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**POTENTIAL VEGETATION INDICES FROM
LANDSAT THEMATIC MAPPER IMAGERY
FOR CROP MONITORING**

by

MICHAEL J. MANORE, B.A.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Arts
Department of Geography

Carleton University
Ottawa, Ontario

February 27, 1991

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Studies and Research acceptance of the thesis**

**"POTENTIAL VEGETATION INDICES FROM
LANDSAT THEMATIC MAPPER IMAGERY
FOR CROP MONITORING"**

submitted by MICHAEL J. MANORE

B.A. (Hons), Carleton University

**in partial fulfilment of the requirements for
the degree of Master of Arts.**

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February 27, 1991

ABSTRACT

A series of arithmetic combinations of spectral data, so-called 'Vegetation Indices', were generated from Multispectral Scanner (MSS) and Thematic Mapper (TM) imagery for a site in the grain producing region of western Canada. The vegetation indices were correlated with crop yield and plant height for a total of five different crops in the region in an effort to compare their relative performance for providing information on crop condition and yield prediction. Among the grains (i.e., wheat, barley) there was no improvement offered by the TM over the traditional near-infrared/red vegetation indices available from the MSS. For crops in flower at the time of imaging (in particular canola), new indices incorporating TM spectral bands in the middle-infrared significantly outperformed those from the MSS. The results are discussed with reference to operational crop monitoring in Canada.

The earliest applications of remote sensing to agriculture involved aerial surveys and the use of natural-colour and colour-infrared photography (Colwell, 1983). Visual interpretation of these images was used successfully for crop identification and the early detection of plant stress. In the early 1970's the first of a series of large experiments using multi-spectral, digital data for agricultural purposes was conducted. The Corn Blight Watch Program (1971) used airborne scanners to assess the ability of multi-spectral sensors to detect disease in corn in the U.S. Corn Belt (Clifton, 1972). Soon after, the Spring Wheat Experiment (1972-1973) examined the (then) newly available Landsat MSS data for the identification of crops and the estimation of acreages in the grain producing regions of the Canadian and U.S. prairie (NASA, 1980; Mack, 1982). Both of these programs were considered successful, although they were limited to very specific crop types and restricted geographic areas (Quelle-Wisstech Communications, 1984).

In 1974, the Large Area Crop Inventory Experiment (LACIE) was started (MacDonald and Hall, 1978). This was a large experimental programme with the objective of developing remote sensing and other techniques to estimate reliably U.S. national grain production, and that of other nations. Through a complex sampling scheme, Landsat MSS data were used to estimate crop areas while agro-meteorological models were used to estimate crop yield. Combined, these two pieces of information permitted the estimation of crop production. While the methodology for estimating crop areas was successful for most areas, there were problems of crop discrimination in small

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Agriculture is an activity fundamental to the physical and economic health of Canadians and the people of other nations. The value of Canadian agricultural production in 1985 was estimated at \$20.2 billion, and the processing and sale of agricultural and food products represented approximately ten percent of Canada's economic activity (Statistics Canada, 1990). Agricultural and food goods accounted for over seven percent of the country's exports with a total value of \$8.4 billion. Approximately one million Canadians reside in farm households, and agricultural activity takes place on approximately eight percent of the Canadian landmass.

To maintain their competitive position in agricultural production, Canadians must manage effectively the land resource on which the industry is based. In addition, the materials and energy employed in agricultural production, and the networks for marketing and transportation of the products must be efficiently used. Underpinning effective management is a need for reliable information about the type, location, and condition of crops under cultivation across Canada and elsewhere. An increasingly

important source of this information is the analysis of remotely sensed images from earth observation satellites.

The use of remote sensing techniques for agricultural applications has been strongly promoted since before the launch of the first earth resource monitoring satellites in the early 1970's. Image data from satellites are now recognized as a valuable tool by agencies requiring information on the extent and condition of agricultural crops. This is because of their relatively low cost, their geographically large area of coverage, and because the cyclic orbits of the spacecraft permit viewing of the same area on the ground several times during the growing season. This paper will explore one aspect of the use of remotely sensed data for monitoring agricultural resources. Specifically, it will examine the potential benefits to agricultural monitoring offered by a new generation of satellite sensors which offer high spatial resolution and record data in new regions of the electromagnetic spectrum. In this case, imagery from the relatively new Thematic Mapper (TM) instrument on-board the Landsat satellite will be compared to data from its predecessor - the Landsat Multispectral Scanner (MSS).

1.2 Remote Sensing in Agriculture: To place in context the work undertaken in this project, a brief history of the development of remote sensing in agriculture follows. Excellent reviews of these developments are presented by McQuillan and Henein (1980), Quelle-Wisstech Communications (1984), and Brown (1986).

The earliest applications of remote sensing to agriculture involved aerial surveys and the use of natural-colour and colour-infrared photography (Colwell, 1983). Visual interpretation of these images was used successfully for crop identification and the early detection of plant stress. In the early 1970's the first of a series of large experiments using multi-spectral, digital data for agricultural purposes was conducted. The Corn Blight Watch Program (1971) used airborne scanners to assess the ability of multi-spectral sensors to detect disease in corn in the U.S. Corn Belt (Clifton, 1972). Soon after, the Spring Wheat Experiment (1972-1973) examined the (then) newly available Landsat MSS data for the identification of crops and the estimation of acreages in the grain producing regions of the Canadian and U.S. prairie (NASA, 1980; Mack, 1982). Both of these programs were considered successful, although they were limited to very specific crop types and restricted geographic areas (Quelle-Wisstech Communications, 1984).

In 1974, the Large Area Crop Inventory Experiment (LACIE) was started (MacDonald and Hall, 1978). This was a large experimental programme with the objective of developing remote sensing and other techniques to estimate reliably U.S. national grain production, and that of other nations. Through a complex sampling scheme, Landsat MSS data were used to estimate crop areas while agro-meteorological models were used to estimate crop yield. Combined, these two pieces of information permitted the estimation of crop production. While the methodology for estimating crop areas was successful for most areas, there were problems of crop discrimination in small

field environments (because of the spatial resolution of Landsat) and problems of data availability (because of cloud cover) (Brown, 1986). However, the techniques were adopted operationally by a number of agencies including the U.S. Department of Agriculture and Statistics Canada (Dobbins, 1984; Merritt, 1985).

The AgriSTARS programme (1979-1985), as a follow-on to LACIE, had the goal to "assist the U.S. Department of Agriculture (USDA) assess satellite remote sensing to improve the reliability, timeliness and adequacy of information to meet USDA missions" (McQuillan and Henein, 1980). One difference between this experiment and LACIE was an effort aimed at developing techniques for monitoring the condition of crops throughout the growing season in order to improve yield estimates. The success of AgriSTARS is less widely claimed than for LACIE, although important advances were made (see IEEE AgriSTARS Special Issue, 1986). Specifically, new spectral bands for vegetation studies were identified, and there was recognition of the value for crop monitoring of low-resolution (500m - 1000m), but high-frequency (daily) imagery from meteorological satellites such as those operated by the U.S. National Oceanic and Atmospheric Administration (NOAA) (Kidwell, 1986).

Most early applications of satellite remote sensing to agriculture had focused on data captured by the Landsat MSS because until the mid-1980's it was the only sensor providing routine, high-resolution, multi-spectral imagery available for such use. However, data from the Landsat Thematic Mapper (TM) have become the preferred data

source for agricultural applications since their widespread availability in 1984. The TM offers improved spatial resolution over the MSS (30m versus 79m), an increase in the number and range of spectral bands that are sensed, and more sensitive detectors. Following recommendations from the AgriSTARS programme, the TM offers new spectral bands in the visible blue portion of the spectrum ($0.45\mu\text{m}$ - $0.52\mu\text{m}$) and in two windows in the middle-infrared ($1.55\mu\text{m}$ - $1.75\mu\text{m}$ and $2.08\mu\text{m}$ - $2.35\mu\text{m}$). In addition, the bands previously available from the MSS have been refined to optimize their sensitivity to vegetation condition. A comparison of the characteristics of the two sensors is presented in Chapter Two.

Today, in Canada, remotely sensed data are used operationally within the agriculture community, most notably to assist the Agriculture Division of Statistics Canada and the Canadian Wheat Board Canada to make estimates of crop production. Both Landsat MSS and TM data have been used by Statistics Canada to estimate the acreages of grain and oilseed crops in Manitoba and of potatoes in New Brunswick and P.E.I. (Pokrant and Magahay, 1986; Dobbins, 1984; Dobbins and Epp, 1986). Data from the TM are normally preferred over those from the MSS because of their better spectral information and finer spatial resolution which permit more accurate crop identification and field discrimination. More recently, data from the low-resolution (1km) NOAA meteorological satellite have been used to generate image and map products which summarize regional crop conditions in western Canada (Korporal *et al.*, 1989). These products are based on weekly, 'pre-processed' NOAA images produced

operationally by the Canadian Crop Information System located at the Manitoba Remote Sensing Centre in Winnipeg (Brown *et al.*, 1990). Among the other users of these data are the Canadian Wheat Board, the Prairie Farm Rehabilitation Administration (PFRA), grain trading and transportation firms, and provincial Ministries of Agriculture which use them to assist in yield prediction, market and transportation planning, and the allocation of drought relief payments.

One of the processing techniques used within the Crop Information System is the creation of a so-called 'vegetation index' from the image data. Vegetation indices are the focus of this thesis and their development and use are described in some detail below and in later chapters.

Vegetation Indices: Vegetation indices were among the techniques developed from the LACIE and AgriSTARS experiments described earlier in this chapter. Vegetation indices are arithmetic combinations or transformations of data from two or more spectral bands which have been shown to correlate strongly with the presence and vigour of green, photosynthetically-active vegetation (Tucker, 1979). For example, a common vegetation index is the ratio between reflectance in the near-infrared and the visible-red portions of the electromagnetic spectrum. This ratio exploits the complementary relationship between the absorption of incident light by plants in the red wavelengths and the high reflection of this light in the infrared. The spectral properties of plants which permit this relationship are dealt with at some length in the next chapter. For now, let it be said

that vegetation indices are considered to be an effective method of data reduction and a valuable tool for summarizing in a single number multi-band relationships that are sensitive to vegetation condition. Some indices also have the added benefit of reducing the effects of different atmospheric attenuation and scene illumination between images acquired on different dates, thus simplifying multi-temporal comparisons of satellite data (Tucker, 1979; Jackson *et al.*, 1983).

Because of the dominance of MSS data in the early development of agricultural remote sensing (for reasons of data availability), the most widely used vegetation indices comprise only spectral bands captured by the MSS. With new spectral information available from the Thematic Mapper instrument, what new combinations of spectral bands are available which might improve the quality or type of information about vegetation condition than is available from the MSS? Does the improved spatial resolution of the TM offer new information about the variability of crop condition within an agricultural field? These questions are the focus of the work described in this paper.

1.3 Objectives

On the premise that the improvements in the spectral bands of the TM do offer new and refined information over that available from the MSS, the general objective of this work was to compare the performance of vegetation indices derived from the TM and MSS sensors for crop condition assessment and yield forecasting. This was done through the comparison of vegetation indices employing spectral bands common to both

sensors, as well as novel indices using the new bands of the TM. For the new bands, the intent of the project was not to examine an exhaustive list of potential indices, but rather to explore a sample from the different spectral regions based on theoretical considerations and on the experience of previous investigators. In addition, the greater within-field detail available from the TM (resulting from its higher spatial resolution) was examined for information about the uniformity of plant condition and the relationship of this information to final crop yield.

The context in which the results were interpreted was that of operational crop monitoring in western Canada, as briefly described above. To this end, the work examined the performance of MSS and TM data at a test site near Melfort, Saskatchewan. The site lies within a predominantly grain and oilseed producing region of the northern Canadian prairie which is generally representative of cultivation practices over much of western Canada, except those in the dry-land farming regions of the southwest prairies.

The specific objectives of the work were:

- to generate a series of traditional and new vegetation indices from simultaneously acquired MSS and TM imagery;
- to correlate these with measures of crop yield and plant height (as indicators of crop condition); and
- to compare the performance of the TM indices as measures of these parameters with the performance of the traditional indices derived from the MSS.

The paper is organized in the following way. Chapter Two provides background to the work through a description of the TM and MSS sensors and a review of previous comparisons of the data from them. Chapter Two also summarizes the development and use of vegetation indices. Chapters Three and Four describe the data and the methods used in the analysis, and the results are presented and summarized in Chapter Five. Chapter Six examines the significant results of the project, the conclusions, and offers discussion on their implications to operational crop monitoring in Canada.

CHAPTER 2

BACKGROUND

2.1 Introduction

The intent of this chapter is to provide readers with the necessary technical and contextual background for an understanding of the work undertaken. Key to the understanding of remotely sensed data is knowledge about the spectral response of the target and of the sensor systems. Thus it is useful to review the spectral characteristics of vegetation, followed by a comparison of the technical characteristics and information content of MSS and TM data. Also key to this project is an understanding of the basis and development of vegetation indices and their current uses. These will be discussed, as will the results of previous studies which have compared vegetation indices derived from the MSS and TM.

2.2 Spectral Characteristics of Vegetation

A generalized reflectance curve for green, photosynthetically-active vegetation appears in Figure 2.1. A detailed description of the reflectance characteristics of various crops and the effects of crop stress is available from Gardner *et al.* (1982). In summary, reflectance of photosynthetically-active vegetation in the visible (VIS) region of the electromagnetic spectrum is generally low because of absorption by leaf pigments. The

Figure 2.1: Typical Reflectance Curve for Green, Photosynthetically-active Vegetation. Also illustrated are the MSS and TM sensor channels, the spectral regions in which they lie, and the characteristics of leaves which control reflectance (from Gardner *et al.*, 1982).

strongest absorption (primarily by chlorophyll and carotenoids) is between $0.4\mu\text{m}$ - $0.5\mu\text{m}$ and $0.6\mu\text{m}$ - $0.7\mu\text{m}$ (visible BLUE and visible RED). A relative peak of reflectance occurring between $0.5\mu\text{m}$ - $0.6\mu\text{m}$ (visible GREEN) accounts for the green colour of chlorophyll-bearing vegetation. Reflectance in the near infrared (NIR, $0.8\mu\text{m}$ - $1.2\mu\text{m}$) is very high relative to the VIS resulting from multiple reflections within air spaces in the leaf cell structure. Transmission of the NIR wavelengths by vegetation is also relatively high, and can result in considerable inter-leaf scattering below the plant canopy. This behaviour causes the NIR band to be sensitive not only to leaf cover at the plant canopy, but to the depth of photosynthetically-active leaf biomass in a canopy. Changes to the internal cell structure of leaves brought on by stress from disease, moisture deficiency or by natural plant senescence generally increases NIR reflectance in individual leaves, but decreases the overall NIR reflectance of a plant canopy because of reduced inter-leaf transmission and the appearance of the soil background (Colwell, 1983). The middle infrared (MIR) region ($1.55\mu\text{m}$ - $2.8\mu\text{m}$) is characterized by strong water absorption. Reflectance from vegetation in this region has been demonstrated to be affected by some leaf structure but is most sensitive to in-leaf water content (Tucker, 1980). Absorption increases directly with leaf moisture resulting in higher reflectance in moisture stressed or senescing plants.

2.3 Sensor Characteristics

The first Landsat satellite was launched by the U.S. National Aeronautics and Space Administration (NASA) in 1972 carrying a Multi-spectral Scanner (MSS). Since

then, MSS data of the Earth have been available continuously from a series of five Landsat spacecraft. In 1984, data from the TM became routinely available offering the improved sensor performance mentioned briefly in the previous chapter. The spatial, spectral, and radiometric characteristics of the two sensors are summarized in Table 2.1 and discussed in the following sections. The spectral channels of the two sensors in relation to the spectral characteristics of vegetation are illustrated in Figure 2.1.

Spectral: The MSS senses in four broad spectral bands corresponding to the visible GREEN (MSS1), visible RED (MSS2), and the near-infrared (NIR) regions of the spectrum (MSS3 and MSS4)¹. The TM, on the other hand, offers data in seven spectral bands including three in the visible region (VIS - TM1, TM2, TM3), one in the NIR (TM4), and two in the 'short-wave' or 'middle' infrared (MIR - TM5, TM7). An additional band sensing emitted radiation in the thermal infrared (TM6) is also available. The bands on the TM are generally narrower than those on the MSS in order to correspond better to the spectral regions most sensitive to plant physiology. Table 2.1 and Figure 2.1 summarize the plant characteristics to which each of the spectral bands is sensitive (from Tucker, 1978; and Gardner *et al.*, 1982), and Plates 1 and 2 provide examples of imagery from the two sensors. Of note in Table 2.1 and Figure 2.1 are the two new bands of the TM in the middle-infrared which offer information about plant moisture not previously available in MSS data.

¹ Band designations for the MSS changed with the launch of Landsat-4 from MSS 4-7 to MSS 1-4. The new naming convention is used in this paper.

Table 2.1 Spectral, Spatial, and Radiometric Characteristics of the Landsat MSS and TM Sensors.

Spectral Region	TM		MSS				Band Sensitivities	
	Wavelength (μm)	Resolution (m)	Wavelength (μm)	Resolution (m)				
BLUE	TM1	0.45-0.52	30	MSS1	0.5-0.6	79	leaf pigments (carotenoids, chlorophyll)	
GREEN	TM2	0.52-0.60		MSS2	0.6-0.7			
RED	TM3	0.63-0.69		MSS3	0.7-0.8			
	TM4	0.76-0.90		MSS4	0.8-1.1			
Near Infrared (NIR)	TM5	1.55-1.75						in-leaf water
Middle Infrared (MIR)	TM7	2.08-2.35						
Thermal Infrared	TM6	10.4-12.5		120	temperature and emissivity of plant

Plate 1: Example of Landsat Multispectral Scanner (MSS) Imagery.

The five frames in this plate illustrate the appearance data from the four spectral channels of the MSS sensor, and a combination of three channels into a colour composite over an agricultural area. The scene is a portion of the image data used in this study (see Section 3.3). MSS1 is characterized by relatively bright tones because of reflectance in the visible GREEN portion of the spectrum. MSS2 (visible RED portion of spectrum) is very dark because of absorption by chlorophyll in the vegetated targets, except in flowering canola fields which appear in bright tones. Both MSS3 and MSS4 demonstrate the typical bright reflectance of vegetation in the near-infrared spectral region. The colour composite image is composed of MSS1, MSS2, and MSS4 displayed in blue, green, and red respectively. Green vegetation (i.e., wheat, barley, peas, flax) appear in red tones, flowering canola appear bright grey, and unvegetated fallow fields appear dark blue-green. Some cloud and cloud-shadow are also visible in the scene.

MSS1	MSS2	
MSS3	MSS4	MSS1 - b MSS2 - g MSS4 - r

Plate 2: Example of Landsat Thematic Mapper (TM) Imagery.

The frames in this plate illustrate the appearance of data from the six reflective bands of the TM sensor over an agricultural area. The area is the same as that illustrated in Plate 1. TM1 (visible BLUE) has overall poor contrast because of its sensitivity to atmospheric haze. The data from TM2, TM3, and TM4 (visible GREEN, visible RED, and near-infrared) appear similar to the imagery from the same spectral bands in the MSS data (Plate 1). TM5 demonstrates a wide range of tones, but they appear unrelated to the patterns observed in the other bands. TM7 is characterized by dark tones resulting from strong in-leaf water absorption in the vegetated fields, and bright returns from bare soil in fallow fields.

TM1	TM2	TM3
TM4	TM5	TM7

Spatial: The Thematic Mapper offers a significant improvement in spatial resolution over the MSS; 30m x 30m versus 79m x 79m. This permits the detection of targets less than 0.1ha in size and significantly increases the level of detail visible in an image.

In agricultural scenes, it permits the detection of within-field variations in the reflectance of crops not previously visible in MSS data, which may be of value in the assessment of crop condition. Plate 3 illustrates the difference in spatial resolution between the two sensors. A comprehensive review of the spatial characteristics of the Landsat sensors is provided by Markham (1985).

Radiometric: In addition to improvements in the spatial and spectral characteristics, an improvement in the radiometric resolution of the TM over the MSS was introduced. Both sensors use mirror scan systems and detectors to convert radiance at the sensor (the total energy received at the sensor from all sources, including atmospheric contributions) into digital numbers. The TM provides analog-to-digital conversion with 8-bit (256 grey level) precision compared to 6-bits (64 grey levels) for the MSS. Also, the location of the TM's detectors on the focal plane of the instrument results in a higher signal-to-noise ratio and greater sensitivity than is possible for the MSS which receives its signals through fibre optic links from the sensor's focal plane (Wrigley *et al.*, 1984).

2.4 TM - MSS Comparisons

As background to this project, it is useful to examine previous comparisons of the TM and MSS systems. A large volume of work exists which evaluates all aspects of the

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Plate 3: Comparison of the Spatial Resolution of the Landsat MSS and TM Sensors.

This plate illustrates the higher level of spatial detail available from the TM sensor (30m resolution) versus the MSS (79m resolution). Within-field drainage features and variability in crop development which are not visible in the MSS are discernable in the TM.

MSS (79m)
TM (30m)

sensors, including the information content of the data and their utility in a variety of applications. The information content is of particular interest because of its potential impact on the generation of new vegetation indices.

Information Content: Much of the documented work which directly compares the information content and utility of TM versus MSS data was performed shortly after TM data were first available in 1982. Williams (1983) summarized twenty-four papers describing early results from the use of TM for a wide variety of applications, including land-use mapping and agriculture. Most of this work compared the accuracy of digital classifications achieved from the two sensors, although several papers were based on visual interpretation techniques. Most investigators found TM data to be significantly better than MSS for their own applications and that the improvement in spectral content, especially the addition of the two new MIR bands, was the most important factor. Improvements in spatial resolution were also seen to be important by many investigators, but few cited benefits from the increased radiometric resolution.

Williams *et al.* (1983), Acevedo *et al.* (1984), and Irons *et al.* (1985) performed analyses which isolated the effects of each of the improvements in the TM and also found that improvements in digital classifications were mostly attributable to the new bands, but also the increased radiometric sensitivity of the detectors. They also found that with all other factors held constant, the finer spatial resolution of the TM data offered no significant improvement or even reduced classification accuracies when using per-pixel

classifiers. This was attributed to greater spectral heterogeneity within classes resulting from the sensor's ability to resolve small areas of variation in ground cover. On the other hand, the higher spatial resolution was cited as a benefit by several investigators (including DeGloria, 1984; Bernier *et al.*, 1985), particularly in small-field agricultural environments where data from the MSS were too coarse for reliable field discrimination. Also, the improved spatial resolution was clearly identified as a major benefit for visual interpretation by Sadowski *et al.* (1983) and many others. In this thesis, it was speculated that the increased within-field heterogeneity contains useful information about the uniformity of the condition of crops, and may be potentially useful.

Several investigators have compared the information content of TM and MSS data through the examination of inter-band correlations and principal component analysis (Anuta *et al.*, 1984; Crist, 1983; Crist and Cicone, 1984a; Sadowski *et al.*, 1983; Vickers and Brown, 1986). These investigations were conducted over primarily vegetated or agricultural areas except in the case of Sadowski *et al.* who worked with scenes of mixed urban and rural land cover. All reported strong correlations ($r^2 > 0.95$) between MSS and TM channels of equivalent wavebands (i.e., MSS1-TM2, MSS2-TM3, MSS4-TM4) suggesting similar performance could be expected from vegetation indices derived from the two sensors using these equivalent bands. Within each sensor, the strongest correlations were observed between bands within the same spectral region ($r > 0.87$) indicating some information redundancy. Moderate to strong correlations were also observed between the VIS bands and the MIR bands in the TM data. Data

from the NIR bands from both sensors were negatively correlated with all other bands for vegetated targets with the strongest negative relationships occurring with the visible red ($r < -0.87$).

Principal component analysis by the same authors revealed that MSS data are essentially two-dimensional with the first two components accounting for between 96% and 99% of the within-scene variance. The TM data were demonstrated to be essentially three-dimensional with the third component being attributed to additional information contained in the new MIR bands. The third component accounted for between 5% and 10% of within-scene variance depending on land cover in the scene. Anuta *et al.* (1984) found that the variance accounted for by the third component was higher for a mixed urban/rural scene than for a predominantly agricultural one.

Price (1984) and Malila (1985) took an information theoretic approach to evaluate the information content (entropy) of agricultural MSS and TM scenes. Both concluded that although the information content of typical imagery is well below the system design capacity for both TM and MSS, significant gains in information content are made in the TM resulting from the new bands in the MIR (TM5 and TM7) and the improved radiometric sensitivity. Large gains were not attributed to improvements in spatial resolution because of the high degree of redundancy between adjacent pixels in large-field agricultural environments.

In summary, most investigators found the information content of TM data to be significantly higher than that of the MSS. This was attributed most often to the additional spectral information available from the new MIR bands and, for visual analysis and small target applications, the improved spatial resolution. However, the finer spatial resolution was also seen to introduce greater heterogeneity within some spectral classes which limited the improvements anticipated in the accuracy of digital classifications. Correlation analysis revealed that radiance information in MSS and TM data from the same wavebands was very similar, and that comparable results should be expected when using these equivalent data in vegetation indices. The new MIR bands correlated only moderately in some cases with the other spectral regions, confirming that new information is contained within those bands, and implying opportunities for exploitation in vegetation indices.

2.5 Vegetation Indices

Development: A variety of different band combinations have been developed by many investigators which allow simple measures of plant parameters to be derived from multi-spectral imagery. Elvidge and Lyon (1985) note that there are two basic forms of vegetation indices; ratio-based indices and n-space indices. The ratio-based ones are computationally simple and are the most widely used. N-space indices are usually more complex arithmetic transformations in which vegetation condition is indicated by distance away from the signature of bare soil within the transformed data space. They rely on

the definition of the so-called 'bare soil line' - the normally linear data space occupied by bare soil targets - which requires some ground truth to establish.

Excellent reviews of the principles and development of vegetation indices are available from Tucker (1979, 1980), Elvidge and Lyon (1985), Gardner *et al.* (1982), Colwell (1983), Aase *et al.* (1986), and Bartholomé (1987). A special emphasis on n-space indices is presented by Jackson (1983). Because of its earlier availability, most of this development involved indices derived from the spectral bands of the MSS. However, several investigators have recently explored the use of the additional bands in the TM. These studies will be reviewed later in this section.

Ratio Indices: Early ground-based spectroscopy provided the basis for the development of ratio-based vegetation indices. Pearson and Miller (1972) and Colwell (1973) both used field radiometer data to recognize the utility of a ratio of NIR/RED reflectance for estimating grass canopy biomass. In a later study, Tucker (1979) investigated the basis for this index. He compared detailed VIS and NIR plant spectra against a variety of plant parameters and found that both GREEN and RED reflectance have non-linear, inverse relationships with green, photosynthetically-active biomass. Near-IR reflectance was found to have a non-linear, but positive relationship with green biomass. He determined that simple band combinations incorporating the NIR and RED (including the NIR/RED ratio) were superior in all cases to similar measures using RED/GREEN and NIR/GREEN reflectance. The NIR/RED ratio exploits the negative correlation between

high reflectance in the NIR and strong pigment absorption in the visible RED in green vegetation. Since this early work, a large number of investigators have reported moderate to strong correlations between this index and a variety of plant parameters, including plant biomass, Leaf Area Index (LAI), plant height, and yield (see references to review articles, page 23).

A variation on the NIR/RED ratio is the simple difference between the same bands (i.e., NIR minus RED). This index also attempts to exploit the complementary reflectance characteristics of the RED and NIR, but is very sensitive to the absolute values of recording and units of measurement. Rouse *et al.* (1973, 1974) modified the simple difference to what is now commonly called the "Normalized Difference Vegetation Index" (NDVI), where;

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

This index attempts to reduce the variability of the simple difference (caused by changes in atmospheric, illumination, or sensor conditions between measurements) by 'normalizing' it over a measure of the dynamic range of the data; in this case, the sum of the same bands. The range of values resulting from this expression always lie between -1.0 and +1.0, with bare soil vegetated targets normally occurring within the range 0.0 to +0.7.

Rouse *et al.* (1973) also developed a variation on the NDVI called the 'Transformed Vegetation Index' (TVI) to avoid working with negative values and to linearize its distribution, where:

$$TVI = \sqrt{NDVI + 0.5}$$

Tucker (1979) later reported that no real improvement in the linearity of the NDVI was achieved through the square root function, so the TVI has largely fallen into disuse.

The two dominant ratio-based indices used in vegetation studies are the simple NIR/RED ratio and the NDVI. The NDVI is used extensively for continental scale vegetation monitoring using data from the NOAA-AVHRR sensor (Townshend *et al.*, 1985; Goward *et al.*, 1985; Malingreau *et al.*, 1989; Brown *et al.*, 1990; and many others), and has become a widely accepted spectral measure of green biomass and Leaf Area Index from many sensors. The simple NIR/RED ratio is also used, although less extensively because of its sensitivity to the absolute digital values of measured radiance and, consequently, atmospheric conditions at the time of imaging. Wiegand *et al.* (1986) proposed equations which interrelate these two common indices with Leaf Area Index, the intercepted photosynthetically-active radiation (IPAR) in a plant canopy, and final yield in grains. Important features of this so-called 'Spectral Components Analysis' are the integration of index values over the entire growing season and their incorporation into numeric plant development and yield models. This approach to vegetation indices

represents the current trend in their use for both high (Landsat) and low (AVHRR) resolution image data.

N-Space Indices: Kauth and Thomas (1976) and Richardson and Weigand (1977) each developed n-space indices for Landsat MSS data. Kauth and Thomas developed a four-dimensional linear combination of bands (based on a principal components transformation and extensive empirical observations) to produce the Soil Brightness Index (SBI) and the Green Vegetation Index (GVI) where:

$$\text{SBI} = 0.43(\text{MSS1}) + 0.63(\text{MSS2}) + 0.59(\text{MSS3}) + 0.26(\text{MSS4})$$

$$\text{GVI} = -0.29(\text{MSS1}) + -0.56(\text{MSS2}) + 0.60(\text{MSS3}) + 0.49(\text{MSS4})$$

The SBI (Brightness) is the weighted sum of all four MSS bands and is a measure of total scene and soil background brightness. The GVI (Greenness) deviates from the signature of bare soil in proportion to the presence of green vegetation. Greenness values plotted in this data space throughout crop development have been used in the identification of crop types, and as a measure of their condition. The resulting pattern resembles a 'Tasselled Cap', which has since become the familiar name for this technique. Single date GVI measurements have been related to total green biomass by many investigators, but because the greenness index is a function of the SBI, it is sensitive to changes in soil background resulting from changes in soil moisture or location (Tucker, 1979, Crist *et al.*, 1983). Coefficients for third and fourth indices were also developed for this

transformation ('Yellowness' and 'Non-such'). Yellowness has been correlated to the presence of brown vegetation and has also been shown to be a measure of atmospheric scattering (Jackson, 1983). As its name implies, Non-such contains little useful information.

Richardson and Weigand (1977) proposed the 2-dimensional Perpendicular Vegetation Index (PVI) to account for variations in soil background. The PVI was defined as:

$$PVI = \sqrt{(RED_{SOIL} - RED_{VEG})^2 + (NIR_{SOIL} - NIR_{VEG})^2}$$

where the subscripts *SOIL* and *VEG* represent the reflectance or radiance measurements in the appropriate waveband for soil background and vegetated targets. The index measures the perpendicular distance of a vegetated target from the signature of bare soil and is equally applicable in wet and dry soil conditions (Jackson, 1983).

Neither of the two n-space indices has enjoyed widespread use, nor have others been forthcoming as replacements. The computational complexity of the indices and their sensitivity to differences in local soil background are factors in this lack of acceptance. However, for a single location (i.e., an unchanging soil background) these indices do offer valid mechanisms for characterizing green biomass.

Vegetation Indices from TM: Surprisingly little work has been published which examines potential vegetation indices comprising the new spectral bands of the TM. Much of what has been published is based on spectral information from field radiometers and has not been extended to actual satellite imagery. Gardner *et al.* (1982), Dusek *et al.*, (1985), and Ripple (1985) all used radiometer data to explore the relationship between a variety of plant parameters and a large number of spectral band combinations. Gardner *et al.* generated 105 different band combinations ranging from simple band ratios comprising two bands up to those including all six reflective bands of the TM. These were correlated with Leaf Area Index (LAI), the percentage of green ground cover, and various measures of wet and dry biomass for corn, soybean, and winter wheat. The results were then ranked by the coefficient of determination (r^2).

Dusek *et al.* (1985) performed a similar experiment with radiometer data, but generated over 1300 band combinations ranging from individual TM bands to 6-D greenness transformations calculated from soil and vegetation reference targets. Ripple (1985) calculated all possible two-band ratios (i.e., Band A/Band B) in a similar experiment, but for tall fescue grasses typical of rangeland vegetation. All reported that the top ranked indices for correlations with LAI and biomass were not the commonly used NIR/RED ratio and NDVI, but more complex indices incorporating new TM bands. For example, Table 2.2 presents the results of correlations with LAI for winter wheat (from Dusek *et al.*, 1985).

Table 2.2: Rankings of TM vegetation indices when correlated with the LAI of Winter Wheat (from Dusek *et al.*, 1985).

RANK	INDEX	r ²
1	$(TM4 * TM5)/TM3$	0.85
2	$(TM4 * TM7)/TM1$	0.85
3	$(TM1 * TM4 * TM5)/(TM2 * TM3)$	0.85
4	$(TM2 * TM4 * TM5)/(TM1 * TM3)$	0.85
21	PVI	0.81
131	$TM4/TM3$	0.68
167	$(TM4 - TM3)/(TM4 + TM3)$	0.64

As can be seen, there was little variation in the strength of correlation between the top ranked indices, suggesting that the majority of useful information was contained in only a small number of the bands. The authors noted that, among the top ranked indices, TM3 appears in the denominator of all but one, and TM4 appears in the numerator of all. However, the straight ratio of TM4/TM3 (equivalent to the simple NIR/RED ratio) is ranked well out of the top (131), and the normalized difference even more so (167). In general, the ratios and multi-band combinations scored higher than the n-space transformations, except in the case of the PVI when correlated with LAI which ranked quite highly (21).

Gardner *et al.* (1982) reported similar results in their work, although the simple NIR/RED ratio (TM4/TM3) ranked among the best indices for soybean and wheat when correlated with LAI. This may be because fewer permutations of the bands were examined in this study than by Dusek *et al.* (150 versus 1300), thus eliminating the more complex indices from the consideration. Also of interest in the results of Gardner *et al.* was the appearance of the simple TM1/TM3 ratio (BLUE/RED), ranked third in the wheat-LAI correlations. Unfortunately, no explanation was offered for this unusual occurrence. The authors suggested that the most 'complete' index is one which includes data from each of the spectral regions (and thus provides information about the different plant characteristics to which each region is sensitive), but this was not supported by their results. However, the ratio $(TM1*TM4*TM5)/(TM2*TM3)$ which does contain bands from all spectral regions was the only index which appeared among the top rankings for both Dusek *et al.* (1985) and Gardner *et al.* (1982) thus supporting their suggestion. Ripple (1985) reported that ratios with TM4 (NIR) in the numerator and TM5 or TM7 (MIR) in the denominator were the highest ranked among the simple two-band ratios tested for tall grasses.

Crist *et al.* (1983), Crist and Cicone (1984b) and Jackson (1983) both treated n-space transformations using TM data. Christ and Cicone reported on the adaptation and preliminary testing of a 'Tasselled Cap' transformation for the TM based on simulated (prior to launch) and real TM data. They identified three significant components to the structure of TM data - Brightness, Greenness, and Wetness - with the first two being

highly analogous to the SBI and GVI of the original Tasseled Cap from the MSS. The 'Wetness' index compares the brightness of the VIS and NIR with that of the MIR, and is claimed to be sensitive to moisture in both soil and vegetated targets. However, the authors also state that Wetness may be most sensitive to variations in soil moisture, and therefore of less interest as an index of in-leaf water for plants.

Jackson (1983) calculated and compared a variety of greenness indices (2-D to 7-D) for MSS, TM, and the wave bands of other sensors using ground radiometer data. Of all of the sensors, the TM was found to exhibit the greatest variations (i.e., highest dynamic range) of 'greenness', and it was argued that this demonstrated a higher sensitivity to changes in vegetation cover in the TM versus the other sensors. In general, the TM transformations scored higher than those derived from the MSS, except when the NIR band (TM4) was not included.

In summary, the limited number of investigations in this area have found that band combinations and n-space transforms derived from the TM perform better than conventional indices from the MSS when correlated to a variety of plant parameters. The top ranked indices were generally complex combinations of more than two bands of the TM, often comprising data from the MIR region. Also, the traditional NIR/RED ratio and normalized difference ranked relatively poorly in comparison with the new indices. An exception to this was the TM4/TM3 ratio which was ranked highly by Gardner *et al.*, (1982) when correlated with Leaf Area Index for winter wheat. These results suggested

that the TM should offer advantage over the MSS in the derivation of vegetation indices in this study, although it must be remembered that most of the studies described above treated only field radiometer data, and not real satellite imagery (thus eliminating atmospheric attenuation and spatial resolution effects). Also, the previous studies were conducted with crop varieties and growing conditions which are certainly different from those in Canada. In the next chapter, the study site and data sets used to test TM indices in the Canadian context are described.

CHAPTER 3

DATA

3.1 Introduction

The purpose of this chapter is to describe the test site and the data used in this work. The test site is near Melfort, Saskatchewan, and the data collected included satellite imagery, multi-level aerial photography, and extensive observations in the field. All imagery and data used in this work were acquired in July, 1985 as part of a continuing research programme by the Canada Centre for Remote Sensing (CCRS) into the agricultural applications of remote sensing.

3.2 Test Site

The area near Melfort, Saskatchewan, has been used as an agricultural test site by the CCRS since 1973. The site extends over a 17 mile by 2 mile area (27.2km by 3.2km) southwest of the town of Melfort (52°52'N, 104°34'W, elev. 463m) in the northern agricultural region of Saskatchewan (Figure 3.1). The site is typical of the landscape and agricultural practice of the dark brown chenozoic soil zone in which it lies and which extends over much of the northern portion of the prairies. The area is very flat with local relief limited to approximately 15m along a north-south oriented ridge near the eastern edge of the site. The land use pattern of the area is characterized by the

Figure 3.1: Map of Melfort Study Site. The site falls within Township 29, Ranges 18 to 21A, West of Second Meridian. The bold lines and large numbers identify the Sections. The thin lines and small numbers indicate the location and numbers of the individual fields. (source: interpreted from July, 1985 Landsat imagery.)

square mile sections of the Dominion Land Survey. The fields are typically 32ha or 64ha in size ($\frac{1}{8}$ or $\frac{1}{4}$ section) although in 1985 the fields sampled ranged between 8ha and 130ha. A more detailed description of the site is available from Brown *et al.* (1984).

Average annual precipitation at the Agriculture Canada Melfort Research Station (contained within the study site) is 411mm, of which over half (227mm) is normally received between May and August (Environment Canada, 1981). This level of rainfall is sufficient to permit near-continuous cropping of the land without great risk of moisture deficiency. Because of this, approximately 85% of the fields are cultivated each season, with the remainder left to summer fallow for nutrient restoration. The climate and soil of the region support a wide variety of crops including spring grains (wheat, barley, oats), canola, peas, and flax. Increasing plantings of speciality crops such as lentils and canary seed have also been observed in recent years. Conditions in 1985 were typical for the site, with near-average levels of rainfall (253mm, May-August). Crop yields in the region were average to above-average in 1985 with, for example, mean yields within the test area of 50bu/ac for wheat and 25bu/ac for canola.

The crops examined in this work were the most predominant in the 1985 growing season: barley, wheat, canola, peas, and flax. The condition of the crops at the time of imaging was generally very good. Virtually all the grains were at or near heading, the stage of plant growth at which the grain head first emerges from the plant stalk. Canola, peas and flax were all in various stages of flower and thus presented spectral

characteristics different from the generalized reflectance curve presented in Figure 2.1. Canola blooms with bright yellow flowers which dominate the plant canopy when viewed from above. The flowers have the effect of greatly increasing reflectance in the visible RED and visible GREEN portions of the spectrum, thus reducing the effects of absorption by green leaf pigments. Peas have a small white flower which, though visible from above, does not occupy a large percentage of the canopy. The effect of this is to marginally increase reflectance across all the visible bands. Flax has a blue-violet coloured flower with the effect of increasing reflectance in the visible BLUE band. The effects of flowers on the appearance of these crop types can be observed from the aerial photographs presented in Plates 5 and 6 and described in Section 3.4.

3.3 Satellite Data

The TM and MSS data used in this study were simultaneously acquired by the Landsat-5 spacecraft on July 16, 1985 (Plate 4). As noted above, this fell within the period of heading for the grains which is the period of peak biomass, and therefore generally considered to be a preferred period for the estimation of potential crop yield (Hatfield, 1983). On the date of image collection, the study area was generally cloud free, although scattered cloud (< 5% cover) was present in the eastern and central portions of the site. The extent and location of cloud cover can be observed in Plate 4.

The satellite data were delivered as computer compatible tapes (CCTs) after standard radiometric and geometric corrections had been applied at the satellite ground receiving

Plate 4: Landsat MSS and TM imagery of the Melfort Study Area, July 16, 1985. The study area is outlined on these two false-colour composites of the test data set. Note the effects of spatial resolution on the clarity of the images. Also note the presence of some cloud and cloud-shadow within the test area.

station (Ahern *et al.*, 1987). The radiometric corrections included image destriping and the use of look-up tables to linearize the digital values in the image with respect to radiance. In the case of MSS, this 'stretches' the original data collected by the sensor at 6-bits (64 grey levels) to 8-bits (256 grey levels), thus changing the apparent radiometric resolution of the imagery. Because of this transformation, direct comparisons between the radiometric resolutions of the TM and MSS were not made. However, the MSS data were used in this format because it represents the standard product available from CCRS and is typical of data used in Canada for agricultural monitoring.

3.4 Aerial Photography

To supplement the information from the satellite data, two scales of aerial photography were used in this work. Vertical colour infrared photography (23cm format) was acquired by the CCRS Convair-580 aircraft at a nominal scale of 1:20 000, and oblique hand-held natural colour and colour infrared 35mm photography was acquired from a light aircraft flying at an altitude of 2500ft (760m) above ground level. Examples of the hand-held, oblique photography illustrating the appearance from the air of several crops are presented in Plates 5 and 6.

The 1:20 000 vertical photography offered improved definition of field boundaries, farmsteads, small woodlots, and water features over the TM imagery and was useful during the delineation of training areas on the digital data. The large scale oblique

Plate 5: Example of Natural-colour, Oblique Photography acquired over the Study Area (Sec. 24, Rng. 19, Twp. 29, W. 2). The bright yellow flower of the canola fields are evident in this aerial photograph acquired on July 13, 1985. The pea field (19-24-05) has paler green tone than the barley fields because of its white flower.

Argyle barley 19-24-04	Trapper peas 19-24-05	Westar canola 19-24-06
Westar canola 19-24-03		
Bonanza barley 19-24-02

Plate 6: Example of Natural-colour, Oblique Photography acquired over the Study Area (Sec. 12(E), Rng. 21 and Sec. 25(W), Rng. 21A, Twp 29, W. 2). This photograph illustrates several differences in condition between fields of the same crop. Field 21-12-04 (top left) and field 21A-25-01 are both Trapper peas, but 21-12-04 has a lighter tone because of the presence of flowers. There is also considerable difference in the advancement and uniformity of flowers among the canola fields (21-12-01, 21A-36-02, and 21A-25-03 (extreme right)).

Trapper peas 21-12-04	Westar Canola 21A-36-02
fallow 21-12-05	Coulter wheat 21A-25-02
Westar canola 21-12-01	Trapper peas 21A-25-01
Katepwa wheat 21-1-03	

photography was used for the visual inspection of fields which were found to be anomalous in the statistical analyses.

3.5 Ground Data

The collection of adequate ground data in support of remote sensing studies is by far the most difficult and time consuming aspect of remote sensing research. While the satellite scanned and recorded the entire test site in seconds, the accompanying ground information required many person weeks to collect.

Two types of ground data were collected for the Melfort test site in 1985:

- descriptions of agricultural practice and final yield;
- *in-situ* observation and measurement of plant condition in each field close to the time of imaging.

The data were collected by experienced agricultural technicians using guidelines for the collection of agricultural data in support of remote sensing studies (King and Mack, 1984). Table 3.1 summarizes the data items collected during 1985. The cultivation practice and crop yield information was acquired through farmer interviews early in the growing season and after harvest. The detailed plant condition information was collected for each field accessible by road over a period of six days between July 12 and July 17. To supplement the field observations, a series of four 35mm colour

Table 3.1: Ground Data Collected in 1985 (from King and Mack, 1984). The table lists the parameters collected through farmer interviews regarding agricultural practice, and the parameters collected during the field programme.

Agricultural Practice	<i>in-situ</i> Observations
crop	crop
variety	development interval (growth stage)
field size (acres)	growth detractants (weeds, etc)
seeding (date, rate)	ground cover (% green, brown, soil)
chemical applications (date, rate) - fertilizers - pesticides - herbicides	observed quality (on scale of 1-5) - uniformity - density - colour - estimated yield
harvest date	plant height (cm)
yield (bushels/acre)	plant density (plants/m)
	soil moisture (qualitative description)
	tillage - row direction - row height - row spacing - implement used

transparencies was also taken at each field which could be consulted later during analysis in the laboratory. Complete ground data were acquired for a total of 187 fields. In addition to the systematic collection of ground data for each field, several days were spent at the study site during which personal observations and notes on general plant condition were made.

This ground collection program was intended to provide support for the interpretation of radar imagery; therefore not all categories of the data collected had relevance or were used in this work (i.e., surface roughness, row orientation). Listings of the parameters used in this analysis are tabulated in Appendix A. Unfortunately, the best parameters to describe plant condition (such as wet and dry biomass, and Leaf Area Index) were not collected because of the great expense and effort required to do so. As a result, the only direct measures of plant material collected were plant height, plant density, and the percentage of green cover when viewing the ground vertically. Through personal observation in the field, measures of density are not a good indicator of the volume of plant material, particularly in the grains. The number of grain stalks is more indicative of the success of tillering (the propagation of new stalks from a single plant) rather than total plant material. An informal attempt to create an index of plant biomass from the product of plant height, density, and green cover was not very successful because the resultant values were strongly controlled by plant height. It was concluded from this that plant height was the best available direct measure of plant material among the variables collected in the field. This approach is supported by data from

Ripple (1985) who reported strong positive correlations between plant height and a variety of common plant measures for tall fescue grasses (i.e., total wet biomass, $r = 0.953$; total dry biomass, $r = 0.948$, Leaf Area Index, $r = 0.922$). However, it is recognized that these grasses have a shorter overall plant height and different plant structures than the crops examined in this thesis, thus reducing the direct applicability of these results to this project.

To assist in the cataloguing of the ground data, unique identifiers for each field based on the land survey system (meridian, township, range, section) were used. Because the test site falls within a single township (Township 29, west of second meridian), unique field identifiers could be maintained by specifying the range, section, and number of each field. For example, field '19-22-02' refers to Range 19, Section 22, Field 2 (Figure 3.1, map of site). Field numbers within each section were normally assigned sequentially in a clockwise direction from the southeast corner of the section.

In summary, the principal data set used in this study was a pair of Landsat MSS and TM scenes of the test site acquired simultaneously in mid-July, 1985. Supporting ground data and aerial photography collected at the same time as the satellite overpass, and a follow-up survey of crop yield, provided measurements of ground conditions. In the next chapter, the pre-processing and analyses applied to these data are described.

CHAPTER 4

METHODS

4.1 Overview of Methods

To compare the performance of vegetation indices derived from the MSS and TM sensors, three separate series of correlation analysis were performed. The first examined the relationship between the different bands of the sensors. The purpose of this analysis was to compare the information content of the test data set with the results of previous investigators, and to explore inter-band relationships in the TM which might render new vegetation indices. These inter-band relationships were examined for all vegetated fields together, as well as for each of the major crop types in the test site (wheat, barley, canola, peas, and flax).

The second, and principal, analysis of this work correlated a series of spectral indices with two crop parameters - yield and plant height. These two parameters were chosen as the best measures of plant condition available from the ground data collected. Yield is of obvious interest to crop monitoring because it permits the calculation of crop production when multiplied by crop area. Plant height was identified in the previous chapter as the best available direct measure of plant biomass and condition from among

the limited quantitative plant measurements made in the field. The results from this correlation analysis permitted a direct comparison of the performance of the indices derived from the two sensors.

The third analysis used rank correlation to examine the relationship between the spectral variance within each agricultural field and crop yield. The purpose of this analysis was to determine if the improved spatial resolution of the TM contained information useful for crop condition assessment.

In order to perform these analyses, considerable pre-processing of the data was required. These steps and the procedures of the analysis are described in this chapter. The results are presented and discussed in Chapter 5.

4.2 Pre-processing

4.2.1 Satellite Data

Image Registration: The first step in the digital processing of the satellite imagery was the geometric co-registration the two Landsat images to ensure that the spectral values extracted from each would be representative of the same area on the ground. The MSS image was registered to the 30m resolution TM image using a best-fit affine transformation developed from six control points (CCRS, 1986). The root-mean-square (RMS) error of the fit was 0.380 pixels (X) and 0.321 pixels (Y) indicating a very good registration accuracy. Warping of the MSS image was performed using nearest-

neighbour resampling in order to preserve the original digital values of the MSS data. More sophisticated resampling algorithms (i.e., bilinear interpolation, cubic convolution) would have altered the original digital values, thus changing the within-field variance and affecting the later correlation of that parameter with yield. As the orientation and geometry of the two images were identical (because they were acquired simultaneously from the same satellite) the real effect of the image registration was simply to change the pixel spacing of the MSS data to match that of the TM through pixel replication.

Training Areas: To extract spectral statistics from individual fields within the study site, polygonal training (sampling) areas were visually delineated on an image display screen. One training area was created for each field (where possible) ensuring that it did not extend over spectrally mixed pixels at field boundaries. It was not possible to generate training areas for every field within the site because of the presence of cloud and cloud shadow, and in some cases because of small field size. Training areas were created for fields only partially affected by cloud or shadow provided that more than 50% of the field was clear. Large areas of permanent slough or woodlot within a field were not included in training areas, although small areas of anomalous or mottled tone (perhaps indicative of variations in crop condition) were. In total, 168 training areas were created ranging in size from 27 to 940 pixels (2.5 to 84.6 ha).

Generation of Vegetation Indices: A series of conventional and novel vegetation indices was generated from the MSS and TM imagery (Tables 4.1 and 4.2). From the MSS

data, the traditional NIR/RED ratio and NDVI were calculated using MSS4 and MSS2, as well as an NDVI calculated from MSS3 and MSS2 as suggested by Tucker (1979). The N-space transformations generated from the MSS data were the Soil Brightness Index (MSS_SBI) and the Green Vegetation Index (MSS_GVI) of the 'Tasselled Cap' (using published coefficients, Kauth and Thomas, 1976) and a principal components (PC) transformation based on sample statistics from all land cover types over the full test site. The PC analysis was performed in order to generate spectral indices that maximized variance for the specific data set used, rather than coefficients derived from other sources. Given that the test scene was predominantly vegetated, it was anticipated that the first or second components from the transformation would represent a 'vegetation' or 'greenness' axis.

A larger variety of indices could be calculated from the TM imagery because of the larger number of channels compared to the MSS. These fell into four general classes;

- 1) MSS 'equivalent' indices in which MSS channels were substituted with channels of equivalent waveband from the TM (i.e., ratios, NDVI);
- 2) MSS 'equivalent' multi-channel transformations using published coefficients or scene specific statistics (i.e., TM Tasselled Cap, Principal Components);
- 3) simple ratios and normalized differences of two TM channels in wavebands not available in the MSS; and,
- 4) complex ratios of three or more TM bands.

Table 4.1: Vegetation Indices Calculated from MSS Data.

INDEX (I)	COEFFICIENTS	TYPE
MSS1	-	I
MSS2	-	I
MSS3	-	I
MSS4	-	I
$\frac{MSS4}{MSS2}$	$27(I) + 0$	I
$\frac{MSS4-MSS2}{MSS4+MSS2}$	$304(I) + 10$	I
$\frac{MSS3-MSS2}{MSS3+MSS2}$	$324(I) + 3$	I
SOIL BRIGHTNESS INDEX (MSS_SBI)	$I = 0.43(MSS1)$ $+ 0.63(MSS2)$ $+ 0.59(MSS3)$ $+ 0.26(MSS4)$	NI
GREEN VEGETATION INDEX (MSS_GVI)	$I = -0.29(MSS1)$ $+ -0.56(MSS2)$ $+ 0.60(MSS3)$ $+ 0.49(MSS4)$	NI
PRINCIPAL COMPONENT 1 (MSS_PC1)	$I = 0.39(MSS1)$ $+ 0.47(MSS2)$ $+ 0.02(MSS3)$ $+ 0.49(MSS4)$	NI
PRINCIPAL COMPONENT 2 (MSS_PC2)	$I = 0.01(MSS1)$ $+ 0.47(MSS2)$ $+ -0.19(MSS3)$ $+ -0.29(MSS4)$	NI

I - Image Index NI - Non-image Index

The indices calculated from the TM data are tabulated in Table 4.2. The choice of TM indices to investigate was influenced by several factors. To permit direct comparison with the MSS, all possible 'equivalent' indices and transformations were calculated. For the remainder, emphasis was placed on the new TM bands in the MIR (TM5, TM7) because of their reported sensitivity to in-leaf moisture. Ratios and normalized differences which included those channels in combination with TM4 were generated. Single ratios of TM3 with TM5 and TM7 were also produced. Early published experimentation by Gardner *et al.* (1982) indicated strong correlations of the TM1/TM3 ratio with LAI for wheat, so that index was also included in this investigation. As noted in Chapter 2, Dusek *et al.* (1985) reported that the highest correlations with a variety of plant parameters (such as LAI, wet and dry biomass) were achieved with relatively complex combinations of three or more TM bands drawing from all spectral regions. The seven top ranked of these indices were reproduced in this analysis. A principal components transformation including the channels of principal interest from the TM (TM3, TM4, TM5, and TM7) was also performed. Unfortunately, the software capability to perform a six channel principal components analysis on the TM data did not exist at the time of analysis.

Two methods were required to calculate the index data. The preferred technique was to perform the calculations directly on the image data on a pixel-by-pixel basis

Table 4.2: Vegetation Indices Calculated from TM data.

INDEX (I)	COEFFICIENTS	TYPE
TM1	-	I
TM2	-	I
TM3	-	I
TM4	-	I
TM5	-	I
TM7	-	I
$\frac{TM1}{TM3}$	-	NI
$\frac{TM4}{TM3}$	$29(I) + 0$	I
$\frac{TM4-TM3}{TM4+TM3}$	$304(I) + 13$	I
$\frac{TM4}{TM5}$	$78(I) + 0$	I
$\frac{TM4-TM5}{TM4+TM5}$	$232(I) + 117$	I
$\frac{TM4}{TM7}$	$112(I) + 0$	I
$\frac{TM4-TM7}{TM4+TM7}$	$208(I) + 179$	I
$\frac{TM5}{TM3}$	$59(I) - 19$	I
$\frac{TM7}{TM3}$	$115(I) - 22$	I
$\frac{TM7}{TM5}$	$348(I) - 3$	I
$\frac{TM2}{TM5*TM7}$	-	NI

cont'd...

Table 4.2 (cont'd)

INDEX (I)	COEFFICIENTS	TYPE
$\frac{TM3}{TM1*TM7}$	-	NI
$\frac{TM2*TM3}{TM4*TM5}$	-	NI
$\frac{TM2*TM3}{TM4*TM7}$	-	NI
$\frac{TM4*TM5}{TM3}$	-	NI
$\frac{TM3*TM4}{TM1*TM7}$	-	NI
$\frac{TM1*TM4*TM5}{TM2*TM3}$	-	NI
TM BRIGHTNESS INDEX (TM_BRIGHT)	I = 0.43(MSS1) + 0.63(MSS2) + 0.59(MSS3) + 0.26(MSS4)	NI
TM VEGETATION INDEX (TM_GREEN)	I = -0.29(MSS1) + -0.56(MSS2) + 0.60(MSS3) + 0.49(MSS4)	NI
TM WETNESS INDEX (TM_WET)	I = -0.29(MSS1) + -0.56(MSS2) + 0.60(MSS3) + 0.49(MSS4)	NI
PRINCIPAL COMPONENT 1 (TM_PC1)	I = 0.021(TM3) + 0.986(TM4) + -0.009(TM5) + -0.164(TM7)	NI
PRINCIPAL COMPONENT 2 (TM_PC2)	I = 0.334(TM3) + 0.084(TM4) + 0.784(TM5) + 0.510(TM7)	NI

I - Image Index NI - Non-image Index

within the image analysis system. This method was preferred because the result was a new image containing the calculated value in each pixel, thus maintaining the variance in the population of pixels within each agricultural field. This information was used later in the analysis when the relationship of within-field variance to crop yield was explored. Indices calculated in this manner are referred to as 'image' indices.

Because of limitations in internal storage within a digital image file (to 8-bit, unsigned integers), the index values generated by the method above were linearly scaled using coefficients estimated by the software. This ensured that the calculated values fell within the useable range of integers (0 - 255) without under- or over-flow. Histograms of all index images were visually examined to ensure that the output values were well distributed over the full dynamic range permitted by the image format.

A second method of calculating index values was required because of software limitations in the analysis equipment. In general, a maximum of two input bands could be used in the generation of index images. Therefore, indices with three or more input channels were calculated from the mean radiance values from each field. This was performed within the statistical software package after raw image values from each field had been extracted from the imagery. Because the output values calculated within the statistical package were not constrained by the 8-bit format of image files, the indices were left unscaled. Indices calculated in this manner are referred to as 'non-image' indices. A disadvantage of calculating vegetation indices using only the mean radiance

of a field is that the variance of the index within the field cannot be determined. This prevented their inclusion in the analysis of within-field variance and crop yield. The method of index calculation (image (I) or non-image (NI)) for each index investigated is indicated in Tables 4.1 and 4.2.

To validate the substitution of non-image indices for image-based ones, a comparison was made between the output of each approach. Table 4.3 summarizes the results of a correlation/regression analysis between three indices calculated by both the image and non-image methods. The analysis was performed on all fields within the test site including summer fallow (N=168). In all cases the coefficients of determination were above $r^2 = 0.999$, indicating an extremely high degree of correlation between the two index types. Based on the strength of the relationships, it was resolved for this study that valid comparisons could be made between the image and non-image indices.

Table 4.3: Correlation of Image and Non-image Indices (n=168).

INDEX	r^2	RMS Residual (digital number)	Max. Residual (digital number)
TM4 TM5	0.999	0.095	-2.62
TM4 TM3	0.999	0.108	-1.86
TM4-TM3 TM4+TM3	0.999	0.311	4.04

- all correlations are significant at the 0.001 level.

4.2.2 Image Statistics

The correlation of spectral data with the ground parameters required that the image and ground information be brought together in a single data base. To achieve this, the means and variances of pixel values for every training area (i.e., every agricultural field) and for all available bands (i.e., all raw bands and index images) were extracted from the image data and were entered in tabular format into the RS/1 statistical package for subsequent analysis (BBN, 1988). These data were then added to an existing data base containing the ground information. All subsequent analysis was performed on the spectral and ground information contained in this data base.

A special procedure was required for the extraction of image statistics from the MSS data because of the rescaling of the image to match the pixel spacing of the TM. In this procedure, the within-field variance in each field was altered because of the replication of pixels inherent in the image registration. As within-field variance was a variable to be used in later analysis, the effects of this oversampling needed to be removed. Therefore, a sub-sampling from every second pixel and every second line within the training area was made for all the MSS bands and MSS index images. Because this sub-sample only approximates the effects of the image registration it was known that some oversampling of the MSS did still occur. But, because of high correlation between adjacent pixels in MSS data, this was not considered to have a significant effect on the results.

4.2.3 Statistical Data

Data Cleaning: All ground and spectral values were examined for integrity once they had been entered into the statistical package. Initially, all fields with missing or incomplete ground or spectral data were eliminated from further analysis. Spectral data for each crop were then plotted versus crop yield and examined for spurious data points (i.e., those which radically deviated from the general population). The majority of aberrant points identified in this process were attributable to key-punch error and were corrected. Those points not explained were examined further with reference to all the available ground information and aerial photography and corrected when possible. The remaining anomalies (n=3: one barley, two canola) were attributed to parameters of crop condition or cultivation not adequately recorded in the ground information (i.e., loss of flowering in canola since the date of ground visit) and removed from the data set.

After cleaning, the data were stratified into separate tables by crop. Five crop tables were created; one each for barley, wheat, canola, peas, and flax. A stratification by crop variety was also done, but only for barley and canola where more than 50% of the fields were of a single variety. For wheat, the mix of varieties in the sample fields had no single dominant variety. For peas and flax, the sample populations were considered too small to fragment further by stratification. Table 4.4 summarizes the data tables resulting from the cleaning and stratification procedures.

Data Transformation: One assumption of Pearson's correlation analysis is the normal distribution of data. To validate the use of correlation in this work, the Wilk-Shapiro test of normality (level of significance = 0.05; BBN, 1988) was applied to all variables. The distributions of non-normal variables were examined and a variety of transformations were applied in an attempt to normalize them. Generally, a log, square root, or square transform was sufficient to render the data normal, although some variables required higher order transforms. For variables which could not be normalized to a significance level of 0.05, the transform which most closely approximated normal (i.e., to highest significance level) was applied.

Table 4.4: Data Tables used in Statistical Analysis

CROP	VARIETY	NUMBER OF FIELDS
BARLEY	all	37
	Bonanza	23
WHEAT	all	22
CANOLA	all	34
	Westar	28
PEAS	all	14
FLAX	all	6

4.3 Statistical Analysis

4.3.1 Inter-Band Correlations

The following sections describe the procedures of the three correlation analyses undertaken in this work. The first of these was a series of inter-sensor band correlations undertaken to develop a broad sense of the relationships between the two sensors. These were first undertaken on the full population of cultivated fields (all crops, excluding fallow fields) and then individually on the five principal crops (barley, wheat, canola, peas, and flax). The purpose of this analysis was to examine the information content of the test data set and compare this to the observations of previous investigators. The relationships between MSS and TM channels of the same spectral region were also examined to determine if similar performance could be expected from indices calculated from common wavebands. Also, these correlations were used to explore the inter-band relationships in the TM which might point to potential new indices.

4.3.2 Correlation with Yield and Plant Height

The second, and principal analysis of this work was the correlation of various plant parameters with the spectral values obtained from the MSS and TM imagery. As discussed earlier, the traditional and most rigorous measures of vegetation condition such as Leaf Area Index (LAI), plant biomass, and leaf moisture content were not available for this study because of the enormous effort required to collect them reliably. For this work, correlations were performed with crop yield and plant height. As discussed in

Chapter 3, yield is an important parameter for crop monitoring, and its prediction is considered to be one of the goals of remote sensing applications to agriculture. As also discussed, plant height was selected from among the ground data as the best available quantitative characterization of plant biomass.

Linear, bivariate correlations were performed between all spectral values and indices extracted from the imagery and the two plant parameters of interest. The results were sorted by the coefficients of determination (r^2) and significance levels for each correlation based on a Student's-t test were calculated (Gregory, 1963). Levels of significance for the difference between correlation coefficients were calculated (as required) using formulae contained in Spiegel (1981). The results of this analysis are presented and discussed in Chapter 5.

4.3.3 Rank Correlation with Within-Field Variance

To determine if the improved spatial resolution of the TM data contains useful information about crop condition not previously available in the MSS, a series of rank correlations were performed between the within-field variance of image values and crop yield. It was anticipated that, because the variance of radiances within an agricultural field is related to the uniformity of the condition of the crop, there would be an inverse relationship between the variance of spectral signatures within a field and crop yield. The purpose of this analysis was to verify if within-field variance is, indeed, correlated with crop yield, and to determine whether or not the additional spectral resolution of the

TM offers any advantage over the MSS for exploiting this information. Rank correlation was used in this analysis because the distributions of within-field variances were highly skewed (towards low variance) and difficult to render normal.

The rank correlations were performed on raw, untransformed data for each crop and variety. The results were sorted by the rank correlation coefficient (ρ) and significance levels for each correlation based on a Student's-t test were calculated (Gregory, 1963). The results of this analysis are also presented and discussed in Chapter 5.

CHAPTER 5

RESULTS

5.1 Introduction

The results of the three correlation analyses (inter-band relationships, correlations with yield and plant height, and rank correlations with within-field variance) are presented and discussed in this chapter. Observations are first made about the results for all crops, followed by discussion of the results for each crop individually. The discussion will often refer to the three spectral regions covered by the sensors: the visible (VIS), the near infrared (NIR), and the middle infrared (MIR). As a reminder, Table 2.1 identifies which satellite channels fall into each of these regions. Also worthy of reminder is that the correlations reported in this chapter were performed between the mean radiance values extracted from the imagery for each field, not on a pixel-by-pixel basis. The procedures for developing the training areas and extracting the statistics were described in Section 4.2.

5.2 Inter-band Correlations - All Fields

The results of the inter-band correlations for the MSS and TM sensors for all fields appear in Tables 5.1 to 5.3. This analysis used the population of all available fields (excluding summer fallow) in order to summarize the overall inter-band

relationships for the particular crop mix and conditions in this one agricultural scene. This is similar to the analyses performed by Vickers and Brown (1986), Ripple (1985), Crist (1983) and Crist and Cicone (1984a). The results of the correlations within each sensor are discussed first, followed by the relationships between the two sensors.

MSS: The inter-band correlations for the MSS data (Table 5.1) exhibited strong positive correlations within, and generally weak correlations between the two spectral regions covered by the sensor (VIS and NIR). The positive, between-region relationship (i.e., MSS1 - MSS3) was unusual and is not consistent with the results of previous investigations. This anomaly was attributed to the flowering state of canola, peas, and flax which caused higher than normal reflectance in the VIS in this scene. The flowers in the canopy contribute to high reflectance in the VIS because of their bright colours and because they obscure some of the underlying, chlorophyll-bearing foliage (thus reducing absorption). The positive correlations observed were the result of the high VIS reflectance paralleling the normally high reflectance in the NIR, instead of the more normal negative relationship driven by pigment absorption (VIS) and strong leaf-structure reflection (NIR). The presence of the flowers also had consequences on the performance of vegetation indices which will be discussed later in this chapter.

TM: Inter-band correlations among the TM bands (Table 5.2) exhibited relationships that were generally strong and positive within spectral regions, and generally weak or negative between regions, similar to the results found for the MSS. The new MIR bands

Table 5.1: Inter-band Correlations (r) between MSS Bands for all fields (n = 113).

	VISIBLE		NIR	
	GREEN MSS1	RED MSS2	MSS3	MSS4
MSS1	1.000			
MSS2	0.982	1.000		
MSS3	0.659	0.547	1.000	
MSS4	0.423	0.297	0.956	1.000

Table 5.2: Inter-band Correlations (r) between TM Bands for all fields (n = 113).

	BLUE	VISIBLE		NIR	MIR	
	TM1	GREEN TM2	RED TM3	TM4	TM5	TM7
TM1	1.000					
TM2	0.850	1.000				
TM3	0.865	0.476	1.000			
TM4	0.250	0.447	0.309	1.000		
TM5	0.129	-0.044	-0.052	-0.202	1.000	
TM7	0.202	0.002	0.099	-0.542	0.806	1.000

- correlations above ± 0.298 are significant at the 0.001 level.
- correlations above ± 0.204 are significant at the 0.01 level.
- correlations above ± 0.093 are significant at the 0.05 level.

in the TM data had very weak relationships with the VIS and weak to moderate negative relationships with the NIR. As observed in the MSS, the VIS bands demonstrated unusual positive correlations with the NIR. Also of interest was the difference in correlation between the NIR (TM4) and the two MIR bands (TM5 and TM7). Both MIR bands are considered to be water absorption bands, but differences in the information content between the two are confirmed by this result. These findings are consistent with those of Ripple (1985) who also found differences between the two bands and determined that TM7 was more sensitive to the in-leaf moisture of tall fescue grasses than TM5. The implication of this result is that indices including TM5 or TM7 should not be expected to behave similarly, even though both bands are often believed to contain very similar information. Visual evidence of these differences can be seen clearly in Plate 3.

MSS-TM: Like the results for the individual sensors, the band correlations between sensors (Table 5.3) were dominated by strong within spectral region relationships. The equivalent wave bands from the two sensors (shaded) showed very high positive correlations ($r \geq 0.997$) and the relationships between the different spectral regions were generally the same as those observed in the TM data alone. This was expected given the high correlations observed between the equivalent MSS and TM bands.

These inter-band correlations identified several relationships that are important in the derivation of vegetation indices. First, the MSS and TM channels in equivalent wave

Table 5.3: Inter-Band Correlations (r) between MSS and TM Bands for all fields (n = 113).

	VISIBLE			NIR	MIR	
	BLUE TM1	GREEN TM2	RED TM3		TM5	TM7
MSS1 GREEN	0.862	0.995	0.977	0.440	-0.049	0.005
MSS2 RED	0.859	0.979	0.998	0.316	-0.055	-0.092
MSS3 NIR	0.418	0.626	0.492	0.967	-0.180	-0.457
MSS4 NIR	0.194	0.409	0.264	0.996	-0.187	-0.537

- correlations above ± 0.298 are significant at the 0.001 level.
- correlations above ± 0.204 are significant at the 0.01 level.
- correlations above ± 0.093 are significant at the 0.05 level.

bands were very highly correlated, suggesting that similar performance could be expected between indices employing these equivalent bands. Second, because the date of the satellite overpass captured several crops in their flowering state, the traditional reflectance characteristics of green vegetation were not present. It was expected that this would significantly affect the performance of the traditional indices as indicators of plant condition. Third, the new MIR bands of the TM were only weakly or moderately correlated with most other bands, suggesting that they might contribute new information to band combinations that were not previously available from the MSS.

5.3 Discussion of Results - By Crop

5.3.1 Correlations with Crop Yield, Plant Height, and Within-Field Variance - Overview

The correlations of the spectral indices with yield, plant height, and within-field variance on a crop-by-crop basis resulted in a large volume of data for interpretation. This section provides a summary of those results in order to highlight the trends in the analysis and the general performance of the two sensors. More detailed discussions of the results for each individual crop are made in Sections 5.3.2 to 5.3.5. The results of the correlations with yield and plant height are also tabulated in Appendices B and C and presented graphically in Figures 5.1 to 5.7.

Yield and Height: When correlated with crop yield and plant height, the spectral indices revealed a variety of relationships over a wide range of positive and negative correlation coefficients. In general, stronger relationships with yield were observed for the grains (barley, wheat, flax) than for the broadleaf crops such as canola and peas. On the other hand, the strongest relationships with plant height were found among the broadleaf species. The highest correlation coefficients were observed for flax (generally $r > 0.90$, sig. = 0.01), although it is presumed these are artifacts of the small sample size for that crop ($N = 6$ fields).

When correlated with yield, all but two crop types (barley and wheat) had their strongest relationships with new indices or bands available only from the TM. This supported the notion that vegetation indices derived from bands other than the traditional

NIR and RED regions can offer superior information on vegetation condition for some crops. However, the significance of the differences between MSS and TM correlation coefficients was often very low (i.e., sig. > 0.40).

When correlated with plant height, TM indices ranked highest for all crops and varieties, often by large margins over the top ranked MSS index. The average improvement in correlation strength achieved by the TM indices over those from the MSS was +0.141, with a maximum increase of +0.397. For example, when correlated with plant height, the index TM7/TM3 outperformed the best MSS index for both wheat ($r = -0.665$ vs. $r = -0.268$, sig. of difference = 0.09) and barley ($r = -0.640$ vs. $r = -0.359$, sig. of difference = 0.11).

Within-field Variance: The results of the rank correlation of within-field variance with crop yield are tabulated in Appendix D and illustrated graphically in Figures 5.1 to 5.7. The number and complexity of indices used in this analysis was lower than in the previous sections because of the constraint on the creation of index 'images' (see Section 4.2.1), and so the volume of data for analysis was not as large. The analysis revealed predominantly negative correlations (i.e., high variance was associated with low yield), thus confirming the inverse relationship anticipated between these two variables. The top ranked indices had rank correlation coefficients in the range of $Rho = -0.65$ (Westar canola) to $Rho = -0.45$ (peas) indicating only moderately strong relationships at best. An exception to this was flax which had a remarkable $Rho = -0.97$ for the top

ranked index, although this was attributed to the small sample size for that crop. All but one crop (canola) had their highest rank correlations with data from the TM, indicating that the TM is, indeed, more sensitive to crop condition (as expressed through spatial heterogeneity in the field) because of its higher spatial resolution. Within the TM data, there did not appear to be any advantage to the measurements of variance from single bands or more complex band combinations. Both appeared among the top ranked across all of the crop types, although some band combinations did perform better for specific crops. For instance, indices incorporating TM4 and TM7 performed consistently well for wheat.

One observation from this overview is that each individual crop exhibited different relationships with yield, plant height, and within-field variance because of their unique spectral characteristics. In the following sections the results for each crop are examined and discussed in greater detail. The discussion is accompanied by three tables which present the inter-band correlations and three figures which graphically illustrate the correlations with yield, plant height, and within-field variance. The inter-band correlations are presented first in order to establish the fundamental relationships between the different spectral regions for each crop. For the analyses with yield and height, only the top twenty ranked indices are illustrated in the body of the text. The detailed results are tabulated in Appendices B and C. Each crop is treated individually, except for barley and wheat which are discussed together because of their similar results and their comparable physical and spectral characteristics. The results for the specific varieties

of barley and canola are treated within the discussion of the parent crop type.

5.3.2 Barley and Wheat

Inter-band Correlations: The inter-band correlations for the two barley classes (Tables 5.4 and 5.5) were characterized by moderate to strong positive relationships between the VIS and MIR bands, and negative or very weak correlations between the NIR and all other bands. These relationships are in agreement with previous work (Vickers and Brown, 1986; Crist and Cicone, 1984a) and represent what may be considered a model case for inter-band correlations for chlorophyll-bearing, photosynthetically-active plants (Tucker, 1979). The strong positive VIS-MIR relationships highlight the complementary nature of absorption by leaf pigments in the VIS (MSS1, MSS2, TM1, TM2, TM3) and absorption by leaf moisture in the MIR (TM5, TM7). The negative relationships between the NIR (MSS3, MSS4, TM4) and the other bands also supports the premise that healthy, unstressed leaves which absorb strongly in the VIS and MIR bands have a vigorous internal cell structure which is highly reflective in the NIR. In common with the other crops, there was a difference in the strength of correlation for TM5 and TM7 (the two MIR bands) when related to the NIR. In this case, TM7 exhibited a moderately strong inverse relationship with the NIR, while TM5 showed none at all, further suggesting quite different information content in the two bands that may be useful in the derivation of a new vegetation index.

Table 5.4: Inter-band Correlations (r) for Barley (n = 37).**(a): MSS**

	VISIBLE		NIR	
	GREEN MSS1	RED MSS2	MSS3	MSS4
MSS1	1.000			
MSS2	0.701	1.000		
MSS3	-0.131	-0.711	1.000	
MSS4	-0.210	-0.747	0.991	1.000

(b): TM

	BLUE TM1	VISIBLE		NIR TM4	MIR	
		GREEN TM2	RED TM3		TM5	TM7
TM1	1.000					
TM2	0.804	1.000				
TM3	0.829	0.660	1.000			
TM4	-0.526	-0.171	-0.764	1.000		
TM5	0.779	0.726	0.496	-0.062	1.000	
TM7	0.867	0.593	0.896	-0.669	0.713	1.000

(c): MSS-TM

	TM1	TM2	TM3	TM4	TM5	TM7
MSS1	0.854	0.968	0.665	-0.221	0.762	0.636
MSS2	0.829	0.685	0.967	-0.744	0.508	0.885
MSS3	-0.455	-0.087	-0.718	0.990	-0.002	-0.637
MSS4	-0.512	-0.166	-0.752	0.995	-0.050	-0.662

- correlations above ± 0.520 are significant at the 0.001 level.
- correlations above ± 0.415 are significant at the 0.01 level.
- correlations above ± 0.335 are significant at the 0.05 level.

**Table 5.5: Inter-band Correlations (r) for Bonanza barley
(n= 28).**

(a): MSS

	VISIBLE		NIR	
	GREEN MSS1	RED MSS2	MSS3	MSS4
MSS1	1.000			
MSS2	0.649	1.000		
MSS3	-0.019	-0.712	1.000	
MSS4	-0.092	-0.747	0.996	1.000

(b): TM

	BLUE	VISIBLE		NIR	MIR	
	TM1	GREEN TM2	RED TM3	TM4	TM5	TM7
TM1	1.000					
TM2	0.799	1.000				
TM3	0.860	0.640	1.000			
TM4	-0.499	-0.076	-0.743	1.000		
TM5	0.800	0.782	0.555	-0.035	1.000	
TM7	0.911	0.646	0.893	-0.591	0.794	1.000

(c): MSS-TM

	TM1	TM2	TM3	TM4	TM5	TM7
MSS1	0.849	0.959	0.637	-0.113	0.815	0.694
MSS2	0.877	0.602	0.963	-0.762	0.545	0.887
MSS3	-0.425	0.022	-0.682	0.993	0.036	-0.534
MSS4	-0.480	-0.050	-0.719	0.997	-0.014	-0.571

- correlations above ± 0.587 are significant at the 0.001 level.
- correlations above ± 0.481 are significant at the 0.01 level.
- correlations above ± 0.380 are significant at the 0.05 level.

Table 5.6: Inter-band Correlations (r) for Wheat (n = 22).

(a): MSS

	VISIBLE		NIR	
	GREEN MSS1	RED MSS2	MSS3	MSS4
MSS1	1.000			
MSS2	0.836	1.000		
MSS3	-0.023	-0.400	1.000	
MSS4	-0.104	-0.473	0.992	1.000

(b): TM

	BLUE	VISIBLE		NIR	MIR	
	TM1	GREEN TM2	RED TM3	TM4	TM5	TM7
TM1	1.000					
TM2	0.668	1.000				
TM3	0.531	0.842	1.000			
TM4	0.398	-0.100	-0.436	1.000		
TM5	0.785	0.288	0.207	0.527	1.000	
TM7	0.698	0.448	0.548	0.066	0.864	1.000

(c): MSS-TM

	TM1	TM2	TM3	TM4	TM5	TM7
MSS1	0.707	0.916	0.808	-0.127	0.371	0.550
MSS2	0.460	0.818	0.929	-0.482	0.116	0.470
MSS3	0.479	-0.004	-0.364	0.989	0.582	0.137
MSS4	0.421	-0.091	-0.422	0.996	0.549	0.093

- correlations above ± 0.648 are significant at the 0.001 level.
- correlations above ± 0.531 are significant at the 0.01 level.
- correlations above ± 0.425 are significant at the 0.05 level.

The inter-band correlations for wheat (Table 5.6) were very similar to those for barley, except for a weaker BLUE-RED relationship (TM1 vs. MSS2). This suggests a different colouring between the two plants, perhaps a result of the earlier maturing of wheat. Ground data indicated that wheat was at an advanced growth stage and that some senescence had begun. This maturity results in an increase in RED reflectance as the plant begin to lose absorption from chlorophyll. Of note also is the unusual positive relationship between the NIR and the MIR bands (in particular TM5), which might also be explained by the onset of senescence. A decrease in both NIR leaf reflection and MIR water absorption accompanies this growth stage, thus weakening the normally negative relationship between reflectance in those two regions.

Yield: Figures 5.1(a) and 5.3(a) illustrate that, for barley and wheat, traditional indices from the MSS were ranked highest when correlated with yield. However, they offered only marginally (and not statistically significant) better performance than the indices derived from TM. For barley, the normalized difference of TM4 and TM7 was the highest ranking TM index, followed by more complex indices incorporating bands from all spectral regions. For wheat, TM equivalent versions of the high ranking MSS indices were closely ranked behind the top indices. These patterns did not hold true for Bonanza barley, however, where TM indices dominated (Figure 5.2(a)) and only one MSS index appeared in the top ten.

Height: Non-traditional indices incorporating the new bands of the TM clearly dominated over MSS indices when correlated with plant height (Figures 5.1(b) to 5.3(b)), although with generally weaker relationships than for yield. The highest ranked MSS indices were MSS1 for both barley and Bonanza (ranked 15th and 8th respectively), and $(MSS3-MSS2)/(MSS3+MSS2)$ for wheat (16th). This indicates that the traditional bands used for measures of plant biomass (MSS2, MSS4 and their TM equivalents) are of significantly less value for the determination of plant height in the grains when compared to the new bands. The new MIR bands figured most prominently in the top ranked indices, either alone or in the denominator of indices with a VIS band in the numerator. As individual channels, the short-wave VIS (TM1, TM2) and the MIR bands were the most strongly related to plant height for barley and wheat with moderately strong, negative correlations.

Given the relatively small population of sample fields available for these analyses, it was resolved for this study that significance at the 0.10 to 0.15 levels (i.e., the results have an 85%-90% likelihood of being statistically valid) was sufficient to demonstrate a 'real' difference between the strength of correlations achieved by the MSS and TM. The significance of the difference between the top ranked TM and MSS indices when correlated with height were sig. = 0.12 for barley, sig. = 0.33 for Bonanza, and sig. = 0.09 for wheat, indicating good statistical significance to the results, except in the case of Bonanza.

(a) Yield

(b) Height

(c) Within-field Variance vs. Yield

Figure 5.1: Results of Correlation Analyses for Barley (n=37).

(a) Yield

(b) Height

(c) Within-field Variance vs. Yield

Figure 5.2: Results of Correlation Analyses for Bonanza Barley (n=28).

(a) Yield

(b) Height

(c) Within-field Variance vs. Yield

Figure 5.3: Results of Correlation Analyses for Wheat (n=37).

Within-field Variance: The rank correlations for the grains (Figures 5.1(c) to 5.3(c)) were dominated by indices comprising TM4 and TM7. For barley, Bonanza barley, and wheat the highest ranked index was the ratio of those two bands, closely followed by their normalized difference. The highest ranked MSS index among the grains was MSS4/MSS2 for wheat (fourth). The normalized difference of MSS3 and MSS2 was the highest MSS index for both barley and Bonanza ranked twelfth and sixth respectively.

Of note in these results are the very weak relationships of all simple, two-band ratios which had the visible RED band in the denominator (TM4/TM3, TM5/TM3, TM7/TM3). All of these indices were consistently among the lowest ranked for all three grain classes. Ironically, the normalized differences which included the RED band (i.e., TM4-TM3, MSS4-MSS2, MSS3-MSS2) were among the highest ranked. This suggests that a single multiplicative function (such as a simple ratio) can have the effect of suppressing the within-field variance found in the individual bands, but that a normalized difference can preserve that information. However, as will be seen in later results, this was not the case for the other crops examined in this project.

5.3.3 Canola

Inter-band Correlations: The inter-band correlations for canola and its dominant variety Westar were clearly affected by the crop being in flower at the time of imaging (Tables 5.7, 5.8). The results revealed strong positive correlations between all the VIS bands, especially between the GREEN and the RED, because of high reflectance from

Table 5.7: Inter-band Correlations (r) for Canola (n = 34).**(a): MSS**

	VISIBLE		NIR	
	GREEN MSS1	RED MSS2	MSS3	MSS4
MSS1	1.000			
MSS2	0.988	1.000		
MSS3	0.613	0.519	1.000	
MSS4	0.452	0.354	0.978	1.000

(b): TM

	BLUE	VISIBLE		NIR	MIR	
	TM1	GREEN TM2	RED TM3	TM4	TM5	TM7
TM1	1.000					
TM2	0.525	1.000				
TM3	0.569	0.983	1.000			
TM4	0.019	0.429	0.327	1.000		
TM5	0.349	0.088	0.090	-0.103	1.000	
TM7	0.346	0.081	0.168	-0.461	0.796	1.000

(c): MSS-TM

	TM1	TM2	TM3	TM4	TM5	TM7
MSS1	0.520	0.994	0.982	0.433	0.041	0.058
MSS2	0.554	0.983	0.996	0.334	0.062	0.150
MSS3	0.120	0.606	0.507	0.969	-0.048	-0.375
MSS4	0.024	0.145	0.345	0.993	-0.079	-0.442

- correlations above ± 0.547 are significant at the 0.001 level.
- correlations above ± 0.444 are significant at the 0.01 level.
- correlations above ± 0.348 are significant at the 0.05 level.

Table 5.8: Inter-band Correlations (r) for Westar canola (n = 23).**(a): MSS**

	VISIBLE		NIR	
	GREEN MSS1	RED MSS2	MSS3	MSS4
MSS1	1.000			
MSS2	0.992	1.000		
MSS3	0.459	0.389	1.000	
MSS4	0.277	0.208	0.978	1.000

(b): TM

	BLUE TM1	VISIBLE		NIR TM4	MIR	
		GREEN TM2	RED TM3		TM5	TM7
TM1	1.000					
TM2	0.672	1.000				
TM3	0.669	0.986	1.000			
TM4	-0.019	0.238	0.141	1.000		
TM5	0.497	-0.147	-0.133	-0.116	1.000	
TM7	0.582	0.139	0.229	-0.477	0.784	1.000

(c): MSS-TM

	TM1	TM2	TM3	TM4	TM5	TM7
MSS1	0.644	0.996	0.987	0.271	0.190	0.110
MSS2	0.639	0.985	0.996	0.196	-0.177	0.181
MSS3	0.214	0.466	0.380	0.971	-0.164	-0.433
MSS4	0.089	0.289	0.202	0.990	-0.122	-0.467

- correlations above ± 0.638 are significant at the 0.001 level.
- correlations above ± 0.521 are significant at the 0.01 level.
- correlations above ± 0.417 are significant at the 0.05 level.

(a) Yield

(b) Height

(c) Within-field Variance vs. Yield

Figure 5.4: Results of Correlation Analyses for Canola (n=34).

(a) Yield

(b) Height

(c) Within-field Variance vs. Yield

Figure 5.5: Results of Correlation Analyses for Westar Canola (n=23).

the bright yellow flower. The unusually high reflectance in the RED band also resulted in positive correlations between the RED and the NIR which undermined the premise of the simple NIR/RED ratio indices in the later analyses. Generally weak negative relationships were observed between the NIR and MIR bands, and extremely low correlations existed between the VIS and MIR for both canola and Westar.

Yield: For the canolas, TM indices clearly dominated when correlated with yield, although the strengths of the correlations were generally weaker than those observed for the grains. The top ranked index for both classes was $TM4-TM5/TM4+TM5$. Among the top ranked were virtually all of the complex indices derived from new bands of the TM, and including the n-space TM_WET transformation which is dominated by contributions from the MIR bands. The highest ranking MSS index for both canola and Westar was not a traditional one, but rather the first Principal Component (MSS_PC1). These results clearly illustrate the ineffectiveness of the traditional vegetation indices for characterizing plant condition during the period of plant flowering. It is interesting to note that even when the plant was in such a different spectral condition than the traditional model of green vegetation, the new indices were able to achieve moderate correlations with yield, although not as strong as those achieved for the grains.

Height: Generally stronger relationships were achieved between the spectral indices and canola plant height than were found with crop yield. Again, the complex TM indices were the highest ranked for both canola and Westar, although these were closely

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followed by more simple TM and traditional indices (Figures 5.4(b) and 5.5(b)). The GREEN and RED channels (MSS1 and MSS2, TM2 and TM3) were the single spectral bands most strongly correlated with plant height, and the RED band is represented in all of the top ranked indices for both canola and Westar. As the RED - plant height relationship is strongly positive, and the RED reflectance is largely due to flowering, this suggests that the state of flowering in this particular scene is an indicator of advanced growth stage, and thus related to plant height. Examination of the ground data and ground photographs confirmed that the fields in greatest flower normally had the greatest plant height.

Within-field Variance: The rank correlations of variance with yield for the two classes of canola generally exhibited stronger relationships with the TM (MIR bands and TM1) than with the MSS, except for the top-ranked index for all canola fields which was $MSS3-MSS2/MSS3+MSS2$. This was unusual because it was the only top ranked MSS index in the correlations with variance (over all crops!), and because it does not include data from the MIR which had figured so prominently in all other correlations with canola. The same index was also the highest ranked MSS index for Westar (eighth). It is speculated that because MSS3 actually straddles the transition between the RED and NIR, that it might have a particular sensitivity to variations in the state of flowering within a canola field as portions of a field enter or leave the bloom period. The strength of the relationships between within-field variance and yield was notably higher for Westar than for all canola fields ($Rho = -0.649$ vs. $Rho = -0.489$), largely because of

greater uniformity in development and more consistent yields within the sample of Westar fields than for the whole population of canola.

5.3.4 Peas

Inter-band Correlations: The inter-band correlations for peas (Table 5.9 (a)) exhibited weaker within VIS relationships than observed for the other crops, likely due to the transition into flowering of only some of the pea fields. Despite the ground notes indicating all peas fields at the same general growth stage, examination of the aerial and ground photography indicated that the pea fields were in transition between flowering and non-flowering states. Normally, the plants' white flowers increase reflectance in all the VIS bands, thus creating positive relationships between the bands in that region. However, with only some fields in flower, the reflectances in the population of pea fields were scattered resulting in generally weaker relationships. The GREEN bands (MSS1, TM2) had higher than expected positive correlations with the NIR bands, which is likely due to an increase in GREEN reflectance from the flowers in parallel with high reflectance in the NIR from fields at the more advanced growth stage. Plates 5 and 6 both contain examples of pea fields in the flowering state.

Yield: The highest ranking spectral index for peas was the simple band TM1 (BLUE), although there was no statistical difference between it and the next ranked index MSS4/MSS2 (Figure 5.6(a)). The remaining ranked indices for peas included a mixture of individual bands, band transformations, and complex indices from both the MSS and

Table 5.9: Inter-band Correlations (r) for Peas (n = 14).**(a): MSS**

	VISIBLE		NIR	
	GREEN MSS1	RED MSS2	MSS3	MSS4
MSS1	1.000			
MSS2	0.481	1.000		
MSS3	0.570	-0.258	1.000	
MSS4	0.486	-0.330	0.990	1.000

(b): TM

	BLUE	VISIBLE		NIR	MIR	
	TM1	GREEN TM2	RED TM3	TM4	TM5	TM7
TM1	1.000					
TM2	0.510	1.000				
TM3	0.396	0.634	1.000			
TM4	0.286	0.410	-0.285	1.000		
TM5	-0.318	-0.278	-0.009	-0.002	1.000	
TM7	-0.254	-0.301	0.398	-0.595	0.737	1.000

(c): MSS-TM

	TM1	TM2	TM3	TM4	TM5	TM7
MSS1	0.513	0.914	0.425	0.507	-0.207	-0.384
MSS2	0.399	0.647	0.975	0.282	0.013	0.371
MSS3	0.292	0.453	-0.265	0.992	-0.029	-0.611
MSS4	0.265	0.363	-0.343	0.994	0.028	-0.592

- correlations above ± 0.764 are significant at the 0.001 level.
- correlations above ± 0.655 are significant at the 0.01 level.
- correlations above ± 0.536 are significant at the 0.05 level.

(a) Yield

(b) Height

(c) Within-field Variance vs. Yield

Figure 5.6: Results of Correlation Analyses for Peas (n=14).

TM indicating that no single spectral region was dominant. There was no statistical significance to the differences in correlation strength among the different indices for peas, and it was speculated that the mix of flowering and non-flowering pea fields prevented any reliable patterns of relationships from becoming evident.

Having a population of fields at different growth stages is not at all out of the ordinary because of variations in planting date, plant variety, and plant development rates as influenced by soil, moisture, and agricultural practice (tillage, chemical applications, etc). Because of the already small number of sample pea fields in this study ($n = 14$), and the absence of distinct groups of flowering and non-flowering fields (as observed in scatterplots of spectral data and in the aerial photography), it was decided not to stratify the sample into two populations for separate analyses.

Height: Data from the visible GREEN band (TM2, MSS1) were the highest ranked indices when correlated with plant height, although with no statistically significant difference over the non-traditional, complex TM indices which followed (Figure 5.6(b)). It is speculated that the relationship between plant height and the visible GREEN band may be related to the growth stage of the plant during the flowering period. With increased maturity (and thus plant height), GREEN reflectance will increase because of the presence of flowers. Therefore, in this data set the more mature, higher, flowering plants exhibited higher GREEN reflectance than the less mature, shorter, non-flowering plants.

Variance: The eight top ranked indices for peas in the correlations between variance and yield were dominated by contributions from the NIR. The top ranked index was the individual band TM4 closely followed by various combinations incorporating the NIR (i.e., TM4/TM7, TM4/TM5, TM4/TM3, $(TM4-TM7)/(TM4+TM7)$, MSS4). Interestingly, the MSS indices which include the NIR bands ranked relatively poorly compared to their TM equivalents, despite the relatively high rankings of the single NIR bands MSS4 and MSS3. This result indicates that the within-field variance in the NIR channels of the MSS is masked when combined with data from the RED, suggesting that, (for peas in this growth stage) within-field variance might have a spectral, as well as a spatial dependence in MSS data.

5.3.5 Flax

Inter-band Correlations: The inter-band correlations observed for flax (Table 5.10) were similar to those for the grains, demonstrating moderate to strong positive relationships between the VIS and the MIR, negative correlations between the VIS and the NIR, and strong negative correlations between the NIR and the MIR. The BLUE band (TM1) differed from the grains by exhibiting a moderately strong positive relationship with the NIR which was explained by the high reflectance from the purple flowers on the plants at the time of imaging.

Yield: The analysis between spectral indices and yield resulted in extremely high correlation coefficients which were presumed to be an effect of the small sample size

($n = 6$). However, the correlations were statistically significant at the 0.01 level. The top ranked indices were characterized by data from the MIR, including TM_WET (which is highly influenced by the MIR) and the single band TM7. The highest ranked MSS index was the ratio MSS4/MSS2 (sixth) closely followed by the other NIR/RED ratios and normalized differences from both sensors.

Interestingly, despite the similarities between the spectral correlations for flax and the grains, there was an important influence of the MIR in the relationship with yield for flax which did not appear as strongly in barley or wheat. Also, flowering in the flax plant appeared to have little influence on the traditional NIR/RED ratio as had been seen for canola and peas. This was not unexpected because the purple flower of the flax plant does not contribute to either of those spectral regions.

Height: When correlated with plant height, TM_BRIGHT was the highest ranked index, closely followed by several complex TM indices and MSS_SBI. Individual MSS bands and the traditional MSS indices also appear within the top rankings.

Within-field Variance: The rank correlations for flax exhibited a very strong relationship between yield and variance in TM7 ($\text{Rho} = -0.971$), followed by an assortment of single bands and indices from all parts of the spectrum. Again, the small sample size appeared to introduce an artifact into the results, as seen in the unusually high rank correlation coefficients.

Table 5.10: Inter-band Correlations (r) for Flax (n = 6).

(a): MSS

	VISIBLE		NIR	
	GREEN MSS1	RED MSS2	MSS3	MSS4
MSS1	1.000			
MSS2	0.597	1.000		
MSS3	0.058	-0.764	1.000	
MSS4	0.038	-0.778	0.999	1.000

(b): TM

	BLUE TM1	VISIBLE		NIR TM4	MIR	
		GREEN TM2	RED TM3		TM5	TM7
TM1	1.000					
TM2	0.490	1.000				
TM3	0.023	0.763	1.000			
TM4	0.612	-0.159	-0.738	1.000		
TM5	-0.290	0.599	0.707	-0.588	1.000	
TM7	-0.456	0.380	0.797	-0.878	0.750	1.000

(c): MSS-TM

	TM1	TM2	TM3	TM4	TM5	TM7
MSS1	0.670	0.938	0.637	0.026	0.501	0.285
MSS2	-0.054	0.718	0.995	-0.783	0.750	0.854
MSS3	0.613	-0.124	-0.720	0.999	-0.546	-0.857
MSS4	0.607	-0.152	-0.735	0.999	-0.563	-0.861

- correlations above ± 0.951 are significant at the 0.01 level.
- correlations above ± 0.841 are significant at the 0.01 level.
- correlations above ± 0.814 are significant at the 0.05 level.

(a) Yield

(b) Height

(c) Within-field Variance vs. Yield

Figure 5.7: Results of Correlation Analyses for Flax (n=6).

5.4 Summary of Results

The previous sections have dealt with a large volume of correlation results and have offered detailed discussions of these on a crop-by-crop basis. This section is intended to summarize these results and to highlight those of greatest importance. A review is presented for each of the three analyses undertaken (inter-band correlations, correlations with yield and plant height, and within-field variance). The conclusions of the work, and their implications to crop monitoring, are discussed in Chapter 6.

Inter-band Correlations: The results of the inter-band correlations provided the necessary background on the relationships between the different spectral bands to enhance the interpretation of the results of the later analyses. In general, the pattern of strong correlations within spectral regions, and negative or weak correlations between spectral regions reported by previous investigators was observed in the test data. However, flowering in several of the crops affected these relationships by increasing reflectance in specific VIS bands depending on the colour of the flower.

An important result of the inter-band correlation analysis was the confirmation of very strong relationships between MSS and TM channels from 'equivalent' spectral bands. This indicated that despite their narrower bandwidth, the TM channels contained essentially the same information as the wider MSS bands, and that based on spectral information alone, similar performance should be expected from indices comprising 'equivalent' bands. This was observed in the results of the later analyses.

The inter-band correlations also provided insight into the relationship of the new spectral bands in the MIR to the other spectral regions. For the non-flowering crops, the MIR correlated with moderate to high strength with the VIS (in particular the BLUE and RED) because of the complementary absorption by leaf pigments (VIS) and in-leaf water (MIR). In the flowering crops, the high reflectance in particular bands of the VIS due to flowers resulted in the MIR being only weakly or even negatively correlated with those bands. With the NIR, only very weak to moderate negative relationships were observed in the flowering crops, with TM5 (MIR) demonstrating virtually no relationship at all to the NIR. This confirmed that 'different' information existed in the MIR than in the other spectral regions, and that significant differences existed between the two MIR channels. This latter observation was visually evident in the imagery itself (Plate 2) and corroborated the results of both Tucker (1980) and Ripple (1985).

Correlations with Yield and Height: The correlations of the spectral indices with crop yield and plant height resulted in a wide variety of different relationships influenced by crop type, flowering, and growth stage. Overall, moderate to strong relationships were observed between the top ranked indices and the plant parameters, which substantiated the fundamental motivation of investigating spectral indices as an indicator of crop condition. When correlated with the yields of barley and wheat, indices using the traditional RED and NiR bands from the MSS were the highest ranked, although they were closely followed by a variety of 'MSS-equivalent' and new indices from the TM. For canola and flax, indices incorporating the MIR bands of the TM clearly dominated.

For peas, a scattered population of fields in transition between non-flowering and flowering growth stages resulted in an unusual mixture of single bands, traditional, and complex indices being ranked highly. When correlated with plant height, all crops had their strongest correlations with indices derived from the TM.

For barley and wheat, MSS indices were the top ranked when correlated with yield, indicating that neither the 'improved' spectral, nor spatial, information in the TM bands offered any advantage in the creation of vegetation indices for these crops. However, there was no statistically significant difference between the top-ranked MSS and TM indices, indicating that the TM was equally useful. The top ranking TM indices included not only those which were 'MSS-equivalent', but also those incorporating new bands from the MIR.

For the flowering crops, the strength of the relationships with yield were weaker than those for barley and wheat. Because of the single date of imagery examined, it could not be determined whether this was an effect of the flowering, or a characteristic of the crops at all growth stages.

When correlated with plant height, the NIR bands were absent from the top ranked indices for barley and wheat, yet very prominent among the broadleaf crops and flax. This suggests that for the barley and wheat, water absorption in the MIR is a stronger indicator of canopy depth (and perhaps biomass) than either the VIS or NIR.

This is consistent with the results of Dusek *et al.* (1985) and Tucker (1980).

Rank Correlation with Variance: The results of the rank correlations between crop yield and within-field variance confirmed the hypothesis that the increased spatial resolution of the TM sensor increases its ability to detect crop condition as expressed through within field heterogeneity. In all but one case TM indices ranked higher than those from the MSS, often by significant margins. The rank correlation coefficients achieved in this analysis were lower in all but one case than the values obtained in the linear correlations between the spectral indices and yield, indicating that within-field variance is not as reliable an indicator of crop condition as straight spectral reflectance.

CHAPTER 6

CONCLUSION

6.1 Introduction

The objective of this work was to compare the performance of vegetation indices derived from the MSS and TM sensors for crop condition assessment, and to evaluate the results within the context of crop monitoring in western Canada. In this chapter, a statement of the technical conclusions is made followed by discussion of their implications for crop condition assessment and crop monitoring. In addition, recommendations for future work will be forwarded. First, however, let us consider how the date of image acquisition and the growth stage of the crops has affected the significance of the project.

As discussed in the previous chapter, the flowering state of canola, peas, and flax radically affected their spectral characteristics in the VIS portion of the spectrum and had a significant effect on the results. Flowering in those crops occurs over a two- to three-week period starting in early- to mid-July, during which time the fields take on the characteristic colour of their flower.

It might be considered unfortunate that the results were so affected by a state of the crops that lasts for such a short time. However, the data used coincides with what

is considered to be the most critical period for estimating potential crop yield because it is characterized by the highest levels of photosynthetically-active biomass in the growing season and because the best single-date correlations between vegetation indices and crop yield (for non-flowering crops, i.e., wheat, corn) have been achieved during this growth stage (Hatfield, 1983). Plant condition during this period, which immediately precedes grain filling (in barley, wheat, flax) and fruit production (in canola and peas), can be a limiting factor in crop yield. The ability to detect plant condition reliably in this period is of great importance, thus pointing to the need for spectral indices that operate under flowering conditions. The timing of the data used in this project has provided a look at the new TM bands for just that requirement. To balance the special conditions encountered with the flowering crops, the results for barley and wheat offered an examination of more conventional green vegetated targets.

6.2 Conclusions

The conclusions presented in this section focus on the specific objective of the project - the relative performance of vegetation indices derived from the MSS and TM sensors. Of course, the conclusions are drawn only from the limited data set that was analyzed - that is, a single image captured on a single date. However, it is believed that in terms of crop mix, the test area is generally representative of the Dark-brown and Black soil zones which cover roughly one-third of the agricultural region of western Canada. Also, as noted in the previous section, the timing of the image coincided fortuitously with an important phenological period. While the windows for heading and

flowering may shift by several weeks, they do occur every crop year and are a normal condition in the cycle of crop development. These observations, combined with the fact that 1985 was a normal year meteorologically in Melfort, lend promise to the portability of the results to other locations. However, recommendations for future work to extend the results of this project beyond the geographic and temporal limitations of the data set will be made in a later section.

Another issue of note was the relatively small sample sizes of peas and flax compared to the other crops. In general, it is believed they contributed to anomalous index rankings for peas and unusually strong correlation coefficients for flax. Although the top ranking correlations for these crops were statistically significant, the differences between the correlations achieved by the best TM and MSS indices were not. These factors, combined with the transitional population of flowering and non-flowering peas, made the interpretation of the results for these crops difficult and put into question their utility for drawing conclusions. For this reason, the conclusions focus only on the results from barley, wheat, and canola.

The specific conclusions of the project are:

- 1) For barley and wheat, vegetation indices derived from the TM offered no significant advantage over those derived from the MSS when correlated with crop yield. TM indices composed of 'MSS-equivalent' bands, and those incorporating the MIR, offered comparable performance to the traditional indices from the MSS for those crops.

- 2) For canola in the flowering stage, vegetation indices derived from the TM did offer a significant advantage over traditional indices derived from the MSS when correlated with crop yield, although with generally weak relationships (max. $r = 0.562$, sig. of difference = 0.01). The disruption of the classical spectral reflectance for green vegetation in the VIS undermined the premise of the traditional NIR/RED ratio indices, resulting in extremely weak relationships between crop yield and the traditional indices.
- 3) When correlated with crop height, the indices derived from the TM did offer significant advantage over those from the MSS. In particular for the barleys and wheat (sig. of difference = 0.12 (barley), 0.09 (wheat)), for which indices including only the NIR and VIS demonstrated virtually no relationship with height.
- 4) No single index from the TM was consistently stronger than others in correlations with crop yield or plant height, suggesting that a 'universal' vegetation index using the bands from the TM does not exist. The top ranked indices normally comprised data from more than one spectral region, and often from the NIR and MIR when correlated with yield.
- 5) The n-space indices ranked comparably with the ratio-based indices when correlated with yield and height, particularly TM_WET which appeared among the top rankings for all crops (except wheat) when correlated with yield. Among the n-space 'greenness' indices, the TM versions ranked above the MSS in most cases, although not significantly and by only small margins.
- 6) The finer spatial resolution of the TM offers significant advantage over the MSS for the determination of crop condition as expressed through spatial heterogeneity in the field. The correlations confirmed that there is, indeed, an inverse relationship between within-field variance and crop yield, but that this relationship is generally weaker than for spectral indices. The value of textural information, alone, or as a contribution to the spectral indices is considered limited.

6.3 Discussion and Recommendations

What are the implications of the conclusions on the use of MSS and TM data for crop monitoring? As mentioned in the first section in this chapter, the time period during which the data for this project were collected (heading in the grains, flowering

in the broadleaf crops) corresponds to one of the most important periods for the estimation of potential crop yield. The conclusions indicate that the traditional NIR/RED ratio indices offer relatively poor measures of crop condition for crops in flower (in particular canola) during this period. However, new indices from the TM appear to offer potential to overcome this limitation.

An interesting issue concerning the weak performance of the NIR/RED ratios for the flowering crops is how this is currently affecting the interpretability of data from monitoring systems such as the Canadian Crop Information System (Brown *et al.*, 1990). This system uses data from the NOAA Advanced Very High Resolution Radiometer (AVHRR) sensor to calculate the NDVI to monitor regional vegetation condition in western Canada. The data collected at 1km resolution by the sensor captures the aggregate signature of all land cover within each resolution cell, thus mixing the responses from all crop types. If significant areas are in flowering crops (approximately 25-30% of the Melfort study area was in canola and peas), it will have an effect on that average signature. This will likely become a more significant issue as the percentage of fields planted in flowering speciality crops increases with depressed world prices for grains.

Two recommendations follow from the discussion above. The first one advocates more basic research - that is, to examine full season crop spectra to determine the value of the novel TM indices during non-flowering periods. Ideally, actual TM data acquired

at regular intervals would provide the best data source, but it is virtually impossible to acquire TM data of a site at every orbit opportunity in western Canada because of cloud cover. Therefore, this work would initially have to be performed using ground or aircraft data. The added temporal frequency made possible through these approaches would be beneficial in isolating short-lived phenomena such as flowering. An airborne imaging spectrometer with narrow bandwidth capabilities would further permit experimentation with different and more precise spectral bands, although the volume of data and the effort of analysis would be considerably higher. To extend the geographic applicability of the work, it would be desirable to perform such experiments at test sites representative of different crop mixes and agricultural practices across the Canadian prairie.

The second recommendation addresses the implications the results of this project might already be having in existing crop monitoring systems. It is recommended that the impact of flowering in canola and other specialty crops on the interpretation of NDVI values from the Crop Information System be examined. In addition, the potential value of the novel indices at coarse resolutions (i.e., 500m to 2000m) should be examined in preparation for sensors at those resolutions currently being planned for global vegetation monitoring. Both of these could be accomplished at this time using existing TM and AVHRR imagery acquired during flowering and non-flowering periods using procedures described by Ormsby *et al.* (1987).

6.4 Concluding Remarks

As noted in the introduction to this paper, the effective management of Canada's agricultural resources is critical to the Canadian economy and to the well-being of Canadians. While the contribution of remotely sensed data to this task is relatively new, it is gaining increased acceptance as the 'technology' improves to meet real operational needs. The technology, in this case, includes not only the hardware which is placed in orbit, but also the knowledge of how to extract useful information from the raw data which is captured. This paper has identified one potential improvement to this technology - one which could enhance our ability to monitor the condition of flowering crops when in bloom. Moreover, it has identified a potential weakness in our understanding of how data from satellites are currently used, such as the products from the Canadian Crop Information System. Continued improvements in the technology will only come from more work such as this which has contributed to our knowledge about energy-target-sensor interactions and has related them to specific operational needs for better information. The technology of remote sensing will continue to improve, not only because of advances in engineering, but because of the efforts of earth scientists - including Geographers - in putting the data to work.

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APPENDIX A: LISTING OF GROUND DATA

FIELD I.D.	AREA (ac)	SEEDING DATE	SEED RATE (lb./ac)	YIELD (bu./ac)	HARVEST DATE	CROP	VARIETY	DEV. INT. *	SCIL COVER (%)	QLTY. UNIF. *	QLTY. DENS. *	QLTY. COND. *	HEIGHT cm	PLANT DENSITY (pl/m)
18-19-05	210	10-MAY-85	120	55	01-OCT-85	PEAS	TRAPPER	4	1	3	3	3	60	22
18-19-06	150	17-MAY-85	38	35	01-OCT-85	FLAX	NORLIN	4	0	3	3	3	42	99
19-19-01	260	26-MAY-85	72	80	18-SEP-85	BARLEY	BONANZA	4	0	3	3	3	60	68
19-19-02	45	12-MAY-85	120	50	11-SEP-85	WHEAT	KATEPWA	5	0	3	3	3	82	86
19-19-03	155	21-JUN-85	72	80	03-OCT-85	BARLEY	BONANZA	4	0	3	3	3	64	67
19-19-04	160	27-MAY-85	72	70	01-OCT-85	BARLEY	BONANZA	4	0	3	3	3	56	83
19-20-01	80	20-MAY-85	120	45	01-OCT-85	PEAS	TRAPPER	4	0	3	3	3	46	25
19-20-03	150	23-MAY-85	6	25	01-OCT-85	CANOLA	WESTAR	5	0	3	3	3	70	21
19-20-04	100	15-MAY-85	90	45	01-OCT-85	WHEAT	KATEPWA	4	0	3	3	3	70	139
19-20-06	40	20-MAY-85	120	45	01-OCT-85	PEAS	TRAPPER	4	20	2	2	3	44	25
19-20-07	20	13-MAY-85	175	50	01-OCT-85	BEANS	TRAPPER	4	20	3	3	3	47	20
19-21-01	70	16-MAY-85	105	45	17-SEP-85	WHEAT	KATEPWA	4	0	3	3	3	60	98
19-21-03	80	24-MAY-85	72	80	12-SEP-85	BARLEY	ARGYLE	4	0	3	3	3	40	75
19-21-05	40	24-MAY-85	45	30	24-OCT-85	FLAX	NORLIN	3	20	2	2	3	30	69
19-21-06	120	18-MAY-85	50	30	15-OCT-85	CANARY	NORLIN	4	0	3	3	2	41	162
19-21-07	108	24-MAY-85	45	20	21-OCT-85	FLAX	NORLIN	4	10	2	2	3	21	123
19-22-01	38	23-MAY-85	72	80	20-OCT-85	BARLEY	BONANZA	4	0	3	3	3	46	72
19-22-02	40					FALLOW			60					
19-22-03	105	16-MAY-85	105	45	19-OCT-85	WHEAT	NEEPAWA	4	0	3	3	3	69	112
19-22-04	186	20-MAY-85	50	30	09-OCT-85	CANARY	NEEPAWA	4	0	3	3	3	42	126
19-23-01	30	05-MAY-85	90	50	21-OCT-85	WHEAT	KATEPWA	4	0	3	3	3	65	86
19-23-05	40	11-MAY-85	120	45	17-SEP-85	WHEAT	NEEPAWA	5	0	3	3	3	76	152
19-23-09	65	25-MAY-85	6	30	13-OCT-85	CANOLA	WESTAR	5	0	3	3	3	68	26
19-23-11	113	27-MAY-85	72	85	13-SEP-85	BARLEY	JOHNSTON	4	0	3	3	3	44	89
19-24-01	25	24-MAY-85	8	25	11-OCT-85	CANOLA	WESTAR	4	0	3	3	3	68	33
19-24-02	100	17-MAY-85	72	75	10-OCT-85	BARLEY	BONANZA	4	0	3	3	3	64	76
19-24-03	80	25-MAY-85	8	25	11-OCT-85	CANOLA	WESTAR	4	0	3	3	3	52	24
19-24-04	160	01-JUN-85	70	95	11-SEP-85	BARLEY	ARGYLE	4	0	3	3	3	72	83
19-24-05	110	09-MAY-85	120	55	01-OCT-85	PEAS	TRAPPER	4	0	3	3	3	62	25
19-24-06	105	23-MAY-85	6	30	01-OCT-85	CANOLA	WESTAR	4	0	3	3	3	72	29
19-25-01	80	04-JUN-85	72	85	27-OCT-85	BARLEY	BONANZA	4	0	3	3	3	36	63
19-25-04	160	07-JUN-85	65	85	19-OCT-85	BARLEY	BONANZA	3	0	3	3	3	32	89
19-25-05	160	18-MAY-85	90	60	01-OCT-85	WHEAT	NEEPAWA	4	0	3	3	3	56	79
19-25-06	75	25-MAY-85	5	40	27-OCT-85	PEAS	TRAPPER	4	0	3	3	3	32	24
19-26-03	110	28-MAY-85	72	75	14-SEP-85	BARLEY	JOHNSTON	4	0	3	3	3	44	102
19-26-04	40					FALLOW			90					
19-26-05	80	16-MAY-85	40	30	19-OCT-85	FLAX	NORMAN	4	0	3	3	3	36	100
19-26-07	80	17-MAY-85	120	40	22-OCT-85	PEAS	TRAPPER	4	20	2	2	2	28	24
19-27-01	140	11-JUN-85	72	70	16-OCT-85	BARLEY	BONANZA	3	0	3	3	3	22	58
19-27-02	150					FALLOW			60					
19-27-03	177	27-MAY-85	72	65	14-SEP-85	BARLEY	BONANZA	4	0	3	3	3	39	71
19-28-01	120	27-MAY-85	84	80	23-SEP-85	BARLEY	BONANZA	4	0	3	3	3	39	63
19-28-02	110	21-MAY-85	105	50	19-OCT-85	WHEAT	NEEPAWA	4	0	3	3	3	35	122
19-28-03	90	25-MAY-85	45	20	22-OCT-85	FLAX	NORLIN	3	10	3	3	3	28	101

* from King and Mack (1984)

FIELD I.D.	AREA (ac)	SEEDING DATE	SEED RATE (lb/ac)	YIELD (bu/ac)	HARVEST DATE	CROP	VARIETY	DEV INT. *	SOIL COVER (%)	QTY. UNIF. *	QTY. DENS. *	QTY. COND. *	HEIGHT cm	PLANT DENSITY (pl/m)
19-28-04	100	11-MAY-85	120	50	15-OCT-85	PEAS	TRAPPER	4	0	3	3	3	65	22
19-29-01	50	24-MAY-85	6	30	02-OCT-85	CANOLA	WESTAR	5	0	3	4	4	76	27
19-29-02	50	24-MAY-85	6	30	11-OCT-85	CANOLA	WESTAR	5	0	3	3	3	70	31
19-29-03	160	22-MAY-85	8	30	03-OCT-85	CANOLA	WESTAR	5	0	3	3	3	66	32
19-29-07	90	16-MAY-85	105	50	23-OCT-85	WHEAT	KATEPWA	5	0	3	3	3	64	145
19-30-01	240	16-MAY-85	90	45	01-OCT-85	WHEAT	KATEPWA	4	0	3	3	3	52	105
19-30-02	80	24-MAY-85	60	70	12-SEP-85	BARLEY	BONANZA	4	0	3	3	3	56	75
19-30-05	25	24-MAY-85	6	25	14-OCT-85	CANOLA	WESTAR	4	10	3	3	3	56	14
20-19-01	215	17-MAY-85	105	50	18-SEP-85	WHEAT	KATEPWA	4	0	3	3	3	56	81
20-19-03	115	16-MAY-85	105	45	18-SEP-85	WHEAT	KATEPWA	5	0	3	3	3	82	108
20-19-04	320	15-MAY-85	120	40	10-SEP-85	PEAS	TRAPPER	4	0	3	3	3	42	22
20-20-04	60	25-MAY-85	7	20	16-OCT-85	CANOLA	REGENT	5	0	3	3	3	76	33
20-20-05	140	27-MAY-85	72	75	14-SEP-85	BARLEY	BONANZA	4	0	3	3	3	68	64
20-20-06						FALLOW			90					
20-21-01	160	07-JUN-85	6	35	17-OCT-85	CANOLA	TORIN	5	0	3	3	3	80	56
20-21-02	200	11-MAY-85	120	50	24-OCT-85	PEAS	TRAPPER	4	0	3	3	3	68	16
20-21-03	140	16-MAY-85	90	40	15-OCT-85	BARLEY	BONANZA	5	0	3	3	3	94	98
20-21-04	30					FALLOW			40					
20-21-04A/5	30	10-JUN-85	96	75	09-OCT-85	BARLEY	BENITO	4	0	3	3	3	50	84
20-22-01	100	06-JUN-85	72	65	12-OCT-85	BARLEY	BONANZA	4	0	3	3	3	40	99
20-22-04	200	24-MAY-85	72	70	13-SEP-85	BARLEY	BONANZA	4	0	3	3	3	66	99
20-22-06	150	16-MAY-85	6	33	18-OCT-85	CANOLA	REGENT	5	0	3	3	3	90	16
20-23-04	160	21-MAY-85	45	25	10-OCT-85	CANARY		4	0	3	3	3	52	110
20-23-05A	160	16-MAY-85	6	30	18-OCT-85	CANOLA	REGENT	5	0	3	3	3	94	19
20-23-05B	160	16-MAY-85	6	30	18-OCT-85	CANOLA	REGENT	5	0	3	3	3	94	19
20-23-06	160	03-JUN-85	80	65	01-OCT-85	BARLEY	BONANZA	3	10	2	2	3	34	53
20-23-07	20					FALLOW			30					
20-24-02	26					PEAS	TRAPPER							
20-24-03	26	10-MAY-85	120	50	20-SEP-85	PEAS	TRAPPER	4	0	3	3	3	40	41
20-24-05	30	22-MAY-85	70	50	12-OCT-85	BARLEY	HARINGTON	4	0	3	3	3	44	66
20-24-06	30					FALLOW			40					
20-24-07	155	19-MAY-85	40	22	23-OCT-85	FLAX	MCGREGOR	3	0	3	3	3	34	54
20-24-08	80	22-MAY-85	75	35	29-OCT-85	WHEAT	KATEPWA	4	0	3	3	3	45	117
20-24-09	60	24-MAY-85	150	40	01-OCT-85	BARLEY	BONANZA	4	0	3	3	3	34	95
20-24-09	80	08-JUN-85	60	60	17-OCT-85	PEAS	TRAPPER	4	20	2	2	3	48	16
20-25-01	78	17-MAY-85	160	45	25-SEP-85	PEAS	TRAPPER	4	0	3	3	3	52	25
20-25-02	77	04-JUN-85	105	105	13-OCT-85	BARLEY	BONANZA	4	0	3	3	3	48	89
20-25-03	78	23-MAY-85	8	43	10-OCT-85	CANOLA	WESTAR	4	0	3	3	3	74	27
20-25-04	78	22-MAY-85	50	45	17-SEP-85	CANARY		4	0	3	3	3	40	151
20-25-05	90	05-JUN-85	105	90	13-OCT-85	BARLEY	BONANZA	4	0	3	3	3	34	79
20-25-06	230	14-JUN-85	72	50	29-OCT-85	BARLEY	BONANZA	2	10	3	3	3	18	76
20-26-01	100	01-JUN-85	72	60	01-OCT-85	BARLEY	BONANZA		0	3	3	3	38	72
20-26-02	70	01-JUN-85	68	60	01-OCT-85	OATS			20	2	2	2	34	65
20-26-03	185	25-MAY-85	72	75	14-OCT-85	BARLEY	BENITO	4	0	4	4	4	58	105

* from King and Mack (1984)

FIELD I.D.	AREA (ac)	SEEDING DATE	SEED RATE (lb/ac)	YIELD (bu/ac)	HARVEST DATE	CROP	VARIETY	DEV. INT. *	SOIL COVER (%)	QTY. UNIF. *	QTY. DENS. *	QTY. COND. *	HEIGHT cm	PLANT DENSITY (pl/m)
20-27-02	200	15-JUN-85	100	40		WHEAT	NEEPAWA	5	0	3	3	3	80	107
20-27-03	160	08-MAY-85	120			FALLOW			70	3	3	3		
20-27-04	160	09-MAY-85	100	40	01-OCT-85	WHEAT	NEEPAWA	5	40	3	3	3	96	115
20-27-05	90					FALLOW								
20-28-01	100	05-JUN-85	80	75	11-OCT-85	BARLEY	BONANZA	4	0	3	3	3	48	66
20-28-02	90	06-JUN-85	8	20	13-OCT-85	CANOLA	WESTAR	3	10	2	2	2	20	32
20-28-04	145	24-MAY-85	5	21	13-SEP-85	CANOLA	T081N	5	0	3	3	3	100	35
20-28-05	20	11-MAY-85	68	60	09-SEP-85	OATS		0	0	2	2	2	76	53
20-28-06	140	22-MAY-85	7	7	17-SEP-85	CANOLA	WESTAR	5	10	2	2	2	92	26
20-29-01	60	10-MAY-85	90	60	14-OCT-85	WHEAT	HY320	5	0	3	3	3	62	51
20-29-02	160	06-JUN-85	8	15	21-OCT-85	CANOLA	WESTAR	2	20	2	2	2	18	21
20-29-03	160	22-MAY-85	6	30	30-SEP-85	CANOLA	WESTAR	5	0	3	3	3	92	31
20-29-04	160	25-MAY-85	72	100	25-OCT-85	BARLEY	JOHNSTON	4	0	4	4	4	62	62
20-29-05	100	15-MAY-85	90	45	21-OCT-85	WHEAT	KATEPWA	5	0	3	3	3	80	72
20-30-02	160	16-MAY-85	120	35	28-SEP-85	PEAS	TRAPPER	4	10	3	3	3	56	14
20-30-03	160	20-MAY-85	85	60	19-OCT-85	WHEAT	COULTER	3	0	3	3	3	44	107
20-30-04	160	20-MAY-85	85	65	25-OCT-85	WHEAT	COULTER	4	0	3	3	3	66	97
21-01-01	315	25-MAY-85	90	90	15-OCT-85	BARLEY	BONANZA	4	0	4	4	4	98	73
21-01-02	160	17-MAY-85	100	60	12-OCT-85	WHEAT	BENITO	5	0	4	4	4	96	130
21-01-03	130	10-MAY-85	100	55	27-SEP-85	WHEAT	KATEPWA	5	0	4	4	4	103	105
21-02-01	160	17-MAY-85	100	55	14-OCT-85	WHEAT	BENITO	3	0	3	3	3	46	43
21-02-03	55					FALLOW		60						
21-02-04	62	20-JUN-85	7	25	11-SEP-85	CANOLA	T081N	5	0	4	4	4	92	22
21-02-05	100	21-MAY-85	6	20	01-OCT-85	CANOLA	WESTAR	4	0	3	3	3	98	24
21-02-06	60	18-MAY-85	75	45	01-OCT-85	WHEAT	KATEPWA	4	0	3	3	3	76	96
21-02-07	160	23-MAY-85	8	35	11-OCT-85	CANOLA	WESTAR	5	0	3	3	3	82	38
21-03-01	63	28-MAY-85	7	27	30-SEP-85	CANOLA	T081N	4	0	2	2	2	82	22
21-03-06	40	18-MAY-85	120	30	01-OCT-85	PEAS	TRAPPER	4	0	3	3	3	68	13
21-03-07A	80	04-JUN-85	72	70	30-SEP-85	BARLEY	BONANZA	4	0	3	3	3	62	82
21-03-07B	80	04-JUN-85	72	70	30-SEP-85	BARLEY	BONANZA	4	0	3	3	3	62	82
21-03-08	40					FALLOW		50						
21-03-10	40	20-MAY-85	120	25	01-OCT-85	PEAS	TRAPPER	4	0	2	2	2	72	11
21-10-01	100	25-MAY-85	72	70	01-OCT-85	BARLEY	BONANZA	4	0	3	3	3	64	79
21-10-03	60	19-MAY-85	72	30	15-SEP-85	BARLEY	CONQUEST	4	0	2	2	2	56	83
21-10-04	50					FALLOW		60						
21-10-05	50	23-MAY-85	72	40	02-OCT-85	BARLEY	BONANZA	4	0	3	3	3	60	54
21-10-06	60	16-MAY-85	72	30	27-AUG-85	BARLEY	KLAGES	4	0	3	3	3	70	91
21-10-07	50	22-MAY-85	72	40	02-OCT-85	BARLEY	BONANZA	4	0	3	3	3	82	78
21-10-08	160	12-JUN-85	7	12	01-OCT-85	CANOLA	WESTAR	4	0	3	3	3	78	24
21-10-09	55	26-MAY-85	5	13	30-SEP-85	CANOLA	T081N	4	0	3	3	3	74	55
21-11-01	65	24-MAY-85	60	24	11-SEP-85	BARLEY		3	0	1	1	1	60	50
21-11-02	115	18-MAY-85	30	30	07-OCT-85	FLAX	NORLIN	4	0	3	3	3	47	61
21-11-03	105	08-MAY-85	84	100	22-AUG-85	BARLEY	BONANZA	5	0	3	3	3	104	105
21-11-04	100	26-MAY-85	8	25	20-SEP-85	CANOLA	WESTAR	4	0	3	3	3	78	31

* from King and Mack (1984)

FIELD I.D.	AREA (ac)	SEEDING DATE	SEED RATE (lb/ac)	YIELD (bu/ac)	HARVEST DATE	CROP	VARIETY	DEV. INT. ★	SOIL COVER (%)	QTY. UNIF. ★	QTY. DENS. ★	QTY. COND. ★	HEIGHT cm	PLANT DENSITY (pl/m)
21-11-05	150	20-MAY-85	6	20	01-OCT-85	CANOLA	WESTAR	5	0	3	3	3	100	32
21-12-01	115	20-MAY-85	6	25	30-SEP-85	CANOLA	WESTAR	5	0	3	3	3	104	20
21-12-02	160	20-MAY-85	6	25	30-SEP-85	CANOLA	WESTAR	5	0	3	3	3	80	22
21-12-03	155	22-MAY-85	72	75	10-SEP-85	BARLEY	BONANZA	5	0	3	3	3	90	98
21-12-05	120	11-MAY-85	110	25	30-SEP-85	FALLOW			40					
21A-24-01	160	05-JUN-85	6	15	12-OCT-85	CANOLA	WESTAR	3	0	2	2	2	50	23
21A-24-02	135	21-MAY-85	50	20	18-OCT-85	FLAX	MORLIN	3	10	2	2	2	38	82
21A-24-04	65	17-MAY-85	100	63	16-OCT-85	WHEAT	COULTER	4	0	4	4	4	88	124
21A-24-05	80	22-MAY-85	7	20	24-OCT-85	CANOLA	WESTAR	4	0	2	2	2	60	18
21A-25-01	260	18-MAY-85	120	46	26-OCT-85	PEAS	TRAPPER	4	0	3	3	3	68	17
21A-25-02	116	11-MAY-85	120	45	10-OCT-85	WHEAT	COULTER	4	0	3	3	3	72	106
21A-25-03	160	20-MAY-85	6	20	13-OCT-85	CANOLA	TT	4	20	2	2	2	52	17

• from King and Mack (1984)

**APPENDIX B: RESULTS OF CORRELATIONS BETWEEN
SPECTRAL INDICES AND CROP YIELD**

(d) CANOLA			(e) WESTAR CANOLA			(f) PEAS		
INDEX	r	r**2	INDEX	r	r**2	INDEX	r	r**2
1	0.562	0.316	1	0.583	0.340	1	0.508	0.258
2	0.556	0.310	2	0.579	0.335	2	0.413	0.171
3	0.549	0.301	3	0.579	0.335	3	0.382	0.146
4	0.509	0.259	4	0.577	0.333	4	0.369	0.136
5	0.449	0.202	5	0.537	0.289	5	-0.368	0.136
6	0.444	0.197	6	0.515	0.265	6	0.367	0.135
7	0.435	0.190	7	0.474	0.225	7	0.364	0.133
8	-0.434	0.188	8	0.466	0.217	8	0.362	0.131
9	0.413	0.170	9	0.444	0.197	9	0.361	0.130
10	0.411	0.169	10	0.440	0.193	10	0.358	0.128
11	0.407	0.166	11	0.422	0.178	11	0.358	0.128
12	0.406	0.165	12	-0.421	0.177	12	0.355	0.126
13	0.403	0.162	13	0.418	0.174	13	0.352	0.124
14	0.402	0.161	14	0.410	0.168	14	0.352	0.124
15	0.392	0.153	15	0.388	0.151	15	0.350	0.122
16	0.369	0.136	16	0.386	0.149	16	0.341	0.116
17	0.350	0.122	17	0.380	0.144	17	0.340	0.115
18	0.341	0.116	18	-0.385	0.148	18	0.337	0.114
19	-0.318	0.101	19	-0.350	0.123	19	0.335	0.112
20	0.309	0.095	20	0.327	0.107	20	0.333	0.111
21	0.296	0.088	21	0.310	0.096	21	0.324	0.105
22	0.290	0.084	22	0.296	0.087	22	0.313	0.098
23	-0.281	0.079	23	-0.289	0.084	23	0.312	0.098
24	-0.222	0.049	24	0.259	0.067	24	0.298	0.089
25	-0.222	0.049	25	0.252	0.064	25	0.296	0.087
26	0.199	0.040	26	0.243	0.059	26	0.282	0.080
27	0.192	0.037	27	-0.241	0.058	27	-0.268	0.072
28	0.172	0.030	28	0.227	0.052	28	-0.245	0.060
29	0.161	0.026	29	0.223	0.050	29	-0.233	0.054
30	0.111	0.012	30	0.188	0.035	30	-0.215	0.046
31	-0.111	0.012	31	-0.185	0.034	31	0.185	0.034
32	-0.100	0.010	32	-0.177	0.031	32	-0.183	0.033
33	0.097	0.009	33	0.131	0.017	33	-0.175	0.031
34	-0.085	0.007	34	-0.117	0.014	34	-0.150	0.022
35	0.074	0.006	35	-0.082	0.007	35	-0.140	0.020
36	0.064	0.004	36	0.063	0.004	36	-0.093	0.009
37	0.060	0.004	37	-0.055	0.003	37	0.060	0.004
38	0.055	0.003	38	-0.038	0.001	38	-0.031	0.001
39	-0.040	0.002	39	0.033	0.001	39	-0.028	0.001
40	0.037	0.001	40	-0.017	0.000	40	0.006	0.000
41	0.002	0.000	41	-0.016	0.000	41	0.003	0.000

(g) FLAX

INDEX		r	r**2
1	TM4-TM5/TM4-TM5	0.985	0.971
2	TM4-TM7/TM4-TM7	0.983	0.967
3	TM7/TM5	-0.978	0.956
4	TM_WET	0.976	0.953
5	TM4/TM7	0.971	0.944
6	MSS4/MSS2	0.971	0.942
7	TM4/TM3	0.970	0.942
8	TM7	-0.967	0.935
9	TM4/TM5	0.966	0.933
10	MSS3-MSS2/MSS3-MSS2	0.962	0.925
11	MSS4-MSS2/MSS4-MSS2	0.960	0.921
12	TM4-TM3/TM4-TM3	0.959	0.921
13	TM3-TM4/TM2-TM7	0.958	0.918
14	TM_PC1	0.955	0.911
15	TM3-TM4/TM1-TM7	0.954	0.910
16	MSS_PC2	-0.954	0.910
17	MSS_GV1	0.951	0.904
18	TM4	0.949	0.900
19	TM_GREEN	0.948	0.899
20	TM3/TM1-TM7	0.946	0.895
21	TM2/TM5-TM7	0.944	0.891
22	MSS4	0.940	0.883
23	MSS3	0.936	0.876
24	TM7/TM3	-0.930	0.865
25	TM1-TM4-TM5/TM2-TM3	0.928	0.861
26	MSS_PC1	0.927	0.859
27	TM1/TM3	0.922	0.851
28	MSS2	-0.912	0.832
29	MSS_SBI	0.909	0.827
30	TM4-TM5/TM3	0.903	0.815
31	TM3	-0.870	0.757
32	TM2-TM3/TM4-TM5	-0.863	0.744
33	TM_BRIGHT	0.791	0.625
34	TM_PC2	-0.790	0.624
35	TM5	-0.758	0.574
36	TM2-TM3/TM4-TM7	-0.574	0.329
37	TM1	0.421	0.177
38	TM2	-0.395	0.156
39	TM5/TM3	-0.307	0.094
40	MSS1	-0.264	0.070
41	TM_PC3	0.097	0.009

**APPENDIX C: RESULTS OF CORRELATIONS BETWEEN
SPECTRAL INDICES AND PLANT HEIGHT**

(a) BARLEY				(b) BONANZA BARLEY				(c) WHEAT			
INDEX	r	r ²		INDEX	r	r ²		INDEX	r	r ²	
1	-0.640	0.409		1	-0.702	0.493		1	-0.665	0.442	
2	0.628	0.394		2	0.668	0.446		2	0.616	0.379	
3	0.600	0.360		3	-0.666	0.444		3	-0.594	0.353	
4	-0.595	0.354		4	0.657	0.432		4	0.558	0.312	
5	-0.541	0.293		5	-0.646	0.417		5	0.549	0.302	
6	-0.522	0.273		6	-0.640	0.410		6	-0.510	0.260	
7	-0.497	0.247		7	-0.608	0.370		7	-0.477	0.228	
8	0.469	0.220		8	-0.593	0.351		8	0.454	0.206	
9	0.454	0.206		9	0.539	0.291		9	-0.452	0.204	
10	0.450	0.202		10	0.528	0.279		10	0.421	0.177	
11	0.443	0.196		11	0.515	0.265		11	-0.389	0.151	
12	0.431	0.185		12	-0.510	0.260		12	-0.376	0.141	
13	0.400	0.160		13	-0.508	0.258		13	-0.305	0.093	
14	0.397	0.158		14	0.503	0.253		14	-0.297	0.088	
15	-0.359	0.129		15	0.463	0.215		15	-0.292	0.085	
16	-0.356	0.127		16	0.456	0.208		16	-0.268	0.072	
17	0.320	0.102		17	-0.450	0.202		17	-0.247	0.061	
18	0.314	0.098		18	-0.445	0.198		18	-0.243	0.059	
19	0.305	0.093		19	-0.424	0.180		19	-0.239	0.057	
20	-0.297	0.088		20	0.369	0.136		20	0.238	0.057	
21	-0.292	0.085		21	0.348	0.121		21	-0.237	0.056	
22	-0.287	0.083		22	0.328	0.108		22	-0.232	0.054	
23	-0.286	0.082		23	0.325	0.106		23	-0.230	0.053	
24	0.279	0.078		24	0.322	0.103		24	0.228	0.052	
25	0.276	0.076		25	0.319	0.102		25	-0.227	0.051	
26	-0.264	0.070		26	0.293	0.086		26	-0.223	0.050	
27	0.259	0.067		27	-0.288	0.083		27	-0.218	0.047	
28	0.257	0.066		28	-0.242	0.059		28	-0.198	0.039	
29	0.256	0.066		29	0.236	0.056		29	-0.196	0.039	
30	0.253	0.064		30	0.233	0.054		30	0.195	0.038	
31	0.247	0.061		31	0.227	0.051		31	0.194	0.038	
32	0.243	0.059		32	0.223	0.050		32	0.193	0.037	
33	0.243	0.059		33	0.222	0.049		33	-0.187	0.035	
34	0.238	0.057		34	0.215	0.046		34	0.177	0.031	
35	0.230	0.053		35	0.197	0.039		35	0.170	0.029	
36	0.206	0.043		36	0.183	0.034		36	-0.164	0.027	
37	-0.169	0.029		37	-0.141	0.020		37	0.142	0.020	
38	0.118	0.014		38	-0.106	0.011		38	0.103	0.011	
39	-0.101	0.010		39	0.058	0.003		39	0.082	0.007	
40	0.090	0.008		40	-0.048	0.002		40	-0.076	0.006	
41	0.058	0.003		41	0.016	0.000		41	-0.041	0.002	

(d) CANOLA			(e) WESTAR CANOLA			(f) PEAS		
INDEX	r	r**2	INDEX	r	r**2	INDEX	r	r**2
1	-0.759	0.576	1	-0.820	0.673	1	0.738	0.544
2	0.746	0.556	2	0.800	0.641	2	0.714	0.510
3	0.744	0.554	3	0.792	0.628	3	-0.608	0.370
4	-0.735	0.540	4	0.788	0.620	4	0.592	0.351
5	-0.715	0.511	5	-0.784	0.615	5	0.583	0.340
6	-0.700	0.490	6	-0.782	0.611	6	0.558	0.311
7	0.696	0.485	7	-0.781	0.610	7	0.538	0.289
8	0.696	0.484	8	-0.741	0.549	8	0.536	0.287
9	-0.694	0.482	9	-0.735	0.541	9	0.534	0.285
10	-0.689	0.474	10	-0.732	0.536	10	0.520	0.270
11	-0.683	0.467	11	0.717	0.514	11	0.518	0.268
12	0.678	0.459	12	0.715	0.511	12	0.474	0.225
13	0.665	0.442	13	-0.712	0.507	13	0.472	0.223
14	-0.664	0.440	14	-0.697	0.486	14	0.471	0.222
15	0.571	0.326	15	-0.684	0.467	15	0.469	0.220
16	0.532	0.283	16	-0.680	0.463	16	0.469	0.220
17	0.442	0.195	17	0.679	0.462	17	0.469	0.216
18	0.415	0.172	18	0.664	0.441	18	0.460	0.212
19	0.368	0.136	19	0.550	0.303	19	0.456	0.208
20	0.360	0.129	20	0.514	0.264	20	0.455	0.207
21	0.346	0.120	21	0.430	0.185	21	0.446	0.199
22	0.345	0.119	22	0.424	0.180	22	-0.438	0.192
23	0.335	0.112	23	-0.391	0.153	23	-0.437	0.191
24	0.278	0.077	24	0.355	0.126	24	0.397	0.158
25	0.249	0.062	25	-0.321	0.103	25	0.397	0.158
26	0.225	0.051	26	0.312	0.098	26	0.385	0.148
27	-0.221	0.049	27	0.208	0.043	27	-0.365	0.133
28	-0.197	0.039	28	-0.147	0.022	28	0.334	0.112
29	0.156	0.024	29	0.130	0.017	29	-0.326	0.106
30	-0.135	0.018	30	0.114	0.015	30	0.302	0.091
31	0.134	0.018	31	0.114	0.013	31	-0.297	0.088
32	-0.116	0.013	32	-0.113	0.013	32	0.292	0.085
33	0.062	0.004	33	-0.112	0.013	33	0.275	0.076
34	-0.031	0.001	34	-0.107	0.012	34	0.274	0.075
35	0.023	0.001	35	-0.103	0.011	35	0.266	0.071
36	0.018	0.000	36	0.088	0.008	36	-0.235	0.055
37	-0.014	0.000	37	0.080	0.006	37	0.203	0.041
38	-0.008	0.000	38	0.080	0.006	38	0.099	0.010
39	0.006	0.000	39	0.025	0.001	39	-0.079	0.006
40	0.006	0.000	40	-0.007	0.000	40	-0.063	0.004
41	-0.003	0.000	41	0.004	0.000	41	-0.018	0.000

(9) FLAX

INDEX		r	r**2
1	TM_BRIGHT	0.905	0.819
2	TM2*TM3/TM4*TM5	-0.883	0.781
3	TM4*TM5/TM3	0.866	0.750
4	MSS_SB1	0.833	0.695
5	TM1*TM4*TM5/TM2*TM3	0.822	0.676
6	MSS3	0.817	0.667
7	TM4-TM3/TM4*TM3	0.816	0.665
8	MSS_PC1	0.810	0.657
9	MSS1-MSS2/MSS4-MSS2	0.810	0.656
10	MSS3-MSS2/MSS3-MSS2	0.809	0.655
11	MSS4	0.797	0.635
12	TM_GREEN	0.795	0.632
13	MSS_GVI	0.792	0.627
14	TM4	0.788	0.622
15	MSS_PC2	-0.784	0.615
16	TM4/TM7	0.783	0.612
17	TM_PC1	0.780	0.609
18	TM2*TM3/TM4*TM7	-0.773	0.597
19	TM7/TM5	-0.767	0.589
20	TM4-TM7/TM4*TM7	0.759	0.577
21	TM4/TM3	0.739	0.547
22	MSS4/MSS2	0.727	0.529
23	TM4-TM5/TM4*TM5	0.722	0.521
24	TM3*TM4/TM1*TM7	0.672	0.452
25	TM4/TM5	0.659	0.434
26	TM3*TM4/TM2*TM7	0.649	0.422
27	TM_MET	0.592	0.351
28	TM3/TM1*TM7	0.573	0.329
29	TM7/TM3	-0.564	0.318
30	TM7	-0.548	0.300
31	TM1	0.512	0.262
32	TM2/TM5*TM7	0.501	0.251
33	TM_PC3	-0.444	0.198
34	TM1/TM3	0.433	0.188
35	MSS2	-0.417	0.174
36	TM3	-0.372	0.138
37	MSS1	0.352	0.124
38	TM2	0.302	0.091
39	TM5/TM3	0.240	0.058
40	TM_PC2	-0.119	0.014
41	TM5	-0.062	0.004

**APPENDIX D: RESULTS OF RANK CORRELATIONS BETWEEN
WITHIN-FIELD SPECTRAL VARIANCE AND CROP YIELD**

(a) BARLEY			(b) BONANZA BARLEY			(c) WHEAT		
VARIANCE OF INDEX	rho		VARIANCE OF INDEX	rho		VARIANCE OF INDEX	rho	
1 TM4/	-0.636		1 TM4/TM7	-0.485		1 TM4/TM7	-0.590	
2 TM4.../TM4+TM7	-0.629		2 TM4-TM7/TM4+TM7	-0.464		2 TM4-TM7/TM4+TM7	-0.550	
3 TM4-TM3/TM4+TM3	-0.572		3 TM2	-0.429		3 TM4-TM5/TM4+TM5	-0.478	
4 TM4-TM5/TM4+TM5	-0.552		4 TM4-TM3/TM4+TM3	-0.406		4 MSS4/MSS2	0.449	
5 TM7	-0.510		5 TM4	-0.359		5 TM4-TM3/TM4+TM3	-0.397	
6 TM PC2	-0.483		6 TM PC2	-0.357		6 TM7	-0.372	
7 TM7/TM5	-0.481		7 MSS3-MSS2/MSS3+MSS2	-0.354		7 TM5	-0.347	
8 TM2	-0.466		8 TM PC3	-0.352		8 TM3	-0.327	
9 TM3	-0.458		9 TM4-TM5/TM4+TM5	-0.345		9 TM4/TM5	-0.319	
10 TM PC3	-0.448		10 MSS4-MSS2/MSS4+MSS2	-0.343		10 MSS3	-0.310	
11 TM5	-0.444		11 TM7/TM5	-0.327		11 TM7/TM5	-0.306	
12 MSS3-MSS2/MSS3+MSS2	-0.425		12 TM5	-0.327		12 TM PC2	-0.279	
13 MSS4-MSS2/MSS4+MSS2	-0.400		13 TM7	-0.325		13 MSS3-MSS2/MSS3+MSS2	-0.270	
14 TM1	-0.379		14 MSS3	-0.274		14 TM1	-0.269	
15 MSS3	-0.320		15 MSS4/MSS2	0.215		15 MSS4-MSS2/MSS4+MSS2	-0.227	
16 TM4/TM5	-0.314		16 TM1	-0.189		16 MSS2	0.226	
17 TM PC1	-0.288		17 MSS2	-0.181		17 TM2	-0.225	
18 TM4	-0.272		18 TM4/TM5	-0.160		18 TM PC3	-0.201	
19 MSS4/MSS2	-0.249		19 TM PC1	-0.146		19 MSS4	-0.179	
20 TM7/TM3	-0.202		20 TM5/TM3	-0.136		20 TM PC1	-0.133	
21 TM5/TM3	-0.175		21 TM4	-0.135		21 TM4/TM3	0.118	
22 TM4/TM3	-0.124		22 TM7/TM3	-0.086		22 TM4	-0.119	
23 MSS1	0.085		23 TM4/TM3	-0.068		23 MSS1	-0.116	
24 MSS2	-0.063		24 MSS4	0.053		24 TM7/TM3	-0.040	
25 MSS4	-0.060		25 MSS1	0.032		25 TM5/TM3	0.017	

(d) CANOLA			(e) WESTAR CANOLA			(f) PEAS		
	VARIANCE OF INDEX	rho		VARIANCE OF INDEX	rho		VARIANCE OF INDEX	rho
1	MSS3-MSS2/MSS3+MSS2	-0.490	1	TM5/TM3	-0.649	1	TM4	-0.451
2	TM5/TM3	-0.483	2	TM7	-0.611	2	TM4/TM7	-0.451
3	TM7/TM4	-0.443	3	TM1	-0.443	3	TM_PC1	-0.451
4	TM5	-0.434	4	TM7/TM3	-0.564	4	TM4/TM5	-0.447
5	TM4-TM5/TM4+TM5	-0.430	5	TM4/TM7	-0.489	5	TM4-TM7/TM4+TM7	-0.427
6	TM4-TM7/TM4+TM7	-0.426	6	TM4-TM7/TM4+TM7	-0.475	6	MSS4	-0.411
7	TM1	-0.415	7	TM5	-0.470	7	TM4-TM5/TM4+TM5	-0.404
8	MSS4-MSS2/MSS4+MSS2	-0.413	8	MSS3-MSS2/MSS3+MSS2	-0.459	8	TM4-TM5/TM4+TM5	-0.338
9	TM4-TM3/TM4+TM3	-0.402	9	TM4-TM5/TM4+TM5	-0.459	9	TM4-TM3/TM4+TM3	-0.336
10	TM7/TM3	-0.402	10	TM_PC2	-0.447	10	TM5	-0.322
11	TM7	-0.396	11	TM4-TM3/TM4+TM3	-0.394	11	TM1	0.319
12	MSS4/MSS2	-0.383	12	TM4/TM3	-0.340	12	TM5/TM3	-0.304
13	TM_PC2	-0.360	13	MSS4-MSS2/MSS4+MSS2	-0.340	13	TM_PC2	-0.298
14	TM4/TM3	-0.300	14	MSS4/MSS2	-0.295	14	TM_PC3	-0.213
15	TM4/TM5	-0.246	15	TM7/TM5	-0.293	15	TM4/TM3	-0.173
16	TM7/TM5	-0.183	16	TM4/TM5	-0.282	16	TM2	-0.161
17	TM_PC3	-0.176	17	TM_PC3	-0.261	17	MSS3-MSS2/MSS3+MSS2	-0.158
18	TM_PC1	-0.120	18	TM3	-0.240	18	MSS4-MSS2/MSS4+MSS2	-0.156
19	TM4	-0.117	19	TM_PC1	-0.195	19	MSS4/MSS2	-0.142
20	TM3	-0.106	20	TM4	-0.190	20	TM7/TM3	-0.124
21	MSS3	-0.100	21	MSS1	-0.151	21	MSS2	0.118
22	MSS1	-0.044	22	MSS3	-0.147	22	TM7/TM5	-0.051
23	MSS4	-0.043	23	TM2	-0.062	23	TM3	0.049
24	MSS2	0.031	24	MSS2	-0.037	24	MSS1	0.044
25	TM2	-0.024	25	MSS4	-0.029	25	TM7	-0.036

(9) FLAX

VARIANCE OF INDEX		rho
1	TM7	-0.971
2	TM2	-0.883
3	MSS2	-0.883
4	TM4/TM7	-0.883
5	TM4-TM7/TM4+TM7	-0.883
6	MSS4/MSS2	-0.883
7	MSS4-MSS2/MSS4+MSS2	-0.883
8	MSS3-MSS2/MSS3+MSS2	-0.883
9	TM7/TM5	-0.883
10	TM7/TM3	-0.883
11	MSS1	-0.794
12	MSS4	-0.794
13	TM4-TM3/TM4+TM3	-0.794
14	TM4-TM5/TM4+TM5	-0.794
15	TM5/TM3	-0.794
16	MSS3	-0.706
17	TM_PC3	-0.706
18	TM5	-0.618
19	TM_PC2	-0.618
20	TM3	-0.530
21	TM_PC1	-0.530
22	TM1	-0.441
23	TM4	-0.441
24	TM4/TM3	-0.177
25	TM4/TM5	-0.177

END

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FIN