitometry

The density of a film is a measure of the transmission characteristics of the developed emulsion. The optical density (diffuse) of each of the selected field images was obtained using a Macbeth TD-402 densitometer. The components of such a densitometer are schematically illustrated in Figure 3.

Measurements of optical density were obtained using both a 1 mm and a 2 mm aperture disk. The aperture size regulates the amount of light that is radiated on to the emulsion, and as a result, determines the ground area from which a measurement of optical density was obtained.

Rib and Miles (1969) reported that aperture size can affect the measurements of optical density from a field. This could occur since the amount of ground area being

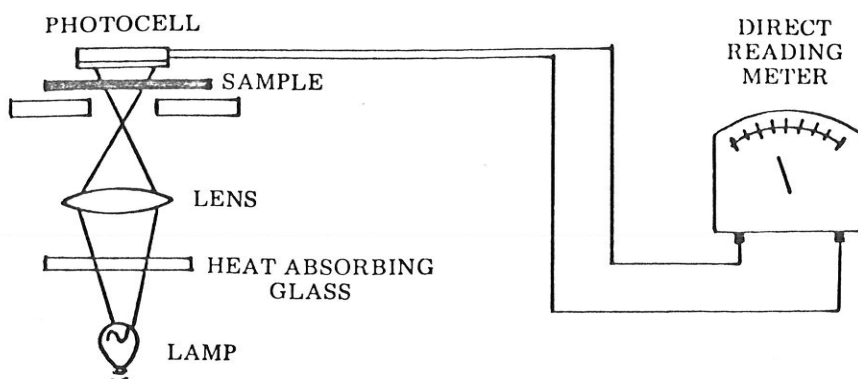


Figure 3. Schematic diagram of the basic components of a direct reading photoelectric densitometer.

measured increases with increasing aperture sizes. At a scale of 1:20,000 a ground area of 20 m in diameter and 40 m in diameter was measured by a 1 mm and a 2 mm aperture size, respectively. Our results showed that the effect of these two aperture sizes on optical density was negligible. No significant differences were observed between measurements of field optical density at either aperture setting. In fact the measurements at both settings were highly correlated ($r=.988$). The 1 mm aperture size proved more advantageous however, in the measurement of small ground targets less than 30 square m (eg. road intersections, holding tanks) which were necessary for accurate normalization of the data. Therefore, the measurement of optical densities were obtained using a 1 mm aperture setting.

Depending on the field size, 15 - 50 measurements of optical density were recorded for each field sampled. The selection of sampling points within a field was partially randomized. Care was taken to insure the entire field was sampled and that measurements were not taken from field edges, ditches or farmsteads within a field.

In an automated environment, it would be very difficult to restrict measurements of optical density from ditches, ponds and other non cropped areas from entering into the data acquisition process. As a result greater variability

would occur in optical density measurements and correspondingly greater errors in classification would result. These errors could be reduced somewhat by incorporating maximum and minimum tolerance limits on the data collected. This would eliminate those measurements of optical density from sources such as ponds and ditches whose density values would be outside the normal range of densities for cropped areas.

Calibration

Differences in photographic optical densities may be crop related or they may be a result of the variability associated with the process of obtaining aerial photographs. In order to minimize these sources of variation the aerial missions were contracted with rigid specifications associated with them. All flights were scheduled at approximately the same time of day to minimize gross errors caused by differences in solar elevation angle between flights. Uniform exposure settings were used for all flights and the processing of the exposed film was standardized to the same specifications throughout the season. These precautions helped minimize the variability inherent in the process of acquiring images from an airborne

platform. They had little effect, however, on the variability related to environmental effects such as humidity, particulate matter and cloud effects, nor did they have an effect on the problem of non uniform films.

A technique was required to standardize the data and allow meaningful comparisons to be made between measurements of optical density for fields from different dates. Two large, steel petroleum tanks (one white, one rust) and two paved highway intersections situated in the test area were used as natural ground targets. The assumption was made that the magnitude of optical density measurements from these targets would not change perceptibly during the summer. Therefore any variations that occurred in the optical density measurements of these targets could be attributed to variations in the data acquisition process regardless of the source of the variability. A technique similar to this was described by Goodman (1964) and Steiner (1970).

The procedure used in this study was to measure the optical densities of the ground targets on all dates during the growing season and then to compare these values against the measurements obtained from the first date. If differences were observed between the optical density values for the ground targets on any date relative to the first date, then the amount of this difference was determined.

This value was then used as a calibration factor and was added to all values of optical density for the crops measured on that date.

Statistical Procedure

The data collected during 1980 and 1981 were subjected to a linear discriminant function analysis. Discriminant analysis is a multivariate statistical procedure that treats the problem of attempting to differentiate between two or more classes of objects (Kendall, 1975; Harris, 1975). A fundamental application of discriminant analysis involves the existence of several populations and a random sample of individuals from each population. The task is to develop a rule or index to allocate new unknown individuals to the correct population with a minimum of error.

The index used is a linear combination of variables that measure characteristics on which the populations are expected to differ. Critical values for this index are established so that if the value of the index falls in a specified range, the individual will be classified into the proper population.

Clearly if populations are similar with respect to their

mean and covariance matrices, discrimination will be poor due to overlap of the populations. Thus derivation of these linear combinations are designed to maximize the separation between groups.

The discriminant functions are of the form

$$D_i = W_{i1}X_1 + W_{i2}X_2 + \dots + W_{ip}X_p + C$$

where

D_i = score on discriminant function i

W_i = weighting coefficients

X = the values of the p discriminating variables

C = constant

Recently, applications of discriminant analysis have increased in the analysis of remotely sensed crop data (Campbell et al, 1982; Searle, 1979). In this study, two similar stepwise discriminant programs were utilized. These were the BMDP P7M program (Dixon and Brown, 1979) and the SAS DISCRIM program (Searle, 1979). Both programs utilize a classification criterion based on a generalized squared distance, have forward or backward stepping routines and optionally incorporate the use of prior probabilities.

Forward stepping routines were used in all cases. That is the classification was initially obtained using only the single best variable (basis Wilks lambda). In each successive iteration the variable that most contributed to improving the accuracy of the classification was added. The resulting increase in accuracy with the addition of each successive variable was determined and plotted.

The data were analysed with and without the use of prior probabilities for comparative purposes. The uneven frequency of different field types in our test area suggested that the probability of a given sample belonging to a certain crop type was not equal. The prior probabilities used in this analysis were set directly proportional to the group sample sizes. That is if 60% of the fields were wheat fields, then the prior probability of an unknown sample being classified as wheat would be 60%.

RESULTS AND DISCUSSION

Temporal Profiles

The mean optical densities and the standard deviations around these means were measured for each crop during the 1980 and 1981 growing seasons (Table 1 and 2). Graphical representation of these data provide temporal profiles of optical density that characterize crop development (Figure 4 and 5).

These crop profiles were similar in shape in both years for many of the crops. The profiles were trough shaped, with minimum values of optical density observed at mid - July and maximum values observed at mid - August. Peak chlorophyll levels at mid - July (anthesis) resulted in the low optical density values on these dates. Similarly, low chlorophyll levels and increasing soil background reflectance account for the high optical density at mid - August, just prior to swathing.

The temporal profiles for canola (rapeseed), included in the 1981 study, were considerably different than those of the cereal grains. On the July 16 flight, the canola was still in flower, and as a result the optical density values

Table 1. Mean optical density and standard deviation for five crops on nine dates in 1980.

Date	Wheat	Barley	Oats	Flax	Fallow
June 06	.699 (.064)	.750 (.040)	.729 (.005)	.736 (.051)	.760 (.076)
June 16	.640 (.036)	.704 (.042)	.631 (.007)	.675 (.076)	.615 (.008)
June 25	.559 (.050)	.647 (.041)	.551 (.037)	.551 (.031)	.668 (.010)
July 05	.521 (.043)	.610 (.038)	.515 (.062)	.502 (.040)	.655 (.042)
July 17	.373 (.040)	.465 (.045)	.465 (.043)	.412 (.027)	.629 (.042)
July 29	.657 (.034)	.625 (.045)	.561 (.039)	.455 (.023)	.726 (0.00)
Aug 07	.845 (.025)	.664 (.038)	.635 (.054)	.533 (.023)	.754 (.010)
Aug 15	.916 (.040)	.793 (.034)	.862 (.023)	.750 (.027)	.766 (.006)
Aug 22	.844 (.060)	.746 (.062)	.784 (.029)	.807 (.010)	.764 (.028)

Table 2. Mean and standard deviation of optical density for five crops on seven dates in 1981.

Date	Wheat	Barley	Oats	Flax	Fallow
June 02	.795 (.084)	.880 (.074)	.774 (.062)	.837 (.056)	.841 (.144)
June 16	.632 (.071)	.707 (.066)	.619 (.059)	.720 (.105)	.677 (.015)
June 29	.519 (.044)	.601 (.032)	.837 (.061)	.602 (.061)	.649 (.064)
July 16	.422 (.063)	.475 (.085)	.534 (.032)	.485 (.045)	.554 (.076)
July 28	.691 (.069)	.831 (.109)	.632 (.071)	.611 (.073)	.554 (.138)
Aug 17	1.073 (.172)	1.202 (.189)	1.010 (.100)	.932 (.108)	.926 (.007)
Aug 28	.990 (.145)	1.145 (.142)	.984 (.088)	.842 (.064)	.830 (.025)

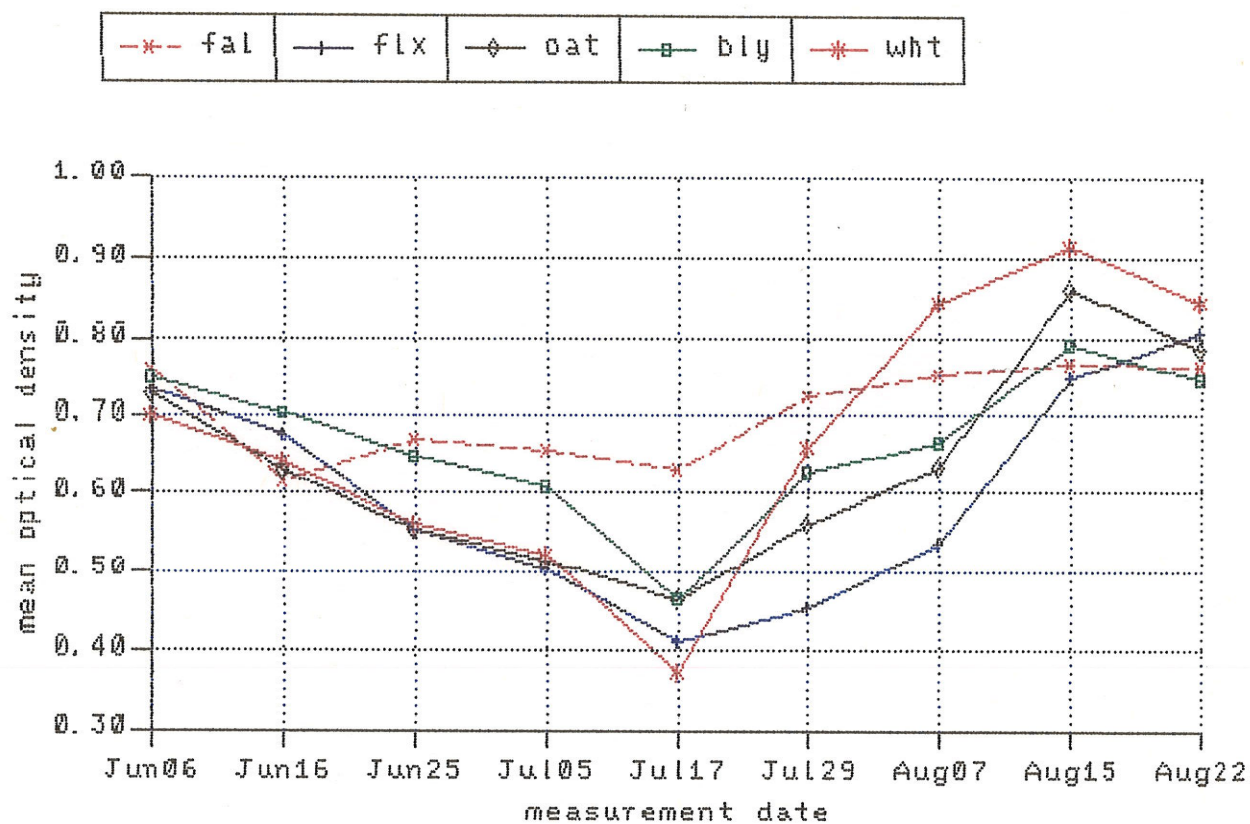


Figure 4. Temporal profiles of mean optical density for five crops in 1980,

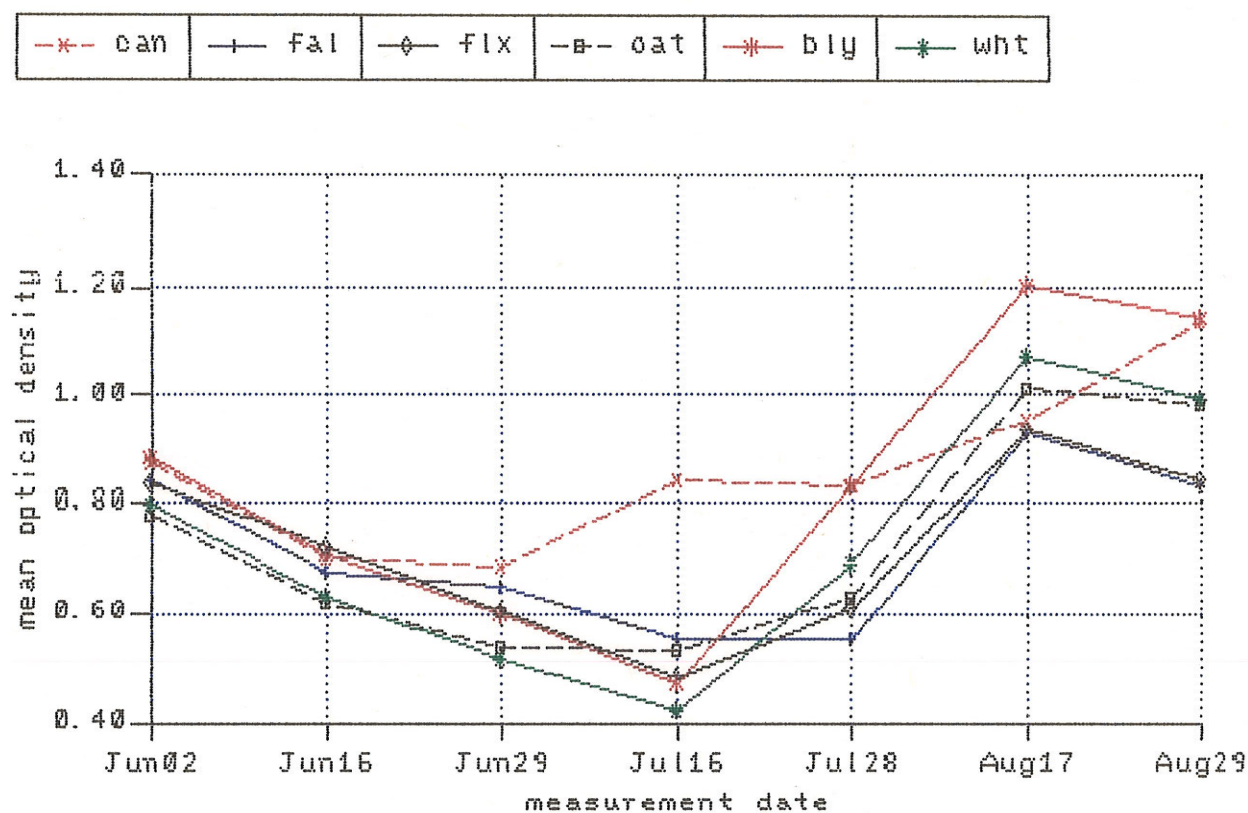


Figure 5. Temporal profiles of mean optical density for six crops in 1981.

were higher than the other crops. These differences in the canola profile were related to differences in its phenological development compared to the grains. During flowering canola fields obtain a deep yellow colour due to the large yellow flowers present which is in marked contrast to the optical appearance of small grain crops during flowering. As a result of these large spectral differences, the separation of canola from small grain fields would be successful on these dates.

The fallow fields had temporal profiles that also differed from those of the crops. In comparison with the cereal profiles, the fallow profiles were quite stable and did not fluctuate as much from date to date. These stable profiles occur since the incident solar radiation reflected from fallow fields is unaffected by chlorophyll or carotene pigment absorption. Like canola, the fallow fields could be successfully separated from cultivated fields on most dates due to these qualitative and quantitative differences in measurements of optical density.

These profiles are similar in shape to those reported by Steiner et al, (1970) who measured the optical density of several crops in Switzerland, including small grain and row crops. The magnitude of the response of the temporal profiles reported by Steiner was different since they utilized panchromatic film sensitive to the entire visible

spectrum (.4 - .7 μm). The magnitude of the optical density reported here is lower since the film/filter combination used in this study was sensitive to only a small portion of the visible red wavelengths (.6 - .7 μm) and less energy was received at the sensor.

The temporal profiles obtained were related to the phenological stage of plant development. With the exception of canola, minimum values of optical density in both years occurred at or close to anthesis, just as the plant began the grain filling and ripening process. Maximum values occurred at or close to physiological maturity. A logical extension of these temporal profiles could provide a means of estimating the phenological stage of crop development for a single field or an entire region using measurements of optical density throughout the growing season. Such estimates of crop growth and development parameters from space and airborne sensor data are currently being investigated (Henderson and Badwhar, 1982). A major limiting factor at this time is the number of acquisitions of data on cloud free days to construct the temporal profile. This is not a serious problem with airborne data since there is considerable flexibility in scheduling overflights.

Crop Identification

Successful crop identification using densitometric techniques requires that the variability in optical density between specific groups be greater than the variability within groups. A one way analysis of variance (ANOVA) test on the mean optical densities for each crop on all dates was used to test this hypothesis (Table 3 and 4), with crop response on a single date comprising a treatment. Significant differences ($p > .01$) were observed on all but the two earliest dates between June 1 and June 15. On these early dates canopy development was not complete and background soil was visible. This resulted in optical densities for the different crops and fallow fields that were similar.

Significant differences in mean optical density were observed on all other dates during both seasons. As expected most of these large, significant differences resulted from the uniquely different optical density profile of the fallow fields relative to the cultivated fields. On several dates however, significant differences in optical density between different crops occurred.

The ANOVA results indicate that the variability of optical density measurements between all the different crops

Table 3. Results of the one way analysis of variance of
the 1980 densitometric data for five crops on nine dates.

Dates	F Values
June 06	2.227
June 16	3.306 *
June 25	6.554 **
July 05	7.532 **
July 17	16.036 **
July 29	30.292 **
Aug 07	73.391 **
Aug 15	23.082 **
Aug 22	3.163 **

* - significant at $p (.05)$

** - significant at $p (.01)$

Table 4. Results of the one way analysis of variance of the 1981 densitometric data for seven crops on seven dates.

Dates	F Values
June 02	1.231
June 16	1.367
June 29	6.003 **
July 16	11.295 **
July 28	5.275 **
Aug 17	2.998 *
Aug 28	3.901 **

* - significant at $p (.05)$

** - significant at $p (.01)$



analysed was larger than the variability of optical density measurements within the crop groups. The potential exists to use these densitometric measurements to classify and identify crops. Complete classification of all crops on any single date was not possible. On each date at least two crops had optical densities that were similar.

Discriminant analysis was used to exploit the temporal variability of measurements of crop optical density. A plot of the 1980 group data for the first two canonical variates shows clear separation of the wheat fields (W & W1) from the other fields (Figure 6). The use of canonical variates has been discussed by Campbell et al, (1982). There was also some separation of the flax fields (F & F1). The oat fields (O) showed little separation from the barley fields (B & B1). There was also some grouping amongst the wheat, barley and flax fields into those sown early and those sown late (1).

The first two canonical roots were 37.91 and 4.35, which together account for 89% of the overall between group variability. When all six canonical variables were used the classification results were marginally better (Table 5).

Two estimates of classification accuracy are included. The normal procedure classified each field into a group using all the classification functions. The jackknifed technique classifies each into a group according to the

Table 5. Normal and jackknifed classification accuracies
for seven crop groups in 1980.

Crop Type	% Correct	
	Normal	Jackknifed

Wheat early	100.0 %	66.7 %
Wheat late	100.0 %	0.0 %
Barley early	100.0 %	100.0 %
Barley late	66.7 %	66.7 %
Flax early	100.0 %	100.0 %
Flax late	100.0 %	100.0 %
Oats	100.0 %	60.0 %
Total	95.7 %	65.2 %

classification functions computed from all the data except the case being classified (Lachenbruch and Mickey, 1968). This effectively removes any bias in the classification and more closely resembles the operational environment where an unknown field is to be classified using existing data.

A plot of the 1981 group data for the first two canonical variates showed less overall separability amongst crop groups (Figure 7). The flax fields (F) showed some separation as did the barley (B & B1). The wheat fields (W & W1; G & G1) showed some separation from other crops although the separation between the utility wheats (G & G1) and the early sown bread wheats (W) was poor. As in 1980 some grouping of the crops into the early and late sown fields was apparent.

The first two canonical roots were 4.89 and 1.08, which together accounted for only 81% of the overall between group variability. Thus the classification based on all the canonical variables was more accurate. Relative to 1980 the accuracy of classification was down in 1981, although slightly different crop groups were utilized (Table 6).

The tendency for crops to separate into subgroups of fields sown early and fields sown late occurred in both years, and in some cases the differences in optical density between early and late fields of a crop were quite large. These differences were related to the larger amounts of

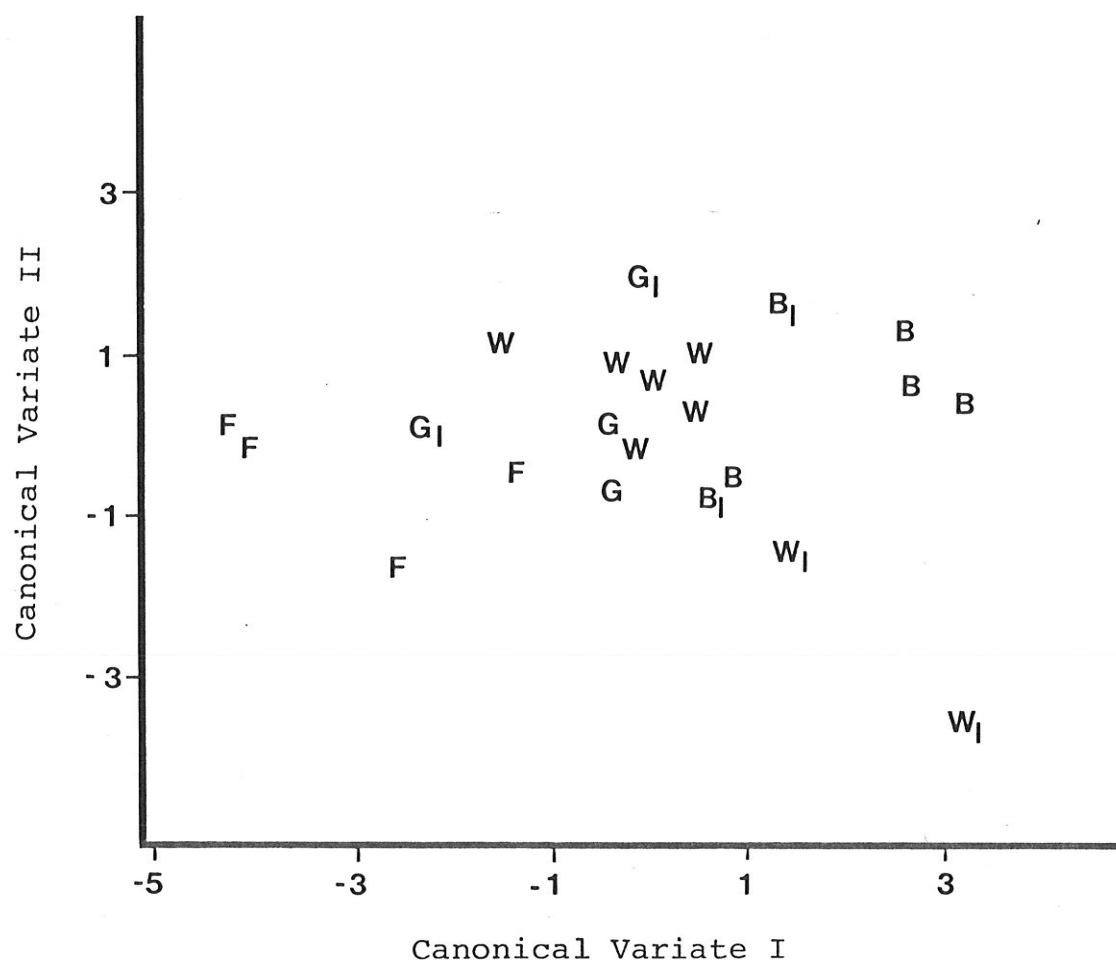


Figure 7. Plot of the first two canonical variates for early and late (l) sown wheat (W), barley (B), glenlea (G) and flax (F) in 1981.

Table 6. Normal and jackknifed classification accuracies
for eight crop groups in 1981.

Crop Type	% Correct	
	Normal	Jackknifed

Wheat early	66.7 %	66.7 %
Wheat late	50.0 %	50.0 %
Barley early	100.0 %	50.0 %
Barley late	50.0 %	0.0 %
Glenlea early	100.0 %	0.0 %
Glenlea late	50.0 %	0.0 %
Flax	100.0 %	75.0 %
Oats	100.0 %	100.0 %
Total	95.7 %	65.2 %

chlorophyllous biomass present in the early sown fields relative to the later sown fields. These differences are far from uniform during the season for the different crops. Two cultivars of wheat sown 15 days apart had similar ratios of green, brown and black ground cover by anthesis (Table 7). The Neepawa field was sown at a rate of 75 kg/ha and was fertilized with 24 kg/ha of actual nitrogen. The Sinton field was sown at a higher rate of 100 kg/ha and fertilized with 35 kg/ha of actual nitrogen. The relative crop growth rate of the Sinton field appeared to be greater than the Neepawa field, allowing it to reach the same stage of development as the earlier seeded Neepawa field. This may have been largely related to the higher rates of seeding and fertilization. By contrast two fields of Dufferin flax sown two days apart had different proportions of green, brown and black ground cover visible during the entire growing season (Table 8). The flax sown on April 28 was sown at a rate of 34 kg/ha and was fertilized with 47 kg/ha of actual nitrogen. The flax sown on April 30 was sown at a slightly higher rate of 44 kg/ha and was fertilized at the heavy rate of 96 kg/ha. This combination of higher seeding rates and higher fertilizer rates resulted in the April 30 sown flax greening up more rapidly and containing more chlorophyllous biomass than the field sown only two days earlier.

These results clearly show the influence of cultural practices on canopy development and ultimately on the

Table 7. Percent green, brown and black ground cover for Neepawa wheat seeded April 29, 1980 and Sinton wheat seeded May 14, 1980.

Date	% Brown		% Black		% Green	
	Neepawa	Sinton	Neepawa	Sinton	Neepawaa	Sinton

June 06	05	05	75	80	20	15
June 16	10	05	65	75	25	20
June 25	10	10	55	65	35	25
July 05	10	10	45	50	45	40
July 17	10	10	45	45	45	45
July 29	15	15	50	45	35	40
Aug 07	30	25	40	45	30	30
Aug 15	40	35	40	45	20	20
Aug 22	40	45	50	50	10	05

Table 8. Percent green, brown and black ground cover for
 Dufferin flax seeded April 28, 1980 (F1) and Dufferin
 flax seeded May 16, 1980 (F2).

Date	% Brown		% Black		% Green	
	F1	F2	F1	F2	F1	F2
June 06	05	05	90	85	05	10
June 16	10	10	85	75	05	15
June 25	10	05	80	75	10	20
July 05	15	10	75	65	10	25
July 17	20	20	60	50	20	30
July 29	30	25	55	55	15	20
Aug 07	25	25	65	60	10	15
Aug 15	40	30	50	60	10	10
Aug 22	40	30	50	60	10	10

relative proportion of green, brown and black ground cover visible to an airborne sensor. As the degree of variability in cultural practices from field to field increases, so does the degree of difficulty of correctly identifying unknown fields from remotely obtained sensor data. If the variability within groups, that is the variability amongst fields of a particular crop type, becomes greater than the variability between groups, then these crop classification techniques will be unsuccessful.

In order to study the variability within each crop group, the early and late sub-groups were combined for each crop. It was thought that combining these groups would increase the variation within each specific group due to the different densitometric response from fields with different cultural practices. A plot of the 1980 group data for the first two canonical variates showed clear separation of the wheat (W), flax(F) and fallow (S) fields (Figure 8). The first two canonical roots were 26.14 and 7.84, accounting for only 81% of the overall variability. The classification of crops using densitometric data from all nine dates was close to perfect (Table 9). Similar results were obtained using only the three best dates out of the total nine dates as input to the discriminant analysis. A plot of the 1980 group values for the first two canonical variates, using only the best three dates, showed similar separation of crops as before, although the separation between barley and

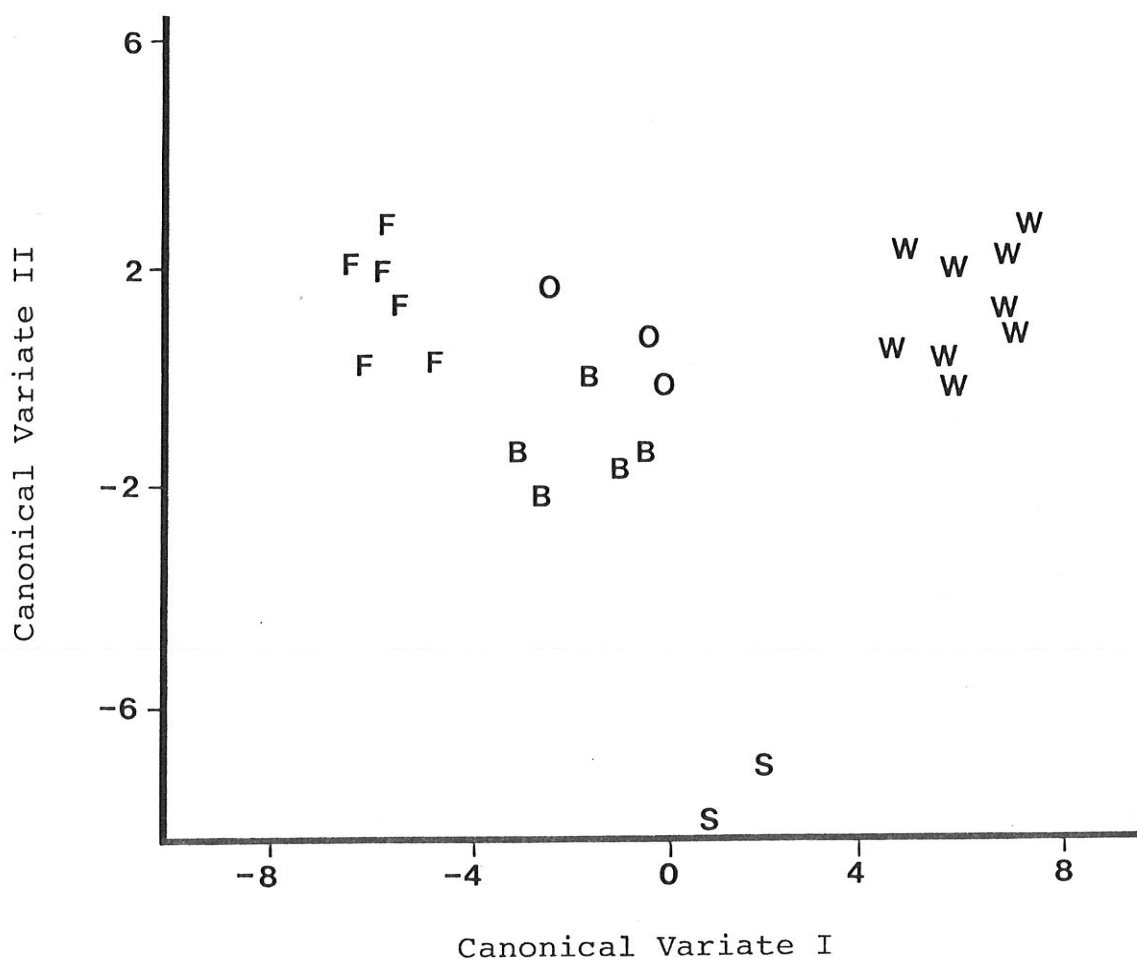


Figure 8. Plot of the first two canonical variates for wheat (W), barley (B), oats (O), flax (F) and fallow (S) in 1980.

Table 9. Normal and jackknifed classification accuracies
for five crops in 1980.

Crop	% Correct	
	Normal	Jackknifed

Wheat	100	100
Barley	100	40
Oats	100	100
Flax	100	100
Fallow	100	100
Total	100	92

oats was not as good (Figure 9). This resulted in slightly lower but still satisfactory classification accuracies (Table 10). The reduced accuracy was due to the misclassification of two oat fields as barley.

Clearly it is advantageous to obtain the desired level of classification accuracy using a minimum of input variables. The acquisition, processing and analysis of densitometric data on each date is labour and cost intensive and a reduction in these requirements would benefit the operational applications of these techniques. The proportional increase in accuracy with increasing variable inputs shows that an accuracy of almost 80% could be obtained using only the data from Aug 7, the best single date (Figure 10). Using data from the best three dates (Aug 7, Jul 17, Aug 15) resulted in an overall accuracy of 98.3%, with only two misclassifications of oat and barley fields. Thus one could obtain a 100% correct classification for wheat, flax or fallow using only the data from these three dates, whereas complete separation of barley and oat fields would require data from additional dates.

A plot of the 1981 group data for the first two canonical variates showed less overall separation amongst crops than in 1980 (Figure 11). The first two canonical roots were 5.12 and 3.20, accounting for 82% of the overall variability. The canola fields showed clear separation,

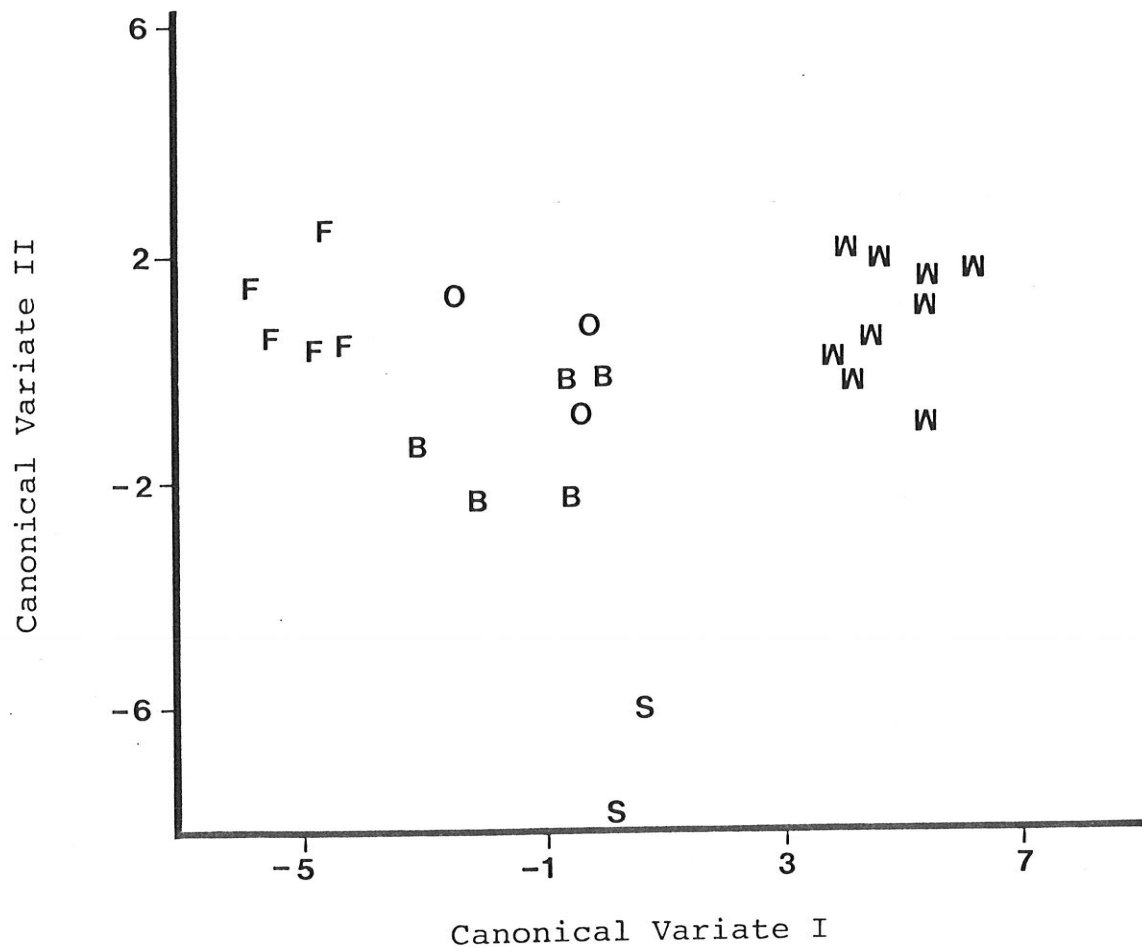


Figure 9. Plot of the first two canonical variates for wheat (W), barley (B), oats (O), flax (F) and fallow (S) in 1980 using only the three best dates.

Table 10. Normal and jackknifed classification accuracies
for five crops in 1980 using only the three best dates.

Crop	% Correct	
	Normal	Jackknifed

Wheat	100	100
Barley	100	40
Oats	75	25
Flax	100	100
Fallow	100	100
Total	96	88

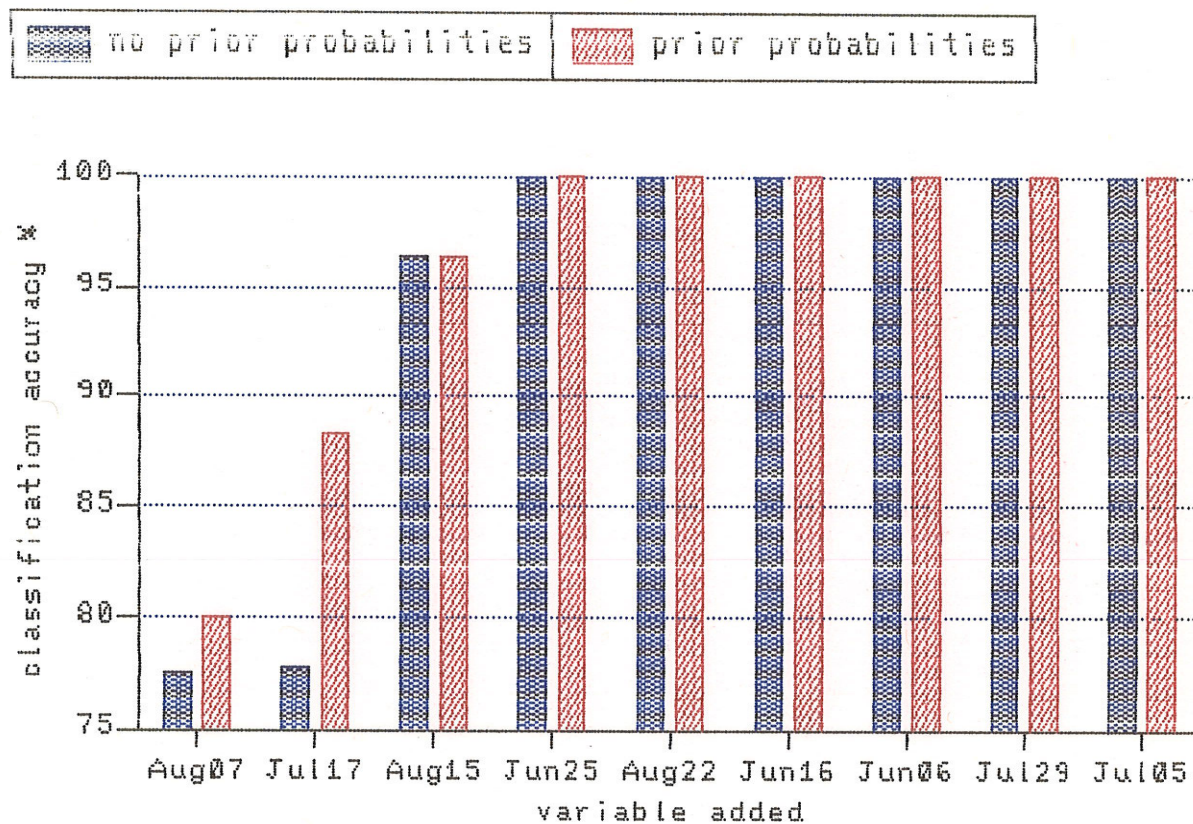


Figure 10. Proportional increase in classification accuracy with stepwise addition of variables in 1980.

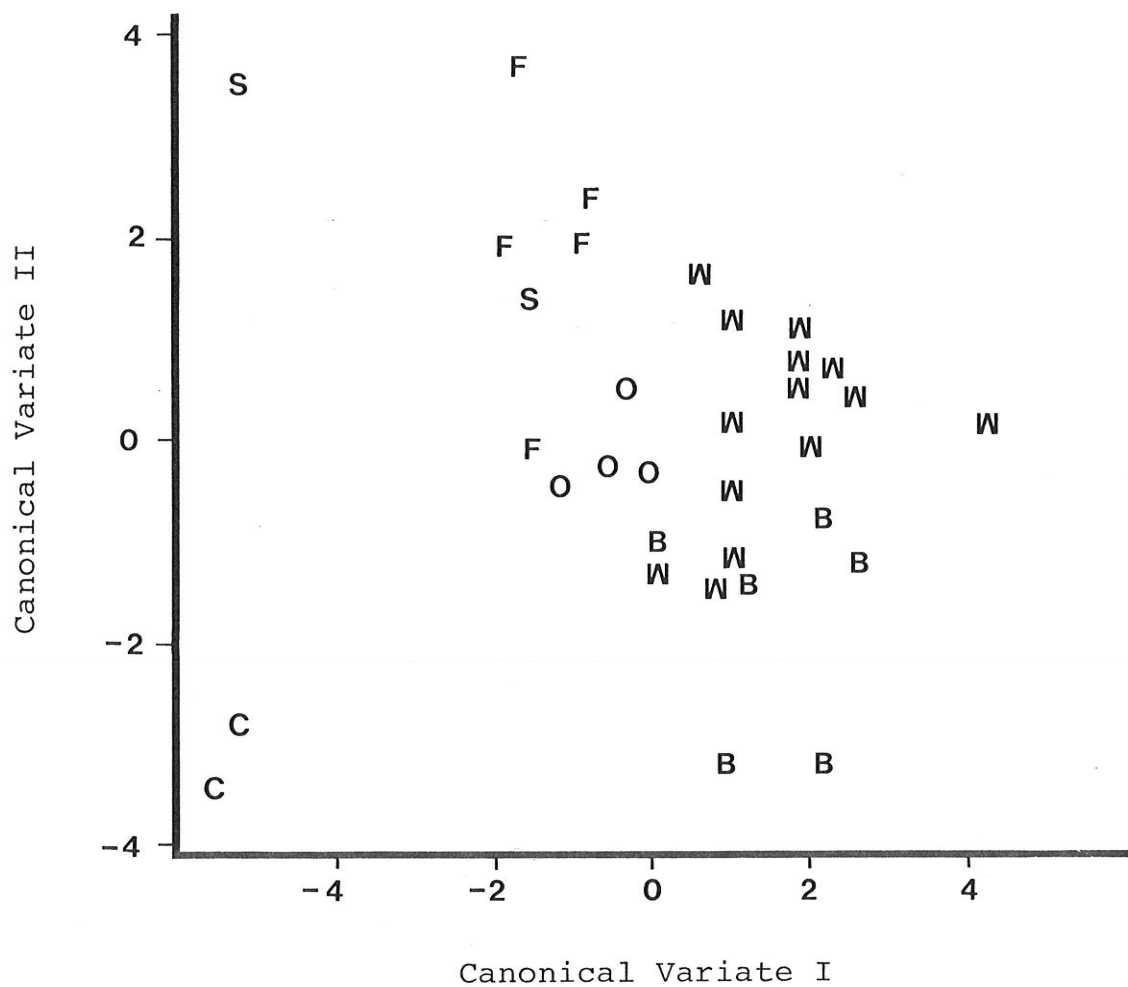


Figure 11. Plot of the first two canonical variates for wheat (W), barley (B), oats (O), flax (F), fallow (S) and canola (C) in 1981.

while all other groups had some fields that were misclassified into other groups (Table 11). The lower separability of crop groups in 1981 was due to the similarity of group means for each canonical variate and the variability of observations around those means.

Using only the data from the best three dates (July 16, July 28, June 29) to derive the canonical variates resulted in an overall classification accuracy of 73% with no prior probabilities and 79.6% with prior probabilities (Figure 12). The reduction in accuracy using only three of the seven dates resulted from misclassifications of wheat, barley and flax fields. All of the fields of oats and canola however, were completely separable and correctly classified.

The dates which offered the greatest potential for separation and discrimination amongst crops in 1980 were those dates in the latter half of the season. One exception was the June 25 flight, which was the fourth best date in 1980 for crop discrimination. In 1981 the trend was different. The dates which offered the best potential for discrimination were those in July and late June. The dates in August and early June were less effective. These differences in the effectiveness of different dates for crop discrimination from year to year were expected since slightly different crops were analysed in each year. It has

Table 11. Normal and jackknifed classification accuracies
for six crops in 1981 with no prior probabilities.

Crop	% Correct	
	Normal	Jackknifed

Wheat	78.6	64.3
Barley	83.2	60.1
Oats	100.0	75.1
Flax	60.0	40.0
Fallow	50.0	0.0
Canola	100.0	100.0
Total	81.1	56.8

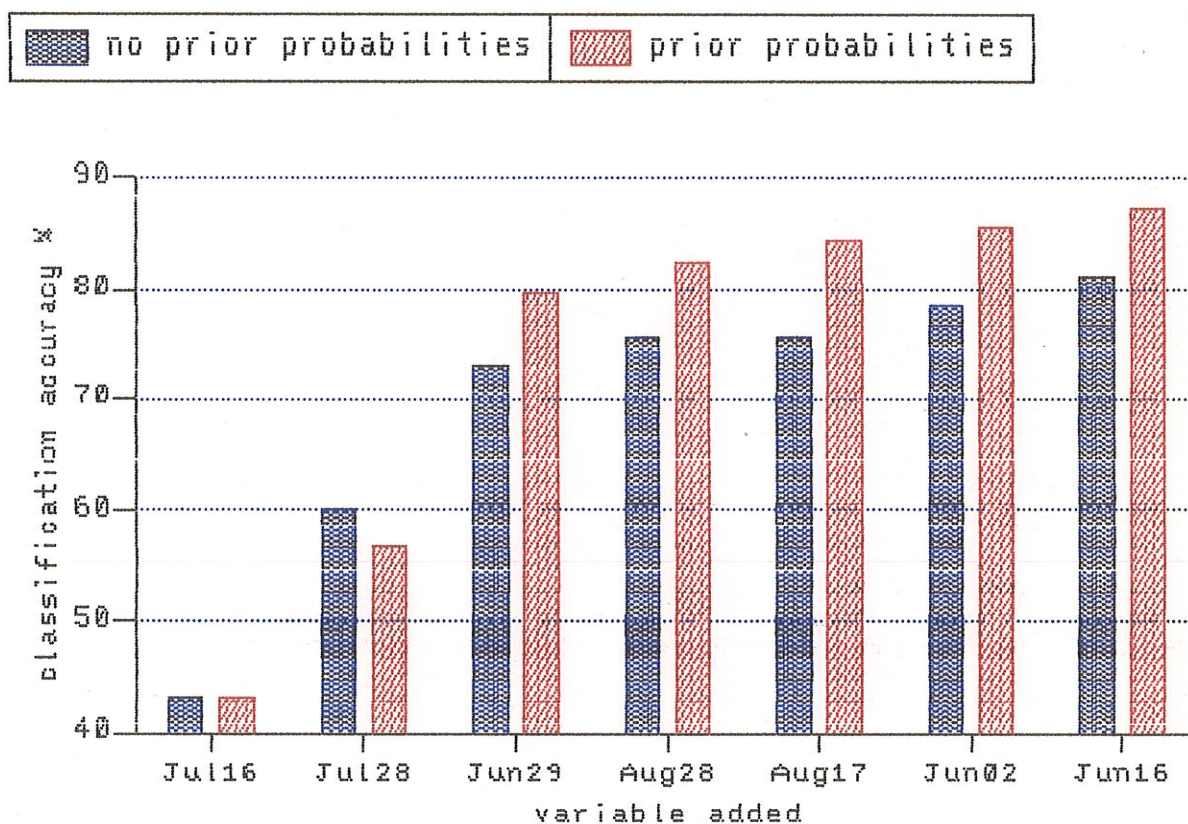


Figure 12. Proportional increase in classification accuracy with stepwise addition of variables in 1981.

also been previously shown that environmental factors and cultural practices can significantly affect the relative crop growth rates of different crops during a season.

The inability to effectively discriminate between crops early in the season has been discussed (Leamer et al, 1978; Glick et al, 1980). Soil background reflectance is the dominant component measured by a sensor at these early dates, causing small differences between crops to be masked. The earlier that crops can be discriminated the more useful such techniques would be in the area of crops acreage assessment studies.

Simulation Study

A major aim of this research was to test the discriminant functions derived in this study on a new, unknown dataset. The accuracies of crop classification discussed in the previous section do not accurately represent the response to these densitometric techniques in a realistic environment, They are merely an indication of data fit, similar to the coefficient of determination (R) in a regression analysis, which test how well the model accounts for the variability in the existing data and not their predictive capabilities for new data. The use of jackknifed classification

techniques reduced some of this bias, but still did not provide an indication of the effectiveness of these techniques on previously unclassified data.

A simulation study was designed to realize these objectives. A new dataset was developed from the 1981 field data. This dataset consisted of 15-30 measurements of optical density in 1981 from each field within the test area. This dataset more closely emulated an operational environment where a scanning densitometer might be used to obtain several observations from many different fields along a flight line. Each of the 600 observations in this dataset were classified into a crop group using the discriminant functions developed from the previous 1981 dataset. In this way, the success of using previously derived discriminant functions on a new dataset was evaluated.

The results of this simulation showed a slightly higher accuracy of classification when prior probabilities were used (Table 12). The overall accuracy was 83% when prior probabilities were used. Almost all the observations of wheat, canola, peas and buckwheat were successfully classified. The misclassification of fields was often related to the use of the prior probabilities. Because the prior probability of an unknown field being classified as a wheat field was large, many observations of barley, oats, flax, fallow and sunflower were incorrectly classified as

Table 12. Jackknifed classification matrix for simulation dataset with prior probabilities.

Crop	Percent	Number of cases classified into group								
	Correct	Wht	Brly	Oat	Flx	Can	Fal	Sun	Pea	Buck
Wheat	92.3	180	12	1	0	0	0	0	0	0
Barley	68.3	16	41	1	1	0	0	0	0	0
Oats	68.9	10	0	31	3	0	0	1	0	0
Flax	88.0	1	0	0	66	0	2	6	0	0
Canola	100.0	0	0	0	0	30	0	0	0	0
Fallow	50.0	1	0	0	14	0	15	0	0	0
Sunflw	20.0	2	0	0	10	0	0	3	0	0
Peas	100.0	0	0	0	0	0	0	0	15	0
Buckwh	100.0	0	0	0	0	0	0	0	0	30
Total	83.0	210	53	33	94	30	17	10	15	30

wheat.

When no prior probabilities were used in this simulation the overall accuracy was 78%, only marginally lower than with prior probabilities (Table 13). More fields of wheat were incorrectly classified as barley or oats, however other crops had higher accuracies. Similar classification accuracies were obtained using data from the best four dates (Figure 13). The data suggest that the use of prior probabilities had only a marginally beneficial effect on improving classification accuracy.. Although the overall classification accuracy was generally greater when prior probabilities were used, they reflect the errors of omission and not the errors of commission. In some cases the individual crop classification accuracy for a specific crop was greater when no prior probabilities were used.

The results of this simulation show that previously derived classification functions can effectively classify a set of unknown observations from many different field types. The classification functions would optimally be derived from field data similar in nature to the unknown fields to be classified. The discriminant functions may be applicable in more than one geographic region, providing they do not differ greatly in climate, topography or cultural practices. This general applicability would eliminate the need to develop a whole new set of discriminant classification

Table 13. Jackknifed classification matrix for simulation dataset with no prior probabilities.

Crop	Percent	Number of cases classified into group								
	Correct	Wht	Brly	Oat	Flx	Can	Fal	Sun	Pea	Buck
Wheat	73.3	143	21	16	4	0	0	8	0	3
Barley	71.7	0	43	3	0	0	0	0	2	7
Oats	93.3	0	0	42	0	0	0	1	1	1
Flax	66.7	0	0	1	50	0	0	14	1	9
Canola	100.0	0	0	0	0	30	0	0	0	0
Fallow	60.0	0	0	0	0	0	18	5	0	2
Sunflw	100.0	0	0	0	0	0	0	15	0	0
Peas	100.0	0	0	0	0	0	0	0	15	0
Buckwh	100.0	0	0	0	0	0	0	0	0	30
Total	78.0	148	64	62	59	30	18	43	19	52

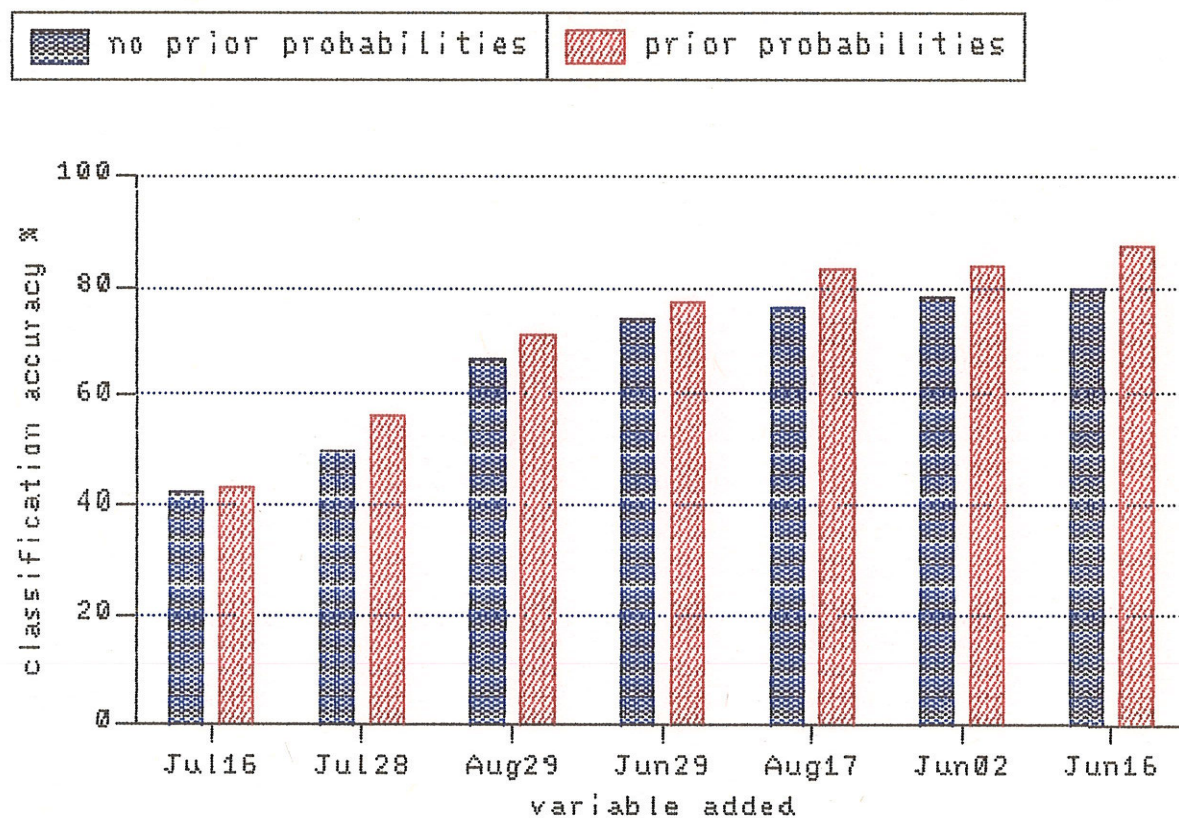


Figure 13. Proportional increase in classification accuracy with stepwise addition of variables in simulation dataset.

functions for each test site or region since only one set would be required. It appears unlikely however, that these functions would be applicable in more than one year, since there is considerable variability in growing conditions from year to year.

Yield Estimation

The yield data collected for each field in the test area were analysed to determine the relationship, if any, between optical density values obtained during the growing season and final grain yield for each of the major crops.

Grain yields were obtained directly from farmers shortly after the harvest. These yield estimates were derived in a subjective fashion and were subject to normal biases. Subsequent visits in the following year, however showed these estimates to be within an acceptable error range of 8%.

The relationship between optical density and yield in 1980 was not well defined. Barley yields were negatively correlated with optical densities measured on July 17 (Table 14). The negative sign of the correlation coefficient is appropriate in physiological terms since lower optical

Table 14. Correlation matrix for yield and optical density measurements in 1980.

Correlation coefficient for each date				
Date	Wheat	Barley	Oats	Flax

June06	-.107	-.043	.617	.632
June 16	.590	-.314	.598	.467
June 25	.251	.363	.913*	-.397
July 05	.213	-.053	.987**	.823*
July 17	.199	-.735*	.871*	.428
July 29	.269	.615	-.773	.488
Aug07	-.363	.194	-.695	.415
Aug 15	-.360	.109	.663	-.632
Aug 22	.403	-.013	.672	-.122

* - significant at $p (.05)$

densities, an indication of higher chlorophyll concentrations, should be related to greater yields. Yields of flax and oats, however, were positively correlated with optical densities measured on July 5. Such a relationship was not meaningful in a physiological perspective and was not considered in this analysis. No significant relationship occurred between wheat yields and optical density measurements on any dates.

In 1981 the results of the correlation were more meaningful, with many significant negative correlations occurring (Table 15). Strong correlations occurred between canola yields and optical density measurements on the first two dates. Yields of wheat, barley and oats were significantly correlated with optical density measurements on July 16 and June 29, respectively, although the relationships were not strong.

Linear regression equations were developed using the optical density values from those dates having the largest correlation with yield for each of the specific crops. Satisfactory R squared values were obtained for some crops in both years, although the variables highly correlated with yield were not similar in the two years (Table 16 and 17). These data indicate that a potential for relating measurements of radiation and grain yields exists. Only certain crop yields were well correlated with measurements

Table 15. Correlation matrix for yield and optical density measurements in 1981.

Correlation coefficient for each date							
	Jun02	Jun16	Jun29	Jul16	Jul29	Aug17	Aug29
Yield	-----						
Wheat	-.041	-.031	-.299*	-.493*	-.180*	-.144	-.284*
Barley	.461*	.524*	-0.12	-.360*	-.043	-.032	.887*
Oat	-.490*	-.180	-.667*	.435*	.735*	.552*	.102
Flax	.009	.376*	.113	.080	-.496*	-.278	-.530*
Canola	-.871*	.847*	-.040	.395	-.333	.612*	.686*

* - significant at $p (.05)$

Table 16. Regression analysis between yield and optical density measurements showing variables used, R squared and t probabilities in 1980.

Crop	R Squared	Variables	Probability > t

Wheat	.410	Intercept	.291
		June 16	.286
		Aug 22	.980
Barley	.690	Intercept	.755
		July 17	.293
		July 29	.429
Oat	.975*	Intercept	.029
		July 05	.047
		July 29	.056
Flax	.716	Intercept	.866
		July 05	.166
		Aug 15	.569

* - significant at p (.05)

Table 17. Regression analysis between yield and optical density measurements showing variables used, R squared and t probabilities in 1981.

Crop	R Squared	Variables	Probability > t

Wheat	.2486*	Intercept	.001
		July 16	.001
		June 29	.215
Barley	.8492**	Intercept	.001
		Aug 28	.001
		June 16	.001
Oat	.7589*	Intercept	.001
		June 29	.001
		Aug 17	.001
Flax	.3429*	Intercept	.001
		Aug 28	.007
		July 28	.011
Canola	.9166**	Intercept	.001
		June 02	.001
		June 16	.001

* - significant at p (.05)

** - significant at p (.01)

of optical density on certain dates. however, and the dates that were most correlated with crop yields differed for each crop in each year. These data suggest that the relationship between crop yield and measurements of optical density was inconsistent, and as a result, the overall predictive capability of these measurements for final grain yield could not be conclusively demonstrated.

The lack of a clear relationship between optical density and yield was partly due to the fact that the reflectance properties of grain crops can be related more to their standing biomass than to their final grain (commercial) yield. The reflectance properties of a crop measured by a visible airborne detector is largely a function of pigment absorption (Gates et al, 1965). Pigment concentration within a crop is under genetic control and modified by environmental parameters. The relationship between standing biomass and grain yield however, is not perfect. A crop with a high biomass (and lower reflectance) may yield a large amount of straw and only a small amount of grain. Conversely, a crop with a small biomass can still yield large amounts of grain. In the greater number of cases however, large grain yields are obtained from crops with a high biomass. It is possible that measurements of optical density are an accurate indicator of plant biomass, but that biomass is not perfectly correlated with grain yield.

Another factor contributing to the lack of a well defined relationship between yield and optical density was related to the close similarity of yields for many of the crop fields. For example the oat fields had crop yields that only ranged from 31 bu/ac to 48 bu/ac in 1980. Similarly, many of the wheat fields had yields that only ranged from 25 bu/ac to 30 bu/ac. In many cases the full potential of crop yields were not expressed, making it difficult to obtain strong coefficients of correlation and regression. This phenomenon was more prevalent in 1980 due to the drought conditions which limited normal crop development.

A final complication further reducing the effectiveness of this yield study was related to a series of hail storms in July and August, 1981 which inflicted variable amounts of damage (5 to 30% according to producers affected) to many of the fields. Thus measurements of optical density obtained prior to the hail storms would be related to yield potentials at the time of measurement and not with a hail reduced yield that finally occurred.

GENERAL DISCUSSION

Temporal profiles of crop optical density in the narrow .6 to .7 μm waveband measured by an airborne detector were successful in characterizing the phenological development of the various crops in the study area. Minimum and maximum values of optical density were well correlated with anthesis and physiological maturity, respectively in both years of the study. Crop phenological data are becoming more important as inputs into large area crop yield models. Jakovlev (1973) reported that spring wheat yields were a function of the length of time between emergence and heading and the time between heading and maturity. Crop growth and development data obtained from measurements of crop reflectance could provide more accurate information than the historical averages that are presently available. These techniques based on reflectance properties would be much more sensitive to anomalous growing conditions resulting from abnormal climatic conditions. For example, a late spring could delay seeding of small grains considerably, rendering the historical averages of crop development inaccurate.

These crop profiles have also been developed from small scale satellite imagery (Henderson and Badwhar, 1982). This has reduced the cost per unit area of ground that is imaged, although user costs of acquisition and analysis have

increased. Greater than three cloud free acquisitions are necessary to develop these profiles, and this may exceed the current operational capability of resource satellites.

The accuracy of crop classification using measurements of optical density in the .6 to .7 μm waveband was generally higher in 1980 than in 1981. This was directly related to the variability in measurements of optical density for each of the crops. The standard deviations of the mean values of optical density were consistently lower in 1980 than in 1981, and were clearly related to the different environmental conditions that occurred during the two years (Table 1 and 2). Mild drought conditions prevailed during the summer of 1980 with rains falling only during the harvest. As a result, grains were seeded early, weed growth was minimal, soils remained uniformly dry throughout the summer and yield potentials were not realized. The temporal profile of optical density measurements for the fallow fields, a good indicator of environmental variability, was quite uniform throughout the season with very little variability observed.

Conditions in 1981 were completely different, with rains commencing early in the season and continuing at timely intervals throughout the season. The crops tillered more in 1981, weed populations were heavier and more varied and soil moisture fluctuated considerably between field capacity and

dry conditions. This is clearly exhibited by the temporal profile for fallow in 1981 which fluctuated considerably during the growing season and had large deviations on most dates.

It is clear that environmental factors will modify the accuracy of crop identification techniques using measurements of optical density. The greater the variability in crop growing conditions, the greater will be the reduction in accuracy. It is encouraging to note that the crop development stages which contributed most to the classification of crops were similar in both years. The early crop growth stages of emergence, tillering and jointing contributed little to the crop classification in either year. During these early stages of growth, the sensor is receiving energy from a field of view dominated by the spectral properties of the background soil. Chlorophyll levels in plant canopies are still low on these dates and do not provide much basis for discrimination. As a result the spectral properties of fields appear similar early in the season. It is only during the later stages of growth that the unique characteristics of crop development from the different crops provide a basis for discrimination. These characteristics include canopy heights, chlorophyll concentration and canopy geometry. The relative importance of each date was quantified by adapting the stepping procedure of the discriminant analysis program to input the

measurements of optical density from each growth stage sequentially. The results confirm that the early stages of growth provide little basis for discrimination (Figure 14).

This similarity in development stages at which optical density measurements were successful in classifying crops suggests that the principles of the technique are sound and can apply in different years. The specific discriminant functions do not appear to apply in more than one year, however. The potential of these techniques are high in years of low environmental variability such as 1980. This potential is reduced in those years where growing conditions fluctuate considerably. It appears that the amount and frequency of precipitation during the growing season was the dominant environmental factor affecting measurements of optical density.

The potential to estimate crop yields from measurements of optical density in the .6 to .7 μm waveband was not conclusively demonstrated in this study. Results from physiological studies on plant photosynthesis suggest that a relationship exists between yield and concentrations of chlorophyll a and chlorophyll b. When all other factors are not limiting, a plant with more chlorophyll pigment can trap more radiant energy and provide more chemical energy for growth and development (Noggle and Fritz, 1976). Thus one would expect that the total plant dry matter yield would be

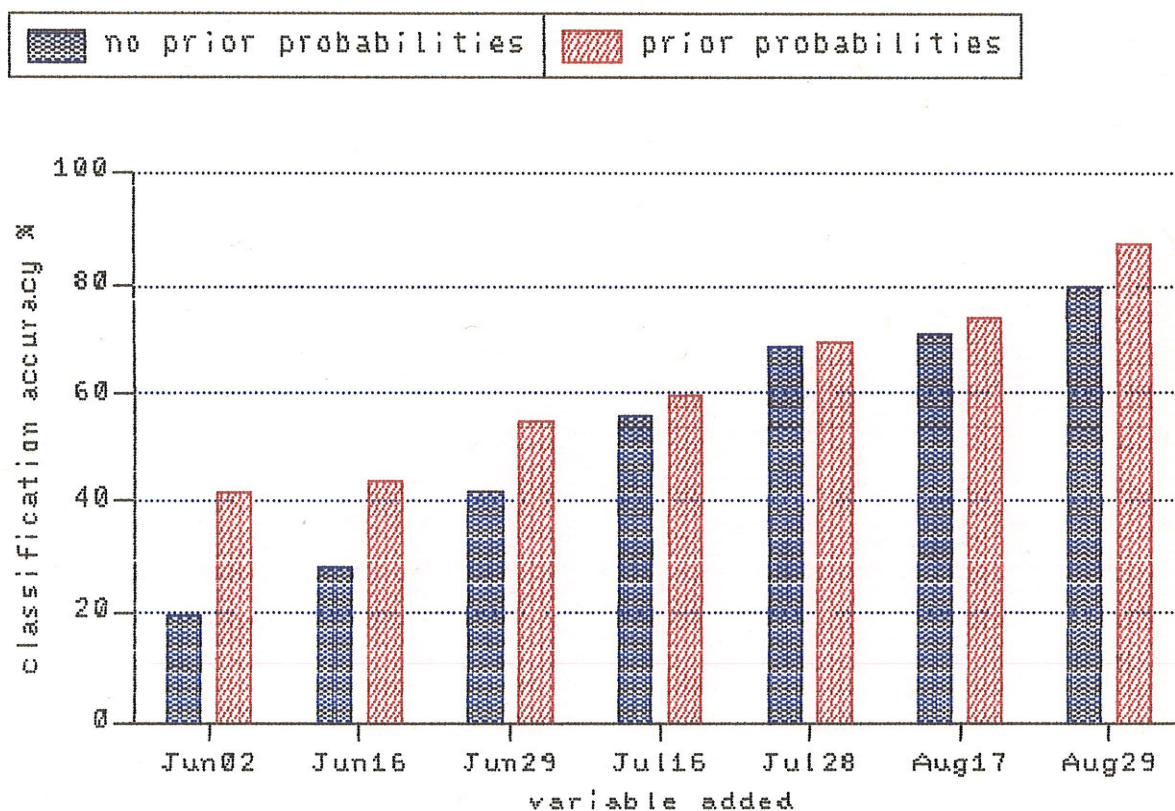


Figure 14. Proportional increase in classification accuracy with sequential entry of variables in 1981.

a function of chlorophyll concentration. Measurements of optical density in the .6 to .7 μ m range can provide indirect information on chlorophyll concentration or the amount of chlorophyllous tissue present in a plant canopy. However, the relationship between chlorophyll concentration and a single specific component of total yield, in this case kernel yield, is not well defined. As mentioned, this relationship is dependent on the particular ratio of grain / grain + straw (Harvest index) for a crop in a particular year. Harvest index is influenced by a variety of environmental and cultural factors which suggest that a consistent relationship between grain yield and chlorophyll concentration does not exist.

Results of this study showed inconsistent patterns, with some crops being highly correlated with measurements of optical density on certain dates (Table 14 & 15). Results were not as good in 1980 due to the drought conditions which limited the full expression of yield potential.

SUMMARY AND CONCLUSIONS

The results of this study demonstrated that measurements of crop optical density in the .6 to .7 μm waveband had the potential to classify several different grain crops and to provide information on crop development. Classification of all crops on any single date was not possible, since on each date at least two crops appeared spectrally similar. However, by exploiting the temporal variability in measurements of crop reflectance during the growing season, quantitative differences occurred in the response from different crops using only a single spectral band.

The accuracy of crop classification based on densitometric analysis of field images on film was a function of the environmental conditions, the number of variables used and the number of crops being classified. A successful classification of only two crops, wheat and canola, would require optical density measurements from only two dates while a classification of all five crops would require data from four or five dates.

Attempts to relate measurements of optical density with final grain yield were inconclusive. Results of regressing optical density measurements with yield were inconsistent, with highly significant R squared values occurring in only

some of the cases.

The transfer of such technology into an operational crop classification environment would offer great potential to various regions within the agricultural sector. The results obtained in this study suggest an inexpensive technique for acquiring, analysing and interpreting the required field data. Variability inherent in the photographic process and the conversion of these analog photographs to digital values can be eliminated by replacing the camera with a digital scanner which can obtain imagery in selected spectral bands and provide output in a computer compatible format for analysis.

A requirement for further research exists since there are limitations to this study and additional information is required for such technology to become useful in an operational fashion. The data presented in this study represent results from only two summers. A minimum of five years of data would be required to develop a suitable data base for interpreting the seasonal trends in optical density and understanding the effect of environmental conditions on the classification results. These data are also limited to a single test site. It is clear that any technique for generating estimates of acreage for the major crops in the prairie region would require several test sites. These sites would be required to account for differences in soil

types (moisture, drainage, texture), differences in climatic conditions and differences in land use.

Further research is needed to investigate the relationship between the scale of imagery and the accuracy of classification obtained. The use of smaller scale imagery would greatly decrease the unit cost of aerial coverage.

LITERATURE CITED

Remote Sensing data. Purdue University, LARS.

Brach, E.J., Tinker, R.W. and St. Amour, G.T. 1977. Improvements in spectral reflectance measurements of field crops. Can. J. Agr. Eng. 19:78.

Campbell, N.A., Honey, F.R., Hick, P.T. and Carlton, M.D. Evaluation of the application of LANDSAT data to crop discrimination in western Australia. Proc. Mach. Processing of Remote Sensing Data Symp., Purdue Univ., Ind., 1982.

Colwell, J.E. 1973. Vegetation canopy reflectance. Remote Sensing Environ. 4:21.

Dixon, W.J. and Brown, M.B. Biomedical computer programs. P-series. University of California Press, Berkley, U.S.A. 1979.

Doverspike, G.E., Flynn, F.M. and Heller, R.C. 1965. Microdensitometer applied to land use classification. Photogramm. Eng. 31:294.

Driscoll, R.S., Reppert, J.N. and Heller, R.C. 1974. Microdensitometry to identify plant communities and components on colour infrared aerial photos. J. Range Management 27:66.

Duggin, M.J. 1980 The field measurement of reflectance factors. Photogramm. Eng. & Remote Sens. 46:643.

Erlich, W.A., Poyser, E.A., Pratt, L.E. and Ellis, J.H. 1959. Reconnaissance soil survey of Winnipeg and Morris map sheets area. Soils report #5. Manitoba soil survey.

Gates, D.M. Physical and physiological properties of plants. In: Remote sensing with special reference to agriculture and forestry. National Academy of Sciences, Washington, D.C. 1970.

Gates, D.M., Keegan, H.J., Schleter, J.C. and Wiedner, V.R. 1965. Spectral properties of plants. Applied Optics 4:11.

Gausman, H.W., Allen, W.A., Escobar, D.E., Rodriguez, R.R. and Cardenas, R. 1971. Age effects of cotton leaves on light reflectance, transmittance and absorptance and on water content and thickness. Agron. J. 63:465.

Glick, H.L., Shaykewich, C.F., Lacroix, L.J., Brach, E.J. and Bell, W.C. 1980. Species and cultivar discrimination of cereals by field spectroscopy. Can. J. Plant Sci. 60:69.

Glick, H.L., Bell, W.C., Shaykewich, C.F., Lacroix, L.J. and Brach, E.J. 1982. Field spectral reflectance measurements of small grain crops. Can. J. Plant Sci. 62:71.

Goodman, M.S. 1964. Criteria for the identification of

types of farming on aerial photographs. Photogramm. Eng. 30:984.

Haralick, R.M., Caspall, F. and Simonett, D.S. 1970. Using radar imagery for crop discrimination: A statistical and conditional probability study. Remote Sensing Environ. 1:131.

Harris, R.J. A primer of multivariate statistics. Academic press. London, England. 1975.

Henderson, K.E. and Badwhar, G.D. 1982. An initial model for estimating soybean development stages from spectral data. Proc. Eighth Int. Symp. Machine Processing of Remotely Sensed Data. Purdue University, Indiana.

Hoffer, R.M., Holmes, R.A. and Shay, R.J. 1966. Vegetative, soil and photographic factors affecting tone in agricultural remote multispectral sensing. In: Proceedings of the Fourth Symposium on Remote Sensing of The Environment, Ann Arbor, Michigan. pp. 115:134.

Idso, S.B., Reginato, R.J. and Jackson, R.D. 1977. Albedo measurement for remote sensing of crop yields. Nature 266:625.

Jakovlev, N.N. 1973. Agrometerological factors influencing spring wheat yield and grain quality in the Soviet Union. UNESCO, 1973. Plant response to climatic

factors. Proc. Uppsala Symp., 1970.

Kendall, M. Multivariate analysis. Charles Griffin and Co. Great Britain, 1975.

King, G.J. and Mack, A.R. 1980. A manual for recording significant agricultural ground information in remote sensing programs. Agriculture Canada, Ottawa.

Lachenbruch, P. and Mickey, J. 1968. Estimation of error rates in discriminant analysis. Technometrics 14:781.

Leamer, R.W., Noriega, J R. and Wiegand, C.L. 1978. Seasonal changes in reflectance of two wheat cultivars. Agron. J. 70:113.

Mack, A.R., Brach, E.J. and Rao, V.R. 1978. Investigation of crop spectra and selection of optimum spectral channels. Can. J. Spectroscopy 23:42.

Manual of Photographic Interpretation. American Society of Photogrammetry. Falls Church, Virginia. 1960.

Myers, V.I. and Allen, W.A. 1968. Electrooptical remote sensing methods as nondestructive testing and measuring techniques in agriculture. Applied Optics 7:1819.

Myers, V.I., Carter, D.L. and Rippert, W.J. 1966. Amer. Soc. Civil Eng. 92:59.

Noggle, R.G. and Fritz, G.J. Introductory plant physiology. Prentice Hall, Inc., New Jersey, 1976.

Polzin, T.T. 1980. The effects of haze on resolution of small scale aerial photography. Dept. of Resource Evaluation, Energy and Natural Resources, Edmonton, Alta.

Powers, W.E. and Kohn, C.F. 1959. Aerial photograph interpretation of landforms and rural cultural factors in glaciated and coastal regions. Northwestern University Studies in Geography 3:76.

Rao, V.R., Brach, E.J. and Mack, A.R. 1979. Effect of surface winds on the spectral signatures of crops. Agron. J. 71:515.

Rib, H.T. and Miles, R.D. 1969. Automatic interpretation of terrain features. Photogramm. Eng. 35:153.

Richardson, A.J., Wiegand, C.L., Gausman, H.W., Cuellar, J.A. and Gerberman, A.H. 1975. Plant, soil and shadow reflectance components. Photogramm. Eng. & Remote Sens. 41:1401.

Robbins, C.R. 1934. Northern Rhodesia: An experiment in the classification of land with the use of aerial photographs. J. Ecology 22:88.

Searle, W.J. 1979. In: Sas user's guide, 1979 edition. Sas institute, N.C. USA.

Sinclair, T.R., Schrieber, M.M. and Hoffer, R.M. 1973. Diffuse reflectance hypothesis for the pathway of solar radiation through leaves. Agron. J. 65:276.

Stanhill, G., Kafkafi, U., Fuchs, M. and Kagan, Y. 1972. The effect of fertilizer application on solar reflectance from a wheat crop. Israel J. Agric. Resources 22:109.

von Steen, D.H., Leamer, R.W. and Gerberman, A.M. 1969. Relationship of film optical density to yield indicators. Proceedings of the Fourth Symposium of Remote Sensing of the Environment, Ann Arbor, Michigan. pp. 1115-1122.

Steiner, D. 1970. Time dimension for crop surveys from space. Photogramm. Eng. & Remote Sens. 36:187.

Steiner, D. and Maurer, H. 1968. Development of a qualitative semi automatic system for the photo identification of terrain cover types. Queens Printer, Ottawa, Canada.

Stoner, E.R., and Baumgardner, M.F. 1980. Physicochemical, Site, and Bidirectional Reflectance Factor Characteristics of Uniformly Moist Soils. LARS Technical Report 111679. Purdue University, West Lafayette, Illinois.

Thomas, J.R., Myers, V.I., Heilman, M.D. and Wiegand, C.L. 1966. Factors affecting light reflectance from cotton. Proceedings of the Fourth Symposium of Remote Sensing of the Environment, Ann Arbor, Michigan.

Tinker, R.W., Brach, E.J., Lacroix, L.J., Mack, A.R. and Poushinsky, G. 1979. Classification of land use and crop maturity, types and disease status by remote reflectance measurements. Agron. J. 71:992.

Tucker, C.J., Holbren, B.N., Elgin, J.H. and McMurtrey, J.E. 1980. Relationship of spectral data to grain yield variation. Photogramm. Eng. & Remote Sens. 46:657.

Verhoef, W. and Bunnik, N.J. 1974. Spectral reflectance measurements on agricultural field crops during the season: Classification of crop types and growth stages by means of an interactive graphics display system. NIWARS publication No. 31. NIWARS, Kanaalweg 3, Delft, the Netherlands.

Willstatter, R. and Stohl, A. 1913. Untersuchungen über die assimilation der kohlenzure. Springer, Berlin.

APPENDIX

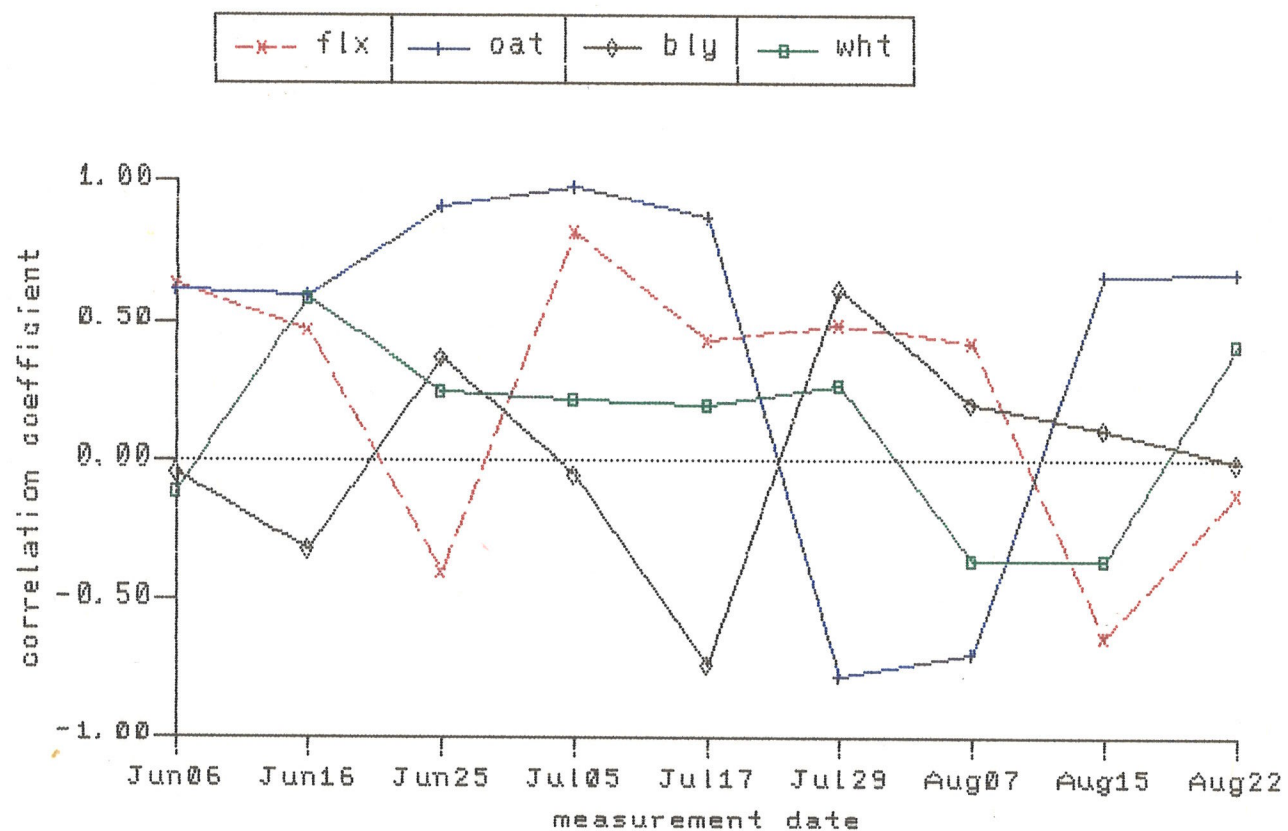


Figure 1. Correlation coefficients between yield and optical density in 1980.

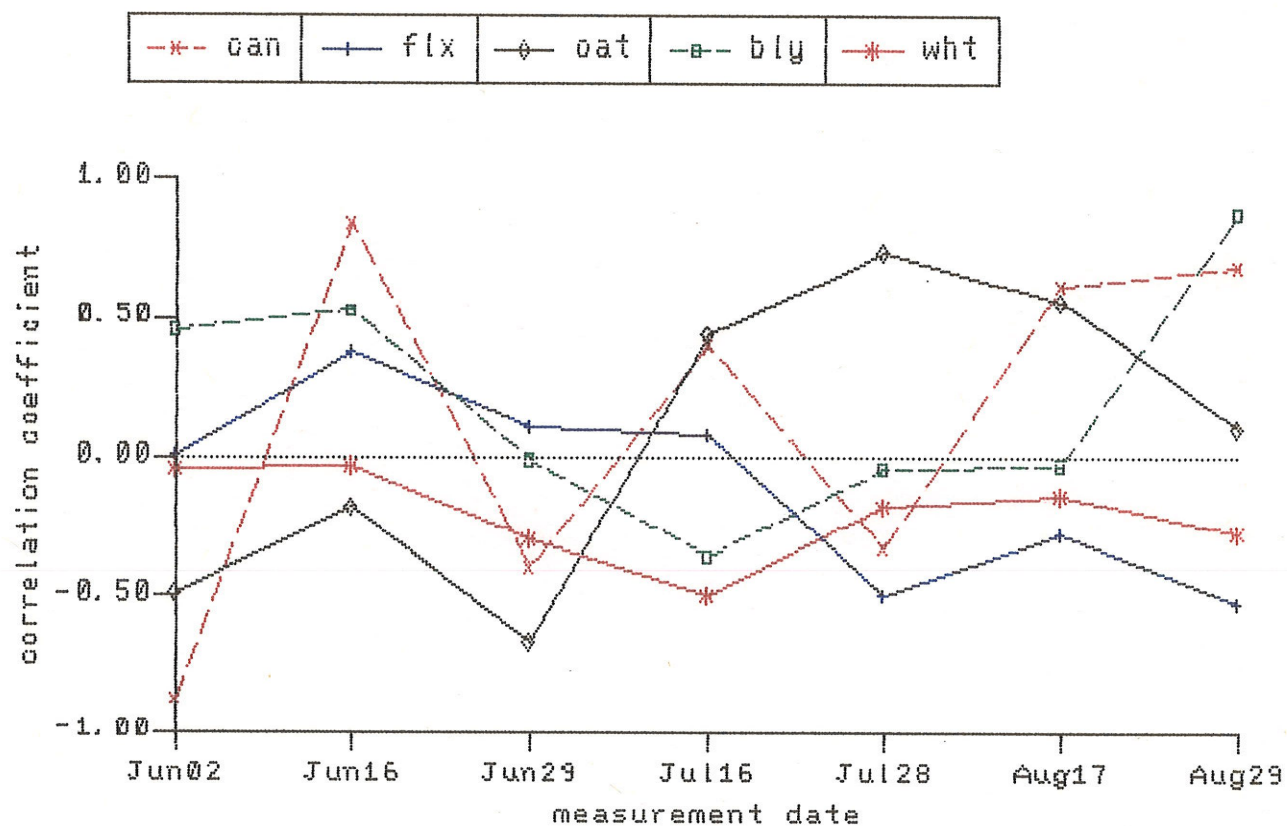


Figure 2. Correlation coefficients between yield and optical density in 1981.

Table 1. Prior probabilities used in the discriminant function analysis.

Crop	Probability
Wheat	0.5400
Barley	0.1300
Oats	0.0600
Flax	0.1600
Canola	0.0300
Fallow	0.0300
Sunflowers	0.0100
Peas	0.0100
Buckwheat	0.0100

Table 2. Discriminant functions used in the classification of nine crops in 1981 using all 15 observations per field.

Crop	Discriminant functions for each variable							Constant
	June 2	June 16	June 29	July 16	July 28	Aug 17	Aug 29	
Wheat	952.441	669.008	1082.362	731.339	906.062	588.814	328.722	-209.107
Barley	1011.151	781.995	1178.398	867.210	1067.137	682.750	391.717	-267.937
Oats	861.062	656.682	1085.762	1161.154	764.577	555.992	375.436	-212.459
Flax	953.851	841.077	1444.639	945.065	698.058	503.826	199.505	-217.117
Canola	1037.293	611.965	1197.077	2218.065	855.509	398.726	481.572	-314.958
Fallow	1020.870	659.355	1651.751	1202.683	515.493	486.157	198.234	-225.135
Sunflowers	1127.230	648.583	1171.552	1014.588	588.851	615.832	124.291	-203.148
Peas	612.771	906.288	1741.234	994.846	969.338	582.865	360.667	-265.660
Buckwheat	863.648	677.496	1601.619	1020.446	1005.862	394.495	269.457	-231.121