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LANDSAT AND GIS FOR INVENTORY AND MONITORING OF SOIL EROSION RISK

BY

CLAUDIA LORRAINE PALYLYK

A THESIS

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submitted by:

CLAUDIA LORRAINE PALYLYK

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY in **REMOTE SENSING** and **LAND USE**

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Dated: June 18, 1991

DEDICATION

To my parents
and
grandparents
for their
lessons of determination
and
respect for the land.

ABSTRACT

This study explored and characterized the integration of land cover from multitemporal LANDSAT TM imagery, digital soil survey and base map data, in an ARC/INFO geographic information system (GIS), for application to county-scale soil erosion risk inventory and monitoring. Six townships in the County of Flagstaff in east-central Alberta, that depicted variations in soils and landscapes were studied. The project proceeded through three phases.

Firstly, multitemporal LANDSAT-5 TM imagery for summer and autumn seasons was analyzed using ARIES-II systems. Image enhancement, principal components analysis and classification procedures were evaluated for utility in extraction of land cover information. Theme files of generalized land cover classes for each date of imagery were derived through parallelepiped classification. As the second phase, theme files were converted from raster to vector format for integration within the GIS. Changes in the structure of theme files due to vectorization and GIS processing were characterized. These included a reduction in the proportion of unclassified areas and the formation of many small polygons <1.5 ha in size.

For the third phase, digital soil survey data from a recent 1:50,000 scale inventory were used in the development of graphic and attribute files for the study areas. Digital base map data were also processed for use as graphic overlays. Spatio-temporal data bases were then developed through the integration of the soils data with vectorized land cover theme files. Changes in vector data structure were characterized at each stage of integration. Of major concern was the polygon fragmentation that resulted in an exponential increase in data volume at each stage of integration.

Selective queries of individual and integrated coverages were used in the determination of seasonal and cumulative soil erosion risk for the study areas. Quantification of the areal extent of soil erosion risk was accomplished through analysis of the attribute data, while graphic products portrayed the spatial distribution of single season, antecedent and cumulative risk. These provided a level of spatial and temporal detail not available with current provincial-scale soil erosion risk maps.

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Claudia L. Palylyk
1991

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I. INTRODUCTION

Soil erosion constitutes one of the most severe forms of land degradation on the Canadian prairies. As a result, there is a growing concern over the sustainability, management and preservation of agricultural land resources expressed on both national and provincial levels (Coote et al. 1981, PFRA 1983, Coote 1984, Sparrow 1984, Bircham and Bruneau 1985, Chanasyk 1986).

The development of effective inventory and monitoring techniques for soil erosion risk should be explored for provincial soil conservation planning and policy development. Although much has been written on the severity of soil erosion with respect to economic and environmental implications (PFRA 1983, Anderson et al. 1984, Desjardins et al. 1986), the inventory and monitoring of soil erosion risk is still quite limited in extent and effort. In Alberta, provincially-based (1:1,000,000) maps of soil erosion risk have been produced, but do not offer the spatial detail required for use in county-level conservation planning. The ability to inventory and monitor localized soil erosion risk on the basis of soil conditions and land management practices at the county level would enable more effective conservation planning. Monitoring of temporal changes in agricultural land cover and land management (e.g. cropping, summerfallowing, post harvest cultivation) would also assist in the development of conservation policies directed at land management.

This dissertation explores some of the problems associated with and presents some solutions for the use of LANDSAT TM imagery, digital soil survey and base map data, integrated within an ARC/INFO geographic information system. These data were evaluated singly and in integrated form for their utility in the inventory of soil erosion risk in the County of Flagstaff, east-central Alberta. The use of multitemporal LANDSAT data in determining the cumulative effects of land management and crop cover is a new approach to soil erosion risk monitoring.

Background

Remote sensing and geographic information systems (GIS) technologies hold considerable potential for large area soil erosion risk inventory and monitoring. Remotely-sensed data, in the form of LANDSAT imagery, can be an integral source of land cover information for mapping and inventory of large geographic regions. LANDSAT data may be acquired on a 16-day cycle, thus enabling seasonal and annual monitoring of land cover changes. The use of digital forms of land related information is a relatively new approach to traditional soil conservation planning and holds much potential for application to future programs. GIS technology enables storage, combination, and analysis of many types of land-related information useful in the inventory, monitoring and modelling of land resources. The integration of remote sensing and GIS technologies for mapping and inventory has been demonstrated for a number of land-related applications. These range from general land use and land cover mapping (Korporal 1983, Nellis et al. 1990) to ecological studies (Johnston and Bonde 1989), soil survey (Imhoff et al. 1982) and forest fire hazard mapping (Chuvieco and Congalton 1989), and span a variety of geographic regions from Greece (Seger and Mandl 1986) to Sri Lanka (Schmid 1986). LANDSAT digital data have also been used as the primary source of information for large-area reconnaissance and mapping of land cover (Marczyk et al. 1984, Trolier and Philipson 1986, Dobbins and Epp 1987). The integration of ancillary information such as soil maps, ecological information and digital terrain models has been shown to enhance the utility of LANDSAT data for soil survey applications (Imhoff et al. 1982), hydrologic mapping (Pettinger 1982), forest site classification (Niemann 1988), analysis of geomorphic change (Stringer et al. 1988), as well as general land use and land cover mapping (Kusaka et al. 1986, Seger and Mandl 1986, Airola and Vogel 1988). More recently, the utility of integrated LANDSAT and GIS has been demonstrated in the adjudication of water rights (Morse et al. 1990), determination of irrigation suitability (Loveland and Johnson 1990), and mapping of ecological changes due to forest fires (Jakubauskas et al. 1990).

Although some applications of satellite data have been demonstrated in studies of agricultural land cover (Crown 1977 and 1982, Thompson et al. 1984, Reichert and Crown 1986) and rangelands (Jaques 1982, Pearce et al. 1984, Thompson 1984), the integration of remote sensing and GIS technologies for the study of agricultural lands remains new in Alberta. In contrast, the application of remotely-sensed data to large area soil conservation planning has been demonstrated in the United States by Morgan et al. (1980), Morgan and Nalepa (1982) and DeGloria et al. (1986). More recently, the integration of LANDSAT satellite data with GIS has been utilized as a fundamental component of operational conservation planning in Iowa (Patterson and McAdams 1982) and in Wisconsin (Ventura 1988; 1990). In Canada, the utility of LANDSAT data combined with GIS for soil conservation planning has been demonstrated in New Brunswick by Cihlar (1987) and in Saskatchewan by Xongchao (1988) and Sauchyn (1989). By comparison, there is a lack of land inventory and monitoring using LANDSAT and GIS technologies directed at soil conservation planning in Alberta.

Problem Statement

The efficient mapping, inventory and monitoring of agricultural land resources requires utilization of computer technologies which enable rapid processing and analyses of large volumes of land-related information derived from various sources. Advancements in GIS technology, which include automated updating, archiving and spatial analysis, as well as the production of map and tabular products, can enhance current capabilities for inventory and monitoring.

For soil conservation policy development and implementation at the county scale, knowledge of both the spatial and temporal distribution of soil erosion potential is essential. To determine erosion risk, seasonal information on land cover, particularly the spatial and temporal distribution of agricultural crops (cereals and oilseeds), fallow and permanent cover (forest or grasslands) is of interest to agencies involved in the inventory, monitoring and policy development of these lands (Pettapiece 1988 pers. comm.[1], Hiley 1990 pers. comm.[2]).

The ability to extract seasonal agricultural land cover information from satellite data is dependent upon the implementation of a system that enables the management and analysis of temporal information. LANDSAT satellite technology provides repetitive coverage of the land surface and a GIS provides a basis for storage, manipulation and retrieval of a variety of land-related information. The integration of both technologies could enable more efficient agricultural land cover inventory and monitoring over large areas.

The development of an agricultural land cover mapping system based on remote sensing technology has only recently been addressed in Alberta, although a number of potential user groups, including Agriculture Canada (Hiley 1989 pers. comm.[3]), Alberta Agriculture (Marciak 1989 pers. comm.[4]), Prairie Farm Rehabilitation Administration (P.F.R.A.) (Stewart 1988 pers. comm.[5]), and provincial soil survey (Howitt 1989 pers. comm.[6]) have expressed interest in such capabilities. Currently, the utilization of remote sensing and GIS technologies for soil conservation planning in Alberta is limited to applications-directed research.

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[1]Pettapiece, W.W. 1988. Acting Inventory Section Head, Land Resource Research Centre, Agriculture Canada, Ottawa, Ontario, K1A 0C6.

[2]Hiley, J. 1989. Land Evaluation Specialist, Alberta Soil Survey Unit, Land Resource Research Centre, Agriculture Canada, Edmonton, Alberta, T6H 5R7.

[3]Hiley, J. 1989. Ibid.

[4]Marciak, L. 1989. Conservation Specialist, Conservation and Development Branch, Alberta Agriculture, Edmonton, Alberta, T6H 5T6.

[5]Stewart, A. 1988. Senior Soil Conservationist, Prairie Farm Rehabilitation Administration, Edmonton, Alberta, T5J 4C3.

[6]Howitt, R.W. 1989. Soil and Land Resource Inventory Unit Head, Environmental Research and Engineering Department, Alberta Research Council, Edmonton, Alberta, T6H 5X2.

Research Objectives

The purpose of this study was to explore and characterize the integration of multitemporal LANDSAT TM imagery with digital soil survey and base map information within a GIS to identify potential soil erosion risk on agricultural lands. Challenges associated with integration of these data for applications to soil conservation planning were also explored in this study.

This study differs from earlier approaches to soil erosion risk determination, in that it considers the temporal changes in agricultural land cover in combination with soil characteristics, to determine seasonal and cumulative soil erosion risk at a scale compatible with county-level conservation planning. It also utilizes raster-to-vector conversion processing techniques for integration of LANDSAT theme files within a vector ARC/INFO GIS.

This study was motivated by the lack of operational inventory and monitoring methods in Alberta to support conservation decisions. Many discussions with personnel involved in land evaluation and soil conservation, and a review of literature on agricultural applications of remote sensing and GIS technologies, led to the following objectives:

1. To extract agricultural land cover information from multitemporal LANDSAT TM digital data for integration within a GIS;

2. To develop criteria for assessment of seasonal and cumulative soil erosion risk; and

3. To determine the spatial distribution and extent of soils thus predisposed to erosion risk in a selected region of Alberta.

Organization of the Dissertation

This dissertation is organized into six chapters with relevant appendices. Chapter I consists of an introduction, a discussion of the problem, research hypotheses, assumptions and delimitations, and a brief overview of remote sensing and GIS technologies. A description of the study region is presented in Chapter II, along with some illustrations of the landscape. Chapter III focuses on the extraction of agricultural land cover information from LANDSAT digital data. A literature review on approaches to image analysis is followed by a description of facilities and methods utilized in this study, and the results obtained. The integration of LANDSAT thematic files within an ARC/INFO GIS is the basis of Chapter IV, which consists of a literature review on integration approaches as well as a description of procedures used and results obtained in the development of an integrated data base for this study. Chapter V focuses on the inventory and monitoring of soil erosion risk through use of integrated LANDSAT and soil survey data. A synthesis of the research, including conclusions and recommendations for future research, are presented in Chapter VI. A glossary of acronyms and terms used in the dissertation is presented as Appendix I.

Assumptions and Delimitations

In this study, a number of factors necessitated the formulation of assumptions and the identification of delimitations to the design and execution of the study. These factors included computer facilities and software available for image analyses, raster-to-vector conversion, GIS capabilities and limitations, the availability and inherent characteristics of digital LANDSAT TM, soil survey and base map data, and characteristics of the study area. These assumptions and delimitations will be addressed under the headings of Computer Systems, Data, and Study Area.

Computer Systems

LANDSAT TM imagery was analyzed through the use of two Dipix Systems Ltd., Aries-II (RMX-11 OS Version 4.2) image analysis systems, housed at the University of Alberta and the Alberta Remote Sensing Center. An Environmental Systems Research Institute (ESRI) ARC/INFO GIS software package (Version 4.01), housed on the Alberta Research Council VAX 6210 (VMS Version 5.2) mainframe, was used for spatial analyses and cartographic and tabular report production. At the time of this study, direct data translation capabilities between the ARIES-II system and ARC/INFO were not available in Alberta. Therefore, intermediate processing of LANDSAT theme files, and raster-to-vector format conversion was accomplished at the Department of Geography, University of Regina, using software developed by Sauchyn and Xongchao (1991). The computer systems used for this stage of data processing were a VAX 8600 and ARC/INFO on a PRIME 9650. Limitations of the ARC/INFO software, in terms of processing limitations given data structure and volume, placed several constraints on the manner in which the data could be integrated and analyzed, and are discussed in Chapter IV.

Data

The data utilized included LANDSAT-5 TM digital imagery, digital soil survey information and digital base map information. All data were spatially referenced to the Universal Transverse Mercator (UTM) system to enable registration and subsequent overlay analysis.

The LANDSAT TM data were geometrically corrected to the UTM system to enable registration of multidate data. As part of the geometric correction procedure, the image data were resampled to 30 m pixels for preservation of spectral integrity through the minimization of resampling. At a 30 m resolution, these data enabled visual recognition of agricultural field boundaries and some within-field features, as well as differentiation of agricultural crops at a level of detail suitable for county-level inventory. Optimal dates of imagery for the identification of agricultural land cover in the study region were determined to be mid-July and late October, as the spectral reflectance characteristics of agricultural land cover tend to be of greatest contrast during the peak growing season and the post harvest period. Actual image availability was limited by the 16-day periodicity of the satellite and by the frequency of cloud cover during each growing season (spanning mid-June to mid-August). Cloud cover limited both image quality and availability throughout most of the growing season in 1987 and 1988, and during the entire growing season in 1989, thereby precluding acquisition of other desired dates of imagery.

Digital soil survey data for the County of Flagstaff, at a scale larger than previous provincial soil surveys for individual counties, were used to develop soils coverages within the ARC/INFO GIS. These data, at a mapping scale of 1:50,000, were based on mapping principles of soil associations (MacMillan et al. 1988) and followed Survey Intensity Level 3 (SIL=3) guidelines (Mapping Systems Working Group 1981). This survey utilized the general proportions and patterns of dominant and sub-dominant soils as basis for development of complex map units, which is the current standard for soil inventory at SIL=3 in Alberta. Field observed variations in soils were identified as "inclusions" but were not designated spatially within individual soil map units given the mapping principles utilized. Although these data are more detailed than many of the other soil surveys currently available in Alberta, they impose a limitation on the interpretations of combined LANDSAT TM and soil survey information. For example, when relating variations in land cover to variations in soil, the precise spatial distribution of inclusions within individual map units cannot be determined, although patterns are described in a qualitative manner within the survey. Consequently, it may not necessarily be the resolution of the satellite data which places constraints on spatial analyses and interpretation of multi-source land information within a GIS framework.

In the development of ARC/INFO coverages of soils information for each study area, it was necessary to manually edit both the graphic and attribute data files of the existing digital soil survey data base to achieve compatibility with published soil survey maps (Appendix II).

Digital base map data were obtained from the Alberta Bureau of Survey and Mapping (ABSM) for the entire study area, in the form of 1:20,000 scale digital positional files. These data are spatially referenced to the UTM system, and consist of graphic and attribute information on Dominion Land Survey, contours, hydrography, and transportation networks, among other features. The study areas spanned the region of intersection of eight digital map files, which necessitated considerable processing for extraction of information relevant to each study area (Appendix III). Manual editing was necessary to correct for discontinuities in these graphics files.

Digital elevation data at a resolution compatible with the LANDSAT TM data were not available for the study area. It is recognized that digital elevation data can contribute information about landscapes that is useful for soil erosion process modelling, however, coarse resolution elevation data can introduce error when utilized in spatial analyses of large geographic areas. In this study, interpretive information on topography was derived from descriptions provided for individual soil map units.

Study Area

Two study areas were selected within the County of Flagstaff. The landscapes and soils of this region are representative of the east-central and north-central agricultural regions of Alberta, where soil erosion constitutes a significant problem. A detailed description of the study region is presented in Chapter II. The limitations associated with this study region included the diversity of landscapes and landforms, heterogeneity in patterns of natural and managed land cover and variations in land management practices. The variations in soils of this region influence crop productivity through direct and indirect effects on moisture holding capacity, drainage patterns, and overall productivity. In this study, these effects were observed due to variations in seasonal rainfall, particularly in the 1987 crop year, when spring drought conditions resulted in late seeding and germination and an overall slower establishment of agricultural crops.

Remote Sensing and GIS Technologies

The integration of remote sensing and GIS technologies provides a potentially powerful tool for the inventory and monitoring of agricultural land resources, and can contribute information for the development and evaluation of policies and practices influencing land management. Advantages of integrating these technologies include computer-based storage and analyses of large volumes of digital data, archival data base management, as well as capabilities for combining many sources of land-related information through spatial analyses, modelling and automated cartographic production. In this regard, the following discussion presents a brief overview of satellite remote sensing and GIS technologies.

Remote Sensing Satellites

Currently, a number of satellite remote sensing platforms provide useful information on land surface characteristics for the North American continent (Table 1.1). Although the choice of satellite image data is influenced by project objectives, data availability and budget, their utility is largely a function of spectral, spatial and temporal resolution.

Table 1.1. Characteristics of Remote Sensing Satellite Systems.

Platform	Sensor	Spectral Range	Number of Bands	Pixel Size	Period
NOAA	AVHRR	NIR/TIR	5	1100 m	Daily
LANDSAT	MSS	VIS/NIR	4	80 m	16 d
	TM	VIS/NIR	7	30 m	16 d
		TIR		120 m	
SPOT	HRV-P	PAN(VIS)	1	10 m	2 d
	HRV-XS	VIS/NIR	3	20 m	

NIR = near-infrared
TIR = thermal infrared
VIS = visible spectrum

(modified after Ehlers et al. 1989)

Spectral resolution, either in the visible, near-infrared or thermal infrared range determines the utility of image data for applications in agricultural land inventory or crop monitoring studies. Individual spectral bands may be more useful in some applications relative to others. As an example, the relatively broad spectral resolution of the LANDSAT Thematic Mapper (TM) sensor has utility for a number of applications (Table 1.2). Visible spectrum data are particularly useful for discerning geographic features, while near-infrared data are more suited to the detection of physiological stress induced by drought, pathogens or insect infestations. Phenological changes in plant structure during various stages of growth (germination, tillering, heading) may be more apparent in some portions of the spectrum than others (Bunnik 1978, Tucker 1978, Saint et al. 1980, Odenweller and Johnson 1984, Hall-Konyves 1990). Combinations of visible and near-infrared data can be effective in determining the relative distribution and vigor of vegetation through use of vegetation indices (Hougham 1987, Izaurralde and Crown 1989).

The spatial resolution of satellite imagery is defined by a ground resolution cell whose size is a function of the sensor parameters and altitude (Table 1.1). Each ground resolution cell is portrayed as a picture element or "pixel" represented by recorded reflectance or emittance values. The spatial resolution of image data influences the clarity and likelihood of recognition of features of interest, but brings with it concerns relating to data volume. For example, in agricultural applications, the portrayal of a quarter-section land area requires a progressive increase in the volume of data as finer resolution imagery is utilized (Table 1.3).

Table 1.2. LANDSAT Thematic Mapper (TM) Applications.

	TM Spectral Range (um)		Applications
Channel 1	.45 - .52	blue-green	coastal water mapping soil/vegetation differentiation deciduous/coniferous species differentiation
Channel 2	.52 - .60	green	vegetation vigor bathymetry sediment concentration
Channel 3	.63 - .69	red	vegetation differentiation geographic features
Channel 4	.76 - .90	near infrared	biomass surveys water body delineation
Channel 5	1.55 - 1.75	middle infrared	vegetation stress cloud/snow differentiation
Channel 6	10.40 - 12.50	thermal infrared	vegetation heat stress measurement soil type differentiation mineral exploration
Channel 7	2.08 - 2.35	middle infrared	hydrothermal mapping surface temperature measurement

(adapted from Freden and Gordon 1983)

Table 1.3. Data Volumes for Quarter-Section Land Area Representation.

Data Type	Nominal Pixel Size(m)	Pixel Area (m^2)	No.Pixels per Quarter Section*
NOAA	1100	1,210,000	0.53
LANDSAT			
MSS	80	6400	100
TM	30	900	711
SPOT			
MLA	20	400	1600
PAN	10	100	6400

*Given a quarter-section = 800 m x 800 m (640,000m^2 or 64 ha)

In the analysis of digital imagery, an increase in spatial resolution can offset classification accuracy because potential exists for an increase in the within-class spectral heterogeneity (Williams et al. 1984). Spatial resolution also predisposes the occurrence of "boundary pixels", which are the reflectance composites of several different features contained withn the area of a pixel. The mixed pixel response consists of both target and background reflectance in addition to atmospheric scattering (Chhikara 1984). In subsequent image classification procedures, boundary pixels often do not meet the spectral class parameters defined for individual targets and therefore remain unclassified as perimeters of fields, forests or water bodies, or as small regions within known targets. Consequently, filtering procedures are often applied to infill the unclassified areas (Korporal 1983, Dobbins and Epp 1987).

Despite these characteristics, satellite data are an important source of historical and current land cover information. Being of digital format, the data are suited to computer processing, analyses and integration with digital databases, and in particular with GIS. Additional information on remote sensing technologies and their applications is presented by Lillesand and Kiefer (1979), Freden and Gordon (1983), Jensen (1986) and Lo (1986).

Geographic Information Systems

The functional components of a GIS include the user interface, a data base management system, a data base creation and data entry system, and capabilities for data manipulation, analysis, display and product generation (Guptill 1989). The utility of a GIS is most often demonstrated by the ability to store, manipulate and retrieve graphic and attribute information in a geo-referenced format. As the spatial location of data is the primary basis for the organization of the system (Estes 1985), data that are spatially referenced can then be analyzed through spatial overlay or modelling techniques. A GIS can also be used to create new information, a major distinguishing feature from computer assisted cartography (Burrough 1986).

A variety of spatially referenced data currently available in Alberta (Table 1.4), can be used in the development of a GIS data base for agricultural lands. These data can be input to a GIS by manual digitization or automated scanning or read from computer compatible tapes. Subsequent processing of this information into GIS data layers often involves the linkage of graphic files with attribute information. For an agricultural GIS, ancillary data may include physical land characteristics, climatic, geologic, hydrologic and vegetation cover information, as well as land ownership, municipal assessment and land use zoning. The utility of a GIS for studying agricultural lands is further demonstrated by capabilities for the combination and spatial analyses of these data. Challenges to the design and implementation of an agricultural GIS may include the

Table 1.4. Data Available for GIS Applications in Alberta.

Source	Data	Scale
NTS Map Sheet	UTM, Cadastral Survey Contours, Surface Water	1:50,000 and 1:250,000
Alberta Bureau of Survey & Mapping (ABSM)	Base Map Dominion Land Survey	1:20,000
Soil Survey	Soil Associations	1:126,720 and 1:63,360 1:50,000 and 1:125,000
Forest Inventory	Species, Age, Height, Density, Volume	
Phase I		1:63,360, 1:50,000, and 1:40,000
Phase II		1: 31,680
Phase III		1:15,000
Satellite	Surface features (Land cover, water)	*f* (resolution)

availability of information, the types of analyses desired, and the inherent capabilities and limitations of the GIS.

The data base management systems of GIS's vary considerably. Their primary functions involve storage, retrieval and updating of spatial information (in digital, graphic and alphanumeric forms), through use data storage structures that minimize data redundancy and aid spatial searches, while handling large archives of data (Guptill 1989). Data storage structures may be relational (Codd 1970, Date 1981a and 1981b, Alagic 1986, Abel 1989), in which entries are related through common items across many files, or they may be of a quadtree structure in which data are hierarchially organized (Samet 1984, Samet 1988, Samet and Webber 1988a and 1988b, Ripple and Wang 1989).

Additional distinguishing characteristics of a GIS include the representation of data, either as a vector or as a raster system. In a vector system, graphic data are represented as points, lines and polygons with relevant information stored in an attribute data base. Polygon coverages may be highly variable in size and complexity, thus influencing data volume within a GIS. In contrast, a raster system is organized as a grid cell structure, where each cell is of similar size and dimension and has associated with it a spatial location and attribute data. For example, with satellite data, each pixel contains attribute information in the form of a spectral reflectance value or a theme number. Because of their grid cell format, LANDSAT data can be readily incorporated within a raster GIS. For their integration within a vector GIS, raster-to-vector conversion is required. A discussion of raster-to-vector and vector-to-raster conversions, and their implications on digital data, is provided in Chapter IV.

GIS technologies are rapidly developing, as is illustrated by the substantial reviews of GIS theory and applications published by Tomlinson and Boyle (1981), Marble (1984), Burrough (1986), Parker (1988) and Ehlers et al. (1989). Relational database structures have been discussed by Codd (1970), Cox (1980), Alagic (1986) and Abel (1989). Quadtree data base structures are detailed by Samet (1984), Samet (1988), Samet and Webber (1988a and 1988b) and Ripple and Wang (1989). A review of guidelines and standards for GIS is provided by Guptill (1988), while commercially available GIS systems are reviewed by Johnson et al. (1988) and Parker (1989). Designs for integrated GIS and remote sensing systems have been proposed and detailed by Goodenough (1988), Ehlers et al. (1989) and Zhou (1989).

II. STUDY AREA

Introduction

Criteria for selection of the study area included locating a region where the predisposition of agricultural lands to soil erosion risk was linked to land management, and where soil inventory information at relatively high resolution (1:50,000 scale) and cloud-free TM image data for sequential growing seasons were available. Additional criteria were that the area be agriculturally productive, typified by landscapes and land management practices common to central Alberta, and that a concern with soil erosion risk exist with agricultural personnel involved in conservation planning.

The County of Flagstaff No. 29, met these criteria and two study areas, each comprised of three townships (Figure 2.1, see also Chapter III), were selected to illustrate some of the variability in soils and land cover in the county. Study Area 1 consists of Townships 43-11, 43-10 and 44-10; Area 2 consists of 42-11, 41-11 and 40-11. Dominion land survey boundaries served as the perimeters for the study areas, as they represent practical management units from the standpoint of county-scale land inventory and monitoring. A brief description of the region follows, with a more detailed discussion of the area presented in a recent soil inventory report by MacMillan et al. (1988).

Climate

This region is characterized by a continental climate, having moderately warm summer seasons (17^{o}C) and cold winters (-17^{o}C). Agroclimatic designations, according to the Alberta Soils Advisory Committee (1987), are Zone 2H for the majority of the region and Zone 2A for the southern region. Zone 2H is characterized by an average rainfall of 400 to 450 mm and a frost-free period of 90 days, permitting dryland agriculture typical of the Canadian prairie region. Zone 2A has a frost free period of greater than 90 days on the average, but receives less precipitation (300 to 400 mm), which limits crop growth in approximately 50 per cent of crop years. About 30 per cent of the precipitation falls as snow throughout December to February, and rain during the May to September growing season accounts for more than 68 per cent of the total annual precipitation. Springtime snowmelt and runoff activity and summer rainstorm events account for the majority of water-induced soil erosion, and prevailing winds cause erosion on fallowed lands during spring and summer seasons.

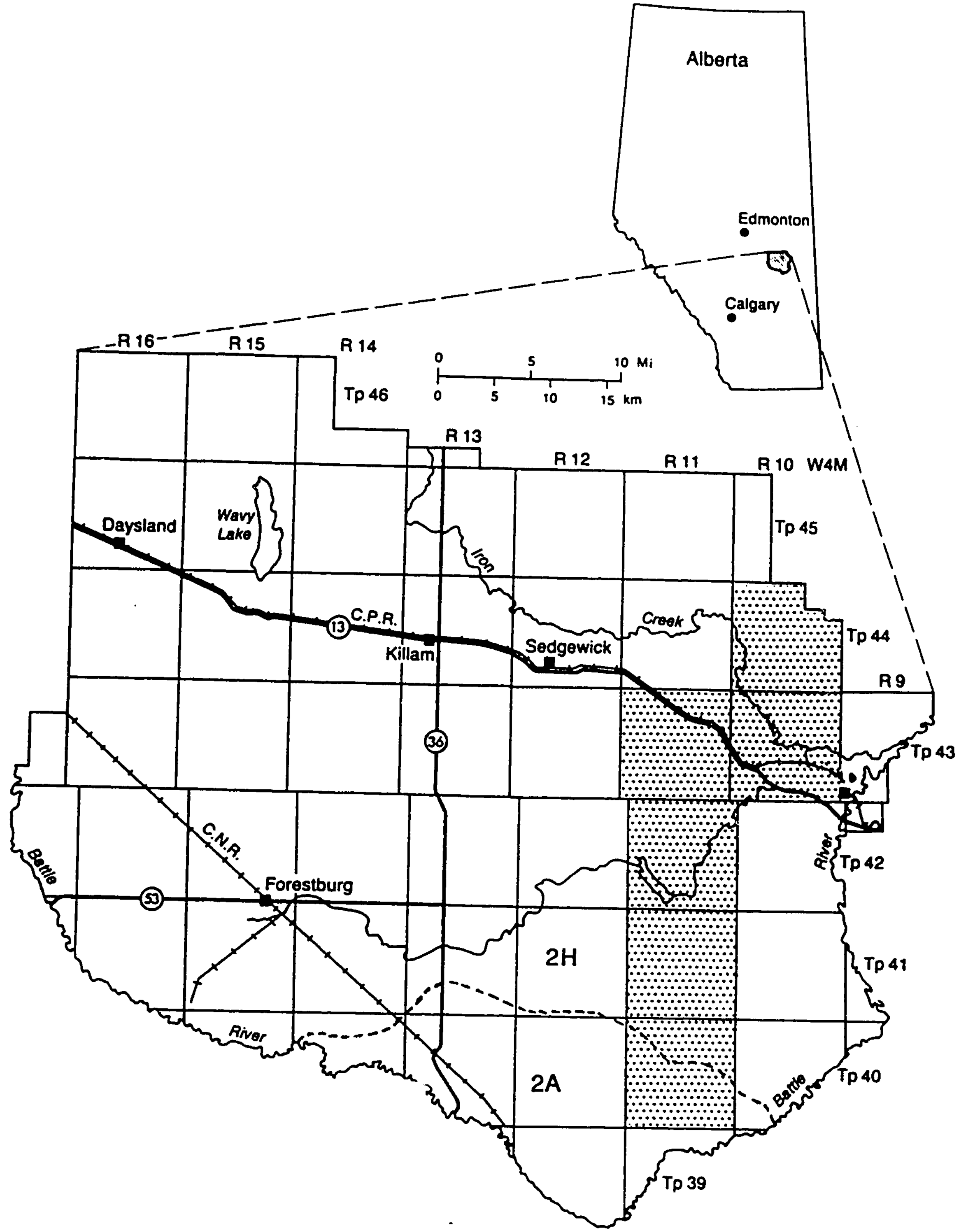

Figure 2.1. Study Area Locations and Agroclimatic Zonation.
(modified after MacMillan et al. 1988)

Vegetation

The County of Flagstaff is located within the Aspen Grove Forest Region defined by Rowe (1972). A gradual north to south transition from an Aspen Subregion dominated by aspen forest cover (*Populus tremuloides)* on noncleared land to a Groveland Subregion with aspen groves alternating with open fescue (*Festuca* spp.) grasslands is observed in this region (Strong and Leggat 1981). Extensive land clearing and cultivation, and prevention of forest and prairie fires, has resulted in disruption of natural vegetation succession patterns in the region, and continued brush clearing and land drainage have been implemented as methods of ensuring maximum agricultural use of available land (MacMillan et al. 1988). The removal of natural vegetation, whether forest or grassland cover, increases the susceptibility of soils to wind- and water-mediated erosion. The practices of summerfallowing, as part of the crop rotation sequence typical of this region, and the post-harvest cultivation of crop residues contribute to seasonal soil erosion.

Physiography, Drainage and Relief

This region lies within the Eastern Alberta Plain, described by Bostock (1970) and has been more recently subdivided into sections and districts on the basis of landform and elevation characteristics by Pettapiece (1987). Major physiographic subdivisions are summarized in Table 2.1 and illustrated in Figure 2.2. and in Plates 2.1 through 2.4.

Table 2.1. Physiographic Subdivisions of the County of Flagstaff.

Region	Section	District	Elevation(m)	Landform
Eastern Alberta Plains	Sullivan Plain	Daysland Plain	610 to 730	morainal blanket over undulating bedrock
	Vermilion Uplands	Viking Upland	608 to 760	hummocky moraine
	Neutral Hills Uplands	Neutral Upland	670 to 790	hummocky moraine and morainal blanket over rolling, ice-thrust bedrock

(modified after MacMillan et al. 1988)

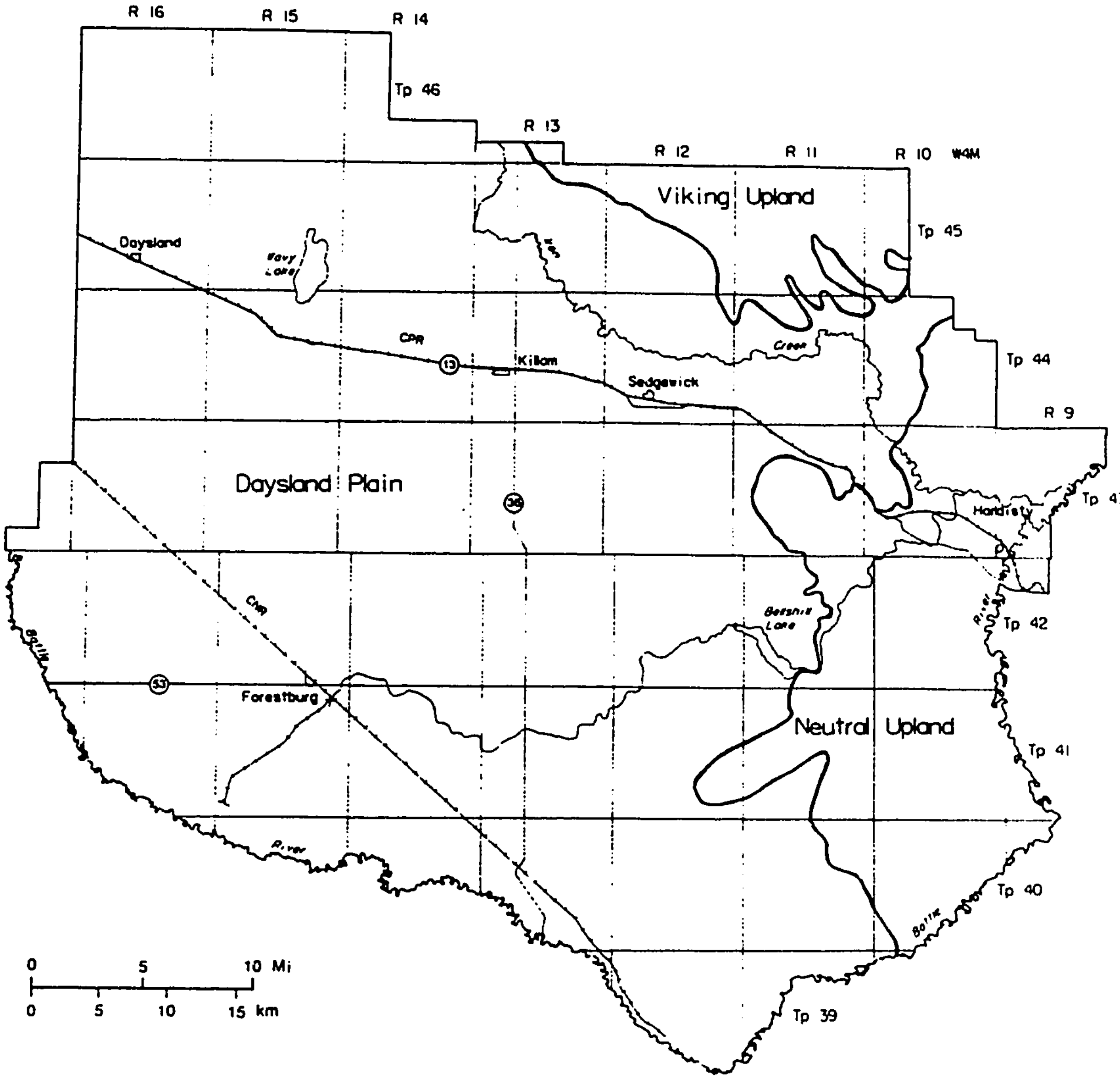

Figure 2.2. Physiographic Subdivisions of the County of Flagstaff.
(as presented by MacMillan et al. 1988, reprinted with permission)

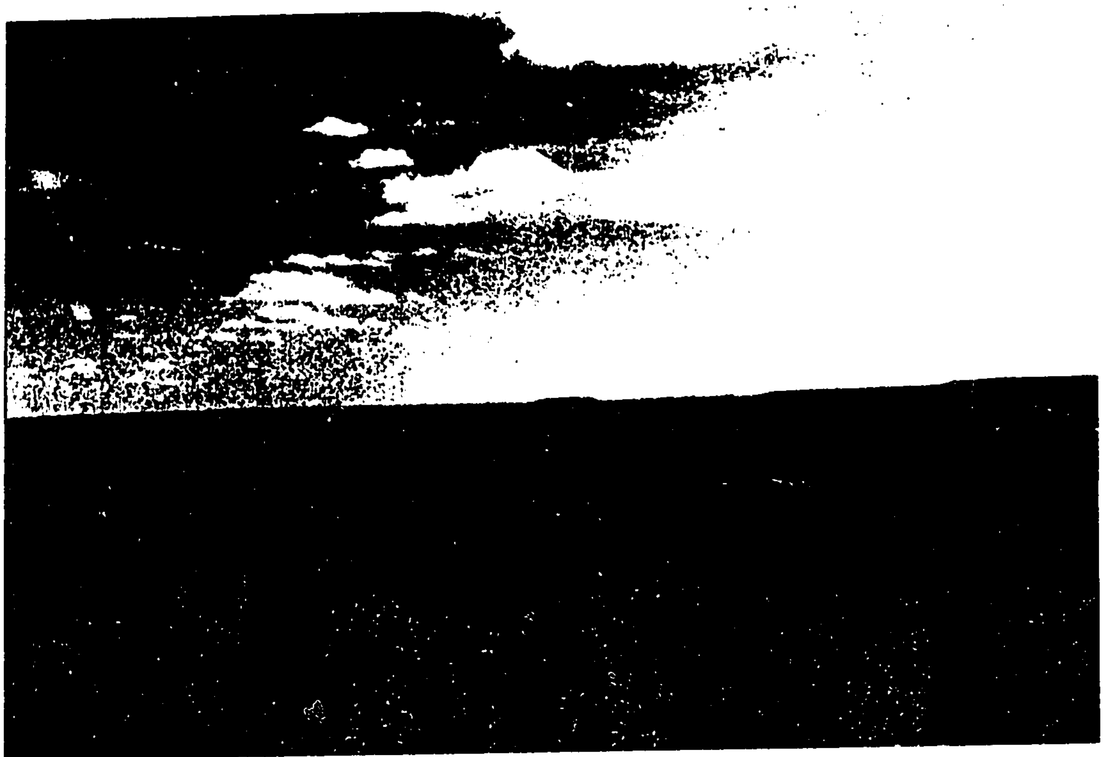

Plate 2.1. Daysland Plain district. Black Chernozemic soils on gently undulating topography. Crop rotations include cereal-canola-fallow.

Plate 2.2. Viking Upland district. Black Chernozemic soils on rolling topography. Crop rotations include cereal-fallow and cereal-canola-fallow.

Local relief varies within each physiographic subdivision. The Daysland Plain is a level to gently undulating moraine, with slopes rarely exceeding 5%. The Viking Upland is a region of hummocky moraine with relief ranging from 5 to 15 m, characterized by short steep slopes with gradients ranging from 5 to 15%. The Neutral Upland district consists of rolling to steeply sloping uplands with long, rolling slopes of 5 to 15% gradient and relief of up to 40 m along drainage channels. Deeply incised glacial meltwater channels containing chain-like patterns of lakes characterize the Neutral Upland district and surficial deposits range from thin veneers to morainal deposits up to 75m in thickness.

Lakes, rivers and streams within this region form part of the Battle River Basin which drains into the North Saskatchewan River. Permanent water bodies serve as recreational sites and waterfowl habitat, and the many potholes and ponds that inundate the landscape serve as local groundwater recharge zones.

Surficial Geology

Surficial geologic features of this region originated from activity of the Keewatin ice sheet during the Wisconsin period (Shetsen 1984) Till deposits constitute the greatest proportion of surficial geologic materials (Figure 2.3), with glacio-fluvial, eolian and glaciolacustrine materials comprising minor components within the region (MacMillan et al. 1988). The physical, textural and chemical compositions of these materials contribute to the diversity of landscapes and soil associations and are detailed within the survey report by MacMillan et al. (1988).

Soils

Soils within this region have developed on the surficial geologic materials of glacial origin (Figure 2.3), primarily on gently undulating to hummocky landscapes. Climatic variation in this region is reflected in a gradual change in surface soil color from black in the northern region to dark brown in the drier, southern portion of the county (MacMillan et al. 1988).

Six soil orders in the Canadian System of Soil Classification (Expert Committee on Soil Survey 1978) have been identified in this region, often occurring as complex associations. The predominant soils are of the Chernozemic order and have developed on moderately fine textured glacial till, with Black soils occurring in the northern three quarters portion of the county and Dark Brown soils in the southern quarter (MacMillan et al. 1988). Additional soils within this region include series of the Solonetzic, Gleysolic, Luvisolic, Regosolic and Organic orders. The predominant soils and their associated erosion risk ratings for each study area are summarized in Chapter 5.

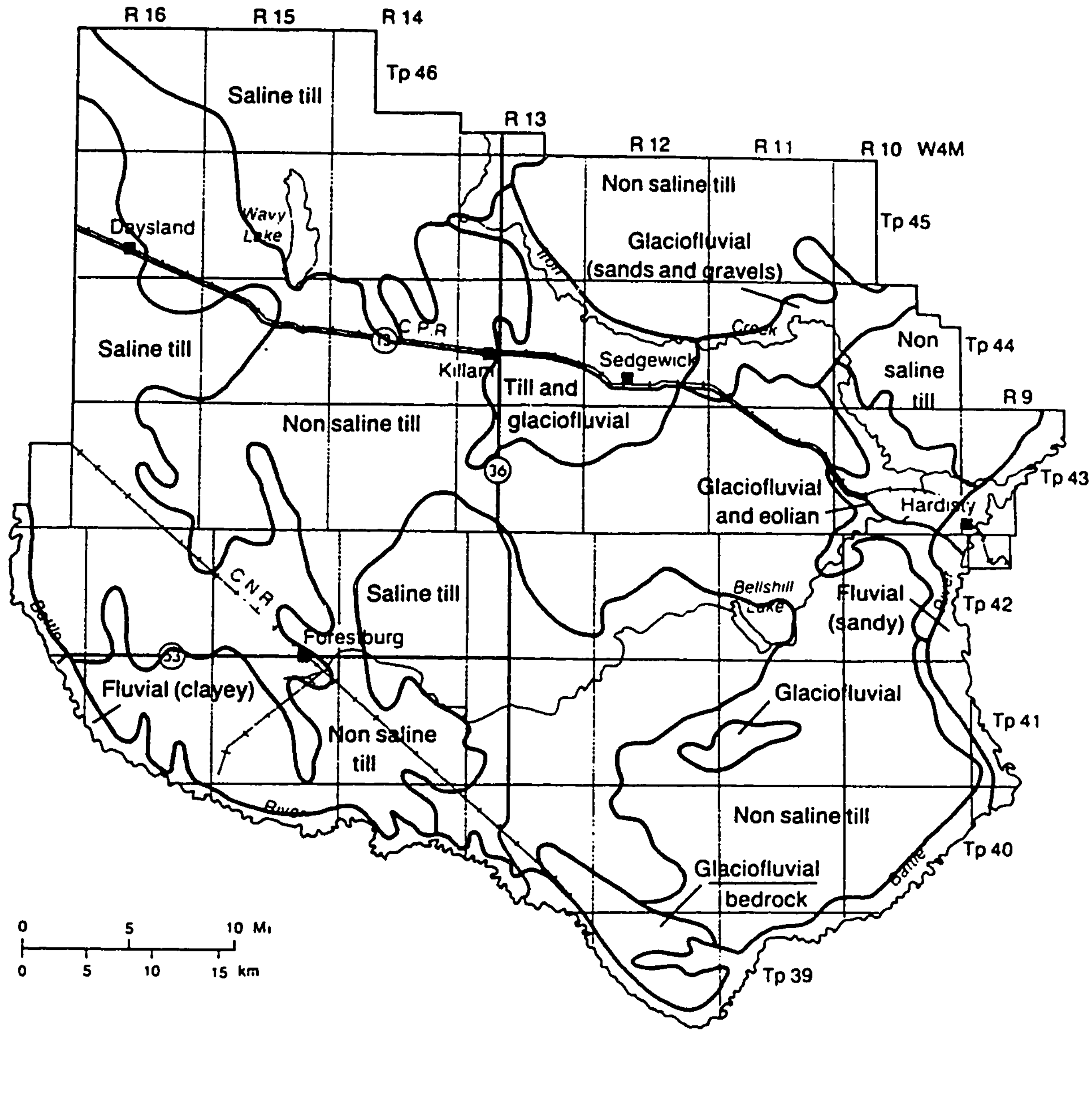

Figure 2.3. Distribution of Surficial Deposits in the County of Flagstaff.
(as presented by MacMillan et al. 1988, reprinted with permission)

Land Use

Agricultural lands within the study regions are utilized primarily for crop production, including wheat (*Triticum* spp), barley (*Hordeum* spp), oats (*Avena* spp.) and canola (*Brassica* spp). The predominant crop rotation sequence involves cereal (usually wheat, followed by barley, oats or canola), followed by summerfallow. Continuous cropping practices, although still relatively new to the region, involve the rotation of wheat with cereal crops or canola. Fluctuations in the market price of canola influence the amount of this crop grown in any given crop year. Recently, the introduction of pulse crops such as field peas (*Pisum* spp.) as a leguminous plowdown for improvement of soil tilth, and the cropping of fall rye (*Elymus* spp) for stabilization of soils on steep slopes has resulted in a departure from traditional crop rotations. Grassland areas, interspersed with Aspen or shrub (*Salix* spp., *Rosaceae* spp , *Prunus* spp) vegetation in regions of extreme topographic variability, and with soil conditions precluding agricultural crop production, are utilized as pasture lands.

Soil Erosion

Within this region, there is a growing concern with wind- and water-mediated soil erosion (Bergum 1989 pers. comm.[1], Grovet 1989 pers. comm.[2]). The practices of summerfallowing as part of the crop rotation sequence, post-harvest cultivation, and removal of crop residues has contributed to soil erosion and non-point source pollution and has raised concern among conservation authorities within the region. For purposes of soil conservation policy development, knowledge of the spatial distribution of seasonally cultivated and non-vegetated lands would assist the implementation of conservation policies and incentives. As part of the soil inventory report, (MacMillan et al. 1988), potential soil loss and erosion risk ratings for soils within the County of Flagstaff were determined utilizing the Universal Soil Loss Equation with individual factors modified for Alberta (Tajek et al. 1985, Macmillan et al. 1988). Potential soil loss for each map unit was computed for bare soil surface soil, cereal, canola and alfalfa cover conditions. These values were ranked according to 6 erosion risk categories that are detailed in Chapter V, along with additional information on soils of the study region.

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[1]Bergum, D. 1989. Municipal Assessor, County of Flagstaff No. 29, Sedgewick, AB, T0B 4C0.

[2]Grovet, T. 1989. Agricultural Fieldman, County of Flagstaff No. 29, Sedgewick, AB, T0B 4C0.

III. EXTRACTION OF AGRICULTURAL LAND COVER INFORMATION FROM LANDSAT TM SATELLITE DATA

Introduction

LANDSAT TM digital data have considerable utility for the inventory and monitoring of land cover and associated erosion risk, particularly in agricultural areas where land cover changes temporally. One of the challenges in the automated derivation of land cover maps from digital satellite data is the determination of the image analysis procedures that will provide the most suitable product for integration within a GIS. This chapter explores methods for the extraction of land cover information from multitemporal LANDSAT data, with emphasis on the derivation of theme files for integration into a GIS for subsequent use in soil erosion risk inventory.

Background

The utility of satellite imagery as a source of agricultural land cover information has been demonstrated since the launch of the first LANDSAT satellite in 1972, through a number of applications ranging from crop inventory, monitoring and yield forecasting to large area soil conservation studies (Bauer et al. 1979, LACIE 1979, Patterson and McAdams 1982, Ventura et al. 1985). The multispectral scanner (MSS) sensor payloads of LANDSAT-1, -2 and -3, provided data of 80 m resolution and was widely used in mapping applications, while the advent of the thematic mapper (TM) in 1982 was expected to significantly improve data quality, information content and utility for a number of applications (Williams et al. 1984). Compared to the MSS, the TM sensor offered finer spatial resolution (30 m), more spectral bands (7 instead of 4), improved radiometric sensitivity and increased quantization levels from 6 bits (0-63) to 8 bits (0-255) (Williams et al. 1984, Toll 1985). While the improved spectral resolution of TM data can enhance classification accuracy, the finer resolution may offset accuracy due to the representation of heterogeneity within targets that contributes to larger within class dispersion (Williams et al. 1984, Toll 1985).

MSS and TM sensors on LANDSAT-4 and -5 collect image data with a periodicity of 16 days. These data have been used in a variety of agricultural land cover mapping and crop inventory applications that have varied with project objectives, complexity of landscape and environment and the type of land cover being mapped. From a historical perspective, the utility of digital LANDSAT MSS data for crop inventory and production forecasting was first demonstrated in the Large Area Crop Inventory Experiment (LACIE) administered by NASA, USDA and NOAA (LACIE 1979). The program focussed on wheat yield estimation in the United States and results supported the utility of satellite data for agricultural crop inventory and monitoring. In Canada, the utilization of LANDSAT data for large area crop inventory has been undertaken by the Canadian Wheat Board, Statistics Canada and the National Grains Bureau. In the prairie regions, experimental crop inventories have included the Peace River region of northern Alberta (Brown et al. 1980, Ryerson et al. 1982), Warner County in southern Alberta (Reichert and Crown 1986), southwestern Saskatchewan (Dobbins and Epp 1987) and southern Manitoba (Horn et al. 1984, Pokrant et al. 1985).

In addition to crop inventories, LANDSAT data are also useful as a source of historical and seasonal information in the development of land inventory and monitoring systems. For these applications, the extraction of land cover information relies upon temporal response of crop growth to environmental conditions and the spectral separability of cover types of interest. When LANDSAT data are integrated with other data in a GIS, they have direct applications to soil conservation planning, as demonstrated in Wisconsin (Ventura et al. 1985; 1988, 1990), in Iowa (Patterson and McAdams 1982), and in Pennsylvania (Jackson and Bondelid 1983). Recently the utility of combining temporal LANDSAT imagery with other forms of land information in a GIS for predictive modelling of soil erosion risk in southern Saskatchewan landscapes has been demonstrated by Xongchao (1988) and Sauchyn (1989).

Analysis of Satellite Imagery

The analysis of satellite imagery may involve visual interpretation of enhanced image products or computer assisted classification of digital data The application of these methods depends upon the type of information required. For example, for integration of LANDSAT data within a vector GIS, an enhanced image can serve as a backdrop for updating a polygon coverage (Aronoff et al. 1987). In order to incorporate land cover information as a data layer within a vector GIS, classification is necessary to produce theme files which are subsequently converted to polygon coverages (Korporal 1983, Sauchyn 1989).

Discussions of image analysis techniques are presented under the relevant sections of "Image Analyses" within the body of this chapter. For greater detail, the reader is referred to Fleming et al. (1975), Lillesand and Kiefer (1979), Freden and Gordon (1983), Jensen (1986) and Lo (1986).

Derivation of Land Cover Classes

Guidelines for land cover classification utilizing remotely-sensed data were developed as early as 1971, within the United States Geological Survey by Anderson (1971), and have since been modified to a multilevel land use and land classification system compatible with different sensors providing data at different resolutions (Anderson et al. 1976). These guidelines recognized that remotely-sensed data was the primary data source and land cover served as the principal surrogate within the classification system, such that the interpreter's reference to pattern and geographic location were important ancillary information in the data interpretation process. Consequently, both land cover and related land use are mapped when remotely sensed data are used (Anderson et al. 1976). In most attempts to inventory agricultural land cover, this premise still holds true, as the interpreter is dependent upon ancillary information such as field geometry, and the spectral characteristics and seasonal variations of land cover. The system of Anderson et al. (1976) has been used by a number of researchers in the United States (Pettinger 1982, Toll 1985, Trolier and Philipson 1986). Similar formalized guidelines for use of remotely-sensed data for agricultural land inventory do not exist in Canada.

Influential factors in mapping and inventory include the inherent spatial, spectral and temporal resolution of the data, in addition to the number of cover classes, their spectral separability and the complexity of terrain being mapped. When agricultural crops are studied using satellite data, a working knowledge of crop growth patterns, spectral characteristics, field patterns and land management practices within a study region are essential to an understanding of classification results. These factors, coupled with the detail of information required will influence the development of an interpretive legend for enhanced images or classification products derived from LANDSAT data.

Crop Calendars

The temporal resolution of LANDSAT imagery allows an area to be viewed several times during the growing season. Documentation of crop growth patterns, in relation to climatic condition and land management enables development of a crop calendar (Figure 3.1), which can be used to select optimal dates of imagery. Physical differences in plant structure and appearance manifest reflectance characteristics that enable discrimination during various stages of growth (Bunnik 1978, Odenweller and Johnson 1984, Hall-Konyves 1990). By relating the observed temporal-spectral response to the expected phenological development patterns associated with different crops, crop identities can be established (Odenweller and Johnson 1984). Hall-Konyves (1990) observed that cereals in stem extension expressed statistically significant differences in spectral reflectance than did cereals in either tillering or heading stages, but that within the same growth stage, cereals species were inseparable. The narrow period of time during which agricultural crops may be differentiated from each other is often referred to as the "biological window" (Dobbins and Epp 1987), and can be identified with the aid of crop calendars. Detailed crop calendars are presented by Crown (1982) for central Alberta, and sensors providing data at different resolutions (Anderson et al. 1976). These guidelines recognized that remotely-sensed data was the primary data source and land cover served as the principal surrogate within the classification system, such that the interpreter's reference to pattern and geographic location were important ancillary information in the data interpretation process. Consequently, both land cover and related land use are mapped when remotely sensed data are used (Anderson et al. 1976). In most attempts to inventory agricultural land cover, this premise still holds true, as the interpreter is dependent upon ancillary information such as field geometry, and the spectral characteristics and seasonal variations of land cover. The system of Anderson et al. (1976) has been used by a number of researchers in the United States (Pettinger 1982, Toll 1985, Trolier and Philipson 1986). Similar formalized guidelines for use of remotely-sensed data for agricultural land inventory do not exist in Canada.

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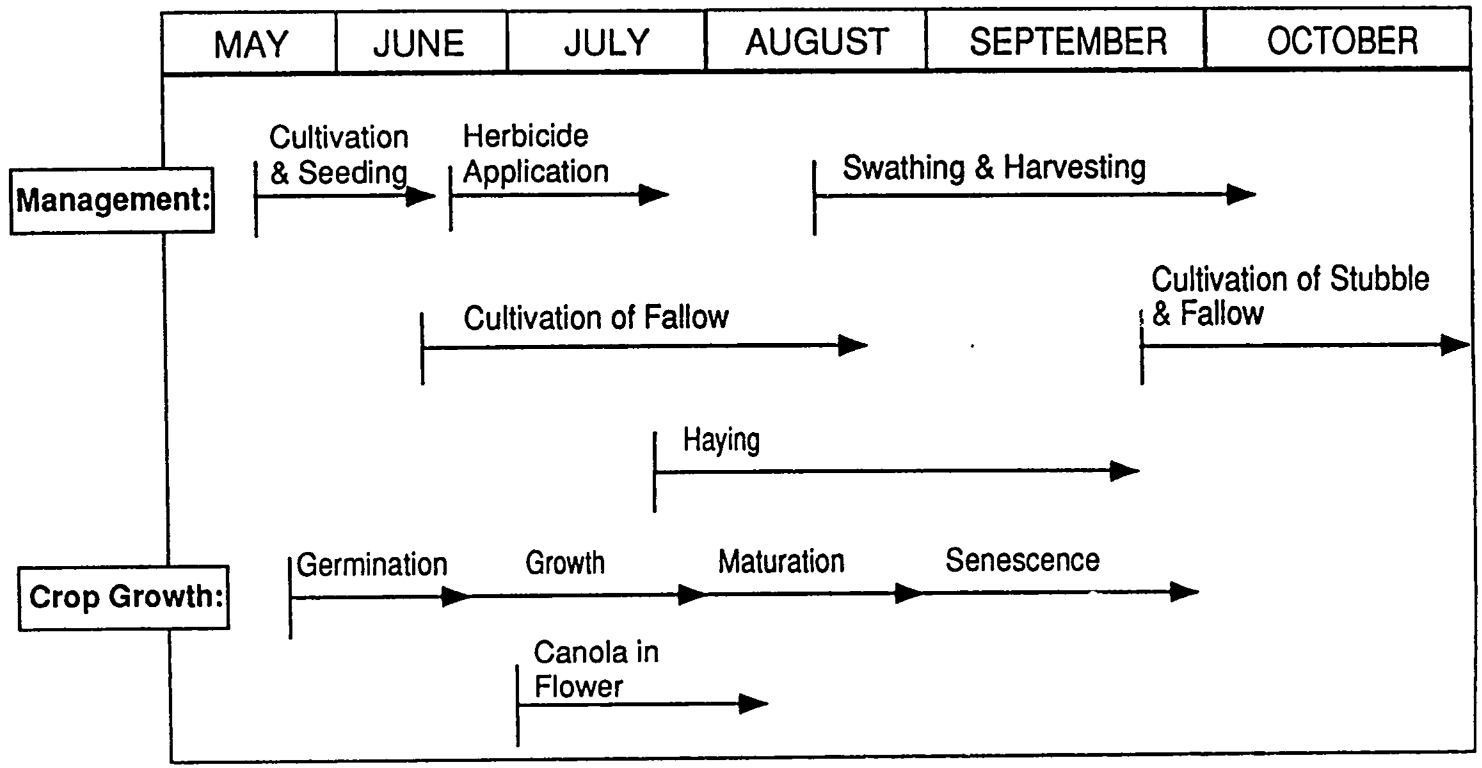


Figure 3.1. Generalized Crop Calendar for east-central Alberta.

Reichert and Crown (1986) for southern Alberta.

In the Canadian prairie region, canola can be distinguished from other agricultural crops, when in the flowering stage during midsummer (Brown et al. 1980), and cereals, when in the jointing stage, can be separated from other crops (Ryerson 1983). Detection of perennial hay and forage crops can be accomplished with early spring imagery, prior to the emergence of cereal crops, or in combination with imagery from late fall. Imagery from mid-September through to the date of the first snowfall is useful for identification of standing stubble, cultivated stubble, and fall-seeded crops. Cultivated fallow can be identified throughout the growing season and late into the fall. The combination of imagery from several dates enables the identification of crop rotation patterns and changes in field boundaries and the differentiation of crops on the basis of spectral-temporal variations. The utility of temporal analysis has been demonstrated in the inventory of canola (Brown et al. 1980, Ryerson et al. 1982, Ryerson et al. 1985), winter wheat (Reichert and Crown 1986), corn and soybeans (Bauer et al. 1979) and rangelands (Brown et al. 1983, Pearce et al. 1984). Additionally, an understanding of the climatic conditions that influence agricultural land management (cultivation, seeding, harvest) and crop growth (germination, maturation, senescence) is essential for selection of optimal dates of imagery through use of crop calendars.

Land Cover Map Units

The number and types of land cover that are to be identified can influence the overall success of the visual interpretation or classification of LANDSAT imagery. High success rates in the mapping of single crop cover types, as for example, canola (Brown et al. 1980, Ryerson et al. 1982, Ryerson et al. 1985), winter wheat (Reichert and Crown 1986) and potatoes (Mosher et al. 1978) have been reported. In attempts to map multiple cover types, success rates are highly dependent upon the spectral separability of the cover types of interest, which is often related to the phenological stage of vegetation growth or season. For example, using classification methods, Bauer et al. (1979) were able to distinguish between corn and soybeans, while Dobbins and Epp (1987) demonstrated the separability of cereal grains, canola and summerfallow with single date data. Multitemporal analysis has been utilized by Belward and de Hoyos (1987) for mapping agricultural crops, but necessitates a thorough understanding of the temporal reflectance characteristics of these cover types.

The selection of map units is dependent on the level of information that can be extracted from the data, as well as the level of detail required for a specific application. For example, in mapping a watershed, Pettinger (1982) used a single category that encompassed cereal crops, hay fields, grassland and pasture. Toll (1984) utilized very generalized classes of agriculture, rangeland, water and urban to produce land use categories based on the Level I classification scheme proposed by Anderson et al. (1976). Irrigated sod, alfalfa and pasture were identified as separate categories, as were winter wheat and rangelands in accordance with the Level II classification. In hydrologic land cover mapping, Trolier and Philipson (1986) also utilized generalized categories of agricultural lands: croplands, orchards, vineyards, pasture, bare soils, forest and shrublands as rural land cover classes. For their purposes, it was not necessary to distinguish between crop types. Generalization of map units, therefore, appears to be a common practice in large area land cover inventories.

For large area erosion risk monitoring through use of satellite imagery, where the objective is to differentiate between vegetated and non-vegetated lands, the generalization of several cereal crop types within one class may be appropriate. In more detailed studies of specific agricultural crops, as for inventory and yield prediction purposes, class generalizations have also been made. For example, in crop inventories for Manitoba, Horn et al. (1984) and Pokrant et al. (1985) identified agricultural crop cover types as "grains", which included spring wheat, barley, oats, rye and mixed grains. In a large area crop inventory of southern Saskatchewan, Dobbins and Epp (1987) also utilized a simple legend comprised of cereals, canola and fallow as individual classes. Canola was the single cover type identified in studies by Brown et al. (1980) and Ryerson et al. (1982), while winter wheat was the only class of interest to Reichert and Crown (1986). Results of these single cover type inventories indicated that spectral confusion was still a problem when dealing with only one cover type.

A summary of analysis methods utilized within studies applying LANDSAT MSS and TM data to agricultural land cover inventory and mapping is presented in Table 3.1. The extent to which digital LANDSAT MSS or TM imagery can be used to identify and map agricultural cover types has been reported with varying degrees of success, with the most commonly reported difficulties caused by spectral confusion of cover types resulting in misclassification or multiple classifications. Therefore, in the process of generalization of map units, the potential for spectral confusion must be considered.

Spectral Confusion

Spectral confusion of agricultural crop cover types during classification has been reported by a number of researchers working in a variety of environments (Table 3.1). It is important to recognize that spectral confusion resulting in misclassification is not necessarily a fault of the particular classification process utilized, although it may result in the grouping of spectrally similar, but phyisognomically distinct cover types. Confusion arises when these spectrally similar pixels are mathematically grouped by classification algorithms. There are two conflicting processes

Table 3.1. Literature References to Spectral Confusion of Agricultural Land Cover Types.

Location	Data Type	Analysis Methods	Confusion Classes	Reference
Melfort, Saskatchewan	MSS July '79 and Aug '79	Supervised and Parallelepiped Classification	canola, wheat, field peas, (dependent on phenological stage)	Brown et al. 1980
Southeast Idaho	MSS August'74	Modified Clustering	aspen, meadows, grasslands, agricultural lands	Pettinger 1982
Peace River, Alberta	not stated	Parallelepiped Classification	canola, native vegetation	Ryerson et al. 1982
Southwestern Manitoba	MSS July '83 and Aug '83	Supervised Classification	woodlands and barley wheat and barley summerfallow, road allowances and sparse vegetation	Horn et al. 1984
Southern Manitoba	MSS July '84	Supervised and Parallelepiped Classification	canola and wetlands	Pokrant et al. 1985
Framlingham, United Kingdom	MSS Nov '79, Feb, Apr, May, June and August '80	Supervised Classification	sugarbeets, beans, peas and bare soil cereals and grasslands spring barley and bare soil	Belward and Taylor 1986
Southern Alberta	MSS Oct '82, May '83, Oct '83, May '84	Supervised Classification	pasture and winter wheat alfalfa and winter wheat	Reichert and Crown 1986

- continued

Table 3.1. (continued)

Location	Data Type	Analysis Methods	Confusion Classes	Reference
Southwestern Saskatchewan	MSS July '85 and '87 MSS August '85	Supervised and Parallelepiped Classification	cereal grains, native pasture and bushlands	Dobbins and Epp 1987
Great Plain, Hungary	TM May '86 SPOT May, July, Nov '86	Visual Interpretation Principal Components Minimum Distance Classification	barley, wheat, forest, maize and sunflower	Buttner and Csillag 1989
Scania and Ostergotland, Sweden	MSS May, June and July '83 TM June,July, August '84, and Sept '86	Band Ratioing Supervised Classification	winter wheat and barley cereals and field peas sugarbeets and rye wheat and oats (dependent on phenological stage)	Hall-Konyves 1990

MSS = Multispectral Scanner, LANDSAT (USA)

TM = Thematic Mapper, LANDSAT (USA)
SPOT = Systeme Probatoire pour l'Observation de la Terre (France)

involved in image classification; one of mathematical interpretation of pixel radiometric values, and one of physiognomic classification based on vegetation types, both attempting to achieve compatible results. Spectral variation within crops and confusion between crops may be attributed to a number of physical variables including boundary pixels (Chhikara 1984, Belward and Taylor 1986, Ioka and Koda 1986, Reichert and Crown 1986) and environmental factors including drought, moisture, nutrients (Saint et al. 1980, Dobbins and Epp 1987) which influence growth and reflectance characteristics, thereby complicating spectrally-based identification of individual crop types.

Drought conditions have also been observed to influence classification results by contributing to spectral variability (Potter et al. 1979, Dobbins and Epp 1987). Spectral confusion of cereal crops with pasture and shrublands, combined with effects of drought on crop germination, compound difficulties in classification (Dobbins and Epp 1987).

Batista et al. (1985) evaluated the effect of 29 variables on classification accuracies for soybeans and corn and determined that field size, proportion of crop, crop variability, stage of growth, soil type, slope and weather were major influential factors. In a more recent study, Buechel et al. (1989) evaluated 12 environmental variables in an attempt to determine relationships between these variables and crop classification accuracies and observed complex regional variations in classification accuracies. They attributed this to the following factors which are applicable to a number of studies reported in the literature, and summarized as follows:

1. TM data were more useful for resolving a broader range of spectral variation due to their higher spectral sensitivity and spatial resolution compared to MSS data;

2. complexity of study area environment (small fields, variability in soil and climatic conditions and variation in cropping practices) contributed to spectral confusion;

3. multiple crop types with a greater range of management patterns and growth stages had been studied in contrast to other studies that focused on single crops; and

4. application of unsupervised classification procedures yielded complex spectral clusters.

In the majority of literature reviewed, the problem of spectral confusion of agricultural crops and other cover types was encountered during image classification (Table 3.1). Phenological differences in growth patterns and spectral characteristics were frequently utilized to identify individual cover types. Field size, shape and spatial distribution were also important criteria in the interpretive process. Classification errors could be attributed to spectral confusion, to the occurrence of boundary pixels, borders between fields, forest types or other features

(Ryerson et al. 1985). To enable development of thematic files for inventory purposes, generalization of land cover classes through the inclusion of several cover types in one class is a frequent approach (Horn et al. 1984, Dobbins and Epp 1987).

Materials and Methods

Data Acquisition

LANDSAT-5 Thematic Mapper (TM) computer-compatible tapes for three dates were acquired from the Prince Albert Satellite Station (Table 3.2). This imagery provided cloud-free

Table 3.2. LANDSAT-5 TM Data Utilized in Study.

Track-Frame	Quadrant	Image Identification #.	Date	Channels
40-23	Q3+3 sec	51218-174203	1987-07-02	1-6
40-23	Q3+3 sec	51314-174425	1987-10-06	1-6
40-23	Q3+3 sec	51602-174750	1988-07-20	1-6

coverage of the eastern half of the County of Flagstaff and surrounding region, and enabled the discrimination of a number of agricultural cover types on the basis of their growth characteristics and crop calendars. Image processing and analyses were performed utilizing Dipix System Ltd. Aries-II (AZASP, RMX-11 OS Version 4.2) facilities at the Department of Soil Science, University of Alberta and the Alberta Remote Sensing Center, Edmonton.

Preclassification Processing

A portion of each LANDSAT scene containing the selected study areas was geometrically corrected to remove distortion errors of skew, displacement, earth rotation and satellite altitude and velocity variations (Bernstein and Ferneyhough 1975, Shlien 1979). The data were registered to the Universal Transverse Mercator (UTM) coordinate system to enable delineation of study areas, registration of multidate data and subsequent registration within the GIS. The 1988-07-20 data were geometrically corrected by manual selection of 32 ground control points from 1:50,000 NTS map sheets and 1:30,000 scale aerial photographs. Ground control points were distributed throughout the scene and along the edges and centers of each image, as recommended by Orti (1981). Coefficients of a second-order affine transformation were applied to each channel of data, followed by cubic convolution resampling to 30 m x 30 m pixels. For the 1988-07-20 data, pixel residual error was maintained below one half pixel, at 12.4 m and 14.5 m for the pixel and line, respectively. The remaining image data were geometrically corrected using image-to-image registration with the 1988-07-20 data. For the 1987-07-02 data, the standard error of the pixel and line were 0.15 pixel and 0.14 pixel, and for the 1987-10-06 data, these values were 0.27 and 0.16, respectively. Two study areas were subset from the corrected image data (Table 3.2, Figure 2.1) and subsequent image analyses were performed on the geometrically corrected data.

Table 3.3. Study Area Locations.

Study Area	Township-Range	UTM Easting (Northwest Corner)	UTM Northing (Northwest Corner)
1	44-10	469312	5854500
	43-10	469250	5844787
	43-11	459458	5844859
2	42-11	460279	5835146
	41-11	460200	5825434
	40-11	460121	5815721

A number of image analyses methods were applied to the image data, to determine their utility in the extraction of suitable agricultural land cover information for the study areas. These included image enhancement, principal components analysis, unsupervised, supervised and parallelepiped classifications.

Image Enhancement

Enhancement of digital image data is done to create contrast between targets of interest to enable visual interpretation. Among the most easily recognized features are water bodies, watershed and drainage systems, mountainous topography, landform patterns, grasslands, forested lands and snowfields (Oswald 1975). Enhancement procedures expand the range of original pixel values to enable their display over a wider dynamic range of values on a display monitor. According to Lillesand and Kiefer (1979), enhancement techniques may be characterized as either "point" or "local" operations as follows:

1. Point operations modify the brightness values of each pixel in an image independent of other pixels; while

2. Local operations modify the value of each pixel in the context of the brightness values surrounding it.

Point operations include contrast stretch, linear and piecewise stretch, histogram equalized stretch, band ratioing and principal components analysis (Taylor 1974, Lillesand and Kiefer 1979). Local operations can either emphasize or de-emphasize abrupt changes in pixel brightness values and alter the textural appearance of an image (Lillesand and Kiefer 1979). Methods include low-pass filtering or "smoothing", and high-pass filtering or "edge enhancement". These applications may vary by geographic location and project objectives. For example, Johnston and Howarth (1981) found that linear contrast stretch and band ratioing were more effective than filtering for emphasizing differences between 5 subarctic wetland cover types. Brown et al. (1983) developed a linear contrast stretch that was useful for visual interpretation of rangelands. A variety of image enhancement techniques useful for general land cover and rangeland interpretations are described by Ahern (1983).

Color additive viewing of single or multiple channels of image data can be more useful when image enhancements are applied to the data. In the additive viewing process, individual bands of data, or multidate data are projected as either red, green or blue light, in registration on a viewing monitor and color, and intensity and saturation of each channel is then varied until the tonal rendition best enhances features of interest (Williams and Goodman 1980). The maximum number of channels of data that can be viewed simultaneously on a color monitor screen is 3, therefore bands must be selected for their utility in representation of targets of interest. For example, a simulated color infrared image can be produced by projecting an infrared channel, a visible red channel and a visible green channel in registration, using red, green and blue light, respectively.

In the production of color infrared or pseudo-color images there is a need to understand the cumulative effects of color additive viewing to enable interpretation of resulting color renditions of targets. A drawback in this procedure is the need for recognizing and relearning new color renditions for cover types as these associations may change with different enhancements (Schubert et al. 1977). The advantages of visual analyses of image data are cost and accessibility; the lower cost of LANDSAT photographic products makes them more accessible than digital data to many users, and the data cost savings increase when fewer than seven TM bands are required (Trolier and Philipson 1986).

The selection of data channels for enhancement and color additive viewing depends upon the reflectance characteristics of features of interest and may vary temporally and by application objective. Trolier and Philipson (1986) compared a number of TM color composites, and concluded that a 3-5-4 channel (visible red, middle infrared, near infrared) composite displayed as blue, green and red, respectively, produced the most useful product for derivation of hydrologic land cover classes through visual interpretation. They also determined that for single channel displays, urban features were best separated using visible channels (TM Channel 3 preferred) and rural and vegetative cover types were best distinguished using infrared channels (either 5 or 7). Studies by Staenz et al. (1980), Gervin et al. (1983) and Chavez et al. (1984) cited by Trolier and Philipson (1986), suggested that it would be sufficient to include one band each from the visible, near infrared and mid-infrared portions of the spectrum to extract most of the information in a TM scene. A similar recommendation for spectral band selection was made by Townshend (1984), for discrimination of agricultural land cover types. The use of multidate data in image interpretation through enhancement has potential for maximization of the reflectance characteristics associated with phenological changes in vegetation. For example, Kirby (1974), demonstrated that by combining phenological knowledge with knowledge of spectral reflectance patterns, visual interpretation of boreal forest cover types could be improved, while Palylyk (1985) demonstrated advantages of multidate enhancements for identification of boreal peatlands.

Enhanced image products have been reported to be useful in rangeland biomass determinations (Jaques 1982) and rangeland quality assessments in Alberta (Pearce et al. 1984). False color composite imagery has also been determined to be useful for mapping vegetative cover and surficial geologic features in Arizona and New Mexico (Williams and Goodman 1980). As enhancements are useful for optimizing color renditions of selected targets, they enable the identification of spectral classes or training areas for subsequent classification procedures (Lee 1980, Tomlins and Thomson 1981).

The utility of enhanced imagery depends upon the resultant color rendition and ease of identification of the cover types of interest. Imhoff et al. (1982) determined that image enhancement by contrast stretch and equal area density slicing produced a product useful in stratification of soil boundaries, and reported that image enhancement was both an economically and logistically attractive processing technique for soil surveys. Because ". . . image enhancement is a fairly objective method, applicable over large areas, and does not require ground truth information in order to generate a viable image product, and is such that definition of spectral classes are open to interpretation . . ." (Imhoff et al. 1982), it has much utility in preliminary reconnaissance of a region for spatial distribution of land cover.

The utility of visual interpretation of imagery may outweigh classification procedures for some applications. For example, Imhoff et al. (1982), reported that image enhancement by a linear contrast stretch technique was more suitable for soil survey applications than either supervised or unsupervised classification. They determined that spatial orientation and geometry of spectral patterns portrayed on composite images were useful in the delineation of soil map unit boundaries, and that patterns portrayed on enhanced imagery were more spatially detailed than the mapped soil units. For forest inventory applications, enhanced image products were found to be just as effective, if not more useful than classification products (Beaubien 1979). For hydrologic land use and land cover, visual analysis of enlarged TM photographic products has potential for identification of a greater number of classes that can be derived through digital analysis (Trolier and Philipson 1986).

Multitemporal color composites, generated through additive viewing of the same band of data, for three different dates, as cyan, magenta and yellow, have been found to be useful for differentiating crop types and delineating field boundaries and urban features in change detection studies (Eyton 1983).

Depending upon the product required, image enhancement may prove useful in a number of applications, and has utility in the development and updating of GIS data bases. Additional advantages of enhanced imagery include the improvement of locational accuracy of boundaries, the definition of cover classes and the assessment of land cover change (Belward et al. 1990). For reconnaissance level surveys, enhanced image products provide a preliminary overview of an area to enable stratification for field sampling design.

Approach

Each study area was viewed by single channels, as grey-scale images for preliminary identification of geographic features and land cover patterns. A piece-wise linear stretch (Lillesand and Kiefer 1979, DIPIX 1984) was applied to channels 4 (near infrared), 3 (visible red) and 2 (visible green) to enable display of the digital data over a wider range of display scale values, first as simulated color infrared composites on the image display monitor, and then as hardcopy imagery for visual interpretation. Color infrared simulations were achieved by projecting Channels 4, 3 and 2 as red, green and blue light, respectively. The recording of color image products was accomplished using a QCR electronic image writer at the Alberta Remote Sensing Center.

Results and Discussion

Simulated color infrared imagery, a standard form of digital image representation, for study areas 1 and 2 (Figure 2.1) are presented as Plates 3.1, 3.2 and 3.3. Interpretive keys are presented as Tables 3.4 and 3.5. The color infrared products were useful for visual interpretation of generalized land cover classes and portrayal of variations in field size and composition. They also indicated potential for spectral confusion of cover types in subsequent classification procedures. Variations in the color renditions of crop cover as the result of the spectral complexity and variability within and between fields would likely cause confusion during classification procedures, and result in unclassified and multiply classified pixels. Additionally, pixel clusters, representing small fields, clearings, gas wells, willow rings, shelterbelts, farmsteads, small ponds and other features typical of the region, indicated potential for many "boundary" pixels. These boundary pixels would likely not be classified during subsequent classification, thereby contributing to a potentially large proportion of unclassified area.

Visual interpretation of the enhanced imagery relied on knowledge of crop calendars, target reflectance characteristics and land management practices for the region to enable the development of interpretive keys (Table 3.4 and 3.5). The July imagery (Plates 3.1, 3.2 and 3.3) portrayed canola in flower, cereal crops, and cultivated fallow in color renditions that enabled their differentiation. Similarities in color rendition between deciduous trees and treed pasture, and between cereal crops and grassland pasture were observed. This indicated potential for spectral confusion of these cover types in subsequent classification. In the July 1987 imagery, cereals could not be distinguished by visual analysis from native grasslands and pastures on the basis of spectral rendition alone. The spectral similarity of these cover types may have been a manifestation of lower than normal spring rainfall which resulted in their slower development in the 1987 crop year relative to 1988. Better discrimination of cereals and grasslands was possible with the July 1988 imagery. This may be due to the later date of imagery for this growing season, with vegetation having been more developed and the spectral variations between cover types more distinct.

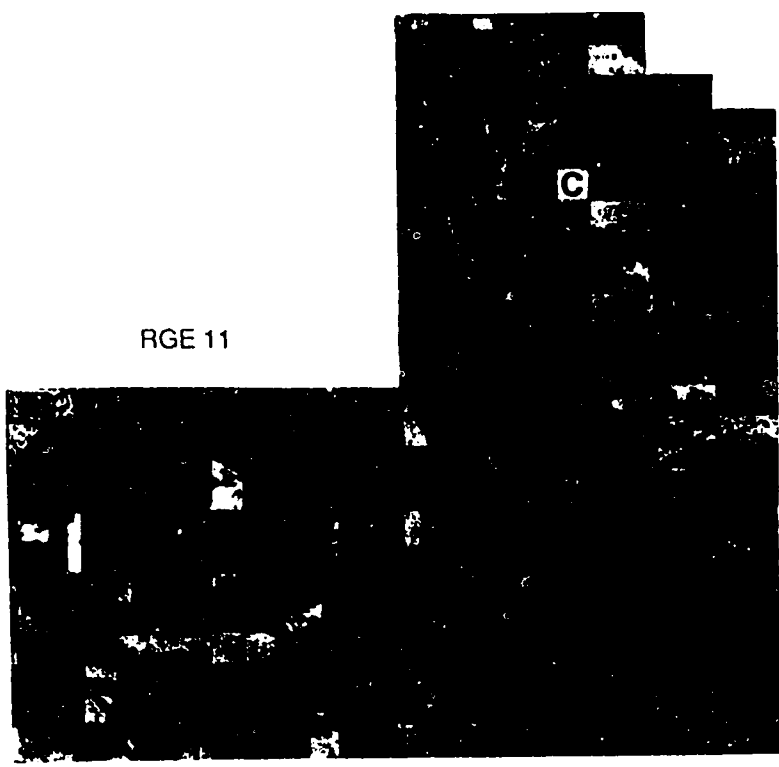
The color renditions observed for the agricultural cover types are due to the cumulative effects of color additive viewing and the reflectance properties of the vegetative cover. For example, canola in bloom appears to be a very bright whitish-pink to bright pink color, a result of high reflectance in all three channels. In comparison, cereal grains, grasslands and forages appear as dark reddish-pink to reddish-rust in color rendition, indicative of a greater reflectance in the infrared region opposed to the visible red and green channels. Deciduous vegetation reflects highly in the infrared and visible green channels, and when coupled with a rough surface geometry causing diffuse scattering, tends to appear darker red to red-brown in color relative to cereal grains or grasses. Bare soil surfaces, such as cultivated fallow, tend to absorb infrared wavelengths while reflecting shorter, visible wavelengths in the visible green range, and as a result appear as various shades of cyan to aqua blue. Presence of vegetative growth on bare soil surfaces causes a slight increase in reflectance in the infrared and visible green channels, imparting a reddish-pink to mauve-red cast to the respective fields. Variations in the color rendition of fallowed fields are the result of combined effects of surface vegetation cover, mineralogical composition, soil color and texture, organic matter content, and moisture condition. For example, a heavy clay-textured field, with high moisture content would tend to appear darker due to the absorbance of infrared radiation relative to a light-textured or sandier dry soil. Water bodies are recognized on the basis of their geometry and low reflectance properties in all channels, resulting in a dark blue-black color rendition. Water bodies that were shallow,

Table 3.4 Interpretive Key for Color Enhanced July Imagery.

Cover Type and Code	Color Rendition	Geometric Configuration
Agricultural Land Cover		
Cultivated fallow and bare soil surfaces (F)	cyan to aqua blue	rectangular and irregular shaped fields
Canola (in flowering stage) (C)	bright pink to whitish-pink	"
Cereal grains (spring wheat, oats, barley) (G)	dark reddish-pink to reddish-rust	"
Pasture, haylands and permanent grasslands (P)	reddish-pink to rusty brown to light greyish-cyan	irregular shapes, occasionally rectangular fields may be associated with forest and shrublands
Non-Agricultural Land Cover		
Water		
Lakes	dark blue-black	lakes and narrow curvilinear drainage channels
Ponds	lighter blue (if sedimented or algal bloom present)	smaller bodies
Forest and Shrublands (T)	rusty-red to bright-red to reddish-brown	irregular areas, curvilinear to string patterns, may be associated with grasslands, present along field boundaries and small areas within fields
Urban areas	medium to light grey	irregular areas, some linear features
Roads	light grey to charcoal grey	linear patterns
Gas Well Sites	light cyan to cyan-grey	small rectangles and irregular areas

Table 3.5 Interpretive Key for Color Enhanced October Imagery.

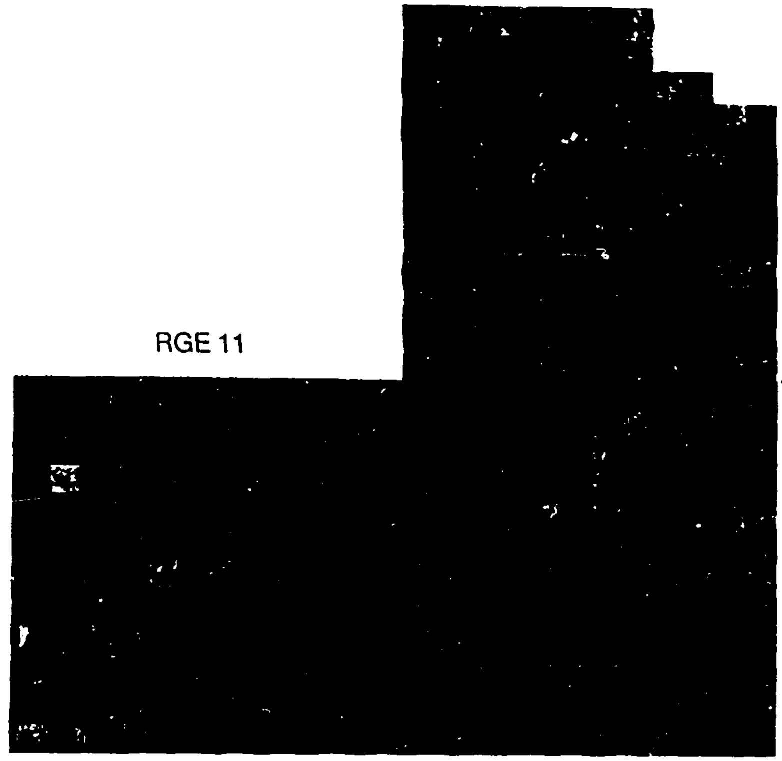
Cover Type and Code	Color Rendition	Geometric Configuration
Agricultural Land Cover		
Cultivated fallow and bare soil surfaces (F)	charcoal grey to black	rectangular and irregular shaped fields
Cultivated stubble (V)	light grey with yellowish undertones	•
Standing stubble (S)	yellowish white to yellowish-grey	•
Pasture, haylands and permanent grasslands (P)	dark rust-red to rust reddish-grey	irregular shapes, occasionally rectangular fields may be associated with forest and shrublands
Fall crops (predominantly fall rye) (R)	bright red	rectangular and irregular shaped fields
Non-Agricultural Land Cover		
Water		
Lakes	dark blue-black to black	lakes and narrow curvilinear drainage channels
Ponds	lighter blue (if sedimented or algal bloom present)	s[illegible]r bodies
Forest and Shrublands (T)	dark rusty-red to reddish-brown	irregular areas, curvilinear to string patterns, may be associated with grasslands, present along field boundaries and small areas within fields
Urban areas	medium to light grey	irregular areas, some linear features
Roads	light grey to charcoal grey	linear patterns
Gas Well Sites	light reddish-grey	small rectangles and irregular areas



1987-07-02 (Channels 4, 3, 2).

1987-10-06 (Channels 4,3, 2).

Plate 3.1. Color Enhanced Imagery of Area1. Consult Tables 3.2 and 3.3 for Interpretive Keys.



1988-07-20 (Channels 4, 3, 2).

Plate 3.2. Color enhanced Imagery of Area 1. Consult Table 3.2 for Interpretive Key.

sedimented, or covered in algal bloom reflected more highly in the visible red and green channels, resulting in a lighter cyan-blue color rendition.

Overall, the July 1987 imagery enabled the differentiation of canola in bloom, some cereal grains and bare soil (cultivated fallow) surfaces, forest cover and water. Some cereal grains, grasslands and haylands could not be differentiated on the basis of color rendition, and therefore size, shape and relative location of features were considered in visual interpretation. The July 1988 imagery enabled better differentiation of canola from cereal grains, due to the greater proportion of canola in bloom at this later date, relative to the 1987 imagery. Pastures, grasslands and shrublands were more distinct in color rendition on the 1988 imagery. This may be due to the vegetation being more developed on this later date of image acquisition. There appeared to be a greater proportion of cultivated fallow in each study area in the July 1988 crop year compared to 1987. This may have been a management response to the antecedent drought in the summer of 1987. Based on the visual analysis of these enhanced images for July, it was hypothesized that better discrimination of agricultural cover types could be achieved using classification methods applied to the July 1988 data as opposed to the July 1987 data.

The October imagery (Plates 3.1 and 3.3) was useful for differentiation of cultivated fallow fields, standing stubble and fall-seeded crops. As with the July imagery, target geometry was an important criterion in interpretation (Table 3.5). At this time of year, fall crops had assumed a vegetative growth stage and were spectrally distinct from senescent vegetation and stubble cover. The fall crops, dominantly fall rye, reflected highly in the infrared channel, typical of actively growing vegetation, resulting in a bright red color rendition. Smaller regions of bright red rendition could be associated with test plots of this newly introduced crop or small haylands. Cultivated fallow appeared dark charcoal grey to black, due to low reflectance in the infrared region in the absence of vegetation cover. Fallow fields with some vegetative growth appear to have a slightly rusty-red cast as a result of increased infrared reflectance. Standing stubble which reflects highly in all channels, a characteristic typical of dry vegetative material, has a bright yellowish-white to yellowish-grey color rendition. Cultivated stubble fields can be recognized on a qualitative basis due to the yellowish cast on lighter grey-black surfaces compared to cultivated fallow fields. Deciduous trees and shrublands appear dark rusty-red to reddish-brown. Tall, dense stands of trees appear much darker in color rendition than shrublands due to their lower reflectance properties resulting from the senescence of leaves. The lower sun angle at this time of year also causes enhanced shadowing.

Pasture lands are highly variable in their color rendition due to mixtures of both actively growing and dry grasses coupled with variable proportions and densities of shrubs and trees. Water bodies appear very dark blue-black to black in rendition, and the many "potholes" and willow rings that inundate this landscape are visible as small black "pitted" markings. Overall, the enhanced October imagery was useful for differentiation of standing stubble and cultivated fallow, and identification of fall-seeded crops.

Of the two study areas, Area 2 was inundated with a greater number of ponds and drainage channels compared to Area 1 (Plates 3.1, 3.2, 3.3). This has potential for the occurrence of a greater number of boundary pixels and may lead to a greater proportion of Area 2 remaining unclassified. The south-east corner of Area 1 is comprised primarily of rough, broken lands used as pasture lands, with a few small fields interspersed on lower slope positions (Plates 3.1, 3.2). This phenomenon also increases the spectral complexity of the area, and may result in confusion between these cover types during classification.

For utility in soil conservation applications, enhanced image products allow for large area reconnaissance of the spatial distribution of spectrally distinct cover types (e.g. oilseeds, fallow, fall crops) and seasonal changes in field size and boundaries. They also enable the deduction of historical sequences of land management and cropping practices. From a soil conservation standpoint, where interest lies in identifying large regions of bare soil surfaces, post-harvest (e.g. October) imagery is useful for determining the proportion of landscape that is predisposed to water erosion during spring melt events. For both study areas, there were a greater number of cultivated surfaces than stubble fields evident in the October imagery, indicative of a trend for post-harvest cultivation of crop residues. Mid-summer imagery (e.g. July) was useful for determining the proportion of seasonally cultivated fallow, as well as the distribution of cereal crops and permanent cover. For both study areas, summerfallow accounted for approximately one third of the cultivated land, based on visual analysis of the July imagery. For purposes of monitoring land cover changes, as related to agricultural land management, the use of multitemporal imagery enables the deduction of crop rotations and determination of the spatial distribution of fallowed fields on both seasonal and annual basis. Seasonal inventory of grains, fallow and conservation tillage practices has been demonstrated by DeGloria et al. (1986) through use of enhanced image products. The separation of grain fields and haylands was complicated by their spectral similarities and by variations in land management practices (DeGloria et al. 1986). Based upon the preliminary evaluation of the enhanced imagery, spectral confusion of cover types was anticipated in subsequent classification procedures in this study.

Principal Components Analysis

Principal components analysis involves the transformation of a correlated n-dimensional set of channels to another n-dimensional set which is uncorrelated and has an ordered maximum variance property (Anuta 1977). The transformation is useful for classification and analysis, because the majority of the variability can be found in the first $m < n$ dimensions rather than distributed in an unknown pattern throughout the data set (Anuta 1977). Each component is a linear combination of the original channels of data, where the weighting coefficients are the components of the corresponding eigenvectors of the n x n covariance matrix (Richards 1984).

The first few components typically contain most of the variability of all the original channels, and as a result, an image made from the first component will generally have as good or better contrast than any original channel (Anuta 1977). Principal components can be used as a basis for production of enhanced imagery or as input to classification, and have been shown to be useful in the enhancement of regions of localized change (Byrne and Crapper 1980, Richards 1984). For change detection purposes, principal components enhancements are a result of high correlation that exists between dates for regions that are relatively constant and low correlation associated with regions that change with time (Richards 1984). A drawback of principal components analysis is that spectral information of interest may be mathematically mapped to one of the unused components, and that a resulting color composite image may be difficult to interpret (Chavez and Kwarteng 1989). As an alternative approach, the development and application of a "selective" principal components analysis based on utilizing only 2 channels of data, was determined to be useful for geologic interpretations (Chavez and Kwarteng 1989).

Principal components analysis has been effective for visual interpretation of imagery (Lee et al. 1977, Rubec and Wickware 1978), for land cover change detection (Byrne and Crapper 1979, Byrne et al. 1980, Richards 1984), forest cover mapping (Beaubien 1980) and wetland terrain classification (Schreier et al. 1982). For soil survey applications, Imhoff et al. (1982) found that principal components enhancements were useful in delineation of soil map unit boundaries. In studying agricultural crops, Ungar and Goward (1981) reported that principal components were useful in distinguishing corn and soybeans, and Badhwar and Henderson (1982) found that various growth stages of spring wheat could be distinguished through use of principal components.

Approach

Principal components analysis (Taylor 1974, Anuta 1977), was performed on channels 1 through 5, for each study area and date of imagery through application of ARIES task "IE". Eigenvalues and eigenvectors were generated and the contribution of each component to total scene variance was determined for each data set. Color additive images of the first three components displayed as red, green and blue, respectively, were produced as hardcopy products using electronic image writing procedures.

Results and Discussion

Hardcopy images of the principal components for Areas 1 and 2 are presented as Plates 3.4 through 3.6. These images represent the first 3 principal components for each date of imagery, projected as red, green and blue, respectively.

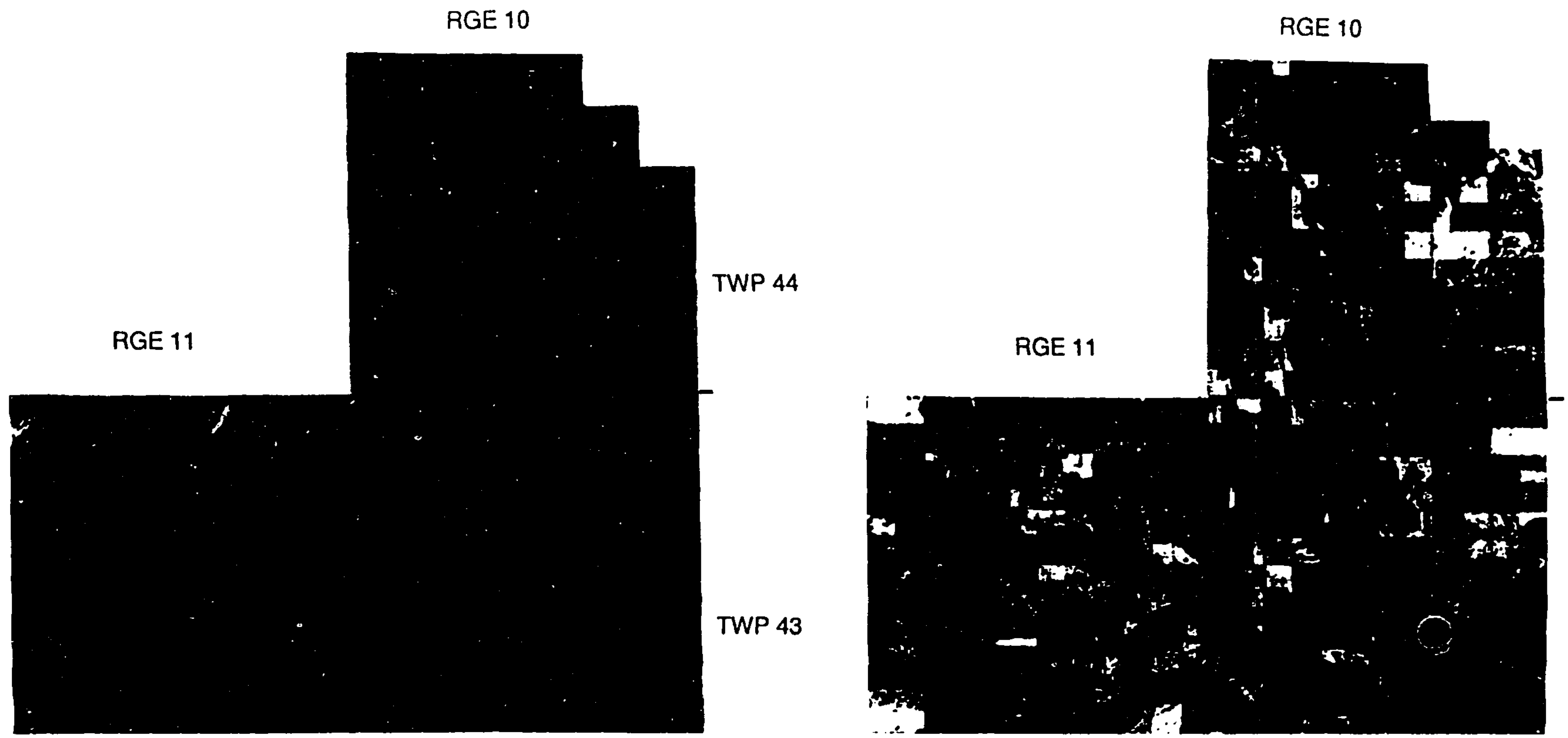
The color renditions of the principal components images (Plates 3.4 to 3.6) are more varied compared to the simulated color infrared enhancements (Plates 3.1 to 3.3) discussed earlier. Interpretation of color additive principal components images is a difficult task, in that the color renditions of targets are not directly representative of actual reflectance characteristics, but are the result of the combination of the selected principal components. If the image is produced through additive viewing of the first three components, then the color renditions can be linked to "brightness", "red/green" and "blue/yellow", represented by the first three components (Taylor 1974). In traditional color infrared enhanced imagery, the color renditions associated with specific targets can be qualitatively described, and interpretations based on knowledge of crop calendars and spectral response.

In comparison, color renditions of principal components images can be qualitatively described but necessitate coincident field surveys for verification. Because field data were not available for these images, the color infrared enhancements (Plates 3.1 to 3.3) were utilized for general interpretations.

Within the July 1987 and July 1988 imagery, cultivated fallow fields appeared bright pink to magenta due to the high weighting coefficients or "loadings" for brightness and blue/yellow components, PC1 and PC3, respectively, that were displayed as red and blue which additively created the magenta rendition. Cereal crops appeared as varying shades of green (high red/green loadings in PC2). Canola crops appeared as bright cyan, due to higher brightness and red/green loadings (PC1 and PC2), projected as green and red, which additively create a cyan rendition for these fields.

In the October imagery, fallow appeared magenta, due to the combination of high brightness and high blue/yellow (PC1 and PC3), additively displayed as red and blue, respectively. The low loadings of red/green (PC2) was the result of sparse vegetative growth on cultivated fallow surfaces. Stubble fields appeared bright yellow in contrast, due to the additive effects of red and green light, representing high loadings for the brightness and red/green components (PC1 and PC2).

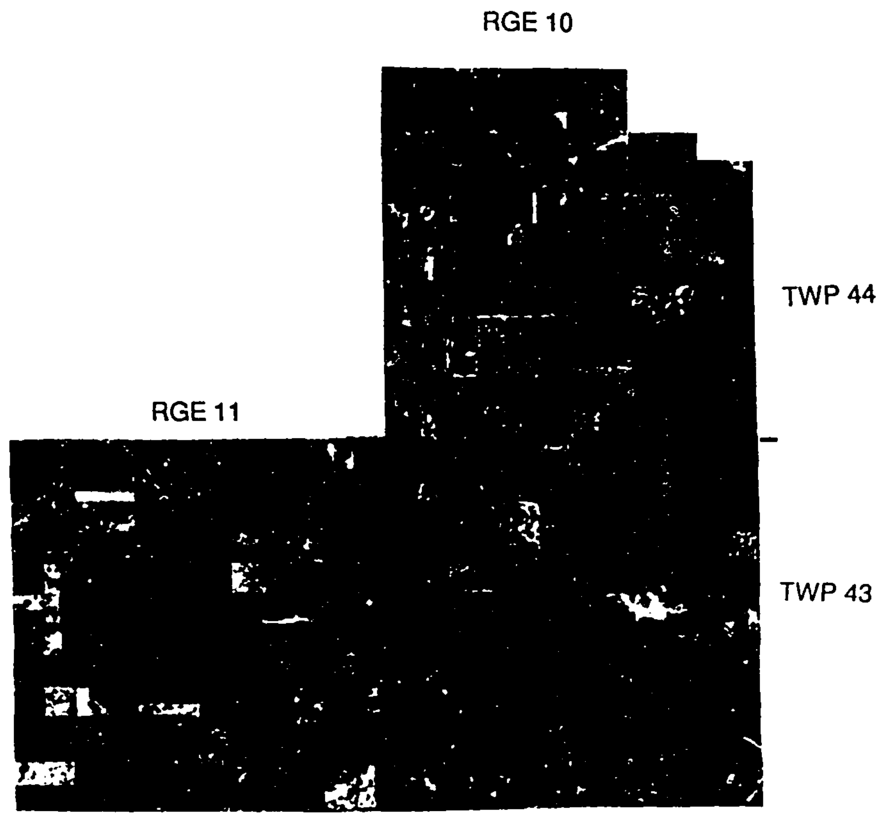
Water appeared as varying shades of blue in all three dates of imagery, due to lower loadings for brightness and red/green components (PC1 and PC2), and a stronger blue/yellow component (PC3) represented by blue light, in the additive viewing.



1987-07-02 (PC1, PC2, PC3)

1987-10-06 (PC1, PC2, PC3)

Plate 3.4. Principal Components Enhanced Imagery of Area 1.



1988-07-20 (PC1, PC2, PC3)
Plate 3.5. Principal Components Enhanced Imagery of Area 1.

In the July imagery, generalized interpretations of cereals, canola and cultivated fallow could be made, while cultivated fallow and standing stubble could be identified in the October imagery. These images have potential utility for updating of archival data bases in land cover monitoring, providing that adequate field survey information can be obtained to differentiate subtleties in color rendition within and between cover types.

Another aspect of principal components analysis is the determination of the greatest sources of variance within the spectral data. This information can be obtained from studying the resulting eigenvalues and eigenvectors (Tables 3.6 and 3.7). Each principal component may be expressed as a linear equation of the form:

$$PCn = (c5 \times CH5) + (c4 \times CH4) + (c3 \times CH3) + (c2 \times CH2) + (c1 \times CH1)$$

where n represents the principal component number, and c1 through c5 are the coefficients (eigenvalues) for the respective spectral channels (CH1 through CH5). These linear combinations of spectral data are independent and uncorrelated relative to the original data.

The proportion of total scene variance represented by each linear component is determined by totalling the respective eigenvalues for each data set, then dividing each eigenvalue by the result. These variance values are presented in Tables 3.6 and 3.7.

In all data sets, principal component 1 contained the greatest variance, followed by PC2 and PC3. For example, in the July 1987 data for study area 1 (Table 3.6), 62.7% of the total scene variance is contained within the first component, 32% by the second and 4.2% by the third. In the October imagery (Table 3.6), PC1 accounted for almost 85% of the total variance, and when coupled with the high coefficient values (loadings) for channel 1 (0.73 and 0.71, for areas 1 and 2 respectively), suggests that either PC1 or channel 1 would be useful in subsequent classification of this data. Slight differences exist in the variances attributed to each of the components for the two study areas, which may be due to differences in type and proportion of land cover within each area.

For all dates of imagery, the first three components contained from 95 to 99% of total scene variance. Overall, the largest coefficients were most frequently associated with Channels 5, 4 and 3. This led to the selection of these three channels for subsequent parallelepiped classification procedures, the premise being that the greater weightings associated with these channels would contribute to better representation of individual targets of interest. Townshend (1984) suggested that in terms of discriminatory potential for land cover, an optimal choice of three channels should include a band from the near-infrared (channel 4), one from the visible (preferably channel 3), and one from the middle or far-infrared. He cautioned that significant discriminatory power may be lost if all bands are not used. In a comparison of principal component analyses, the highest order component contained valuable information for land cover

Table 3.6. Principal Components Eigenvalues and Eigenvectors for Area 1.

1987-07-02 Data

Component	Eigenvalue	%Variance	Eigenvectors: Channel 5	Channel 4	Channel 3	Channel 2	Channel 1
1	1456.2994	62.7	0.86	0.14	0.30	0.17	0.34
2	743.1562	32.0	0.19	-0.97	0.05	-0.09	-0.08
3	98.4933	4.2	-0.46	-0.16	0.45	0.35	0.67
4	24.8177	1.1	-0.06	0.05	0.72	0.25	-0.64
5	1.3998	0.1	-0.05	0.08	0.44	-0.88	0.16
Total =	2324.166	100.1*					

1987-10-06 Data

Component	Eigenvalue	%Variance	Eigenvectors: Channel 5	Channel 4	Channel 3	Channel 2	Channel 1
1	645.4197	84.6	0.73	0.44	0.39	0.20	0.29
2	71.8198	9.4	0.68	-0.55	-0.40	-0.21	-0.19
3	34.3764	4.5	-0.09	-0.67	0.36	0.24	0.60
4	10.7967	1.4	0.03	-0.23	0.69	0.02	-0.68
5	0.8802	0.1	-0.02	0.04	0.28	-0.92	0.25
Total =	763.293	100.0					

1988-07-20 Data

Component	Eigenvalue	%Variance	Eigenvectors: Channel 5	Channel 4	Channel 3	Channel 2	Channel 1
1	1096.0466	62.5	0.76	-0.61	0.19	0.04	0.14
2	580.7427	33.1	-0.57	-0.79	-0.16	-0.14	-0.10
3	70.4974	4.0	-0.32	-0.05	0.75	0.46	0.36
4	4.1409	0.2	0.05	-0.02	0.36	0.18	-0.92
5	1.4656	0.1	-0.03	0.07	0.50	-0.86	0.03
Total =	1752.893	99.9*					

*Rounding error

Table 3.7. Principal Components Eigenvalues and Eigenvectors for Area 2.

1987-07-02 Data

Component	Eigenvalue	%Variance	Eigenvectors Channel 5	Channel 4	Channel 3	Channel 2	Channel 1
1	1171.3047	66.1	0.92	-0.15	0.29	0.12	0.20
2	534.0038	30.1	0.16	0.98	-0.02	0.07	0.00
3	62.4346	3.5	-0.37	0.04	0.69	0.43	0.46
4	4.0208	0.2	-0.01	0.01	-0.50	-0.12	0.86
5	1.3786	0.1	0.04	-0.08	-0.43	0.89	-0.13
Total =	1773.143	100.0					

1987-10-06 Data

Component	Eigenvalue	%Variance	Eigenvectors Channel 5	Channel 4	Channel 3	Channel 2	Channel 1
1	674.6650	84.7	0.71	0.47	0.42	0.20	0.25
2	83.6410	10.5	0.70	-0.56	-0.36	-0.20	-0.17
3	33.7777	4.2	-0.09	-0.67	0.54	0.25	0.42
4	3.1576	0.4	-0.01	0.07	-0.59	0.15	0.79
5	0.8686	0.1	-0.02	0.05	0.22	-0.91	0.34
Total =	796.110	99.9*					

1988-07-20 Data

Component	Eigenvalue	%Variance	Eigenvectors Channel 5	Channel 4	Channel 3	Channel 2	Channel 1
1	1180.0265	62.4	0.83	-0.49	0.21	0.06	0.15
2	646.7008	34.2	-0.46	-0.87	-0.10	-0.11	-0.06
3	59.7376	3.2	-0.03	-0.01	0.74	0.45	0.40
4	4.0755	0.2	0.04	-0.02	0.41	0.15	-0.09
5	1.3407	0.1	-0.03	0.07	0.48	-0.87	0.07
Total =	1891.881	100.1*					

*Rounding error

discrimination although it explained less than 1/1000 of the total statistical variance (Townshend 1984). Lee et al. (1989) reported that the variance of higher-order components represented small spectral variations in cover classes, as well as some data "noise", and that lower-order components enabled discrimination of minor variations in features and highlighting of localized change within multitemporal data sets. Belward et al. (1990) reported that unsupervised classification with the first three principal components resulted in either too few or too many spectral classes for ecological mapping of vegetation. Additional attempts at classification utilizing only the first two components resulted in the formation of 31 classes, of which 14 could be identified in the field (Belward et al. 1990). Therefore, the use of principal components data appears to involve difficulties in target discrimination, similar to those encountered in the use of regular channel data. In both cases, representative training areas and spectral uniqueness of targets determines the success of classification.

The principal components enhanced images were of limited utility in the visual derivation of land cover classes for integration within the GIS due to the variability in the color rendition of cover types. Coincident field survey data would be essential to the interpretation of these variations. If verification field data were available, then these enhanced images may be useful for updating of GIS graphics files for field boundaries, or land cover attribute files. An attempt was made to derive a land cover theme file by applying unsupervised classification procedures to principal components data for 1987-10-06 for Area 1. Classification methods and results are discussed in the following section.

Classification

Classification of image data involves the grouping of pixels according to their statistical similarity in spectral reflectance values within defined probability limits in selected channels, and subsequent coding of each pixel by assignment of a unique class identifier or "theme number". Ideally, each spectral class should represent a unique cover type. The spectral data (MSS bands or TM channels) define a measurement space or "feature space" within which each image pixel is located (Lo 1986). Each axis of the feature space corresponds to a spectral channel or band of data. Classification methods partition the feature space into decision regions, each corresponding to a unique spectral class (Lo 1986). Selection of channels to be used in a classification may include the traditional combination of infrared and visible channels (Chavez et al. 1984), or their principal components (Belward et al. 1990).

Classifiers differ in the methods by which feature spaces are partitioned and how the image pixels are subsequently assigned to classes. A number of algorithms exist by which classification can be accomplished. Those used most frequently include maximum likelihood, discriminant, parallelepiped and minimum distance to means.

The **maximum likelihood classifier** evaluates both variance and correlation of spectral response patterns when classifying an unknown pixel (Lillesand and Kiefer 1979). The variance and correlation are used to compute the statistical probability of a pixel fitting a particular spectral class. This classifier delineates ellipsoidal "equiprobability" contours in the feature space, with the shape of the contours indicating the sensitivity of the classifier to correlation (Lillesand and Kiefer 1979). The maximum likelihood classifier operates on the basis of minimum distance between classes in a feature space composed of spectral channels, with the underlying assumption that each training area signature assumes a Gaussian (normal) distribution. The assumption of normality of spectral signatures is violated by heterogeneous training areas of targets with inherent spectral variability. Therefore, care must be taken to ensure that spectral classes with multimodal probability distributions are subdivided into classes of unimodal distribution (Belward and de Hoyos 1987). This condition may require selection of multiple training areas for single targets to encompass the spectral variability associated with each target (Dobbins and Epp 1987) and tends to increase the time requirement for implementation and data processing (Belward and de Hoyos 1987). In the application of this classifier to imagery of the Canadian prairies, the variability in geographic regions, land management practices, field size (strip farming versus quarter section versus section or larger), and the presence of native forest and grassland vegetation, shelterbelts, willow rings, ponds and drainage networks can complicate selection of homogeneous fields for use as training areas. The principal drawback in use of the maximum likelihood classifier is the large number of computations required to classify each pixel, making it slower and more expensive to implement relative to other techniques (Lillesand and Kiefer 1979).

An extension of the maximum likelihood classifier is the **Bayesian classifier**, which involves the application of weighting factors (*a priori* probabilities) to the probability estimate to optimize the classification process (Lillesand and Kiefer 1979). Another type of classifier, which operates by generating bivariate feature spaces through incorporation of class frequency with multiquadratic equations and subsequent contouring of the resulting surface has been proposed by Kliparchuk (1988). This classifier appears to work more efficiently when applied to data exhibiting high frequencies of the spectral values associated with targets of interest.

The **discriminant analysis classifier** is based upon a set of functions to partition a feature space into distinct regions. Linear combinations of discriminating variables are derived for the spectral data and pixels are subsequently classified on the basis of their scores calculated using the linear equations. The discriminant classifier operates by maximizing between class differences while minimizing within class variation (Niemann 1988). Although this process is mathematically complex, it is useful for incorporating multiple channels of data in a classification.

A **binary pattern classifier** that discriminates spectral classes on the basis of their compactness in feature space has been proposed by Lee and Richards (1985). This classifier operates by identifying linear or piecewise separating surfaces in a multispectral feature space utilizing a decision tree (Quing-Yun and Fu 1983) approach. The reported advantages of this classifier are the speed of classification of multitemporal data and similar accuracies relative to the maximum likelihood classifier. Subsequent work by Belward and de Hoyos (1987) involved the comparison of a manually designed binary tree classifier to a maximum likelihood classifier for classification of agricultural crops using LANDSAT MSS data. Although they reported similar classification accuracies for both algorithms, they advocated the use of the binary classifier for multitemporal classifications due to its computational efficiency.

The **minimum distance classifier** is mathematically simple in comparison to the maximum likelihood and discriminant classifiers. This classifier operates through the calculation of arithmetic means for each class within a feature space. Classification is accomplished by computing the distance of an unknown pixel's radiometric value to the mean value of each spectral class, and subsequent assignment of the pixel to the nearest class (Lillesand and Kiefer 1979). Although the minimum distance classifier is computationally efficient, it is limited in that does not consider the variance in the spectral data, and as a result, may cause suboptimal class assignments.

Another approach to classification involves **parallelepiped classification**. Originally, a simple classifier developed and used during early stages of LANDSAT data availability, it served as a basis for development of more complex classification algorithms. A typical parallelepiped classifier operates by defining a two-dimensional data space into rectangular "boxes", whose boundaries are defined by the upper and lower limits of spectral values for each respective cover type (Jackson and Bondelid 1983). The multidimensional analogs of these rectangular boxes are referred to as "parallelepipeds" (Lillesand and Kiefer 1979). Variance of spectral classes is recognized and represented by the size and dimensions of the parallelepipeds, but spectral class overlap can complicate the classification process. A frequent cause of spectral class overlap leading to misclassification, is that classes exhibiting correlation are not well described by the rectangular decision regions (Lillesand and Kiefer 1979). This may be alleviated in some cases through refinement of the decision regions into a series of smaller, stepped rectangles whose cumulative shape may more closely portray elongated class distributions.

The utility of the parallelepiped classifier in canola inventory has been demonstrated by Ryerson et al. (1985), when representative training areas could not be located due to small field sizes. This method provided a relatively fast method of quantifying canola distribution over a large region (Ryerson et al. 1985). Parallelepiped classifiers have also been used for identification of other agricultural crops in combination with supervised classification procedures (Pokrant et al. 1985, Dobbins and Epp 1987).

A major challenge in classification of image data lies in the choice of the most suitable method of classification for the specific study objective; however the accuracy of classification depends on the nature of the data, particularly pixel size in relation to the degree of homogeneity in land cover type (Lo 1986). An additional challenge involves the selection of spectral bands (or channels) for use with the classifier. Methods of spectral band selection for classification include the **Transformed Divergence (TD), Divergence (D), Bhattacharyva Distance (BD)** and **Jefferys-Matusita Distance (JM-Distance)**, which measure the statistical distance between spectral classes (Mausel et al. 1990).

In the classification process, feature spaces which define spectral classes may be identified on the basis of inherent spectral groupings (clustering or "unsupervised" signature generation) or predefined groupings (interactive training or "supervised").

Clustering, sometimes referred to as "unsupervised" classification, involves the application of a computer algorithm which randomly samples the spectral data without concern for individual targets and separates the data into distinct groupings or clusters (Pettinger 1982). The number of clusters formed is a function of the spectral variability within the image data, but the maximum number of clusters identified is controlled by the algorithm. For example, the ARIES-II image analysis system utilizes a migrating means clustering algorithm which is limited to the production of 32 classes (Letts 1978). Other algorithms may produce anywhere from 3 to 100 classes on the same data set, which can make the procedure impractical (Belward et al. 1990).

The major advantages of clustering are that the spectral stratification of an image is possible without *a priori* field information and that the most com... spectral categories are quantified (Schreier et al. 1982). Furthermore, the random sampling of pixels is assumed to contain a more representative sample of spectral variability in the data than would a subjective supervised approach (Pettinger 1982). Clustering has been reported to be useful in situations where little or no field information is available or where a region is characterized by extreme heterogeneity in groundcover and terrain features, as in forested and wilderness areas (Driscoll et al. 1974, Fleming et al. 1975, Tarnocai and Kristof 1976, Beaubien 1979). In some environments, ecological vegetation classes have been poorly represented by resultant spectral classes (Belward et al. 1990). In agricultural regions, the application of clustering algortihms can also be complicated by overlap of spectral classes, and extreme heterogeneity within targets and landscapes (Table 3.1).

A potential disadvantage to clustering, is the need to identify resultant spectral classes or "clusters" by relating them to actual land cover types. This process may involve interactive merging of clusters to derive more meaningful interpretations. Because spectral clusters are defined on an automated basis, they may represent a number of unrelated cover types from the standpoint of project objectives. Although clusters are statistically defined and often spectrally distinct, they may not correspond to physiognomically distinct cover types. Spectral overlap between classes or mixed spectral response of a cover type due to environmental factors, can prevent the assignment of a unique description to each class (Johnston and Howarth 1981). For example, Belward et al. (1990) found that vegetation classes identified on the basis of field ecological interpretations were poorly represented by the spectral classes generated by clustering, because much spectral overlap occurred between classes.

Supervised classification involves analyst interaction in the delineation of pixel groupings or "training areas" representative of known cover types, and subsequent generation of spectral class parameters, often referred to as "spectral signatures" or "training statistics". In subsequent classification, pixels are assigned to classes on the basis of their spectral similarity to the defined training area signatures. The utility of this approach depends highly upon the availability of *a priori* field information, the spectral uniqueness of cover types and their spectral separability during the mathematically-based classification process.

In environments exhibiting heterogeneity in land cover, or considerable spectral variability due to rugged terrain, the supervised approach may not be suitable. Due to complexity of landscapes and land cover, it is difficult to select training areas that fully represent the range of spectral variability that occurs throughout a study area, which is a requirement in the supervised approach (Pettinger 1982). In agricultural regions, located in lower relief landscapes and characterized by consistent field sizes and crop rotations, there is potential for greater homogeneity within individual targets. Given such conditions, the supervised approach has been useful for inventory of specific crops, including winter wheat (Reichert and Crown 1986), canola (Dobbins and Epp 1987) and corn (Bauer et al. 1979). In the Canadian prairies, requirements for spectral homogeneity can be complicated in agricultural areas due to mixed field patterns, variable land management practices, environmental factors, variability in seeding dates and crop types, and the presence of willow rings, ponds, shelterbelts and native vegetation. As an alternative to the supervised approach, Ryerson et al. (1985) elected to use parallelepiped classification due to difficulties in locating representative training areas, while Dobbins and Epp (1987) utilized multiple training areas for individual targets, to encompass their spectral variability.

Alternatively, modifications and combinations of supervised and unsupervised approaches can be applied to refine spectral class definitions in attempts to improve classification results. Fleming et al. (1975), in a comparison of modified approaches involving "modified supervised", "modified clustering" and clustering, determined that a modified clustering approach (which involved the clustering of selected training areas) produced highest classification accuracy in a forested environment. Rohde et al. (1979) also found utility in a stratified cluster sampling method to map wildlands. Similar applications to agricultural environments were not found in the literature reviewed.

A recurrent problem in application of classification procedures is the spectral confusion between cover types. This may be caused by spectral class overlap, as in the case of transition regions or boundary pixels (Belward and Taylor 1986, Reichert and Crown 1986), spectral similarity in cover types at particular stages of growth (Csillag 1986, Hall-Konyves 1990). Spectral confusion of agricultural cover types may be greater at particular times of the year, as for example, during the germination phase (Belward and Taylor 1986), prior to the flowering of canola or prior to the jointing stage of cereals (Ryerson 1983). This spectral confusion may not necessarily be resolved through application of different classification methods. Examples of spectral confusion in agricultural landscapes reported in the literature are documented in Table 3.1.

An alternative to conventional classification algorithms involves the application of artificial intelligence and expert systems to pattern recognition (Argialas and Harlow 1990, Mehldau and Schowengerdt 1990). In an expert systems approach utilized by Moller-Jensen (1990), the image classification process consisted of per pixel classification of homogeneous areas, intelligent detection of linear features for image segmentation, computation of textural, spectral and contextual features followed by a knowledge-based classification of segments. Results suggested that the incorporation of knowledge-based rules improved the classification of complex TM images for urban land use studies.

Approach

Three approaches to spectral signature generation for classification of image data are available on the ARIES-II, and were explored for their utility in the derivation of land cover theme files for subsequent integration into the GIS. These included unsupervised, supervised and interactive parallelepiped methods.

Unsupervised classification (ARIES task "UC") was applied to channels 1 through 5 for each of the three dates of imagery and to the October 1978 principal components data for Area 1.

Supervised classification (ARIES tasks "IT" and "ML") was applied to the July 1988 data for Study Area 2, with selection of training areas based on aerial photographs and 1989 field surveys. Spectral signatures were developed for the five channels of these data. Signature autocorrelation distance values were derived and evaluated to determine potential for spectral confusion of cover types. Signature extension using Area 2 signatures was then applied to the July 1988 data for Area 1. Both areas were classified and results were compared. Spectral signatures and autocorrelation distance (ACD) values (ARIES task "AU") were also developed for each additional data set for both study areas to determine the likelihood of spectral confusion and potential limitations of signature extension.

An interactive parallelepiped classifier (ARIES task "DP") was applied to channels 5 (middle infrared), 4 (near infrared) and 3 (visible red), for each date of data for Area 1. Contrast stretch values and look-up tables were generated for each data set, and interactive classification was then utilized in preliminary classification of Area 2. Intermediate results indicated that signature extension from Area 1 to Area 2 was not suited to these data due to large areas remaining unclassified, and therefore a separate interactive parallelepiped classification was performed on Area 2. Due to the complexity of the region and the variations in spectral response of each of the targets, multiple classes of each target were developed and then merged into individual themes representing generalized land cover classes through use of ARIES task "CA". This procedure also enabled removal of multiple classifications from the data set. Classification results were organized into theme files such that each land cover class (theme) was identified by a unique numeric code and represented by a unique color when viewed on the color monitor display. Each theme file was then processed through a manual theme generation process (ARIES task "MT") to place individual themes in a predetermined order within each theme file for consistency in image display and subsequent attribute coding within the GIS.

Theme files generated for each date and study area were then filtered (ARIES task "CU") to remove anomalous single pixels and small unclassified areas through application of a 4 x 4 filter with a maximum eat-in depth of 2 pixels, for each theme. Resultant theme files were viewed as color display images for comparison with enhanced images (Plates 3.1, 3.2, 3.3) as an evaluation of land cover mapping. Summaries of classification results for each date, area and filtering option were obtained through use of ARIES task "CT", an automated theme counting process. The theme files were then exported to magnetic tape (ARIES task "TO") for subsequent raster-to-vector conversion and integration within an ARC/INFO GIS.

Results and Discussion

Application of unsupervised classification to channels 1 through 5 for each date of imagery for Area 1 resulted in production of 32 classes for each data set (Table 3.8).

This is the maximum number of classes that can be formed with the ARIES task "UC". Each class is assigned a value number, which represents the number of pixels associated with

Table 3.8. Unsupervised Classification of Study Area 1.

Date	Input Channels	Number of Classes Formed: Total	Number of Classes Formed: with > 50 pixels
1987-07-02	1-5	32	27
1987-10-06	1-5	32	14
1988-07-20	1-5	32	30
1987-10-06	Principal Components PC1, PC2 , PC3	32	5

each class. A cut-off value of 50 pixels, equivalent to approximately 4.5 hectares of land area, was arbitrarily chosen as a minimum area for consideration of a spectral class. Results of unsupervised classification indicated that considerable spectral variation in cover types existed in both sets of July data, with 27 and 30 classes for 1987 and 1988, respectively representing areas greater than 4.5 hectares. The greater number of classes may be due to the variation in vegetation cover and growth stages during the mid summer stage of the growing season coupled with varying land management practices. Fewer spectral classes were formed for the October data (14), and even fewer for the October principal components data (5), indicative of less spectral variation at this time of year.

Classification of these data utilizing signatures derived from unsupervised classification resulted in very mosaicked themes with inconsistent coverages within and between fields. Although these classes represented several spectral classes inherent in the data, they were not representative of physiognomically distinct types. Attempts to merge classes into single themes were not successful because the original classes were representative of multiple cover types. These results of unsupervised classification did not allow for the development of land cover theme files that would be useful for reconnaissance level mapping or county scale conservation applications.

Supervised classification procedures involved the generation of spectral signatures and autocorrelation distance (ACD) values for training areas of major land cover types selected on the basis of enhanced color imagery and 1:30,000 scale infrared aerial photographs. Interpretive guidelines for ACD values are presented in Table 3.9. Spectral signature codes and target descriptions are presented in Table 3.10. Spectral signatures and ACD values are presented in Table 3.11 through to Table 3.22. Classification summaries for the July 1988 data for Area 2, and signature extension to Area 1 are presented in Table 3.23.

Analysis of spectral signatures and ACD values for both Areas 1 and 2 revealed considerable spectral overlap within and between classes associated with individual cover types. For example, for the July 1987 data for Area 1, (Table 3.11) spring grains, canola and grassland pasture signatures overlapped in their standard deviations. This phenomenon would likely result in spectral confusion and multiple classifications of cover types associated with these spectral classes. Signature overlap between wheat, barley and woodlands has been reported in earlier work by Horn et al. (1984). Similar trends in signature overlap were observed in the July 1987 data for Area 2, although respective signature values differed slightly between the two areas. Analysis of the corresponding ACD values indicated that these signatures were closely correlated. In the interpretation of ACD values for signature pairs, the larger the calculated value, the more distinct are the respective signatures. Table 3.9 is adapted from the guidelines for ACD interpretations provided by the ARIES-II Manual (1984):

Table 3.9. Guidelines for Autocorrelation Distance Value Interpretation.

ACD Value	% Correlation of Signature Pair
0	100
0.5	50
1.0	30
2.0	10

ACD values for cereals, canola and grassland pasture (Tables 3.12 and 3.18) indicated that these cover types would not be separable on the basis of their spectral signatures for July of 1987. Generally, signatures were more distinct numerically and in their respective ACD values for the July 1988 data, for both areas (Tables 3.15, 3.16, 3.21, 3.22). This suggests a greater likelihood of separating these cover types through classification procedures applied to July 1988 data, hence the reasoning for trial classifications (Table 3.23). The October signatures tended to be more distinct numerically (Tables 3.13, 3.14, 3.19, 3.20), although some spectral overlap was likely to occur between the two classes of fallow, between fallow and cultivated stubble, and between the pasture and forest cover types.

Trial classification of Study Area 2 using the July 1988 data, as a signature extension procedure, revealed that the training areas selected and signatures developed did not encompass all spectral variations associated with the cover types of interest, resulting in a considerable proportion (18.3%) of the study area remaining unclassified (Table 3.23). This is commonly encountered in the application of classification procedures (Ryerson et al. 1985, Belward and Taylor 1986).

Table 3.10 Spectral Signature Codes and Target Descriptions.

	Imagery		
Target	1987-07-02	1987-10-06	1988-07-06
Water (deep)	7WT1	OWT1	8WT1
Water (shallow)	7WT2	OWT2	8WT2
Fallow (cultivated)	7FA1	OFA1	8FA1
Fallow (some vegetative growth)	7FA2	OFA2	8FA2
Canola (in bloom)	7CA1	OCA1	8CA1
Canola (pre-bloom)	7CA2	OCA2	8CA2
Stubble (standing)		OCS1	
Stubble (cultivated)		OCS2	
Cereal grains (very dark red rendition on simulated CIR enhancement)	7GR1		8GR1
Cereal grains (light red-pink rendition on CIR enhancement)	7GR2		8GR2
Fall rye (vegetative growth stage)		OFR1	
Pasture (with shrubs)	7PA1	OPA1	8PA1
Pasture (predominantly grasses)	7PA2	OPA2	8PA2
Forest (dense trees, predominantly aspen)	7DC1	ODC1	8DC2
Forest (mixed trees and shrubs)	7DC2	ODC2	8DC2

Table 3.11. Spectral Signatures for 1987-07-02 Imagery: Area 1.

Signature and Number of Pixels	Channel 5		Channel 4		Channel 3		Channel 2		Channel 1	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
7WT1 (634)	11.24	13.00	17.11	11.99	25.58	3.30	28.97	2.26	79.59	3.11
7WT2 (547)	12.81	11.35	30.72	8.38	50.27	4.59	43.22	2.61	100.18	3.94
7FA1 (790)	169.08	6.73	74.37	3.61	74.87	3.89	53.26	1.92	112.79	2.76
7FA2 (1916)	156.70	8.19	64.58	6.22	63.49	4.71	47.26	2.61	105.37	3.76
7CA1 (995)	88.16	7.30	149.95	12.14	56.07	4.78	54.78	4.28	92.41	2.08
7CA2 (777)	95.42	6.33	134.01	10.07	53.85	3.26	52.33	2.54	91.96	1.81
7GR1 (557)	87.69	6.84	138.49	15.07	48.36	9.09	49.14	7.05	90.83	1.92
7GR2 (743)	94.74	8.06	114.24	17.24	35.75	3.21	38.63	2.41	89.15	3.02
7PA1 (1074)	123.28	24.20	86.12	8.21	46.43	10.77	40.90	5.18	95.00	7.98
7PA2 (712)	127.80	25.39	81.53	8.68	49.42	8.86	42.05	3.95	95.88	5.89
7DC1 (759)	82.35	18.62	91.61	11.82	30.58	5.37	33.02	3.05	83.56	3.90
7DC2 (532)	94.54	18.84	100.87	17.04	36.07	7.82	37.21	5.74	87.21	5.37

Table 3.12. Autocorrelation Distance Values for 1987-07-02 Signatures: Area 1.

	Signatures										
Signature	7WT2	7FA1	7FA2	7CA1	7CA2	7GR1	7GR2	7PA1	7PA2	7DC1	7DC2
7WT1	11.9	98.9	54.0	35.4	37.4	30.3	24.8	23.6	15.3	10.8	19.2
7WT2	0.0	95.9	57.3	40.6	44.5	36.2	29.2	28.4	18.4	17.4	24.5
7FA1		0.0	2.5	54.4	44.8	54.6	36.7	4.4	4.8	25.7	15.3
7FA2			0.0	33.8	26.5	29.3	17.9	2.9	2.3	15.5	8.6
7CA1				0.0	**1.0**	**0.6**	10.2	13.8	14.3	18.4	7.2
7CA2					0.0	**0.8**	11.6	13.0	13.0	16.2	5.9
7GR1						0.0	2.4	6.7	7.7	7.2	2.7
7GR2							0.0	2.2	2.9	2.1	**1.0**
7PA1								0.0	**0.3**	**1.4**	**1.1**
7PA2									0.0	**2.0**	**1.6**
7DC1										0.0	**0.8**
7DC2											0.0

Table 3.13. Spectral Signatures for 1987-10-06 Imagery: Area 1.

Signature and Number Pixels	Channel 5		Channel 4		Channel 3		Channel 2		Channel 1	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
OWT1 (634)	9.61	9.55	8.54	4.80	16.21	2.74	18.97	1.39	54.72	1.95
OWT2 (547)	9.08	8.51	14.51	3.81	30.09	1.45	26.72	1.03	65.47	1.63
OFA1 (2549)	86.88	5.41	31.36	2.91	33.13	2.44	26.22	1.55	66.32	2.06
OFA2 (4090)	88.80	4.77	38.07	3.34	39.80	3.35	29.57	1.76	70.02	2.53
OCS1 (1254)	111.17	7.95	73.29	6.42	68.53	7.56	43.47	4.02	85.46	5.83
OCS2 (1416)	104.87	12.30	69.10	8.90	62.82	8.50	40.31	4.32	80.34	5.28
OFR1 (960)	74.30	7.47	66.37	8.43	25.14	3.49	25.73	1.58	63.74	2.44
OPA1 (1074)	84.96	14.11	41.26	5.97	34.47	4.38	26.60	2.42	65.48	3.15
OPA2 (712)	81.87	16.30	40.59	6.55	33.20	4.37	26.23	2.50	64.92	3.46
ODC1 (759)	54.87	17.88	31.14	6.95	27.42	4.83	23.08	2.62	60.48	3.93
ODC2 (532)	71.68	15.60	37.87	7.64	33.94	8.14	26.53	4.32	65.31	5.78

Table 3.14. Autocorrelation Distance Values for 1987-10-06 Signatures: Area 1.

	Signatures									
Signature	OWT2	OFA1	OFA2	OCS1	OCS2	OFR1	OPA1	OPA2	ODC1	ODC2
OWT1	19.3	31.1	34.4	40.1	22.3	28.4	11.5	8.5	4.9	8.7
OWT2	0.0	33.1	36.0	46.3	25.2	32.2	20.1	13.3	10.8	12.6
OFA1		0.0	1.8	20.7	10.9	8.9	5.1	5.7	8.2	2.9
OFA2			0.0	14.5	7.8	8.9	4.9	4.8	8.1	1.8
OCS1				0.0	0.4	15.7	9.8	10.2	11.9	6.8
OCS2					0.0	12.8	5.7	6.1	7.1	4.1
OFR1						0.0	6.6	5.9	8.2	7.3
OPA1							0.0	0.1	1.0	0.8
OPA2								0.0	0.7	0.6
ODC1									0.0	0.6
ODC2										0.0

Table 3.15. Spectral Signatures for 1988-07-20 Imagery: Area 1.

Signature and Number of Pixels	Channel 5		Channel 4		Channel 3		Channel 2		Channel 1	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
8WT1 (634)	12.43	18.07	19.79	12.64	24.77	7.14	27.29	4.53	77.51	5.12
8WT2 (547)	11.35	11.9[illegible]	30.26	9.99	44.77	2.29	38.76	1.28	92.42	2.81
8FA1 (1060)	100.46	31.95	109.31	21.26	53.98	10.35	49.08	6.09	92.61	7.44
8FA2 (2713)	82.15	15.68	108.63	13.68	40.28	10.01	40.46	7.18	86.98	4.15
8CA1 (1105)	78.77	8.50	135.23	11.74	50.15	3.67	49.18	2.79	88.95	1.81
8CA2 (934)	84.06	10.47	115.28	11.92	53.59	4.27	50.41	3.11	90.20	1.95
8GR1 (1744)	77.17	10.03	106.17	6.26	32.34	3.07	34.95	1.90	83.67	2.14
8GR2 (1357)	83.30	8.832	132.37	17.41	34.44	3.90	38.51	2.71	36.50	2.94
8PA1 (1074)	104.52	13.30	88.34	5.98	35.85	3.98	36.42	2.46	86.41	3.07
8PA2 (712)	110.35	16.37	87.23	7.20	38.44	4.74	37.92	2.80	88.50	3.74
8DC1 (759)	82.29	15.59	85.62	9.96	30.29	2.98	32.71	2.17	82.19	2.38
8DC2 (532)	88.96	12.57	88.71	6.73	[illegible].30	4.47	34.[illegible]	2.66	84.25	3.14

Table 3.16. Autocorrelation Distance Values for 1988-07-20 Signatures: Area 1.

Signature	Signatures										
	8WT2	8FA1	8FA2	8CA1	8CA2	8GR1	8GR2	8PA1	8PA2	8DC1	8DC2
8WT1	8.6	22.7	35.9	25.6	17.4	19.7	21.9	18.3	14.3	11.3	15.6
8WT2	0.0	37.0	69.0	30.6	24.8	21.4	24.6	21.3	17.3	18.5	18.3
8FA1		0.0	2.3	30.6	19.4	23.8	22.3	12.2	9.1	22.4	13.5
8FA2			0.0	39.1	22.3	31.0	23.7	20.0	14.9	33.1	18.0
8CA1				0.0	1.2	11.2	7.2	16.7	14.3	17.9	13.2
8CA2					0.0	9.7	3.8	10.1	8.8	12.7	8.8
8GR1						0.0	1.6	4.0	3.6	3.6	2.0
8GR2							0.0	4.0	4.3	3.7	3.2
8PA1								0.0	0.2	0.9	0.4
8PA2									0.0	1.4	0.7
8DC1										0.0	0.4
8DC2											0.0

Table 3.17. Spectral Signatures for 1987-07-02 Imagery: Area 2.

Signature and Number of Pixels	Channel 5		Channel 4		Channel 3		Channel 2		Channel 1	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
7WT1 (943)	10.04	6.18	24.67	5.01	39.45	4.76	38.16	3.44	92.00	4.74
7WT2 (142)	19.70	22.86	47.49	11.45	71.59	7.26	60.4[illegible]	4.79	124.54	8.60
7FA1 (823)	171.67	8.40	74.55	6.57	71.[illegible]7	7.65	51.46	4.05	109.49	5.08
7FA2 (488)	158.10	7.94	62.99	5.01	62.26	[illegible]	4[illegible].33	2.74	103.84	3.90
7CA1 (632)	87.22	8.90	[illegible]6.48	12.89	52.[illegible]5	[illegible].09	51.[illegible]8	3.40	92.55	1.83
7CA2 (751)	100.93	11.98	[illegible]20.86	15.89	49.00	[illegible]	47.56	3.02	95.03	3.07
7GR1 (1856)	106.85	8.45	[illegible].62	7.12	39.20	3.5[illegible]	38.50	2.04	90.08	2.59
7GR2 (918)	114.95	14.11	106.79	8.56	39.71	5.74	40.75	2.85	[illegible]1.28	4.04
7PA1 (357)	119.80	17.49	89.73	9.34	44.11	6.97	40.33	3.58	92.17	4.82
7PA2 (549)	136.32	17.28	93.25	1[illegible].09	50.1[illegible]	6.34	44.04	2.87	96.42	4.39
7DC1 (496)	84.95	16.18	92.90	6.95	31.58	6.20	33.62	3.50	83.43	4.61
7DC2 (637)	101.97	17.67	95.64	7.65	37.80	7.95	37.49	4.02	88.10	5.71

Table 3.18. Autocorrelation Distance Values for 1987-07-02 Signatures: Area 1.

Signature	7WT2	7FA1	7FA2	7CA1	7CA2	7GR1	7GR2	7PA1	7PA2	7DC1	7DC2
					Signatures						
7WT1	13.1	130.6	113.3	109.6	100.7	82.3	59.7	54.2	67.6	56.8	62.9
7WT2	0.0	57.4	50.9	36.1	25.6	29.2	30.6	28.8	29.6	29.4	27.7
7FA1		0.0	1.7	34.4	15.1	20.2	16.7	5.8	3.9	15.6	9.0
7FA2			0.0	32.6	12.4	17.6	17.1	5.7	4.5	14.7	9.3
7CA1				0.0	1.2	9.4	9.9	10.3	8.4	12.3	9.9
7CA2					0.0	5.7	5.9	5.1	4.0	8.3	4.7
7GR1						0.0	1.2	0.6	1.9	1.3	0.3
7GR2							0.0	1.4	1.3	2.9	1.6
7PA1								0.0	0.5	1.2	0.4
7PA2									0.0	3.4	1.5
7DC1										0.0	0.5
7DC2											0.0

Table 3.19. Spectral Signatures for 1987-10-06 Imagery: Area 2.

Signature and Number of Pixels	Channel 5		Channel 4		Channel 3		Channel 2		Channel 1	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
OWT1 (1387)	8.24	4.98	15.06	3.13	25.13	2.19	25.76	1.59	63.37	2.64
OWT2 (182)	16.52	17.00	31.95	6.53	43.55	6.06	39.63	3.96	77.45	7.98
OFA1 (1567)	83.39	7.01	31.21	3.67	31.55	3.00	25.58	1.61	65.67	2.61
OFA2 (1342)	91.68	6.54	49.51	7.96	46.23	4.77	32.63	2.27	72.57	2.66
OCS1 (1247)	102.52	4.09	64.39	4.01	56.69	5.58	38.11	3.40	78.75	5.01
OCS2 (667)	89.81	5.59	43.14	4.57	42.08	3.29	30.69	1.52	70.77	2.34
OFR1 (832)	52.26	7.27	65.35	5.55	26.59	2.54	26.32	1.57	60.75	1.69
OPA1 (660)	87.11	7.81	44.36	3.66	34.48	2.33	27.35	1.50	66.58	2.32
OPA2 (182)	96.13	8.82	50.47	5.31	35.22	2.90	28.06	1.66	66.84	2.20
ODC1 (293)	91.68	6.54	49.51	7.96	46.23	4.77	32.63	2.27	72.51	2.66
ODC2 (376)	72.56	9.57	41.01	6.08	30.99	3.38	25.87	1.95	64.31	2.74

Table 3.20. Autocorrelation Distance Values for 1987-10-06 Signatures: Area 2.

					Signatures					
Signature	OWT2	OFA1	OFA2	OCS1	OCS2	OFR1	OPA1	OPA2	ODC1	ODC2
OWT1	17.3	43.5	70.2	108.4	64.0	39.3	39.6	48.9	11.1	23.9
OWT2	0.0	24.1	21.0	30.8	22.[illegible]	22.2	19.2	23.3	14.7	16.5
OFA1		0.0	4.6	20.5	4.4	28.0	3.7	5.0	2.3	4.3
OFA2			0.0	1.8	0.6	31.8	5.3	8.1	7.9	6.1
OCS1				0.0	7.2	36.6	10.1	9.8	12.9	10.3
OCS2					0.0	27.5	3.3	6.6	6.2	4.3
OFR1						0.0	19.6	14.4	11.6	17.3
OPA1							0.0	0.9	1.6	1.0
OPA2								0.0	2.4	2.1
ODC1									0.0	0.4
ODC2										0.0

Table 3.21. Spectral Signatures for 1988-07-20 Imagery: Area 2.

Target	Channel 5		Channel 4		Channel 3		Channel 2		Channel 1	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
8WT1 (634)	7.13	1.36	20.95	0.92	38.59	0.99	36.56	0.95	91.40	1.27
8WT2 (547)	35.90	36.68	39.98	19.42	39.21	8.46	37.50	4.92	88.59	7.79
8FA1 (550)	171.53	9.72	74.76	7.15	67.71	5.14	50.28	2.63	108.07	3.61
8FA2 (920)	144.80	7.22	60.83	6.17	56.27	6.57	43.58	3.37	99.03	4.08
8CA1 (491)	81.64	8.01	142.71	13.90	47.91	5.21	47.66	3.99	90.92	1.98
8CA2 (235)	94.11	5.13	131.94	11.73	52.47	5.78	51.15	4.61	91.05	1.97
8GR1 (710)	90.64	5.50	127.37	7.88	32.85	1.83	37.84	1.53	85.66	1.79
8GR2 (560)	88.32	6.93	141.68	13.57	37.94	7.24	42.27	4.28	88.14	2.76
8PA1 (872)	128.32	15.08	79.98	9.19	44.84	5.35	40.60	3.19	93.05	4.38
8PA2 (632)	110.92	10.82	108.96	10.03	43.86	5.11	43.36	2.86	92.26	3.87
8DC1 (759)	88.66	10.14	97.75	8.71	33.99	3.38	35.79	2.38	85.26	2.45
8DC2 (532)	92.71	14.36	91.05	8.93	35.35	5.43	36.24	3.65	86.33	3.95

Table 3.22. Autocorrelation Distance Values for 1988-07-02 Signatures: Area 2.

Signature	8WT2	8FA1	8FA2	8CA1	8CA2	8GR1	8GR2	8PA1	8PA2	8DC1	8DC2
	Signatures										
8WT1	5.3	404.4	441.9	235.2	366.0	271.8	183.1	123.0	107.7	104.1	108.6
8WT2	0.0	13.2	15.1	15.2	16.[illegible]	24.3	16.5	6.2	8.8	9.5	7.1
8FA1		0.0	5.0	27.7	34.8	35.8	34.1	5.6	14.8	21.2	12.5
8FA2			0.0	28.7	40.6	55.3	41.6	6.1	21.3	22.5	12.1
8CA1				0.0	2.0	6.7	1.2	14.4	5.8	7.0	6.7
8CA2					0.0	7.1	2.2	15.5	6.5	6.1	6.7
8GR1						0.0	1.8	18.1	[illegible].6	3.7	5.8
8GR2							0.0	17.6	4.9	5.9	6.4
8PA1								0.0	9.4	5.0	2.6
8PA2									0.0	2.4	1.9
8DC1										0.0	0.2
8DC2											0.0

Table 3.23. Supervised Classification Summary for 1988-07-20 Imagery.

Cover Type	% Area Classified: Area 2	% Area Classified: Signature Extension to Area 1
Cereals/grasslands	12.1	8.7
Forest	6.5	7.3
Water	5.2	4.7
Canola (in bloom)	9.8	9.2
Cultivated Fallow	29.6	19.6
Pasture	18.5	21.6
Unclassified	18.3	28.9
Total Area	100.0	100.0

Both areas exhibited large unclassified regions within individual fields and pasture lands rather than scattered, isolated pixels. This may be due to variations in localized landscapes, soils, and cropping practices that manifest variations in the spectral response of cover types. Signature extension to the July 1988 data for Area 1, resulted in 28.9% of Area 1 remaining unclassified (Table 3.23), indicating that the signatures derived for Area 2 did not encompass all the spectral variation of similar land cover types identified in Area 1. In previous studies, signature extension over a few kilometers has been complicated by variations in climate, slopes, soil conditions, agronomic practices and past atmospheric conditions (Ryerson et al. 1979). In other studies, however, signature extension has been applied to large area inventories of agricultural crops including wheat (Kauth and Richardson 1978, Minter 1978, Thomas et al. 1978), potatoes (Ryerson et al. 1981) and canola (Ryerson et al. 1982), without reports of similar complications.

From analysis of spectral signatures and ACD values for the remaining data sets, it was concluded that supervised classification and signature extension for the development of land cover themes would not be suitable for the study areas considered. As an alternative, parallelepiped methods were explored. The parallelepiped classifier has been used previously by Ryerson et al. (1982) for inventory of canola in the Peace River region and potato crops in New Brunswick, and by Brown et al. (1980) for canola inventory in Saskatchewan. This approach has been favored for its computational efficiency, and the opportunity to monitor classification results before they are accepted (Ryerson et al. 1982).

The parallelepiped classifier available with the ARIES-II software allows for utilization of 3 channels of data in the definition of feature space and in subsequent classification. This classifier has the advantage of incorporating a third dimension of spectral data for the definition of a classification feature space compared to parallelepiped procedures that utilize only 2 channels.

Channels 5 (infrared), 4 (infrared) and 3 (visible red) were selected for use in parallelepiped classification because they most frequently held the highest coefficients as determined through principal components analysis (Tables 3.6 and 3.7). Parallelepiped classifications were performed for each date and study area with results summarized in Table 3.24 and 3.25. A number of spectral classes representing variations in single cover types (cereal crops, grasslands, forest, water, cultivated fallow, cultivated stubble, fall seeded crops and standing stubble) were identified through manual interaction with a color monitor display of each image. This procedure enabled a greater degree of operator interaction in spectral class selection and the previewing of results, as compared to either the unsupervised or supervised classification procedures. Typically, an analyst selects individual pixels or groups of pixels representing a cover type, generates a classification and views the results in near real time (Dobbins and Epp 1987). This process is repeated iteratively until satisfactory results are obtained. Although the process is time-consuming, it allows for intermediate viewing of classification results as well as for selective addition and removal of pixels from a spectral class.

Given the potential for spectral confusion of cereals, canola and grasslands/pasture as determined through spectral signature and ACD analyses for the July 1987 data, (Tables 3.11 to 3.22), it was decided to incorporate these cover types as a single cover class (cereals/grassland) as they remained spectrally inseparable during parallelepiped procedures (Table 3.24). This spectral confusion may have been due to the earlier date of July 1987 imagery relative to July 1988, coupled with delayed seeding and germination due to insufficient moisture in the spring of 1987. In the past, delayed seeding due to climate conditions has complicated the selection of training areas because of resulting variable crop conditions that lead to spectral confusion (Ryerson et al. 1985).

In the July 1988 data, grassland pastures could not be consistently separated from cereal crops. This lead to the generalization of a cereals/grassland class. A separate class for spectrally distinct pasture that comprised a small proportion of the total area was maintained. Canola in bloom, forest cover, bare soil surfaces (cultivated fallow), and water bodies were spectrally separable. Unclassified regions and pixels in these data were attributed to roadways, farmsteads, urban centers, gravel pits, and field boundaries, as well as variations in agricultural cover types. This was also the case for the July 1987 data, although a greater proportion of these data remained unclassified compared to the 1988 data (Table 3.24).

In the October imagery, bare soil surfaces (cultivated fallow) and cultivated stubble fields could not be consistently separated from each other, although they were distinct from other cover types. This led to the generalization of fallow and cultivated stubble into one class (Table 3.25). Standing stubble, however, was distinct in color rendition on the imagery as well as in its spectral signatures (Tables 3.13, 3.14, 3.19, 3.20), as determined by earlier supervised classification

Table 3.24. Parallelepiped Classification Summary for July Imagery.

Cover Type	% Area Classified			
	Area 1		Area 2	
	1987-07-02	1988-07-20	1987-07-02	1987-07-20
Cereals/grass	38.0	29.2	49.3	48.3
Forest	7.7	6.2	7.7	5.0
Water	2.5	2.4	5.5	4.6
Canola (in bloom)	7.4	5.4	9.9	8.7
Bare soil surfaces (fallow)	12.7	20.3	17.0	20.4
Pasture	NS	[illegible]	NS	2.4
Unclassified	31.7	[illegible]	10.6	10.5
Total	100.0	100.0	100.0	100.0

NS = not separable from other cover types.

Table 3.25. Parallelepiped Classification Summary for October Imagery.

	% Area Classified	
Cover Type	Area 1	Area 2
Fall crops (fall rye)	1.4	1.1
Forest	13.1	6.3
Water	1.7	4.0
Bare soil surfaces (fallow and cultivated stubble)	20.8	30.2
Pasture and grasslands	8.8	19.0
Standing stubble	22.6	28.4
Unclassified	31.6	11.0
Total	100.0	100.0

procedures. Fall-seeded crops, and in particular, fall rye, could be identified on the basis of spectral signatures and could therefore be classified using parallelepiped procedures. Forest cover and some treed pasture lands were separable from agricultural crop lands, which may be attributed to differential reflectance and shadowing as a result of a lower sun angle at this time of year.

Classification summaries (Table 3.24 and 3.25) indicated that a greater proportion of Area 1 was classified as forest cover and pasture/grasslands in the October imagery than with the July imagery. This suggests that October imagery may be more suitable for identification of these cover types than mid-season imagery due to a greater spectral variation in the respective cover types. Furthermore, the reduction in the proportion of each area classified as water in the October imagery relative to the July imagery was expected, due to the seasonal variations in the ground water table and the drying up of small water bodies throughout the growing season. The July 1988 imagery enabled some discrimination of pasture from cereal crops, which is due to the later date (07-20) of imagery relative to 1987 (07-02), at which time vegetation is more developed. Summaries for cereals and grasslands indicated that a greater proportion of Area 2 consisted of cereal crops and grassland cover relative to Area 1, for both dates of July imagery. This is a reflection of the differences in land use within the respective land districts (Figures 2.1 through 2.4, Chapter II). An increase in the proportion of cultivated fallow in both areas in July 1988 compared to July 1987 was observed. This may have been a management response to the relatively dry 1987 growing season. In the interpretation of color enhanced infrared imagery (Plates 3.1, 3.2, 3.3), it was determined that a greater proportion of land area was cultivated as fallow in the 1988 growing season. Parallelepiped classification results provided a means of quantifying this observation. In addition, the proportion of cereals and canola was reduced in the 1988 crop year compared to 1987. This may also have been a management response to lower market prices of canola and cereal in the earlier part of 1988.

The process of filtering classification results has been reported to assist in the removal of anomalous pixels and voids without significant effect on the proportion of area classified (Ryerson et al. 1985, Dobbins and Epp 1987). Furthermore, Korporal (1983) advocated filtering prior to the integration of theme files within a GIS for removal of speckle, for cartographic generalization, and to avoid excessive data storage and computing requirements. The application of filtering methods (custering) caused an overall reduction in the proportion of unclassified area for each date and area. The unclassified regions within individual fields were infilled by the themes of neighboring pixels, which resulted in a less speckled image, a clearer definition of boundaries between cover types and the development of a more complete thematic coverage for each study area. Filtering procedures also reduced the number of anomalous single pixels that would result in single pixel polygons in subsequent raster-to-vector conversion of theme files.

Summary

A number of approaches to image analysis, including image enhancement, principal components analysis and classification, were explored for purposes of extracting agricultural land cover information for use in land cover monitoring. Color infrared enhancements were useful for preliminary visual interpretation of the study regions, and enabled the identification of generalized land cover types: cereals, canola, fallow, stubble, fall-seeded crops, some forest and pasture lands. Interpretations were qualitatively based on known spectral characteristics of cover types, and the quantification of areal extent of cover types was dependent on classification procedures.

Principal components-enhanced image products produced more dramatic color renditions of cover types, but without coincident verification field data, only generalized interpretations could be made. From the standpoint of visual analysis, when coupled with detailed field data, principal components enhancements may serve as an alternative to color-infrared enhancements for updating GIS data bases. For large area conservation planning and erosion risk modelling, enhanced images are useful for the visual extraction of land cover information for incorporation into spatial analyses models. An example of such an application is the derivation of the cropping practice factor, an integral component of the Universal Soil Loss Equation (Wischmeier and Smith 1978), as demonstrated by Morgan et al. (1980) and Morgan and Nalepa (1982), through use of aerial photography, and by Cihlar (1987) through use of LANDSAT imagery. The use of color-infrared enhancements has also proven useful for the determination of conservation tillage practices on an annual basis (DeGloria et al. 1986).

For purposes of integration within a GIS, enhanced images are useful as a backdrop display (Korporal 1983, Aronoff et al.1987) and can be used to update existing GIS coverages (Gugan and Road 1988) and to determine temporal changes in land cover. For agricultural land inventory and soil conservation applications, enhanced image products are useful for observing field boundary changes, land clearing and cropping patterns, but do not provide a ready source of information on the areal extent of cover types. This information may be obtained through other forms of image analysis, such as classification, or through querying the data once it is integrated within the GIS. Areas of specific cover types may then be calculated on the basis of polygons in a vector GIS, or grid cells in a raster GIS.

Several classification approaches were explored to develop theme files for integration as land cover data layers in a GIS. Unsupervised classification resulted in formation of a large number of spectral classes which were not representative of unique ground cover types. Supervised classification procedures were limited by spectral overlap of signatures, as well as the variability in spectral characteristics of land cover, which precluded the identification of all possible spectral variations of the land cover types of interest. Parallelepiped methods, although time consuming, produced the best classification results for development of generalized land cover theme files. These theme files were then filtered to minimize the proportion of unclassified regions within fields. The vectorization of these theme files, as well as other issues in raster-to-vector format conversion and data integration are addressed in Chapter IV.

IV. INTEGRATION OF LANDSAT TM, SOIL SURVEY AND BASE MAP DATA WITHIN A GEOGRAPHIC INFORMATION SYSTEM

Introduction

In order to integrate LANDSAT imagery with other forms of land-related information within a GIS, it is necessary to convert the data to a compatible format. The data must also be spatially referenced to a common projection system to enable registration and overlay analysis. This portion of the study focuses on the integration of LANDSAT theme files with soil survey and base map data in a vector GIS. It also describes raster-to-vector conversion of, and changes in the data structure of LANDSAT theme files, and the development of a spatio-temporal database for subsequent use in soil erosion risk monitoring.

Background

The integration of LANDSAT data with more conventional forms of land information within a GIS holds much potential for improvement in the methods used for inventory and monitoring land resources. According to Marble (1984), the GIS represents an effective mechanism for making use of the data captured by remote sensing systems, and offers potential for increasing the effectiveness of this data through correlation with data already held by the GIS. The process of integration can be quite complex, particularly if there are fundamental differences between data sets in terms of format, structure (raster or vector), quality (age, accuracy, scale) as well as processing and format conversion requirements.

Traditionally, integration of spatial data sets has been carried out by transforming the data sets to a common map scale, creating an overlay for each data set, registering these overlays so that coordinate systems are aligned, and then manually creating a composite overlay sheet that shows where the various phenomena being studied occur in spatial juxtaposition (Marble 1984). The time involved in this process has been so great that it has been utilized far less than one might expect (Marble 1984). The development of data base management systems, and more recently, GIS technologies, has since enabled more efficient storage, processing, integration and spatial analysis of many kinds of land-related information.

Data Structures

Fundamental differences exist between the spatial information commonly used as input to a GIS (see Table 1.4) and LANDSAT digital data. The former are map information represented by points, lines and polygons with associated attribute information, typical of vector data structures.

In comparison, LANDSAT data are raster data, with grid cells containing attribute data in the form of radiometric values or theme numbers.

Although there are significant practical differences in raster (grid) and vector (line) data structures (Table 4.1), the primary theoretical difference is that the grid structure stores information on the interior or areal features, and implies boundaries, whereas the line structure stores information about the boundaries and implies interiors (Berry 1987). Geographic information, derived from field investigations, thematic maps, or statistical data bases commonly contains more than one attribute associated with a given spatial location, whereas remotely sensed data usually have only one attribute (a radiometric value or a theme number) associated with each pixel (Zhou 1989).

Raster data structures are easily handled in computers because arrays of rows and columns can be easily stored, manipulated and displayed (Burrough 1986). In contrast, in a vector system, straight line segments are defined by a begin point and an end point as X and Y coordinate pairs, while curved lines are represented by a series of short line segments (Burrough 1986). The data processing associated with vector data is, therefore, more complex, although the data structure is more compact. A summary of some characteristics of raster and vector data is presented in Table 4.1, while detailed comparisons are presented by Burrough (1986).

Table 4.1. Comparison of Raster and Vector Characteristics.

Characteristics	Raster	Vector
Data Structure:	grid cells	points, lines, polygons
Referencing:	X,Y coordinate pairs	X,Y coordinate chains
Processing:	pixel processing	vector processing
Line Width:	fixed, depends on grid cell size	variable, depends on symbology used
Boundaries:	staircasing phenomenon	curvilinear or straight line

Goodchild (1987) has identified several issues involving the storage of spatial data and distinguishes between raster and vector on the basis of data organization and sampling. He differentiates raster data as being organized according to spatial address whereas vector representations are organized by object and necessitate different approaches to the indexing of information (tiling vs. spatial and object indexes). The issue of sampling is also considered: a vector data set represents a variable intensity of sampling whereas a raster implies a uniform intensity (Goodchild 1987).

The data storage structure of a GIS will influence the manner in which spatial data must be processed for integration. According to Ehlers et al. (1989), the "raster/vector dichotomy" has confounded many attempts at integration, as remote sensing has been oriented towards a raster approach to data analysis, while GIS software tends to be vector oriented. They suggest that the solution to integration of remotely-sensed imagery into GIS technology involves rethinking the data structures of most existing GIS.

A major challenge in the design of an integrated spatial data base is the identification of a data structure suitable for holding all forms of spatial data (rasters, points, lines or polygons) in a compact form which allows for efficient retrieval and processing (Jackson and Mason 1986). The integration of point-referenced spatial statistics and raster format remotely-sensed data necessitates the mixing of point, line and polygon data from several sources and their incorporation into a single computational environment (Jackson and Mason 1986). Subsequent processing of the data may be compared in terms of the algorithms necessary for spatial analysis; polygon overlay is more easily executed in raster than in vector representation (Burrough 1986, Goodchild 1987). On the other hand, overlay analysis involving intersection of polygons through use of newly developed vector algorithms can be competitive with raster overlay procedures (Goodchild 1987).

Approaches to Integration

The integration of LANDSAT image data within a GIS can be accomplished in several ways, but depends largely upon the image analysis and GIS systems available, the type of analyses to be performed, and the desired output products. One approach involves the use of satellite imagery as a backdrop for graphic map (line or polygon) displays for updating or revising data contained in a GIS. This application has been demonstrated by Catlow et al. (1984), Aronoff et al. (1987), and Gugan (1988). The display of satellite imagery through a GIS graphics display may result in degradation of the original radiometric resolution of the image, and integrated display systems for GIS graphics and 24-bit RGB (red-green-blue) images are therefore a precursory requirement for functionality (Archibald 1987). Through use of LANDSAT image displays in a GIS, change detection is possible at larger scales than with primary mapping and the large areas covered by the imagery contributes to cost-effectiveness (Gugan 1988). The interactive interpretation of image data, however, is less efficient than automated classification and raster-to-vector conversion (Sauchyn and Xongchao 1991).

Another form of integration involves using satellite imagery as a GIS data layer. For this type of integration, image data are first processed in an image analysis system to develop a theme file, a density-sliced or a vegetation index image file prior to input to the GIS. In order to achieve topological integration of LANDSAT data with other forms of data in the GIS, raster-to-vector conversion of the image data is required (Sauchyn and Xongchao 1991). The original theme numbers, density-sliced values or vegetation indices associated with individual pixels are retained as attributes for resultant polygons.

For integration within a raster GIS, pixel resolution must be compatible with that of other data in the GIS, otherwise additional processing is necessary (see for example, Welch et al. 1988). This may involve the resampling of image data to a larger pixel size, which often results in data generalization and loss of original image detail, as is the case when one resamples from a 30 m pixel to a 50 m pixel or larger, in geometric correction. On the other hand, the integration of image data within a vector system that necessitates conversion from raster to vector format can also lead to data generalization and loss of original image detail. This occurs when small polygons are eliminated for data volume reduction as well as in the removal of spurious polygons. Generally, in the rasterization of vector map products, as the grid cell size increases the accuracy of the product decreases (Wehde 1982).

The necessity for conversion of raster data to vector format, or vice versa, is dictated by the type of GIS used. An overview of commercially available GIS systems and their characteristics is presented by Parker (1989). The process of raster-to-vector, or vector-to-raster format conversion involving interpolation may cause some loss of image or map detail and may lead to errors in subsequent GIS-based analysis. Spatial interpolation methods that are more commonly used in geographic applications are discussed by Lam (1983). Few methods exist for assessing the accuracy of post-conversion data sets. The process of data inversion, as in pycnophlactic interpolation (Tobler 1979, Lam 1983), has been advocated by Lam et al. (1987) as a test for the reconstruction of the original data in evaluation of conversion algorithms.

Raster-to-Vector Conversion

The process of converting from raster to vector format can be divided into three basic operations: skeletonization, line extraction or vectorization, and topology reconstruction (Peuquet 1981a). Ancillary operations to this process are line smoothing, and spike and gap removal, which are required to eliminate inaccuracies present in either the input data or induced by the algorithms used in skeletonization or line extraction (Peuquet 1981a).

In raster-to-vector conversion, polygon boundary mismatch may arise due to the staircasing phenomenon of the raster data, presence of island polygons, or application of line smoothing (spline) functions. Errors in boundary representation may also occur due to the presence of boundary pixels in the original LANDSAT data, due to original spatial resolution or post-geometric correction pixel resolution. According to Burrough (1986), classification errors occur when grid cells are larger than the features about which the information is desired. He suggests that boundaries on thematic maps should not be regarded as absolute, but as having an associated error bands or confidence intervals.

According to Peuquet (1981a), existing raster to vector conversions vary widely in the algorithms used, and when applied to cartographic data, the resulting inefficiencies may include the thinning of very thick map lines, poor line quality (gaps, variability in thickness, and rounded junctions) which can lead to errors or ambiguities during the conversion process.

Vector-to-Raster Conversion

The process of converting vector data to raster format can be divided into two components: rasterization and line thickening, and are detailed by Peuquet (1981b). Rasterization is the actual process of producing raster format data from vector data, whereas line thickening involves the creation of lines of varying thickness from the skeletonized data (Peuquet 1981b).

The process of vector to raster conversion requires careful consideration of data resolution: if the resolution of the rasterized maps is too coarse, detail in the original map will be lost or distorted, and if the resolution is too fine, the resulting raster product will contain a large volume of pixels and processing time may become prohibitive (Scott 1984). According to Clarke (1985), once a resolution cell size is chosen, conversion of line information such as polygon boundaries is relatively simple; and when areal data are converted, the process is more complex as the gridding of polygons produces sharp discontinuities, a condition which is not compatible with continuous spatial data. Potential also exists for error propagation during vector-to-raster conversion when greater than one polygon intersects with a grid cell (Lam et al 1987, Barker 1988). Additionally, topological mismatch occurs when a polygon is approximated by a grid, as in the case of bisecting true boundaries (Frolov and Maling 1969, Burrough 1986). The effects of these errors could be significant depending upon the GIS application, with common errors in areal estimates being a function of cell size, polygon area and complexity of polygon boundaries (Goodchild 1980). Clarke (1985) has cautioned that all converted data will include error as will further transformations of the resulting data layer.

Cell size for raster analysis also becomes an issue with respect to error in data format conversion. For example, Wehde (1982) reported that as cell size was allowed to increase, the accuracies of mapping products decreased. He recommended that the interboundary distance of polygons is an appropriate measure in determining cell size for rasterization. As an example, Cowen et al. (1988) observed that the 30 m resolution of TM pixels was too small for a 136 km^2 study area, and that the subsequent elimination of single pixel polygons disrupted small areal and linear features.

In vector-to-raster conversion, output grid resolution, staircasing, line splitting, line smoothing, boundary preservation, treatment of island polygons and missing data, and the complexity of the original data may impose functional limitations in terms of product accuracy. Subsequent to data conversion, overlay analysis using raster processing may be limited by variations in polygon boundary locations which cause the formation of spurious polygons. This is also a problem common to vector-based polygon overlay.

Additional sources of error may lie with the conversion algorithm. Error involved in conversion can be attributed to the lack of inversion properties in the algorithm (Lam et al. 1987). Few studies reported in the literature have addressed the issue of preservation of the original data as a result of raster-to-vector or or vector-to-raster format conversion. This may be due to the lack of methods available for assessing the accuracy of the resulting product.

A relatively new area of research in GIS is that of error determination in spatial analysis (Bedard 1987, Campbell and Mortenson 1989, Klinkenberg and Xiao 1990). Errors within the GIS data include locational and attribute errors, as well as errors introduced during data capture and processing (Campbell and Mortenson 1989). Although much has been written on the advantages and potential of GIS applications to natural resource inventories, there remains a lack of guidelines for measuring and ensuring accuracy and precision at different stages of GIS data base development (Campbell and Mortenson 1989).

Case Studies

General applications of integrated remote sensing and GIS technologies have involved land inventory and land use change studies (Nelson et al. 1981, Marsh et al. 1990, Nellis et al. 1990). Specific applications have included the adjudication of water rights (Morse et al. 1990), monitoring of irrigation agriculture (Astroth et al. 1990) and the study of forest fire impact on ecological change (Jakubauskas et al. 1990). The utility of these combined technologies for large area soil erosion risk inventory has also been demonstrated in the United States by Patterson and McAdams (1982) and Ventura (1988), and in Canada, by Xongchao (1988) and Sauchyn (1989).

Of the different approaches to integration reported in the literature, most were governed by the systems used, project objectives and desired output products. Integration has been achieved through such labour intensive efforts as manual interpretation of LANDSAT imagery followed by digitizing for data entry to a GIS (Marsh et al. 1990), or through the use of a zoom transferscope to produce overlay maps of LANDSAT imagery and topographic information for subsequent GIS evaluation (Astroth et al. 1990).

More automated integration has involved the input of LANDSAT theme files as data layers within a GIS through raster-to-vector data format conversion. Korporal (1983) utilized a raster-to-vector conversion process in which classified LANDSAT data (theme files) were vectorized and then converted to a Standard Data Transfer Format (SDTF) (Goodenough et al. 1983) for input to a GIMMS GIS. Problems encountered in integration included topology errors that prevented the formation of closed polygons, and the necessary removal of scattered pixels within theme files to reduce data storage requirements.

Aronoff et al. (1987), in working with ARIES and ARC/INFO systems, developed methods for displaying GIS-derived vector coverages over LANDSAT imagery in the ARIES system, while maintaining image analysis capabilities. This integrated raster/vector processing package enabled interactive raster calculations on the basis of polygons and the subsequent updating of polygon attributes, although only the visual display was integrated. The image data and GIS data remained separate and therefore the integration was done visually and in the mind of the viewer (Aronoff et al. 1987). In this particular system, the calculations applied to polygons during overlay analysis took place in the image analysis system. More recently, Derenyi and Pollock (1990) extended a vector GIS (CARIS) with the raster image handling capabilities of a PCI image analysis system. This configuration enabled delineation of training areas for use in image classification on the basis of forest cover maps stored in the GIS, transfer of training area information to the image analysis system for use in classification and the transfer of classification results back to the GIS. Although both of the preceding approaches utilized the capabilities of an image analysis system and a GIS, the systems remained separate and the integration process involved the transfer of data back and forth between systems.

The use of remotely-sensed imagery in GIS analysis has taken several other forms. Manual interpretation of airborne imagery, followed by digitization of interpreted boundaries was utilized by Marsh et al. (1990) in the development of land use data layers for input to an ARC/INFO GIS. Classified and level-sliced imagery, for comparison with the manually interpreted data, were also entered into the GIS through use of an ERDAS image analysis system export procedure. Although the classified image data were filtered using a 3x3 filter prior to input, additional processing within the GIS was required to remove small polygons, as over one half of the total number of polygons formed during vectorization represented areas of less than four pixels in size (Marsh et al. 1990). The conclusion derived in this study was that supervised classification and GIS map generation required significantly less time and manpower than manual interpretation of airborne image data for generation of land use maps.

The physical integration of image data as vector GIS data layers necessitates their conversion from raster to vector data format. When a raster GIS is used, ancillary data, such as soils, forest cover or base maps require vector-to-raster format conversion As an example, in a study by Goodenough (1988), forest cover maps in digital format were converted to raster format for use in a PAMAP GIS. These data were then used to delineate training areas on TM and SPOT imagery for classification in an LDIAS system. Classified image data were converted to an intermediate grid format, then to a vector representation with smooth polygon boundaries and a linkage to an attribute data base. This study demonstrated that some polygons from the digital map corresponded to nonhomogeneous areas on imagery, that boundaries between water bodies depicted on maps differed in size and shape from those on the imagery, and that ambiguities in map labelling interfered with the vector to raster conversion process. Recommendations made included the utilization of expert systems to improve interpretations and to change the image analysis approach from supervised classification to one of cluster analysis within polygons.

As a comparison of data formats Cowen et al. (1988) performed overlay analysis in both raster and vector modes for timber stand assessment using TM data and digital line maps. They concluded that there were no differences between the results of analyses conducted in vector or grid cell format.

The integration of image data from an ARIES II (Dipix Systems Ltd.) image analysis system within an ARC/INFO GIS necessitated the development of algorithms for translation of image data to a format that can be read into ARC/INFO for subsequent vectorization (Maher et al. 1983, Aronoff et al. 1987, Sauchyn and Xongchao 1991). In this process, image data are converted from binary format to ASCII to single variable format (SVF), and then are vectorized using the "GRIDPOLY" function in ARC/INFO (Sauchyn and Xongchao 1991).

Although the literature reviewed advocates the integration of remote sensing and GIS technologies for improved spatial analysis of land resources, much remains to be done in the development of efficient methods for transferring data between the two types of systems. Commercially available GIS's vary in the level of sophistication of integration routines that enable efficient data exchange with image analysis systems. For example, the ERDAS-ARC/INFO linkage is well documented and available commercially (ERDAS 1990a, 1990b), while the ARIES-ARC/INFO linkage has taken many forms (Aronoff et al. 1987, Goodenough 1988, Zhou 1989). Although many vendors advertise capabilities for integration, this is dependent largely on the user having specific complements of hardware and software available, and often serves as a deterrent to operational integration. For operational applications, users often embark upon development of customized algorithms necessary to transfer data between the image analysis and GIS systems within their access, resulting in repetition of efforts. Most often the integration takes the form of data transfer between systems, rather than the integration of image processing and GIS capabilities in one platform. To this end, a number of theoretical designs for integrated systems have been proposed by Goodenough (1988), Ehlers et al. (1989) and Zhou (1989). As the concept of fully integrated systems is still relatively new, there is much research that remains to be done regarding development, implementation and evaluation of such systems.

Materials and Methods

Data Acquisition

The 1:20,000 scale digital base map positional files were purchased from the Alberta Bureau of Survey and Mapping (ABSM). Digital soil survey information (1:50,000 mapping scale) were acquired through the Soil and Land Resource Inventory Unit of the Alberta Research Council. LANDSAT Thematic Mapper data (see also Table 3.2) were acquired from the Prince Albert Satellite Station in Saskatchewan. Specifications for these data are presented in Table 4.2.

Table 4.2. Data Specifications.

Data	Scale	Format	Cost at Acquisition
Digital Base Map Positional Files NTS Map Sheets: 73D05NE 73D06NW 73D11NW 73D11SW 73D12NE 73D12SE 73D13SE 73D14SW	1:20,000	ISIF (Intergraph Standard Interchange Format)	$190.00 per map sheet
Soil Survey of the County of Flagstaff, No. 29	1:50,000	ASCII "Spaghetti files" converted to ARC/INFO coverages	no charge (internal to the Alberta Research Council)
LANDSAT TM digital image data Channels 1-6: 1987-07-02-Q3 1987-10-06-Q3 1988-07-20-Q3	30 m pixels	Digital Raster files	$1475.00 per image

Data Processing and Integration

An ARIES-II image analysis system (R-Stream) and ARC/INFO software (Version 4.01) on VAX 6210 and PRIME 9650 platforms were utilized. The data processing necessary for integration of the data utilized in this study involved:

1. Image analysis of LANDSAT TM data (see Chapter 3);
2. Vectorization of LANDSAT theme files;
3. Uploading, processing and production of coverages for base map, soil survey and LANDSAT data in ARC/INFO;
4. Extraction of data for the study areas; and
5. Development of integrated LANDSAT theme files and soils coverages for use in spatial analysis of soil erosion risk.

A glossary of terminology relevant to the following discussion is presented in Appendix I.

Base Map Data

Eight, 1:20,000 Provincial Digital Base Maps (positional files) were obtained in digital Intergraph Standard Interchange Format (ISIF) (Intergraph 1982). These data were uploaded from magnetic tape to a VAX 6210 mainframe using VAX system procedures, then loaded into ARC/INFO using ARC.SIF procedures. For each processed base map file, the ARC.SIF procedure generated separate graphic and attribute files. Elements of the graphic files (lines, points, markers and annotation) were referenced by internal record numbers to respective records in attribute files holding graphic feature identification information (graphic characteristics and feature codes). The ARC/INFO procedure "BUILD" was used to create line coverages and arc attribute tables (AAT's) for the graphic data. The attribute data from ARC.SIF were then merged to the AAT's via the "JOINITEM" procedure, using the internal record numbers for relating the data. This was carried out for eight base map coverages.

These base map coverages were then transformed from the X,Y coordinates internal to the Intergraph system to the UTM coordinates for the study area location, through application of an affine transformation using the "TRANSFORM" procedure in ARC/INFO. This process was applied to each of the digital base map files, resulting in eight coverages with graphics and line attribute files, spatially referenced in the UTM system.

Additional processing of these data was required to extract the Alberta Township Survey (ATS) grid, hydrography, and transportation networks for each study area. Preliminary boundary coverages to be used as templates in the extraction of this information were produced using the "GENERATE" procedure through specification of UTM coordinates for the corner points of boundaries slightly larger than each study area. These boundary coverages were then used to extract the ATS quarter section grid data through "RESELECT" and "CLIP" procedures. Topology and polygon attribute tables for these coverages were then created using the "BUILD" procedure.

The portions of the ATS quarter section grid that were external to each study area, due to the larger size of the preliminary boundary file, were removed from each coverage using the "RESELECT" procedure. The end products were quarter-section grid coverages for both study areas. A boundary coverage for each area was then produced using the "RESELECT" command (left-poly or right-poly equivalent to zero) to retain the ATS grid lines corresponding to study area boundaries. Labels were then added to each study area boundary coverage through the "CREATELABELS" procedure, and the "BUILD" procedure with a polygon option was used to generate topology and attributes for the boundary coverages. These boundary coverages were utilized as templates or "clipcovers" in extraction of additional base map information, as well as in extraction of LANDSAT theme files and soil survey information corresponding to each study area, through use of the "CLIP" procedure.

The process of clipping several of the original base map coverages aborted due to an internal processing limitation of the ARC/INFO software that does not allow for the intersection of more than 100 line segments at a node. This necessitated simplification of the original base map coverages to reduce the complexity of the line data. The "RESELECT" procedure was used to separate hydrography and transportation networks, and contour lines into separate coverages. The "CLIP" procedure was then used to extract study areas from these simplified coverages. The clipped portions of each base map were then amalgamated into individual coverages for each study area using the "APPEND" procedure, followed by "CLEAN" and "BUILD" procedures to update attribute files.

Hardcopy output map products of these features were generated for each study area and inspected. Discontinuities in linear features, particularly ATS grid lines and roads, necessitated manual editing through use of "ARCEDIT" procedures to correct the graphic files and to update arc attribute files. The procedure used involved "nodesnapping" and recoding of line feature identification numbers to the appropriate feature designations (e.g. 1=township, 2=section, 3=quarter section). In addition, a point coverage was created for each area, in which section numbers were assigned interactively to the centroid of each section of the ATS grid, for subsequent use as graphic overlays.

LANDSAT Theme Files

Theme files for bare soil surfaces (fallow), cereal crops, grassland/pasture, canola, fall crops, stubble, forest cover and surface water were produced through parallelepiped classification procedures (Chapter 3) for both study areas and respective dates of imagery. Theme files were output to magnetic tape (1600 bpi) via the ARIES task "TO". Processing of theme files prior to vectorization involved uploading of files to a VAX 8600 at the University of Regina, followed by translation of the "TO" files from binary format to ASCII. This was followed by translation to single variable format (SVF) files using software developed by Sauchyn and Xongchao (1991). The SVF files were then read into ARC/INFO on a PRIME 9650 platform and the "GRIDPOLY" function was used to create vector coverages with topology and polygon attribute data. Input information for the vectorization process included specification of a 30 m grid cell size and UTM coordinates for the lower left corner of each theme file. Theme numbers corresponding to the land cover classes were preserved within the item "GRID-CODE" in the respective polygon attribute (PAT) files.

Additional processing of the vectorized theme coverages involved the removal of small polygons (<15,000 m^2), formed by isolated pixels and small pixel groupings present in the original theme files, which contributed to the volume and topological complexity of these data. These small polygons also exceeded the resolution of the digital soils data, given that the minimum legible delineation (MLD) for a survey of 1:50,000 scale is 12.5 ha (Expert Committee on Soil Survey 1987). Elimination of polygons smaller than 1.5 ha in size was accomplished through the "ELIMINATE" procedure with specification of a "keepedge" option to ensure that the perimeters of the study areas were retained. The number of polygons present in each coverage before and after elimination was noted. Because these coverages represented areas that were slightly larger than the study areas, due to the allowance for a buffer region, study areas were then extracted using boundary files and the "CLIP" procedure. The resulting coverages were previewed, converted to an ARC/INFO export format, read to magnetic tape and transfered to an ARC/INFO installation on a VAX 6210 at the Alberta Research Council.

The vectorized LANDSAT-derived land cover data were previewed as color monitor graphic displays and as hard copy maps. The ATS grid coverages derived from the base map data were superimposed on the landcover coverages for preliminary evaluations of data registration and preservation of field boundaries. Areal summaries of land cover distribution for each coverage were produced using the "REPORT" procedure and then compared to the original classification summaries derived in the ARIES system.

Digital Soil Survey Data

The digital format soil survey data, originally mapped at a scale of 1:50,000 (MacMillan et al. 1988), required considerable processing to achieve compliance with published map products and to develop correct topology and attribute files. These data were originally digitized into a Geo-Based Strings GIS (Version 3.1) with attribute data entered into dBase III, and subsequently transferred to ARC/INFO as ASCII text files (Krzanowski et al. 1988). These data were then processed as 4 separate ARC/INFO coverages representing quadrants of the County of Flagstaff and then archived as export files (Krzanowski et al. 1988). The export files of the NE and SE quadrants were then uploaded to the VAX 6210 and imported into ARC/INFO as polygon coverages. Hard copy maps derived from these data were compared against the published survey maps (MacMillan et al. 1988), and discrepancies noted and corrected (Appendix II). Manual editing of the graphics and attribute files to remove multiple label points within polygons and to replace incorrect series names was done through use of "ARCEDIT" and "UPDATE" procedures.

Subsequent application of "BUILD" procedures to update the feature attribute tables resulted in corruption of the attribute files in that polygon identification (ID) numbers were reordered relative to the internal record numbers and in some cases were replicated, causing soil series names to be incorrectly assigned to polygons. Several iterations of editing were performed, in which corruption of the attribute files followed the application of "BUILD" procedures. These data could not be used in subsequent processing, and the creation of new coverages for the soils data corresponding to the study areas was necessary.

New coverages were created for each study area through extraction of the line features of each study area using "UNGENERATE" and "GENERATE" procedures. Single label points for each polygon were created using the "CREATELABELS" procedure, and a polygon attribute data base was developed through application of the "BUILD" procedure to each study area. The resulting polygon attribute tables contained topological information (area, perimeter, internal record numbers and polygon ID numbers) unique to each polygon. Soil series names were then added to the polygon attribute table of each study area through use of a "JOINITEM" procedure. Polygon areas were used as the common link between tabular listings of polygon areas and soil series names obtained from edited versions of the polygon attribute files (i.e. after updating with "ARCEDIT", but before "BUILD" was applied). Manual checking of the resulting polygon attribute tables revealed that all internal record ID numbers were unique and that after application of the "BUILD" procedure, they remained unaltered. Hardcopy map products were generated using the new coverages and compared against published maps for compliance and were determined to be in agreement.

A tabular file of soil map unit names and corresponding soil erosion ratings for bare soil, cereal, canola and alfalfa cover based on the ratings presented in the soil survey report (MacMillan et al. 1988) was developed. The "JOINITEM" procedure was used to update the existing polygon attribute files by using map unit names as the common linkage between data files. Soil erosion risk distributions based on the updated attribute data were produced as hardcopy maps for each area. Additional discussion of the soils information follows in Chapter 5, where it is applied to the spatial analysis of soil erosion risk.

Integrated Coverages

Integrated coverages of soils data and vectorized LANDSAT theme files were created using the "INTERSECT" procedure in a step-wise manner for each area. Firstly, the soils and the 1987-07-02 land cover coverages were combined as an overlay, to produce a new graphics file and a polygon attribute data (PAT) file. The resulting coverage was then combined with a third coverage of 1987-10-06 land cover and a new spatio-temporal coverage generated. During the addition of this third coverage, the ARC/INFO processing limitation of 10,000 arcs per polygon was exceeded which caused the procedure to abort.

To simplify the complexity in structure of the soils coverages, new coverages were created for each study area consisting of polygons whose erosion risk ratings were ≥3 (moderate) to 6 (extreme), through use of the "RESELECT" procedure. This procedure enabled extraction of map features from a coverage based on their attribute values (ESRI 1987). These new soils coverages were then combined with the 1987-07-02 land cover data to create an integrated land cover/soils coverage for each area, and polygons smaller than 1.5 ha were removed using the "ELIMINATE" procedure. This integrated coverage was then combined with the 1987-10-06 land cover and polygons smaller than 1.5 ha in size were eliminated. The final stage of integration involved the combination of each resulting coverage with the 1988-07-20 land cover and the removal of 1.5 ha polygons. At each stage of coverage integration, coverage structure in terms of number of arcs and number of polygons was noted. The resulting spatio-temporal data bases and coverages were used in the spatial analysis of soil erosion risk which is described in Chapter V.

Results and Discussion

Base Map Data

A sample of the arc attribute table (AAT) for a base map coverage is presented in Table 4.3. The coverage name is 73D12NE and represents the northeast quadrant of a 1:50,000 scale NTS map sheet.

Table 4.3. Line Attributes for Base Map Coverage.

Item	Description
FNODE#	"From" node
TNODE#	"To" node
LPOLY#	Left poly
RPOLY#	Right poly
LENGTH	Length (m)
73D12NE#	Internal record number
73D12NE-ID	Internal identification number
LEVEL	Line attribute number, e.g. Level 2=township line, 3=section, 4=quarter-section, 11=perennial lake, 16=perennial river
WEIGHT STYLE COLOR TYPE	Additional Intergraph graphics information

Difficulties encountered in the processing and extraction of these data for the study areas included insufficient central processing unit (CPU) allocation and the internal processing limitations of the ARC/INFO software. The original CPU allocation of one hour, that was subsequently partitioned into a 15 minute sub-process allocation by the operating system, was not sufficient for the processing of individual base map coverages during "CLIP" procedures. The CPU allocation was raised to four hours, and the resultant sub-process allocation of one hour of CPU was adequate for processing the base map coverages.

Another processing limitation of ARC/INFO software does not allow for the intersection of more than 100 line segments at a node. This limitation was encountered during attempts to clip the full complement of each original base map, and caused the procedure to abort. Therefore, extraction of base map data for the study areas required the simplification of the structure and complexity of the original base map coverages. This was achieved by separating the contour lines from the base map data using the "RESELECT" procedure. Other data not required for this project (e.g. international boundary monuments, registration marks, geographic borders) were also eliminated for further reduction of data volume and complexity. Hydrographic information (lakes, rivers, streams), transportation networks (highways, roads, railways) and municipal information (towns, settlements) were retained for use as graphic overlays on final map products. After the reselection process, attribute files were updated through application of the "CLEAN" procedure. When applied to line data, this function performs a geometric analysis on the arcs and label points, identifies intersections between arcs and codes these as nodes, and updates topology and feature attribute information for each arc (ESRI 1987). These simplified base maps were then clipped by the respective study area boundary files. The resulting portions of these base maps were amalgamated into single coverages of contour lines, transportation, and hydrography information for each study area using the "APPEND" procedure with "line" and "features" options (APPENDIX III). The "BUILD" procedure with a "line" option was then applied. This procedure creates or updates feature attribute tables and defines arc-node topology (ESRI 1987).

Graphics display and hardcopy products of the base map data for each study area revealed discontinuities in lines features (e.g. breaks in township grid lines and roads) which necessitated manual editing of graphic and attribute files through use of "ARCEDIT" to correct these discontinuities. The process of deriving suitable graphic overlays of base map information demonstrated the necessity for additional processing when a study area spans the intersection of several base maps, and tested the limitations of the GIS software due to the complexity and volume of the original base map data. The need for manual editing of these data also increased the amount of time required for development of base map coverages corresponding to the study areas.

The final base map coverages for both study areas are presented in Appendix III. The hydrography and transportation networks provide an indication of where boundary pixels are most likely to occur in the LANDSAT imagery, and may serve as a means of stratifying or masking the imagery prior to image analysis or after vectorization.

LANDSAT Coverages

An example of a polygon attribute file for a vectorized LANDSAT theme file is presented in Table 4.4. FLCJ87 is the coverage name, and the item "GRID-CODE" contains the original theme number assigned during image classification.

Table 4.4. Polygon Attributes for a Vectorized LANDSAT Theme File (1987-07-02).

Item	Sample Data	Description
AREA	18,000.00	m^2
PERIMETER	600.00	m
FLCJ87#	22	Internal record number
FLCJ87-ID	21	Internal ID number
GRID-CODE	5	Theme number from classification e.g. 5=Baɪe soil surface

Problems encountered in the vectorization process involved exceeding computer disk space quotas and exceeding the 10,000 arcs per polygon processing limitation of ARC/INFO. Sufficient disk space for the processing (including the building topology) of a polygon coverage may range from 3 to 14 times the disk space needed to store the final coverage (ESR1 1987).

The occurrence of greater than 10,000 arcs in a polygon is a result of the raster to vector conversion process in which each side of a pixel is defined as an arc. The arcs contained in the perimeters of island polygons present within larger polygons contribute to the total number of arcs that define the latter. Therefore, as the complexity of a theme file increases, so does the complexity of the resulting vectorized product. The original raster theme files, which contained small groups of pixels, even after filtering, resulted in the formation of many small islands within larger polygons. When the limit of 10,000 arcs per polygon is reached, polygon topology cannot be created (ESRI 1987). For such cases, the recommendation is that the grid file be smoothed or reclassified before conversion to a polygon coverage (ESRI 1987).

One of the difficulties encountered by exceeding the 10,000 arcs limitation during vectorization was resolved by segmenting the theme file into smaller constituent files of a one half township in size, incrementing the UTM coordinates for the lower left corner of each segment accordingly, and vectorizing each segment independently. The resulting segmented coverages were then combined into one coverage through the "MAPJOIN" procedure, and the boundaries between polygons of similar land cover classes (GRID-CODE number) were removed using the "DISSOLVE" procedure.

A spatially referenced vectorized theme file of the 1987-07-02 LANDSAT imagery for each study area is presented as Plate 4.1. This product is useful for reconnaissance inventory of land cover distribution, and in particular for the inventory of bare soil surfaces that are predisposed to erosion risk.

The effects on coverage structure due to conversion of theme files from raster to vector format and subsequent elimination of 1.5 ha polygons on the areal summaries of land cover classes are summarized for each study area in Tables 4.5 and 4.6 and illustrated in Figures 4.1 through 4.3.

Unclassified areas and small groupings of pixels in the theme files developed in this study, contributed to the total number of polygons smaller than 1.5 ha in size formed during the raster to vector conversion process. The elimination of <1.5 ha polygons in this study resulted in a considerable reduction in the amount of unclassified area in each coverage (Tables 4.5 and 4.6).

Thresholds for filtering classified imagery and subsequent data volume reduction tend to be unique to each project (Korporal 1983, Marsh et al. 1990), and raster-to-vector conversion processing allows for additional generalization of the original data. As an example of data volume reduction, Marsh et al. (1990) reported that over one half of the total polygons formed in vectorization of airborne imagery were areas of less than 4 pixels in size. Based upon the results of coverage simplification in this study, the elimination of polygons to a level that is compatible with the resolution of other data used in the GIS is suggested as an item for future research with respect to data generalization. This could be explored by generalizing the LANDSAT theme files to the level of resolution of the soils data utilized in this study (12.5 ha/MLD) and evaluating map products for their overall spatial detail and utility.

The effects of removing <1.5 ha polygons on the structure of vectorized LANDSAT theme file coverages are summarized in Table 4.7. The elimination of <1.5 ha polygons had the most pronounced effect on the portions of the study areas that were unclassified. These areas represented small pixel groupings in the original image data that did not fit the spectral class parameters of the land cover types being classified. Some of these areas were located within fields and along the boundaries separating different land cover classes. The process of eliminating these small island polygons involved the dissolution of their perimeters, such that they were absorbed by the surrounding polygons. This may be considered analogous to the filtering process in image analysis. The process of eliminating polygons of <1.5 ha in size reduced the

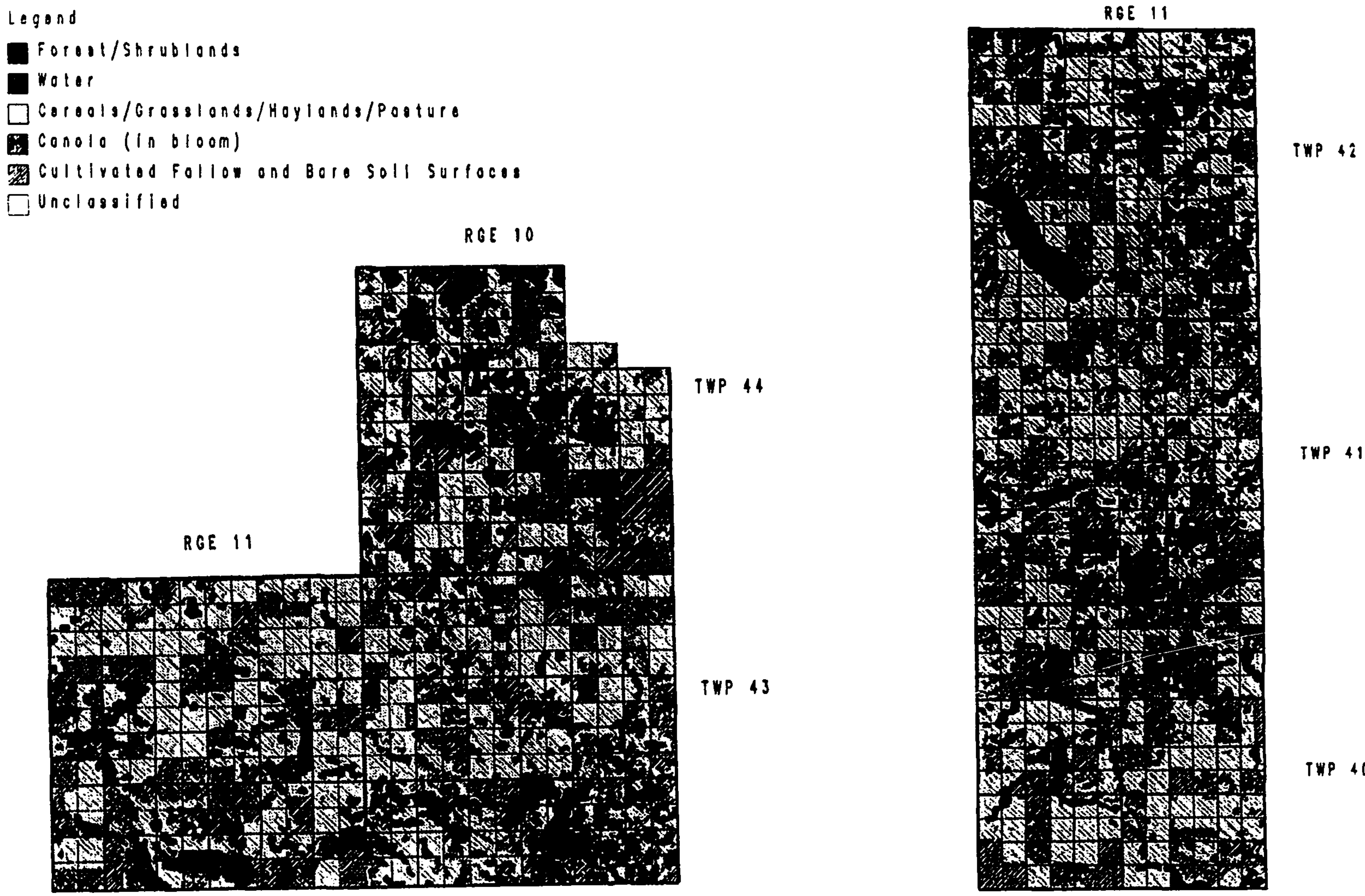


Plate 4.1. Vectorized LANDSAT theme files for 1987-07-02.
(after elimination of <1.5 ha polygons).

Table 4.5. Comparison of Areal Summaries of Land Cover Classes Before and After Raster-to-Vector Conversion: Study Area 1.

Theme Files	Raster themes	Vectorized themes*	Net Change
1987-07-02	% Area	% Area	% Area
cereals/grassland	38.0	56.8	+18.8
forest	7.7	10.1	+2.4
water	2.5	3.5	+1.1
canola (in bloom)	7.4	11.0	+3.6
bare soil	12.7	18.5	+5.8
unclassified	31.7	0.1	-31.6
Total:	100.0	100.1**	+0.1
1987-10-06			
fall crops	1.4	1.9	+0.5
forest	13.1	18.5	+5.4
water	1.7	2.5	+0.8
bare soil	20.8	31.1	+10.3
pasture/grassland	8.8	12.1	+3.3
stubble	22.6	33.8	+11.2
unclassified	31.6	0.1	-31.5
Total:	100.0	100.0	0.0
1988-07-20			
cereals/grassland	28.2	43.5	+15.3
forest	6.2	8.3	+2.1
water	2.4	3.4	+1.0
canola (in bloom)	5.4	7.8	+2.4
bare soil	20.3	30.3	+10.0
pasture/grassland	6.0	6.7	+0.7
unclassified	31.5	0.1	-31.4
Total:	100.0	100.1**	+0.1

*After elimination of 1.5 hectare polygons for data volume reduction.
**Rounding error

Table 4.6. Comparison of Areal Summaries of Land Cover Classes Before and After Raster-to-Vector Conversion: Study Area 2.

Theme Files	Raster themes	Vectorized themes*	Net Change
1987-07-02	% Area	% Area	% Area
cereals/grassland	49.3	57.4	+8.1
forest	7.7	6.4	-1.3
water	5.5	5.0	-0.5
canola (in bloom)	9.9	12.1	+2.2
bare soil	17.0	18.8	+1.8
unclassified	10.6	0.2	-10.4
Total:	100.0	99.9**	-0.1**
1987-10-06			
fall crops	1.1	1.1	0.0
forest	6.3	1.0	-5.3
water	4.0	4.3	+0.3
bare soil	30.2	36.5	+6.3
pasture/grassland	19.0	22.4	+3.4
stubble	28.4	34.1	+5.7
unclassified	11.0	0.6	-10.4
Total:	100.0	100.0	0.0
1988-07-20			
cereals/grassland	48.3	58.5	+10.2
forest	5.0	3.1	-1.9
water	4.6	4.6	0.0
canola (in bloom)	8.7	8.8	+0.1
bare soil	20.4	23.7	+3.3
pasture/grassland	2.4	1.2	-1.2
unclassified	10.6	0.1	-10.5
Total:	100.0	100.0	0.0

*After elimination of 1.5 hectare polygons for data volume reduction.
**Rounding error.

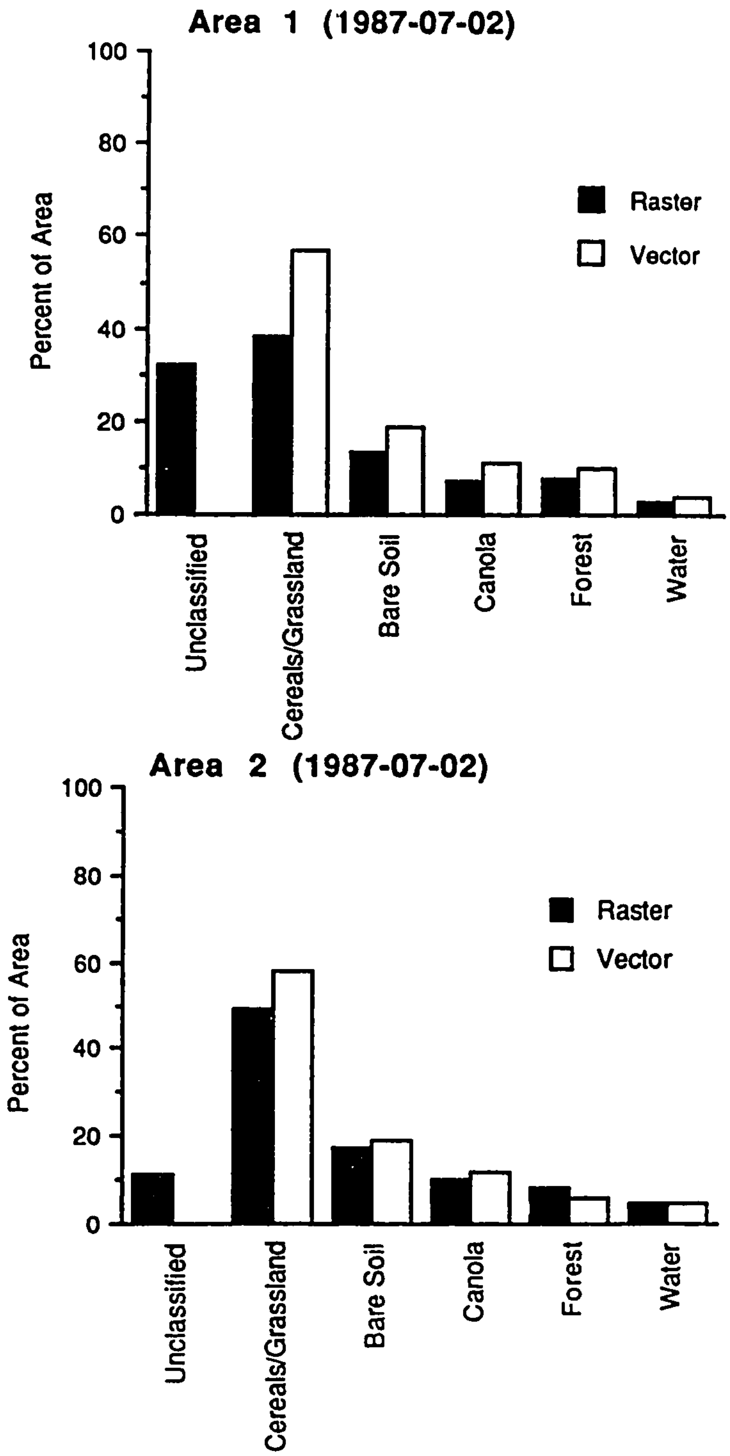


Figure 4.1. Effect of Raster to Vector Conversion on Land Cover Classes (1987-07-02).

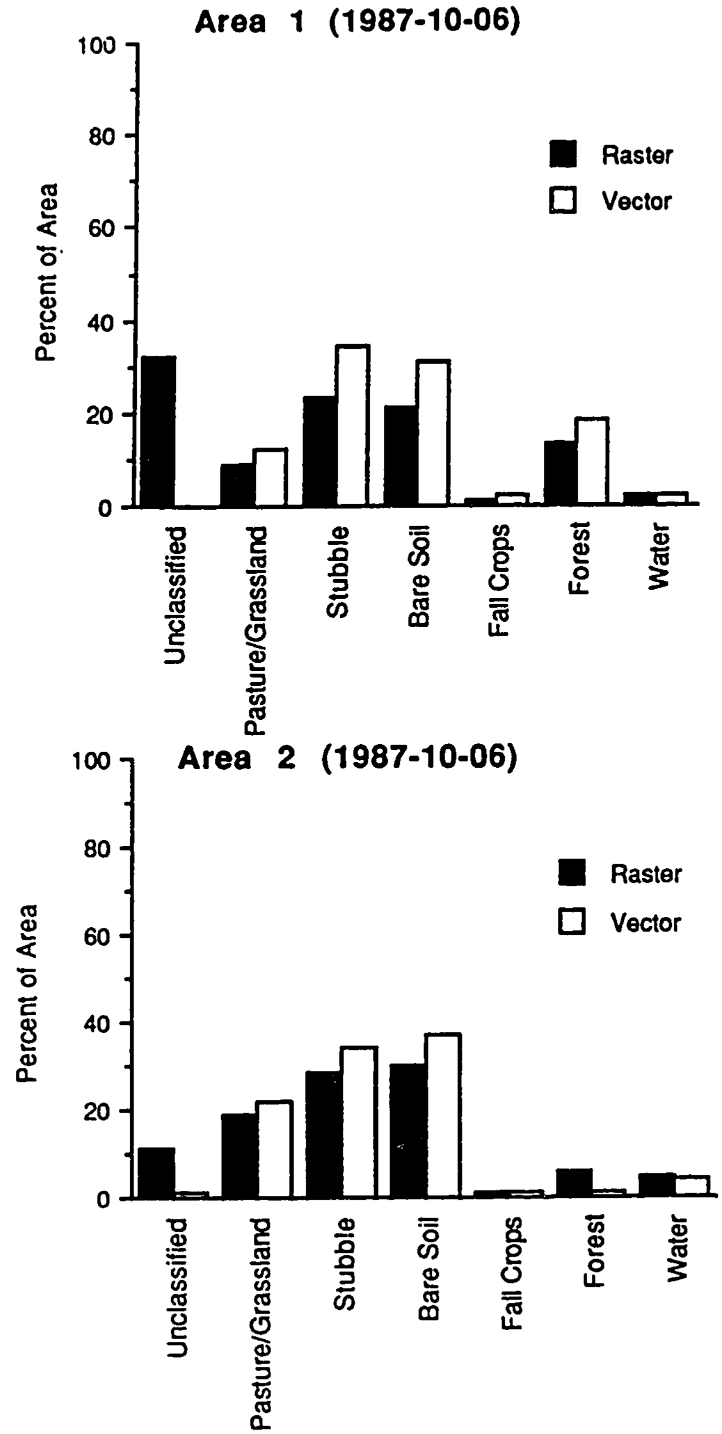


Figure 4.2. Effect of Raster to Vector Conversion on Land Cover Classes (1987-10-06).

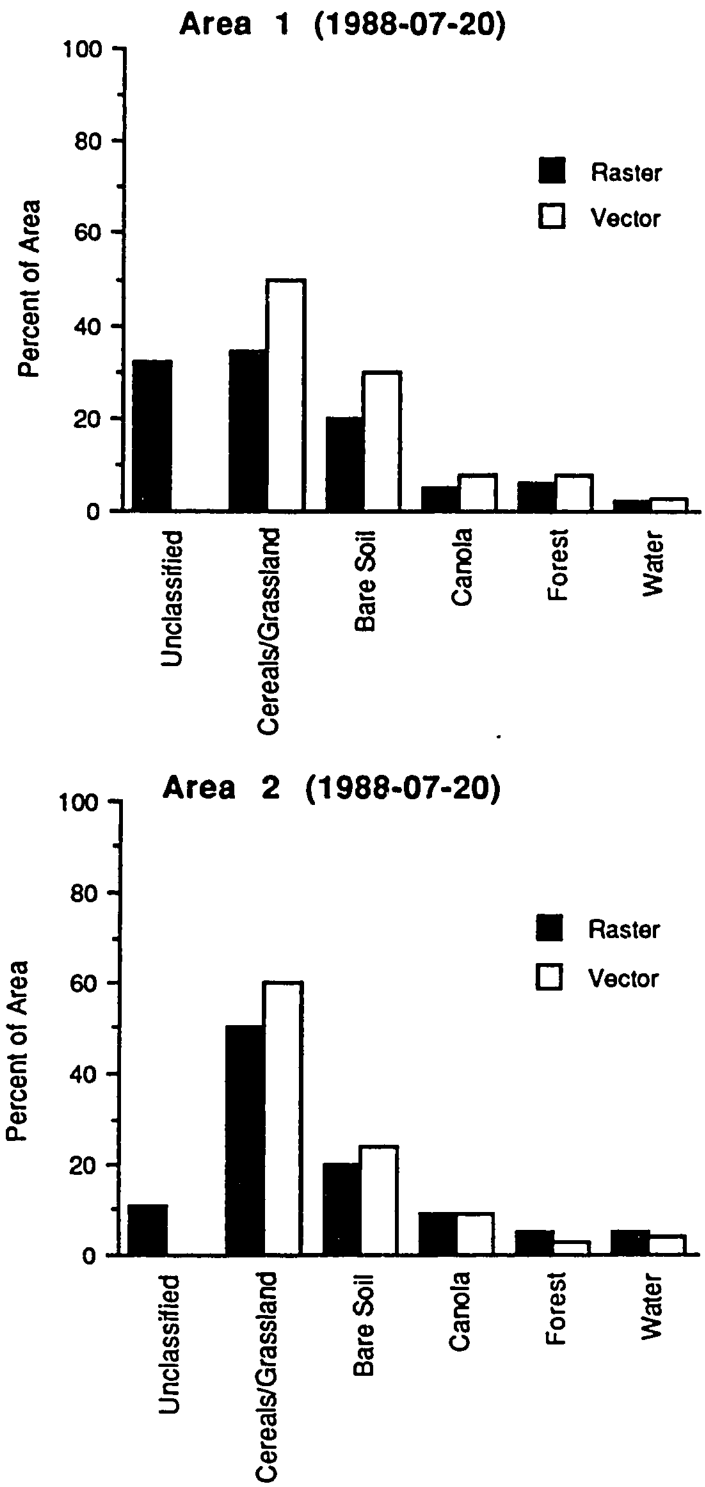


Figure 4.3. Effect of Raster to Vector Conversion on Land Cover Classes (1988-07-20).

Table 4.7. Comparison of Vector Coverage Data Structure Before and After GIS Processing and Integration

	Original Vector Coverage		Elimination of 1.5 ha polygons		Clipping to Study Area		Data Combination	Intersected Coverage	
Area 1	#Arcs	#Polys	#Arcs	#Polys	#Arcs	#Polys		#Arcs	#Polys
a. 1987-07-02	6929	3683	3747	918	3905	942	a+d	6648	2298
b. 1987-10-06	12367	5619	6903	1201	7087	1235	a+d+b*	15939	3020
c. 1988-07-20	21050	9524	10278	1374	10410	1401	a+d+b+c	30425	8566
d. Soils Data					841	261			
Area 2									
e. 1987-07-02	19481	10086	8447	1251	7783	1085	e+h	8009	2274
f 1987-10-06	63322	28273	23403	1624	20933	1208	e+h+f*	18472	3493
g. 1988-07-20	n/a	n/a	2768	1075	2125	807	e+h+f+g	27507	7527
h. Soils Data					1075	350			

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*System crashes occurred at this stage of data overlay process, necessitating elimination of 1.5 ha polygons for data volume reduction.

proportion of unclassified area from 31% to less than 1% for Area 1 (Table 4.5), and from the order of 11% to less than 1% for Area 2 (Table 4.6). The greatest commission of unclassified polygons occurred within the cereal and grassland classes for the July data, and within the bare soil and stubble classes for the October data (Tables 4.5, 4.6; Figures 4.1, 4.2, 4.3). These unclassified regions were the relics of land cover features that did not fit spectral class parameters established in the digital classification of the imagery.

The removal of small polygons present in vectorized theme files has been regarded a necessary task for data volume reduction and thematic generalization (Korporal 1983, Marsh et al. 1990). Classified LANDSAT images often result in a "salt and pepper" effect due to scattered pixels existing in the interior of dominant classes, which make vectorization of the data very difficult (Scott 1984). A post-classification filter is often applied to reclassify areas smaller than a specified size. This results in greater uniformity of the data without destroying large amounts of information and is necessary to reduce the quantity of the corresponding vector data (Scott 1984). With respect to the original classified image, the scattered "salt and pepper" pixels may be either unclassified or incorrectly classified, and either condition may be remedied by application of a filter to reduce voids within fields (Ryerson et al. 1985). After conversion to vector format, additional processing may be required to eliminate polygons below a minimum size threshold (e.g. single pixels) to further reduce the volume of vector data.

The data structure of the LANDSAT theme file coverages, at various stages of processing and integration are summarized in Table 4.7 and illustrated in Figure 4.4. For Area 1, prior to the extraction of the study area, the proportion of polygons of less than 1.5 ha (<15,000 m^2) in size (approximately 17 TM pixels at 30 m, or a 4 x 4 pixel grouping), reduced the proportion of polygons by 75% for the July 1987 data, 79% for the October 1987 data and 86% for the July 1988 data. This high proportion of small polygons is indicative of the spectral complexity of the region, which caused difficulties in the initial application of conventional classification procedures to the LANDSAT imagery, and resulted in a large proportion of isolated pixels and small pixel groupings throughout the theme files.

Removal of <1.5 ha polygons in Area 2 led to a reduction in polygons by 88% for the July 1987 coverage and by 94% for the October 1987 coverage (Table 4.7). The number of polygons per coverage were not recorded during segmentation of the 1988-07-20 data. The reduction in the number of polygons in Area 2 supported the initial observation that this area is also spectrally complex, as was determined through visual analysis of the enhanced image products and evidenced by the many small pixel groupings within the theme files. The spectral complexity of the study areas led to the generalization of land cover theme files, through the grouping of several individual themes for a single cover type into a single theme. The application of filtering

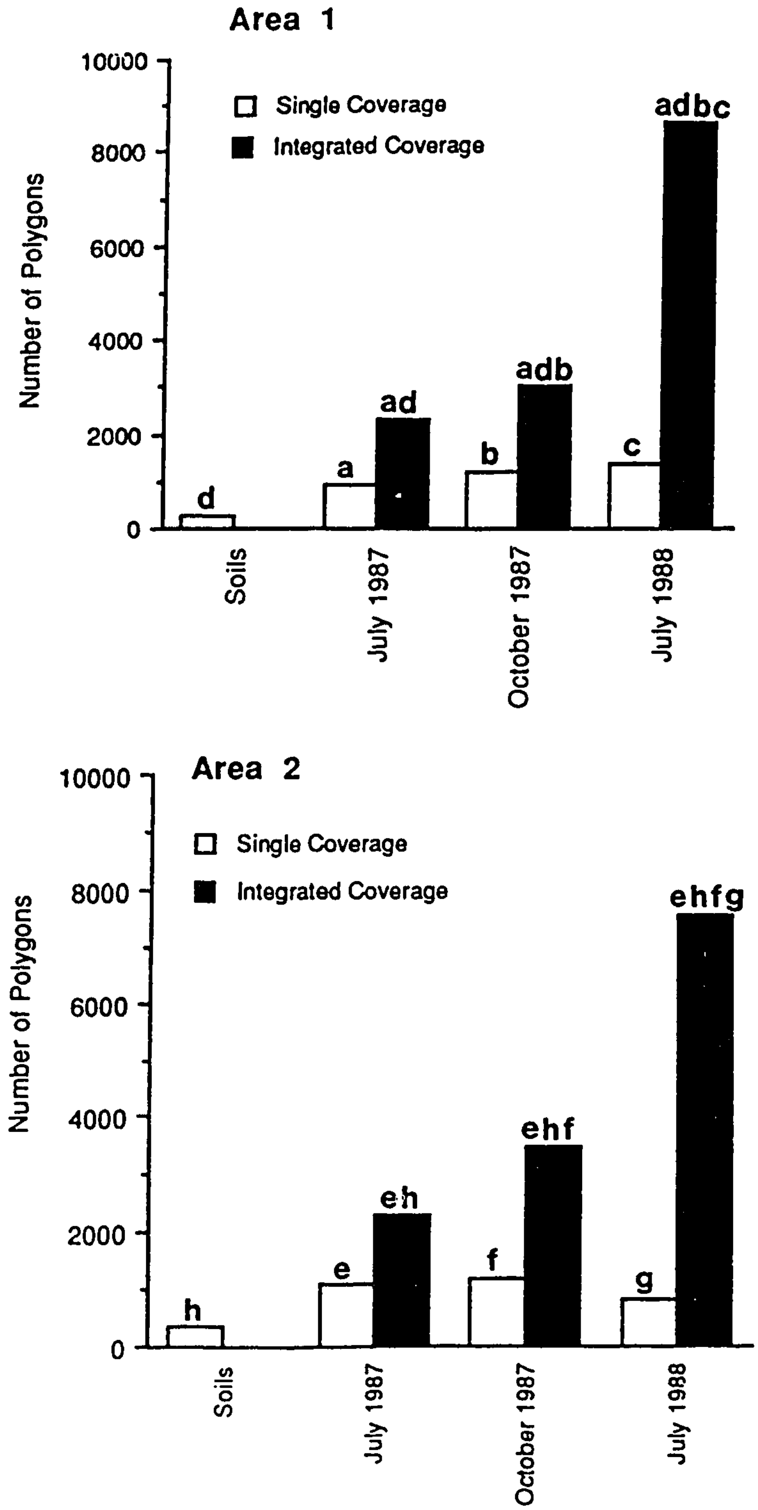

Figure 4.4 Effect of Integration on Vector Data Structure.

procedures, prior to vectorization, also served to generalize the theme files by reducing the proportion of isolated and unclassified pixels within themes.

Removal of small polygons may be viewed as a further generalization of the land cover information, however, it was necessary to reduce the data complexity in order to maintain the original study areas of 3 townships in size. The issue of data generalization through the removal of small polygons has been previously addressed by Burrough (1986) who cautioned that this practice may result in the loss of important detail. In the development of land cover maps for county-scale conservation applications, areas smaller than 1.5 ha do not constitute reasonably sized areas for erosion risk mapping, as conservation management tends to be aimed at individual fields. Furthermore, from an operational perspective, the development of coverages for individual townships may be viewed as inefficient, particularly if the objective is to monitor an entire county.

Soils Coverages

An example of the polygon attribute file for the soils data for Study Area 1 (Coverage AG1) is presented in Table 4.8.

Table 4.8. Polygon Attributes for Soil Survey Data.

Item	Sample Data	Description
AREA	126,056.789	m^2
PERIMETER	1,565.823	m
AG1#	4	Internal record number
AG1-ID	3	Internal ID number
SERIES	EOR1/4	Soil map unit
BARE1	3	Soil erosion risk rating for bare surface condition
BARE2	0	Rating for codominant soil, if present
CER1	1	Erosion rating for cereal cover
CER2	0	Rating for codominant soil
CAN1	1	Erosion rating for canola cover
CAN2	0	Rating for codominant soil
ALF1	1	Rating for alfalfa cover
ALF2	0	Rating for codominant soil

These data were available in digital format as archived ARC/INFO coverages, at a 1:50,000 scale (MacMillan et al. 1988). The survey intensity level (SIL) associated with this scale of field mapping was SIL=3, which is regarded as a reconnaissance level in soil survey applications (Expert Committee on Soil Survey 1987). The corresponding inspection intensity requires at least one field inspection in over 60% of map delineations (i.e. one inspection per 20-200 ha), and the minimum size map delineation ranges in the order of 2 ha to 80 ha, with a median MLD at 12.5 ha (Expert Committee on Soil Survey 1987). These soils data represent a lower resolution of sampling than the LANDSAT TM data used in this study and restrict the potential representation scale of GIS-derived map products to that of 1:50,000 for this study. An additional utility of LANDSAT data, due to their greater spatial resolution, lies in the study of variability within the soil map units.

Errors encountered in processing the original soils coverages derived from ARC/INFO export files were due to the presence of multiple label points for individual polygons and incorrect and missing soil map unit names for polygons (Appendix II). The initial attempts to edit these data did not remedy these problems, due to corruption of the edited attribute files during subsequent processing using "BUILD" procedures. The problems encountered in attempting to utilize the original soils data could not be attributed to a particular stage of data capture, processing, or conversion to ARC/INFO coverages. The presence of multiple label points within polygons may have been a relic of original data processing in dBase III, prior to conversion of these data to ARC/INFO coverages (Krzanowski 1991, pers. comm.[1]). This suggests that there is a need for quality control at every stage in the capture and digital formatting of map data for use in a GIS. In the exchange of digital soil survey data between GIS systems, one must consider the effects on locational information and attribute data, loss of positional accuracy, potential loss of information and the type of exchange and storage media (Krzanowski et al. 1989). In addition, topological information is difficult to transfer because there is no standard way to preserve or code this information, and as a rule, the topology and links between graphic and attribute data base must be rebuilt by the system (Krzanowski et al. 1989).

The continual corruption of the attribute files encountered during this stage processing necessitated the development of new coverages, based on the line graphics of the original coverages and the development of polygon attribute files that contained correct soil series names, as well as the corresponding soil erosion risk ratings for a variety of surface cover conditions

[1] Krzanowski, R.M. 1991. Systems Analyst, Environmental Research and Engineering Department, Alberta Research Council, Edmonton, Alberta, T6H 5X2.

(Table 4.8). Map products derived from these newly generated data were manually inspected and determined to be in compliance with published maps from the soil survey report.

Integrated Coverages

An example of a polygon attribute table derived for an integrated LANDSAT/soils coverage is presented as Table 4.9.

Table 4.9. Polygon Attributes for an Integrated LANDSAT/Soils Coverage.

Item	Sample Data	Description
AREA	52,546.883	m^2
PERIMETER	1,623.171	m
CG1RES3E#	276	Internal record number-final coverage
CG1RES3E-ID	275	Internal ID number
SERIES	EOR1/4	Soil map unit
BARE1	3	Soil Erosion Risk Rating for bare surface condition
BARE2	0	Rating for codominant soil
CER1	1	Erosion rating for cereal
CER2	0	Rating for codominant soil
CAN1	1	Erosion rating for canola cover
CAN2	0	Rating for codominant soil
ALF1	1	Rating for alfalfa cover
ALF2	0	Rating for codominant soil
GRJ87	1	Grid-Code (theme) number (1=Cereals/grassland) (1987-07-02 theme file)
GRO87	5	(5=Bare surface) (1987-10-06 theme file)
GRJ88	1	(1=Cereal/grassland) (1988-07-20 theme file)
CG1RES1#	214	Record number-1st coverage
CG1RES1-ID	213	ID number-1st coverage
CG1RES2#	228	Record number-2nd coverage
CG1RES2-ID	227	ID number-2nd coverage

The integration of soils and multitemporal LANDSAT coverages led to changes in vector data structure, evidenced by the increase in number of arcs and number polygons caused by the recursive fragmentation of polygons at each stage of coverage intersection (Table 4.7, Figure 4.4). For each study area, at each stage of intersection there was a pronounced increase in data volume and complexity due to the resulting number of arcs and polygons formed, with an accompanying increase in the number of elements contained in the attribute files. For Area 1, this was in the order of a 23% increase in the total number of polygons formed with the addition of the second LANDSAT coverage, and an additional increase of 65% after addition of the third coverage (Table 4.7). For Area 2, the corresponding increases in polygon numbers were 35% and 54%, respectively (Table 4.7). This phenomenon leads to a significant practical limitation in the development of similarly integrated coverages for GIS data base development and operational use for monitoring of large areas.

With each subsequent addition of LANDSAT data, polygon fragmentation and data base expansion necessitated the removal of small polygons to prevent against exceeding software processing limitations. The <1.5 ha threshold used served to remove those polygons that were too small for practical implications in erosion risk monitoring.

It is likely that with the addition of more LANDSAT coverages, as would be the case in operational monitoring and data archiving, the process of data volume reduction through elimination of small polygons would be necessary. Seasonal changes in field sizes and orientation would also add to the problem of polygon fragmentation. In this study, changes in field boundaries were evidenced by the relatively small increase in polygon numbers after combination of the July 1987 and October 1987 data, with a much larger number of polygons formed with the addition of the July 1988 data. This was indicative of the changes in field boundaries in the following crop year, as observed through comparison of the enhanced image products for consecutive growing seasons.

Summary

The processing of digital base map, soil survey and LANDSAT theme files for integration in an ARC/INFO GIS, and the resultant coverages were characterized in this study. The need to correct for errors present in the digital soils information, as with the base map information, demonstrated that the availability of data in digital format does not necessarily ensure that it is of reliable quality.

The integration of LANDSAT theme files within the GIS necessitated raster-to-vector conversion of the theme files. Due to the spectral complexity of the original image data which led to the formation of many small pixel groupings representing land cover themes and unclassified areas in the classified imagery, many small polygons (<1.5 ha in size) were formed. The presence of these small polygons taxed the internal processing limitations of the ARC/INFO software, causing termination of the vectorization process and the coverage intersection process due to data complexity. It was therefore necessary to segment the original theme files into smaller constituent areas to enable processing during vectorization.

Subsequent development of integrated soils/LANDSAT coverages necessitated the removal of the small polygons formed at each stage of coverage overlay. While this may be viewed as a generalization of the data, polygons of <1.5 ha do not constitute reasonably sized areas for large scale reconnaissance of soil erosion risk in this region. In addition, these <1.5 ha areas exceeded the resolution of the soils data used, such that their use would be an attempt to stretch the integrated data beyond it's representational accuracy. In the development of spatio-temporal coverages and data bases in a GIS, the effects of polygon fragmentation must be considered with respect to ramifications on system processing capabilities, as well as on data base volume, complexity and integrity.

Additional research into the changes in original data structure and information content as a result of raster-to-vector conversion is necessary, as there is relatively little information that characterizes the process and the ramifications for GIS applications. Methods of quantifying the changes in format conversions must also be developed (Lunetta et al. 1991). Furthermore, the issues related to integration of remotely-sensed data and other digital data also require exploration with respect to the design and construction of appropriate data base management systems (Ehlers et al. 1991).

V. SPATIAL AND TEMPORAL ANALYSIS OF SOIL EROSION RISK

Introduction

Effective monitoring of agricultural soil erosion risk over large regions requires the use of technologies that enable integration of spatial and temporal information in a geo-referenced format. Remote sensing technology provides a source of temporal information on the dynamics of land cover (Hardy et al. 1971), while geographic information systems (GIS) allow for storage, manipulation and retrieval of many types of land-related information (Marble and Peuquet 1983, Burrough 1986).

The inventory of agricultural soil erosion risk over large areas necessitates knowledge of the spatial distribution of soil characteristics and surface cover (e.g. bare, permanent or seasonally changing), as these factors combine to influence predisposition of soil to wind- or water-mediated erosion. Soil characteristics can be considered relatively static, in that the soil formation process is slow and dependent upon climatic, geologic and biologic factors. Therefore, soil survey maps that are based upon soil and landscape characteristics tend to remain relevant for several years and are suited for use in reconnaissance erosion risk assessment. On the other hand, agricultural land cover changes seasonally. Therefore the dynamics of land cover and management practices (e.g. crop rotations, summerfallowing and post-harvest cultivation) should also be considered in the inventory of soil erosion risk.

In this portion of the study, LANDSAT theme files, digital soil survey and base map data that have been integrated in a GIS (Chapter IV), are explored for their utility in soil erosion risk inventory. Integrated coverages and associated attribute files consisted of land cover for two consecutive cropping seasons and a post-harvest season and were used in the temporal analysis of erosion risk for six townships (Figure 2.1) in the County of Flagstaff. This chapter focuses on the use of selective queries of these data, with results presented as graphic and tabular products.

The Problem of Soil Erosion

Soil erosion is considered to be one of the most serious problems affecting agricultural soils in Canada (Coote et al. 1981, Sparrow 1984, Dumanski et al. 1986). Wind- and water-mediated erosion constitute critical forms of land degradation that result in decreased soil productivity and increased economic inputs required for mitigation of these effects (Desjardins et al. 1986). Decreased soil productivity is linked to the loss of organic matter and nutrients adsorbed to transported particles, the breakdown of soil structure, lowered moisture holding capacity, and poor tilth of the remaining soil (Biederbeck et al. 1981, McGill et al. 1981, P.F.R.A. 1983, Anderson et al. 1984).

Land management factors contributing to persistence of soil erosion include intensive tillage, use of large farm machinery, cropping of marginal lands, removal or burning of crop residues, summerfallowing and post-harvest cultivation (P.F.R.A. 1983). Physical implications of these practices on soil include destruction of soil aggregates and exposure of the soil surface to effects of wind and run-off, while economic implications include overall reduction in crop yield. Estimates of crop yield reduction due to erosion vary by geographic location and soil condition. As an example, Lindwall (1980) reported a decrease of 33 kg/ha in wheat yield for the Lethbridge region of Alberta. Earlier studies by Ripley et al. (1961) in Guelph, Ontario, reported a decrease of 48 kg/ha in barley yield for each 1 cm of topsoil removed. In addition to the economic implications of reduced yield, the cost of ameliorative measures has been estimated to range between $2.4 and $531.6 million annually for Alberta farmers (Desjardins et al. 1986). Other implications of soil erosion include introduction of adsorbed nutrients (nitrogen and phosphorus) and herbicides into surface water, resulting in sediment loading and eutrophication, which in turn interfere with aquatic life and water quality.

Erosion processes remove part or all of the topsoil, and often part of the subsoil, with the remaining soil having a lower capacity for production, resulting in poor crop growth and a greater risk of more erosion (Anderson et al. 1984). Agricultural lands in the Canadian prairies have experienced topsoil losses that range from 30% to 50%, while the use of fertilizers and other ameoliorative practices can only restore their former productivity to 75% (Anderson et al. 1984). As the problem of soil erosion persists, so will the environmental, economic and social implications of the reduction in extent and productivity of the agricultural land base.

Although the study of the extent and distribution of soil erosion risk is an integral part of the development of conservation policies and practices, approaches to the inventory of soil erosion risk in Western Canada are lagging behind in application of remote sensing and GIS technologies that have potential utility in both inventory and monitoring of large geographic areas. Assessments of soil erosion potential based on historic monitoring of current, and estimates of future soil losses on a regional basis are urgently needed since soil erosion rates vary with climatic, topographic and soil surface features (Anderson et al. 1984). Evaluation of integrated remote sensing and geographic information systems for large area erosion studies has been undertaken in New Brunswick by Cihlar (1987), and in Saskatchewan by Xongchao (1988) and Sauchyn (1989) which demonstrate their utility. To date, however, similar applications have not been investigated in Alberta.

Inventory of Soil Erosion Risk

Two basic approaches to the inventory of soil erosion risk exist. The qualitative approach is usually applied to large regions and results in the production of soil erosion risk maps at fairly broad scales (e.g. 1:1,000,000). These inventories are based on interpretations of soil survey reports, climate information and landscape characteristics for large areas, most often on a provincial basis (see, for example, Tajek et al. 1985, Desjardins et al. 1986). On the other hand, the quantitative approach is most often applied to smaller regions, most frequently field plots, as demonstrated in Alberta by Chanasyk and Woytowich (1986; 1987).

Quantification of erosion risk often involves utilization of empirical formulae, such as the Universal Soil Loss Equation (USLE) derived by Wischmeier and Smith (1978). The USLE requires that site specific factors (soil characteristics, length and steepness of slope, surface cover and rainfall) be determined for use as the basis for quantitative determination of potential annual soil loss (tonnes of soil/hectare/year). The USLE lends itself well to small plot studies where these factors can be measured. Despite warnings that the application of the USLE to large regions constitutes misuse, and that application to new geographic areas necessitates that all factors be adjusted for local equivalencies (Wischmeier 1976), it is still used as the basis for many large area erosion risk inventories.

Soil Erosion Risk Maps

Soil erosion risk maps produced at broad scales are often based on potential soil loss, as determined through the application of the USLE. When modifications are made for local conditions, the USLE continues to be used for large area soil erosion risk studies (Tajek et al. 1985, Desjardins et al. 1986, Xongchao 1988, Ventura 1988, Sauchyn 1989). Several approaches have been used in the determination of factors for the USLE on the Canadian prairies, and are described by P.F.R.A. (1983), Tajek et al. (1985) and Xongchao (1988).

For large area soil erosion risk inventory, it has been suggested that erosion potential maps which are of sufficient detail at a field scale would also have utility in conservation planning at the farm level (Goddard 1988). To date, a water erosion potential map based on a modified USLE (Tajek et al. 1985) and a wind erosion risk map (Land Resource Research Centre 1987) have been produced at a scale or 1:1,000,000 for Alberta. A schematic map of water erosion risk for crop mixtures, small grains and bare soil conditions, utilizing the USLE and a computerized soils data base referred to as SIDMAP (Hiley et al. 1986), was also produced for Alberta by Desjardins et al. (1986). In these maps, no consideration was made for temporal variation in soil surface cover and the corresponding variation in soil erosion risk. Although these maps provide an overview of soil erosion potential for the province, it is questionable whether the spatial accuracy and interpretive generalizations portrayed would enable either county-scale or on-farm conservation planning. The delineations on these maps are based largely upon interpretation of soil characteristics and landscapes derived from soil surveys of varying scale, survey intensity, and detail. As mapping concepts and mapping scale may vary considerably between surveys, there is potential for misrepresentation of actual soil erosion risk. For soil conservation planning at the county level, more detail than that provided by these maps is required. Detailed soils data, such as that from large scale (e.g. 1:50,000) soil surveys, combined with knowledge of the seasonal dynamics of cropping rotations and land management practices can enable a more precise determination of localized soil erosion risk for conservation planning purposes.

The Temporal Nature of Soil Erosion Risk

Soil erosion risk varies temporally in response to climatic events such as snowmelt, runoff, precipitation and wind. Kirby and Mehuys (1987) reported that soil erodibility varied seasonally, with partially frozen soils under snowmelt conditions being more prone to erosion than thawed soils. Earlier studies by Pall et al. (1982) cited by Kirby and Mehuys (1987), attributed the increased erodibility of soils during snowmelt or spring conditions to the reduced infiltration rates due to the presence of frost layers, coupled with soil water content at or above saturation. In central and northern Alberta, severe soil erosion has been observed to take place during spring melt and runoff events (Chanasyk and Woytowich 1986; 1987), and in southern Alberta, during wind storms (Timmermans 1990).

The physical characteristics of soil also influence potential erodibility. Soil texture, moisture, organic matter content, aggregate size and stability all contribute to erodibility (P.F.R.A. 1983). Generally, fine textured soils form aggregates that disintegrate easily during freeze/thaw cycles which make them prone to wind and water erosion; loams, silt loams and clay loams form more stable and resistant aggregates (P.F.R.A. 1983).

The severity of erosion can also be linked to the relative amount of protective vegetative cover on the soil surface. Over 50 years ago, Smith (1941) identified crop sequence and amount of surface cover as variables that could be manipulated to effect soil conservation. Baver (1972) identified the importance of vegetation for intercepting rainfall, decreasing the velocity of runoff, increasing soil porosity due to root penetration, and contributing to soil organic matter content. Crop rotations can also influence soil erosion. Smith and Wischmeier (1957) presented a discussion of soil loss under different crop rotations in which loss was observed to be greatest for row crops such as corn, and considerably less for cereal crops (wheat, oats) and forages. Generally, rotations that include fallow for more than one season are the most detrimental.

Continuous cropping, minimum and zero tillage, retention of crop residue after harvest and strip farming have been prescribed by conservationists as effective measures against erosion.

The amount of surface cover necessary to prevent overland flow and erosion varies with soil characteristics and topography (Meeuwig 1970). Vegetation cover also protects the soil against wind-mediated erosion. Research has demonstrated that up to 1680 kg/ha of crop residue are required to prevent soil drifting on medium textured soils, with more residue required for sandy and clay soils (Agri-fax 1978). Coarse textured soils may require upwards of 2000 kg/ha of residue (Bisal and Ferguson 1970). Minimum tillage and zero tillage are also effective against wind erosion, as standing stubble serves to trap snow, which in turn can increase spring soil moisture (Agri-fax 1978).

Conservation policies often include suggestions for reducing the proportion of fallowed acreage and avoiding post-harvest cultivation to ensure continuous protective vegetative cover and minimal disturbance of the soil. Because agricultural land management varies seasonally, and with it land cover, soil erosion risk studies should take into account these seasonal dynamics. Remotely-sensed data can provide an effective means of large area monitoring of both surface cover and land management practices.

Technologies for Soil Erosion Risk Inventory

Remote Sensing

Remotely-sensed data, in the form of aerial photographs, airborne scanner or LANDSAT satellite data provide image products useful for monitoring land cover changes, soil surface conditions and land management practices that influence soil erosion risk. Historically, aerial photography has been used to estimate soil loss involving the application of the USLE, with factors such as crop rotations and conservation practices determined through visual interpretation. This approach has been used in Wisconsin (Morgan et al. 1978; 1980) and in New Brunswick (Stephens et al. 1982; 1985).

Frazier et al. (1983) demonstrated the utility of low altitude (300 m) photography for studying rill erosion in the Palouse region of Washington. They were able to identify rill patterns (parallel, dendritic, divergent), as well as determine a record of extent and severity of erosion and related management practices. More recently, Crudge (1988) explored the use of aerial photographs for quantifying soil loss through rill erosion in the lower Fraser Valley of British Columbia. He concluded that estimates of soil loss based on rill measurements obtained from photographs were in the order of 22% lower than estimates obtained from field measurements.

Quantification of soil loss, involving studies of gully formation has been demonstrated in Georgia by Welch et al. (1984) and Thomas et al. (1986). Their work involved stereoscopic analysis of sequential low altitude (180 to 275 m) aerial photographs and computerized derivation of digital elevation models. These models were then used to study changes in gully formation over time.

Limitations associated with the use of aerial photographs include their restriction to fairly small, localized areas and the associated expense of obtaining photographic coverage for large areas. Although LANDSAT data do not provide the spatial resolution inherent in aerial photographs which is useful for identification of site-specific erosion features (rills, gullies), they do provide a means of identifying spectral anomalies on the soil surface. Some of these anomalies have been related to eroded knolls and exposed paleosols (Frazier and Cheng 1989).

While remotely-sensed data and computer analysis do not replace conventional, detailed ground surveys, they do enable identification of areas where conservation activities will be most effective (Pelletier 1985). The advantages of LANDSAT imagery for large area studies include the synoptic view, multispectral and multitemporal capabilities and near orthographic properties, while disadvantages include cloud cover and low spatial resolution (Westin and Frazee 1976). The temporal characteristic of LANDSAT data also enables seasonal inventory and monitoring of agricultural land cover and management practices, including crop rotations, summerfallow and post-harvest cultivation, over large geographic areas.

Application of LANDSAT imagery for large area soil degradation studies has been explored in a number of geographic locations and environments. Pacheco (1977) reported the utility of LANDSAT MSS data for stratification of land units in the development of a soil degradation map for the country of Morocco, and advocated the utility of stratification of land resources on the basis of data gathered under near-real time conditions. A similar approach has been used for delineation and mapping of soil degradation in India with MSS data (Venkataratnam 1984). Both of these studies relied upon spectral variations between soils degraded through salinity and erosion, as the basis for delineation of map units.

In Argentina, Sayago (1986) utilized multitemporal LANDSAT imagery and aerial photographs to delineate map units on the basis of recurrent land use and land form patterns. Field measured USLE factors enabled the identification of soil erosion risk hazards for large areas, at scales ranging from 1:250,000 to 1:1,000,000. The advantage of this approach was the detection of the most severely affected areas leading to subsequent implementation of conservation programs at a regional level.

In addition to delineation of map units for large area soil degradation studies, LANDSAT data is also a useful source of temporal information on agricultural cropping patterns. DeGloria et al. (1986) designed a conservation tillage monitoring program to estimate land area under specific crop cover (grain, stubble, fallow and non-grain) over a five year period based on LANDSAT MSS data for central California. Areal estimates of grain crops derived from the LANDSAT imagery were consistently lower than the annually reported statistics for the five year period. They attributed this to the spectral confusion between wheat, barley and hay crops, and the variable cultivation practices that encouraged growth of volunteer crops and weeds, all of which contributed to commission errors. They also advocated manual interpretation of imagery for field inventories as opposed to digital classification.

Other applications of remotely-sensed data to the study of soil erosion include the determination of physical and chemical conditions of soil. Schreier (1977) demonstrated the relationship between soil reflectance characteristics and soil chemical composition through use of multispectral airborne scanner data. More recently, Frazier and Cheng (1989) demonstrated the use of LANDSAT TM data for identifying paleosols exposed by severe erosion in the Palouse region of Washington. Their approach involved extensive band ratioing of TM data, followed by classification (parallelepiped and maximum likelihood), and subsequent correlation of classification results with laboratory data for field samples. They concluded that band ratios of TM data could be used to distinguish levels of organic carbon and to a lesser extent, the ratio of iron to carbon characteristic of exposed paleosols, thus enabling mapping of erosion over large areas.

The application of LANDSAT data to the study of soil erosion, as reported in the literature, varies considerably in scope and purpose. For application to large area soil erosion risk studies, one of the the most relevant applications is the monitoring of temporal changes in vegetation cover. Examples of this particular application will be discussed with respect to use of this data in conjunction with GIS technology.

Geographic Information Systems

GIS's are gaining considerable importance as tools for use in natural resource management, decision support and process modelling (Clarke 1986, Johnston 1987). A GIS serves as a framework for integrating spatial data from many sources, and enables storage, manipulation, and analysis according to a user's needs (Marble and Peuquet 1983, Burrough 1986). GIS's hold much potential for applications in soil erosion studies. When remotely-sensed data are integrated within a GIS, the system gains a temporal component. This is of extreme utility in monitoring soil erosion risk in agricultural regions where land cover changes seasonally.

A considerable number of theoretical models of GIS for soil erosion studies have been proposed. Welch et al. (1985) suggested that stereoscopically derived elevation values be incorporated with information on soil type, precipitation and cropping practice to develop a data base to be utilized with GIS software for studying gully erosion. Pelletier (1985) provided a detailed description of how a GIS-based USLE could be developed for use in conservation planning and advocated that remotely-sensed data were an important source of land cover information as input into the USLE. The utility of LANDSAT data as input into the USLE has been demonstrated by Cihlar (1987) for erosion risk monitoring of a potato-growing area of New Brunswick. Based on this study, he proposed that a GIS held potential for soil erosion monitoring programs, but that it was first necessary to establish format and data exchange standards to enable the sharing of information between various agencies involved in land management.

From the standpoint of operational applications of GIS to soil erosion studies, few examples exist in the literature. Morgan and Nalepa (1982) demonstrated a simulated type of GIS application through raster processing of USLE factors derived from published maps and land cover from aerial photographs and field surveys. Grid cells of 6.3 ha were used as basic computational units for a 6478 ha watershed in Texas. End products consisted of maps of potential soil loss determined through the USLE, for use in identifying problem areas. Another study, utilizing the Land Resource Information System (LRIS) of the U.S. Army Corps of Engineers, which is based on grid cells ranging in size from 4 to 36 ha and contains information on soil characteristics and land use, augmented with slope data, was used for simulation of soil loss in response to various management scenarios (Logan et al. 1982). This study demonstrated an additional use of a GIS approach to erosion process modelling for conservation planning.

The IOWA LANDSAT demonstration project (Patterson and McAdams 1982) serves as an example of a large area erosion study utilizing the USLE factors derived from conventional soils maps and land cover derived from LANDSAT imagery, through overlay analysis of these data. Another example of operational soil conservation planning, which utilizes the GIS techniques of data overlay and spatial analysis, is the Dane County Soil Erosion Control Plan (Ventura 1988). In this project, soil erosion risk was determined through application of the USLE, with land cover information derived from a single season LANDSAT TM image. Final products included spatially referenced maps of potential soil loss, with grid cells representing quarter-section areas. Additional maps portrayed the potential soil loss given the implementation of conservation tillage and accompanying tabular summaries of soil loss estimates. This project served as the basis for development of a conservation plan for Dane County, and continues to serve as a popular example of operational conservation planning using GIS techniques. This study, like many of the others described here, did not consider the temporal component of soil erosion risk.

More recently, other studies have utilized commercially available GIS software for large area erosion studies. Xongchao (1988) demonstrated the utility of an ARC/INFO GIS for derivation of slope information through a triangulated irregular network (TIN) procedure for subsequent input into the USLE. Single date LANDSAT MSS imagery was utilized as the source detailed description of how a GIS-based USLE could be developed for use in conservation planning and advocated that remotely-sensed data were an important source of land cover information as input into the USLE. The utility of LANDSAT data as input into the USLE has been demonstrated by Cihlar (1987) for erosion risk monitoring of a potato-growing area of New Brunswick. Based on this study, he proposed that a GIS held potential for soil erosion monitoring programs, but that it was first necessary to establish format and data exchange standards to enable the sharing of information between various agencies involved in land management.

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Another application of the ARC/INFO GIS has been demonstrated by Ackerman (1988) in his comparison of soil maps and topographic maps as sources of slope information for input into the USLE. Through application of TIN and a comparison of the results obtained from both types of input data, he concluded that TIN-derived topographic data was superior to the slope information derived from the soils maps of the Swift Current area, in Saskatchewan. In this study, he addressed the errors associated with assuming constant slope lengths, a common practice when slope information from soil map units are used in USLE-based erosion predictions for large areas.

Based upon the literature reviewed, there are definite advantages to integrating LANDSAT imagery and soils data for large area erosion risk prediction. However, the tendency has been to utilize only a single date of imagery as a source of land cover information. The following study considers the temporal aspect of land cover, through the integration of multitemporal LANDSAT theme files within a GIS for soil erosion risk inventory.

Methods

The polygon attribute data for the vectorized LANDSAT theme files and the soils coverages, as well as the integrated LANDSAT/soils coverages (Chapter IV), were used in the derivation of tabular reports and graphic products in the analysis of soil erosion risk.

Tabular Reports

To enable manipulation of the polygon attribute (PAT) files for each of the soils, LANDSAT, and integrated LANDSAT/soils coverages, the respective PAT files were duplicated through the COPYINFO procedure. The duplicate files were then modified through deletion of the universe polygon and sorting on specific items (e.g. grid-code for the LANDSAT data, soil erosion risk rating for the soils data) in preparation for report generation.

The REPORT function was used for generation of summaries of distribution of soil erosion risk given various soil surface cover conditions (bare surface, cereal, canola and alfalfa cover) for each study area. The FREQUENCY function was used to identify the predominant soil map units in each study area. REPORT procedures were also used to generate areal summaries of land cover distribution for each of the vectorized LANDSAT theme files.

In the determination of single season erosion risk using the integrated coverage PAT's, the FREQUENCY function was used to derive areal summaries of land cover and soil erosion rating combinations. A similar approach was used to obtain summaries of the areal extent of specific land cover sequences in the analysis of cumulative erosion risk.

Graphic Products

Graphic products, portraying the extent and distribution of soil erosion risk for different cases, were derived through the incorporation of queries and plot format commands into AML programs written to generate ARC/INFO plot files. These plot files were then converted to plot device files (PDF) through use of Graphics Support Package (GSP) software to enable output on a TEKTRONIX Color-Quick ink jet plotter.

Tabular reports and graphics products for each study consisted of the following:

Soils Coverages :

1. The 10 predominant soil map units, their areal extent, and associated erosion risk ratings.

2. Areal summaries of soil erosion risk given bare surface, cereal, canola and alfalfa cover.

3. Erosion risk maps for bare surface conditions.

Vectorized LANDSAT Theme Coverages:

1. Areal summaries of land cover for each date.

2. Land cover maps, as vectorized theme coverages (see Chapter IV).

3. Fallow cover maps, for continuous growing seasons.

Integrated LANDSAT/Soils Coverages:

1. Erosion risk maps for single season (July 1988), and cumulative season (all three dates) for bare soil surface conditions.

2. Areal summaries of single season erosion risk.

3. Areal summaries of cumulative erosion risk, based on temporal land cover sequences.

Results and Discussion

Erosion Risk Using Soils Data

The soil erosion risk ratings for individual soil map units given a variety of soil surface conditions were derived by Tajek et al. (1985), were presented in the soil survey report for the County of Flagstaff (MacMillan et al. 1988), and are summarized in Table 5.1.

Table 5.1. Soil Erosion Risk Ratings.

Erosion Risk Rating	Risk Category	Potential soil loss (tonnes/ha/year)
1	negligible	< 6
2	slight	6 - 11
3	moderate	11 - 22
4	severe	22 - 33
5	very severe	33 - 55
6	extreme	> 55

(modified after MacMillan et al. 1988)

These erosion risk ratings were used to augment the soils attribute files to include erosion risk (Table 4.8), and tabular summaries and graphic products were then derived through query of these attribute files.

The spatial distribution of erosion risk for bare soil surface conditions is illustrated in Plate 5.1. This type of interpretive product, based on soils information, serves as the basis for many soil erosion risk maps in which erosion potential is mapped as though the entire landscape were devoid of vegetative cover. This type of product is of limited utility in conservation planning in agricultural regions, as vegetative cover changes seasonally and thereby influences the erosion risk. However, it does serve a purpose in illustrating the location of potential problem areas, where summerfallowing and post-harvest cultivation are practised. The ability to quantify how much of the land area is subject to erosion risk necessitates consideration of surface cover conditions. The addition of temporal land cover information, therefore, serves to refine traditional soil erosion risk maps by providing a more representative portrayal of the landscape.

The variations in the distribution of soil erosion risk for each study area, given various surface conditions are illustrated in Figures 5.1 and 5.2. These figures portray the reduction in potential soil erosion risk due to the presence of protective surface cover, with the erosion risk for alfalfa > cereal > canola > bare surface, for both areas.

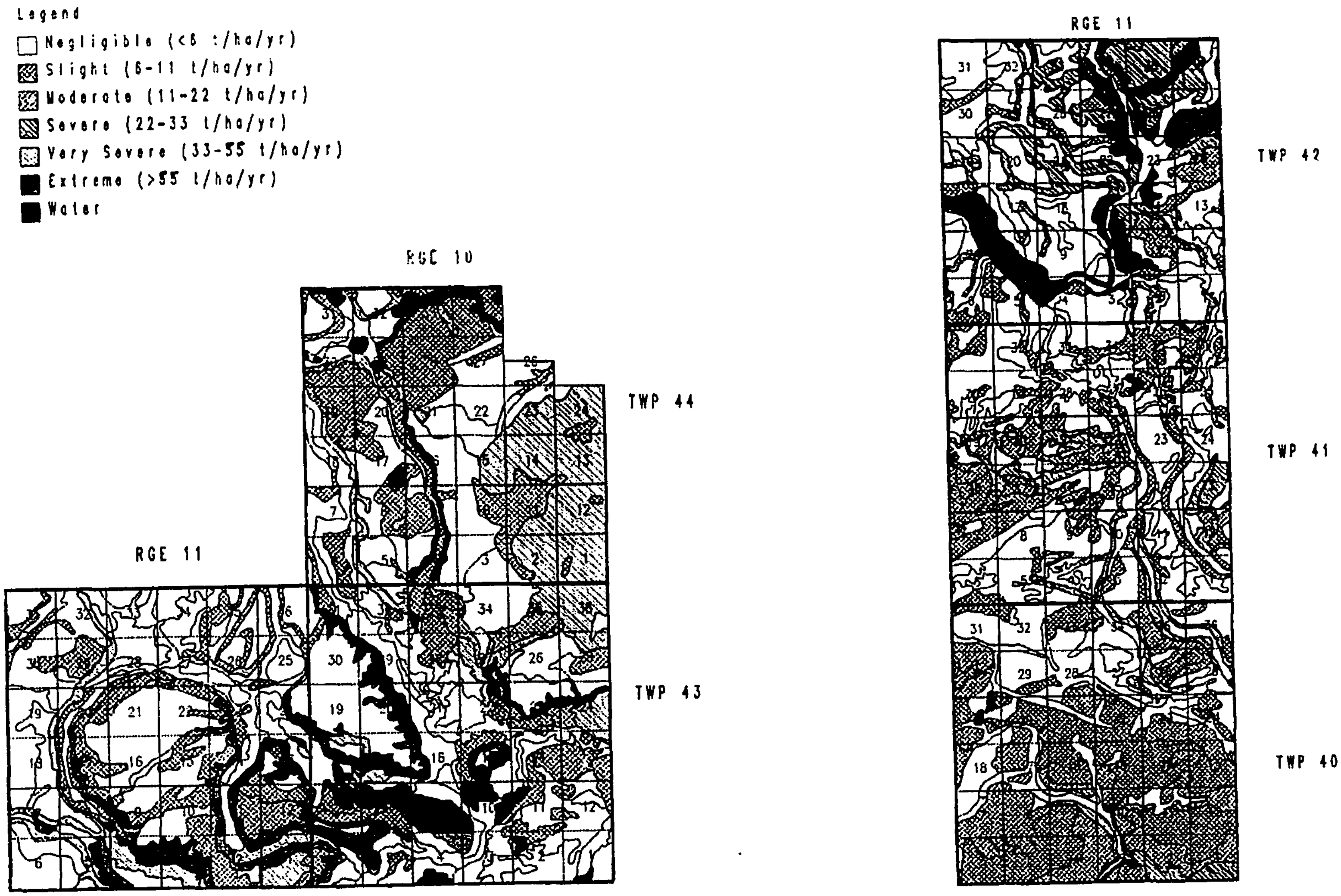

Plate 5.). Soil Erosion Risk for Bare Soil Surfaces.

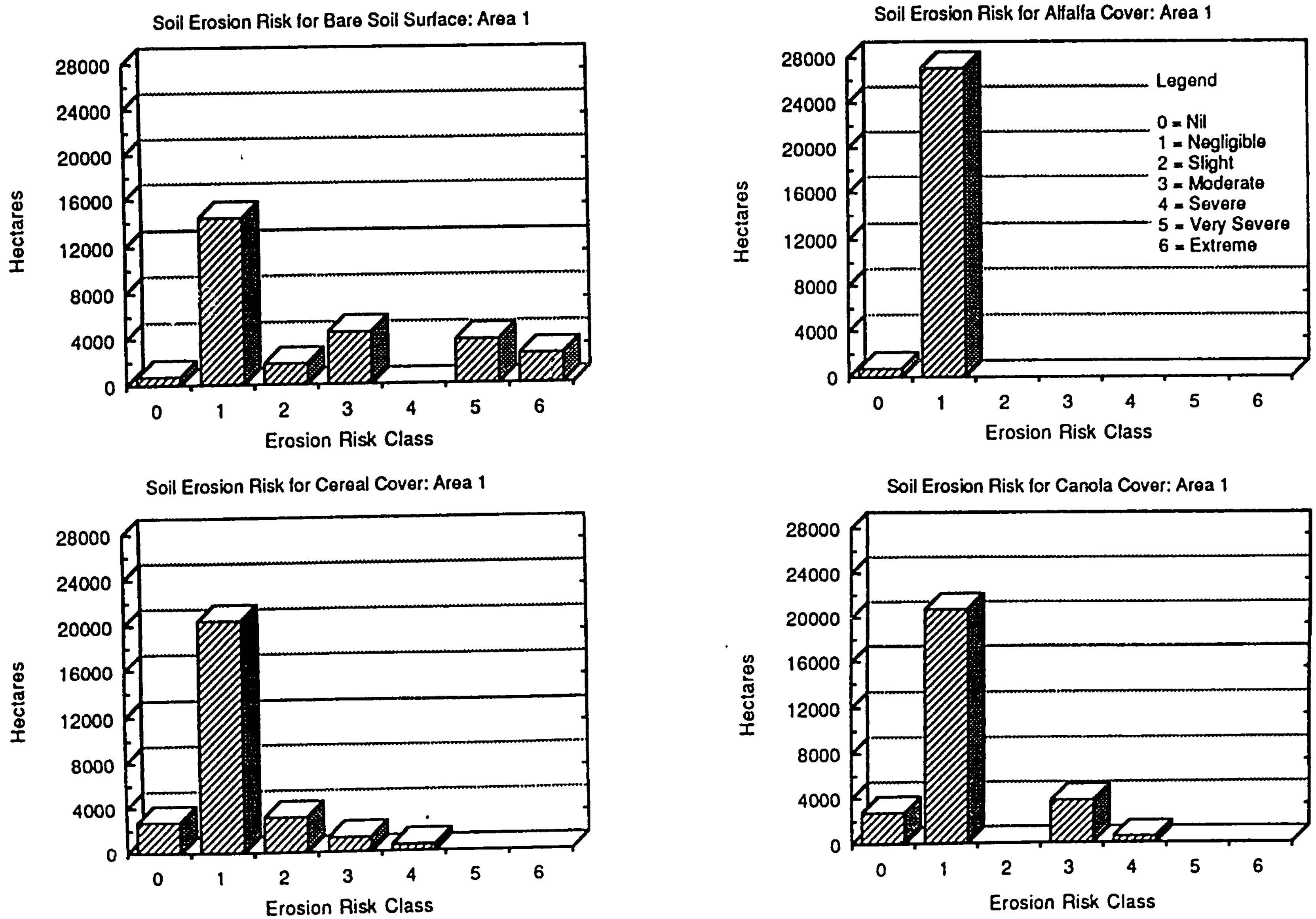

Figure 5.1. Soil Erosion Risk for Various Surface Conditons: Area 1.

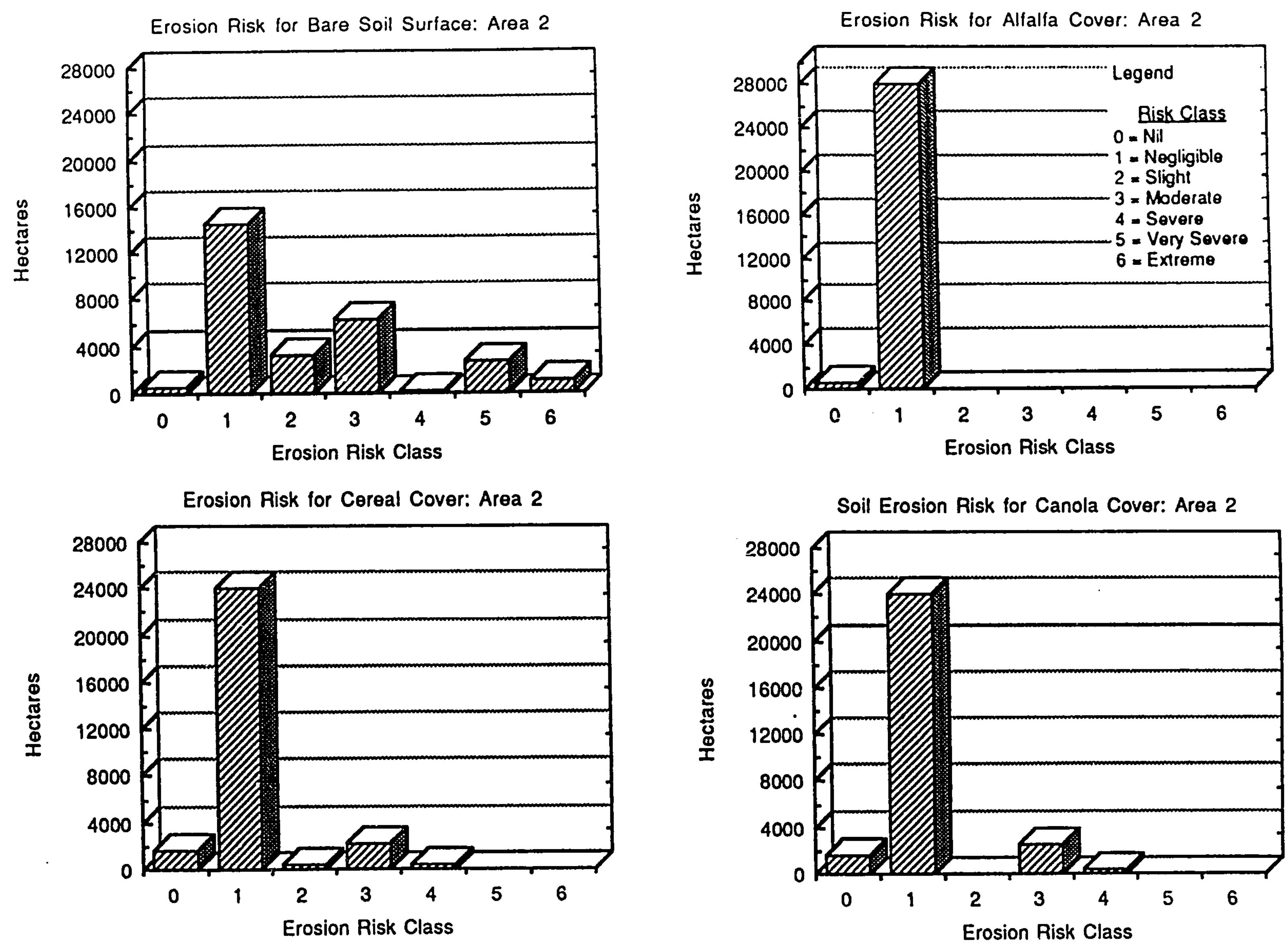

Figure 5.2. Soil Erosion Risk for Various Surface Conditons: Area 2.

The 10 predominant soils of each study area, and their areal extent and associated erosion risk ratings are summarized in Table 5.2 and 5.3. Study Area 1 consists predominantly of soils of the Elnora (EOR) series; Black Chernozems, formed from weakly calcareous till. In this area, soil map units EOR8/5, and RB1 (Regosolics) and EOR10/5 constitute the most severe risk and comprise a total of 5430.1 ha or 19.4% of the total land area (Table 5.2). In comparison, Area 2 consists predominantly of EOR, as well as Hughenden (HND), Haight-Foreman (HGFM) and Heisler (HER) map units, due to differing geologic and parent materials (Figure 2.3). Soil erosion risk is greatest for the EOR10/5 units, which comprise 2040.0 ha, or 6.5% of the total land area. These soils data, as individual coverages in the GIS, were used to portray potential erosion risk for each study area, but did not provide a representative indication of erosion risk as it relates to the distribution of land cover.

Erosion Risk Using LANDSAT Data

The seasonal dynamics of land cover distribution for each area are illustrated in Figures 5.3 and 5.4. These data were derived through querying the attribute data corresponding to the vectorized theme files, and provided a means of quantifying potential erosion risk on the basis of land cover.

In both study areas, the proportion of bare soil surface was greater in the 1988 crop year relative to 1987. The increase in proportion of fallow in the 1988 crop year may have been a management response to the antecedent drought of the 1987 season. The distribution of bare soil surfaces is illustrated in Figures 5.5. and 5.6 for these two consecutive crop years, and encompasses all soil erosion risk classes.

The tabular and graphic products derived from the land cover information are suited to reconnaissance inventory of potential erosion risk on the basis of surface cover, and are useful for determining the seasonal trends in cultivation practices. Determination of the relative susceptibility of soils to erosion, as influenced by soil characteristics, necessitates consideration of both the soil characteristics and the kind and distribution of surface cover. This information can be derived through the application of queries to integrated coverages and associated spatio-temporal data bases, for determination of single and cumulative season soil erosion risk.

Table 5.2 Predominant Soil Map Units: Study Area 1.

				Erosion Risk Class			
Ranking	Soil Map Unit	Characteristics*	Area (ha)	Bare Soil	Cereal	Canola	Alfalfa
1	EOR1/3	70-90% Orthic Black Chernozemic, med.text. weakly calcareous till, <15% imperfectly drained, 2-5% slope, undulating landscape	4872.8	1 (nelgligible)	1	1	1
2	EOR2/3	60-80% Orthic Black Chernozemic, med.text. weakly calcareous till, 15-30% imperfectly drained, 2-5% siope, unudulating landscape	3480.9	1 (negligible)	1	1	1
3	EOR8/5	60-80% Orthic Black Chernozemic, med. text. weakly calcareous till, 10-15% slope, hummocky landscape	2183.6	5 (very severe)	2	3	1
4	RB1	50-80% Chernozemic (mixtures of Orthic, Rego, Dark Brown and Black), inclined landscapes adjacent to rivers and creeks, 10-70% slope	2060.5	6 (extreme)	-	-	1
5	EOR1/4	Orthic Black Chernozemic, med. text. weakly calcareous till, 15% imperfectly drained, slope 6-9%	2055.6	3 (moderate)	1	1	1
6	EORO1/3	80-90% Orthic Black Chernozemic, med. text. weakly calcareous till and glaciofluvial, 15% imperfectly drained, slope 2-5%, gently undulating landscape	1361.0	1 (negligible)	1	1	1
7	EOR10/5	Orthic Black Chernozemic, med. text. weakly calcareous till, inclusions of eroded soils (10-25%), 10-15% slope, hummocky and strongly rolling landscapes	1186.0	5 (very severe)	3	3	1

- continued

Ranking	Soil Map Unit	Characteristics*	Area (ha)	Erosion Risk Class			
				Bare Soil	Cereal	Canola	Alfalfa
8	EOR10/4	as EOR10/5, slope 6-9%, hummocky, gently rolling landscapes	1116.8	3 (moderate)	1	1	1
9	REIR1/3	70-90% Orthic Black Chernozemic, coarse text., weakly calcareous glaciofluvial, slope 2-5%, undulating landscape	1093.0	1 (negligible)	1	1	1
10	AV2	codominant Chernozemic and Gleysolic, med. text. calcareous fluvial, slope 0-2%	921.6	1 (negligible)	1	1	1
		Total:	20,331.8				
		% of Total Area:	72.5				

*Summarized after MacMillan et al. (1988).

Table 5.3. Predominant Soil Map Units: Study Area 2.

Ranking	Soil Map Unit	Characteristics*	Area (ha)	Erosion Risk Class			
				Bare Soil	Cereal	Canola	Alfalfa
1	EOR2/3	60-80% Orthic Black Chernozemic, med.text. weakly calcareous till, 15-30% imperfectly drained, 2-5% slope, unudulating landscape	4082.5	1 (negligible)	1	1	1
2	EOR1/3	70-90% Orthic Black Chernozemic, med.text. weakly calcareous till, <15% imperfectly drained, 2-5% slope, undulating landscape	4061.0	1 (nelgligible)	1	1	1
3	EOR10/4	as EOR10/5, slope 6-9%, hummocky, gently rolling landscapes	3059.5	3 (moderate)	1	1	1
4	HND2/4	60-80% Orthic Dark Brown Chernozemic, med. text. weakly calcareous till, 6-9% slope, hummocky landscapes, lower slope position	2357.0	3 (moderate)	1	1	1
5	EOR10/5	Orthic Black Chernozemic, med. text., weakly calcareous till, inclusions of eroded soils (10-25%), 10-15% slope, hummocky and strongly rolling landscapes	2040.0	5 (very severe)	2	3	1
6	EOR1/4	Orthic Black Chernozemic, med. text., weakly calcareous till, 15% imperfectly drained, slope 6-9%	1936.6	3 (moderate	1	1	1

- continued

				Erosion Risk Class			
Ranking	Soil Map Unit	Characteristics*	Area (ha)	Bare Soil	Cereal	Canola	Alfalfa
7	EOR3/3	40-60% Orthic Black Chernozemic and 30-60% Gleyed Black Chernozemic, med. text. weakly calcareous till, lower slope and depressional areas, slopes 2-5%, hummocky landscapes and drainage channels	1243.6	1 (negligible	1	1	1
8	HGFM1/2	80-100% Gleysolic (Orthic Humic and Solonetzic Humic Gleysols), med. to fine text. weakly saline and sodic, weakly calcareous glaciolacustrine, slope 0.5-2%, nearly level landscapes	1150.6	1 (negligible)	1	1	1
9	HER5/3	40-70% Chernozemic (Solonetzic Black and Orthic Black), med. text., weakly calcareous till, mid and lower slopes, 2-5% slope, gently undulating landscapes	1134.2	1 (negligible)	1	1	1
10	HER4/3	50-80% Chernozemic (Solonetzic Black and Orthic Black), med. text. weakly calcareous till, mid and lower slopes, slopes 2-5%, gently undulating and hummocky landscapes	1117.0	1 (negligible)	1	1	1
		Total:	22,182.0				
		% of Total Area:	70.4				

*Summarized after MacMillan et al. (1988).

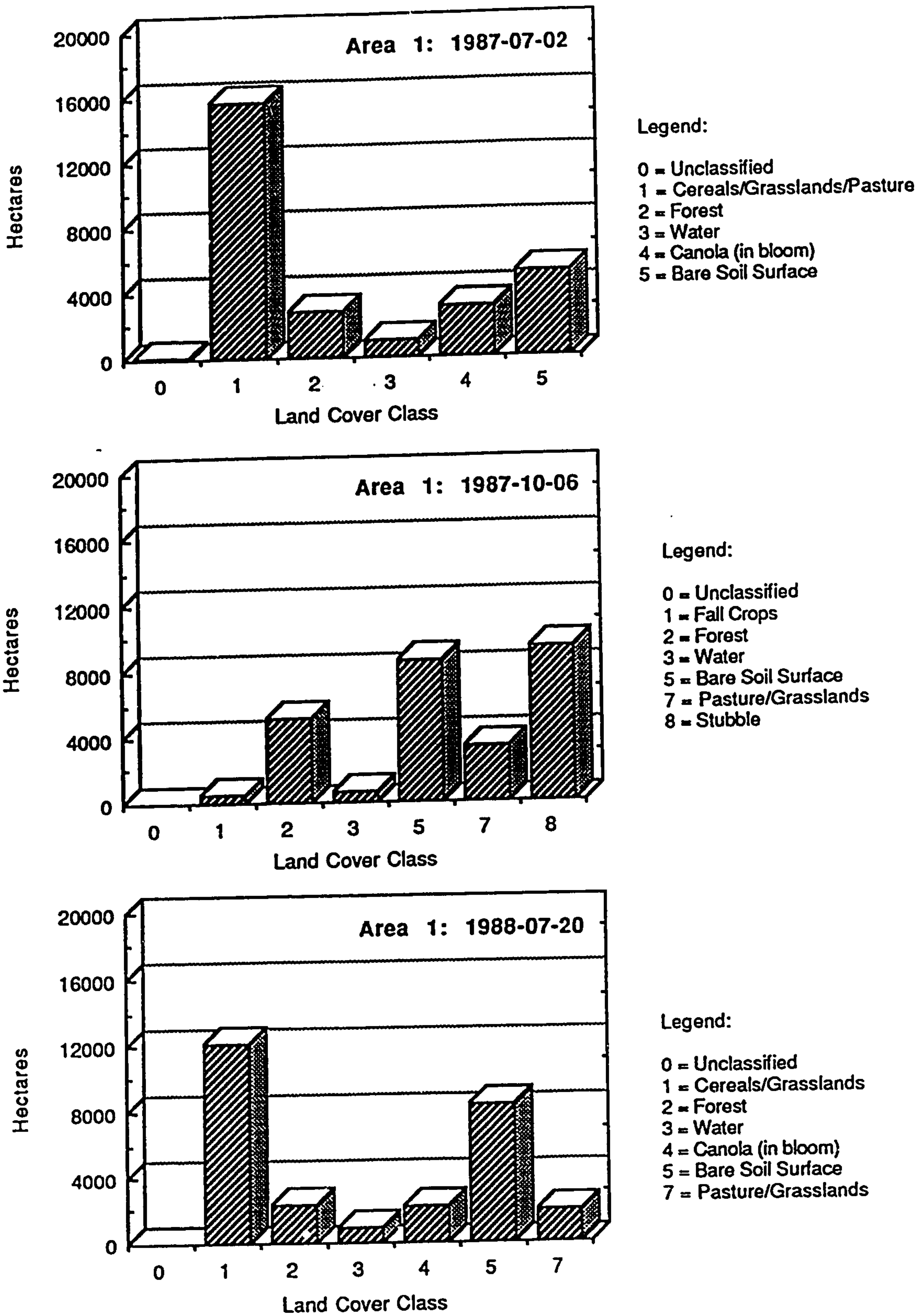

Figure 5.3. Seasonal Dynamics of Land Cover Distribution: Area 1.

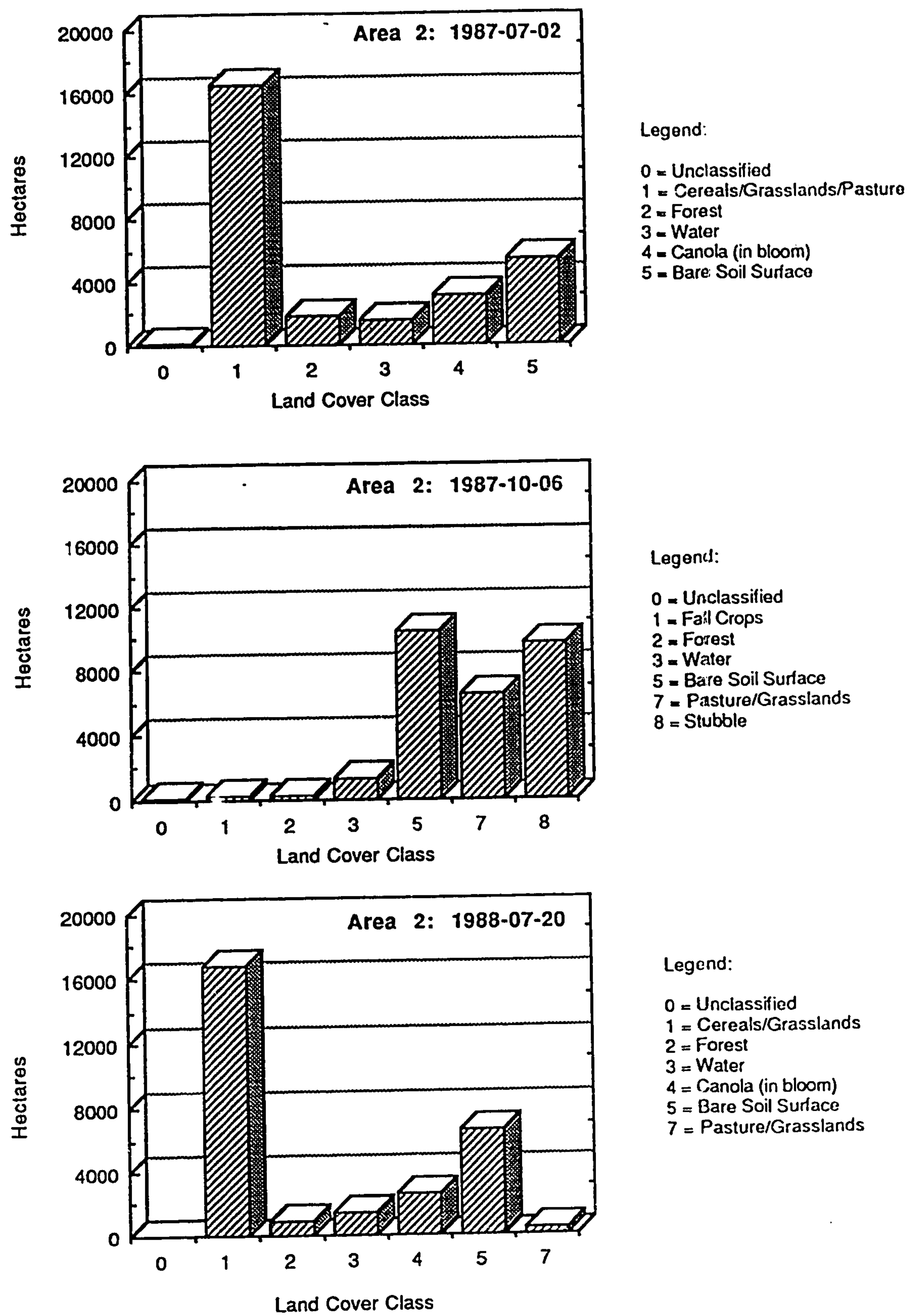

Figure 5.4. Seasonal Dynamics of Land Cover Distribution: Area 2.

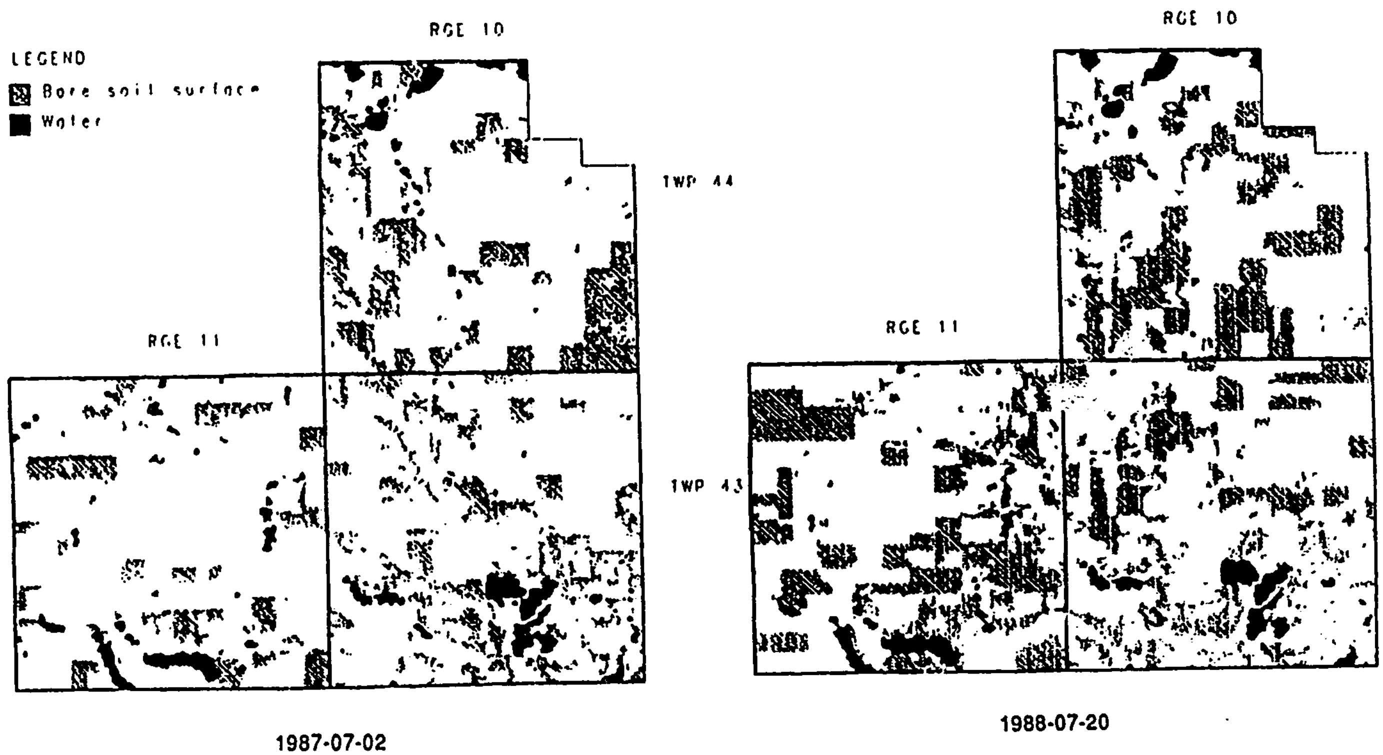

Figure 5.5. Distribution of Bare Soil Surfaces for Two Consecutive Seasons: Area 1.

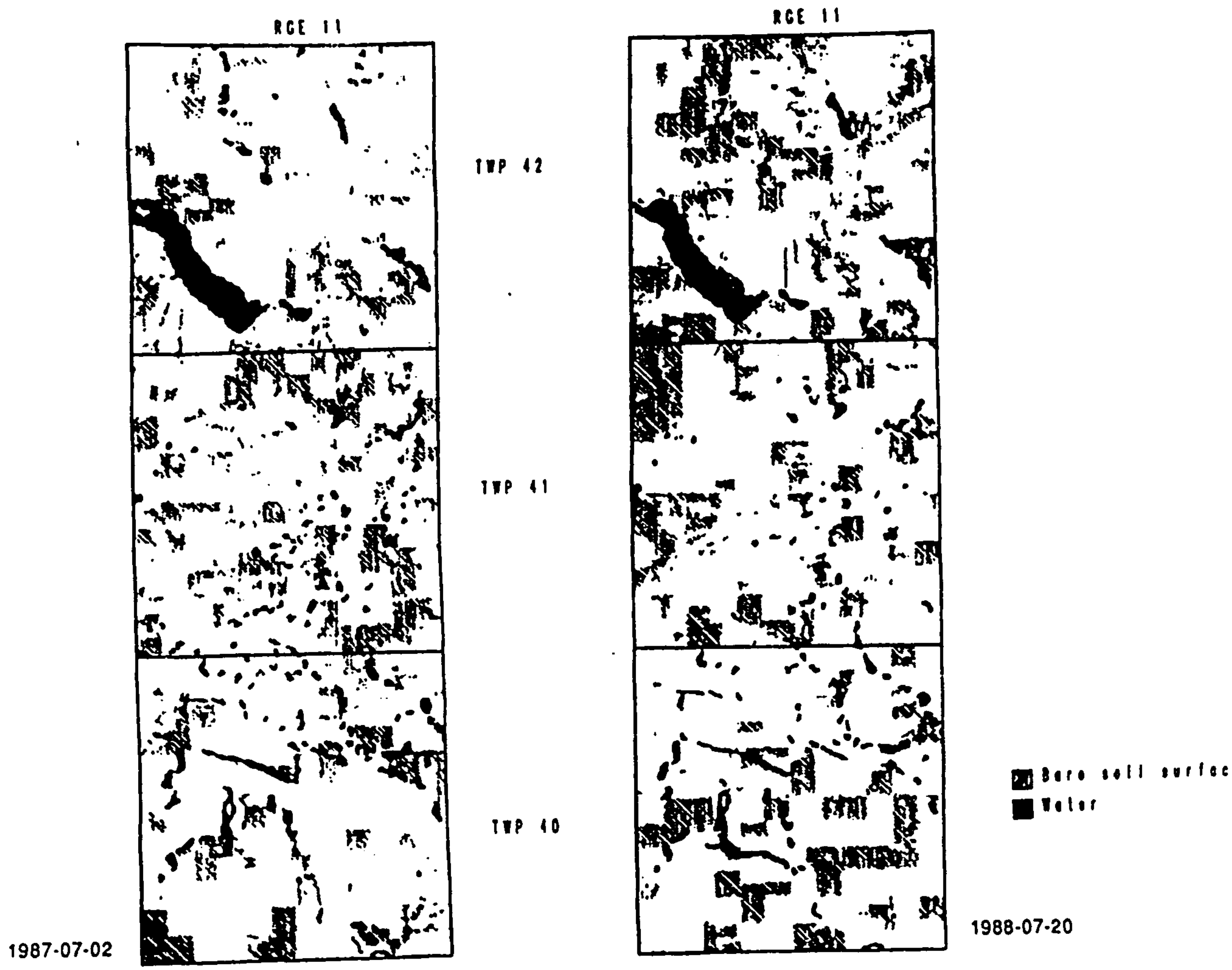

Figure 5.6. Distribution of Bare Soil Surfaces for Two Consecutive Seasons: Area 2.

Erosion Risk Using Integrated LANDSAT and Soils Data

The development of integrated LANDSAT/Soils coverages (Chapter IV), enabled GIS-based queries for specific combinations of land cover and soils in determination of single season and cumulative season erosion risk. Single season erosion risk, based on select combinations of land cover and soil erosion risk ratings, was quantified for each date of imagery and study area (Tables 5.4 and 5.5). These summaries indicated that soils of moderate risk (risk class 3) through extreme risk (class 6) are regularly cultivated for cereal and oilseed production involving fallow rotations, in both study areas. These data also indicate that the growing of canola on soils of very severe to extreme risk constitutes a potentially serious contribution to the erodibility of those soils (Tables 5.4 and 5.5). Canola results in negligible straw residue, and therefore does not contribute to soil organic matter content or the stabilization of erodible soils. From the standpoint of soil management for conservation, the growth of cereal crops, legumes, or forages is a much better management alternative for these areas. The identification of fallow fields on soils of high erosion risk potential also enables conservation planning to be directed at specific areas. This may include incentives for continuous cropping and maintenance of post-harvest crop residues.

The maintenance of stubble cover accounts for only 55% of the cropped land in Area 1, following the 1987 growing season, and 49% in Area 2, for soils of risk class rating 3 through 6 (Tables 5.4 and 5.5). This suggests a need for reevaluating these post-harvest land management practices that contribute to soil erosion during spring melt. An increase in the proportion of bare soil surfaces from the 1987 to the 1988 growing season was noted for both study areas. This increase is in the order of 75% for Area 1, and 15% for Area 2, on soils of erosion risk class 3 through 6. The increase in fallow may have been a management response to low rainfall in the previous cropping season. A decrease in the amount of canola grown in both areas was observed for soils of risk class 3 through 6, from the 1987 to the 1988 crop year (Figures 5.3 and 5.4, see also Table 3.24).

The distribution of bare soil surfaces, in relation to soils of erosion classes 3 through 6, is portrayed in Plate 5.2 as an indication of single season erosion risk for the July 1988 growing season. Distribution of soil erosion risk for the two study areas is represented more realistically with map products derived from integrated data than with maps derived using only the soils data (Plate 5.1) or land cover data (Figures 5.5 and 5.6, see also Plate 4.1). The ability to query for specific combinations of land cover conditions and soils for a given date or season is a distinct advantage of integrating these data within a GIS. In addition, the ability to quantify the distribution of specific cover types on a select range of soils (Tables 5.4 and 5.5), and to portray their distribution graphically (Figures 5.5 and 5.6), is another advantage of utilizing a GIS for erosion risk inventory and monitoring.

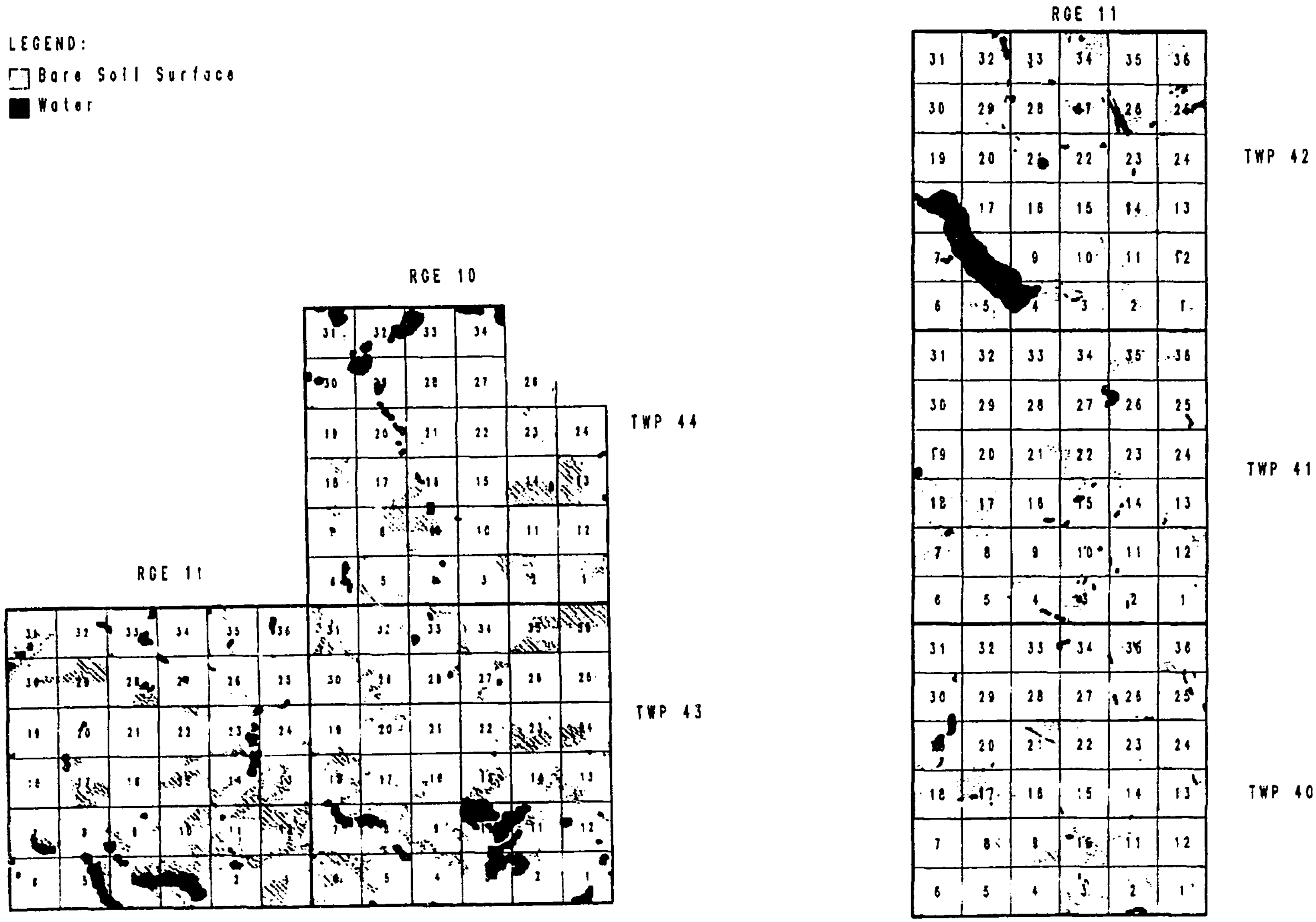

Plate 5.2. Single Season Erosion Risk for 1988-07-02.20 .

Table 5.4. Areal Summary of Single Season Soil Erosion Risk: Area 1.

Land Cover	Soil Erosion Risk Rating Class		1987-07-02	1987-10-06	1988-07-20
			Area (ha)	Area (ha)	Area (ha)
Bare Soil	6		335.7	190.2	919.1
	5		1018.6	914.6	931.9
	4		0	19.2	0
	3		768.7	1524.1	1853.6
		Total:	2123.0	2648.1	3704.6
Cereal/Grassland	6		1552.3	13.6	672.1
	5		1881.9	31.9	1934.6
	4		0	0	0
	3		2725.5	10.9	1684.3
		Total:	6159.7	56.4	4291.0
Canola	6		47.1		59.3
	5		327.5		405.3
	4		0		0
	3		615.7		280.8
		Total:	990.3		745.4
Stubble	6			505.4	
	5			1844.6	
	4			0	
	3			1622.3	
			Total:	3972.3	

Table 5.5 Areal Summary of Single Season Soil Erosion Risk: Area 2.

Land Cover	Soil Erosion Risk Rating Class		1987-07-02 Area (ha)		1987-10-06 Area (ha)	1988-07-20 Area (ha)
Bare Soil	6		113.8		231.4	244.1
	5		408.9		850.0	654.1
	4		0		19.2	26.6
	3		1548.3		2645.2	1462.3
		Total:	2071.0		3745.8	2387.1
Cereal/Grassland	6		672.3		0	594.3
	5		1673.9		33.6	1750.0
	4		101.0		0	49.5
	3		3651.6		58.3	3472.8
		Total:	6098.8		91.9	5866.6
Canola	6		56.6			22.6
	5		368.3			137.7
	4		0			0
	3		561.4			956.3
		Total:	986.3			1116.6
Stubble	6				291.2	
	5				997.2	
	4				8.3	
	3				2181.5	
				Total:	3478.2	

Another approach to the inventory and monitoring of erosion risk is the analysis of soil management on a continuous basis, i.e. consideration of antecedent as well as current management regimes. For example, soils that have been fallowed for two or more consecutive seasons are more predisposed to erosion processes than are soils that have been continuously cropped over the same time period. The continual cultivation of soil, as in fallowing, involves disruption of soil aggregates, disturbance of the soil surface, and subsequent lowering of organic matter and moisture contents. By contrast, vegetation cover contributes to the protection of the soil against wind and water erosion through the production of both protective covering and root mass which also provide a source of soil organic matter when incorporated as crop residues.

The consideration of antecedent land cover and management, as well as current conditions, provides a more representative map of the spatial distribution of soil erosion risk for each study area (Plate 5.3). This map depicts the locations of bare soil surfaces for those soils of erosion risk classes 3 through 6 inclusive, and serves to identify those regions most prone to erosion risk through the historical distribution of bare soil surfaces and land cover sequences.

An additional utility of the GIS involves the ability to quantify the spatial distribution of specific land cover sequences (Table 5.6). From the standpoint of soil conservation, soil surfaces that continuously remain unprotected constitute the worst erosion potential. Locations of continuously bare surface were identified within both study areas (Table 5.6, Plate 5.3). An additional high erosion risk scenario involves the presence of bare soil surfaces for 2 consecutive seasons, as in the case of 2 seasons of fallow followed by crop, or crop followed by post-harvest cultivation and fallowing. These conditions were also observed for both study areas (Table 5.6, Plate 5.3).

The most favorable conservation-directed land management practice involves the cereal-stubble-cereal sequence. This sequence constitutes the greatest proportion of land area for soils of erosion risk categories 3 through 6, for both study areas (Table 5.6). The retention of crop residues after harvest, particularly for fields that will be managed as fallow in the following growing season, was observed for both areas (Table 5.6). This is indicative of some conservation management being practised in these areas. Overall, the variety of land cover and management sequences examined indicated that land management practices and crop rotation sequences vary considerably within these localized areas, and that the cultivation of soils of high inherent erosion risk persists within both areas.

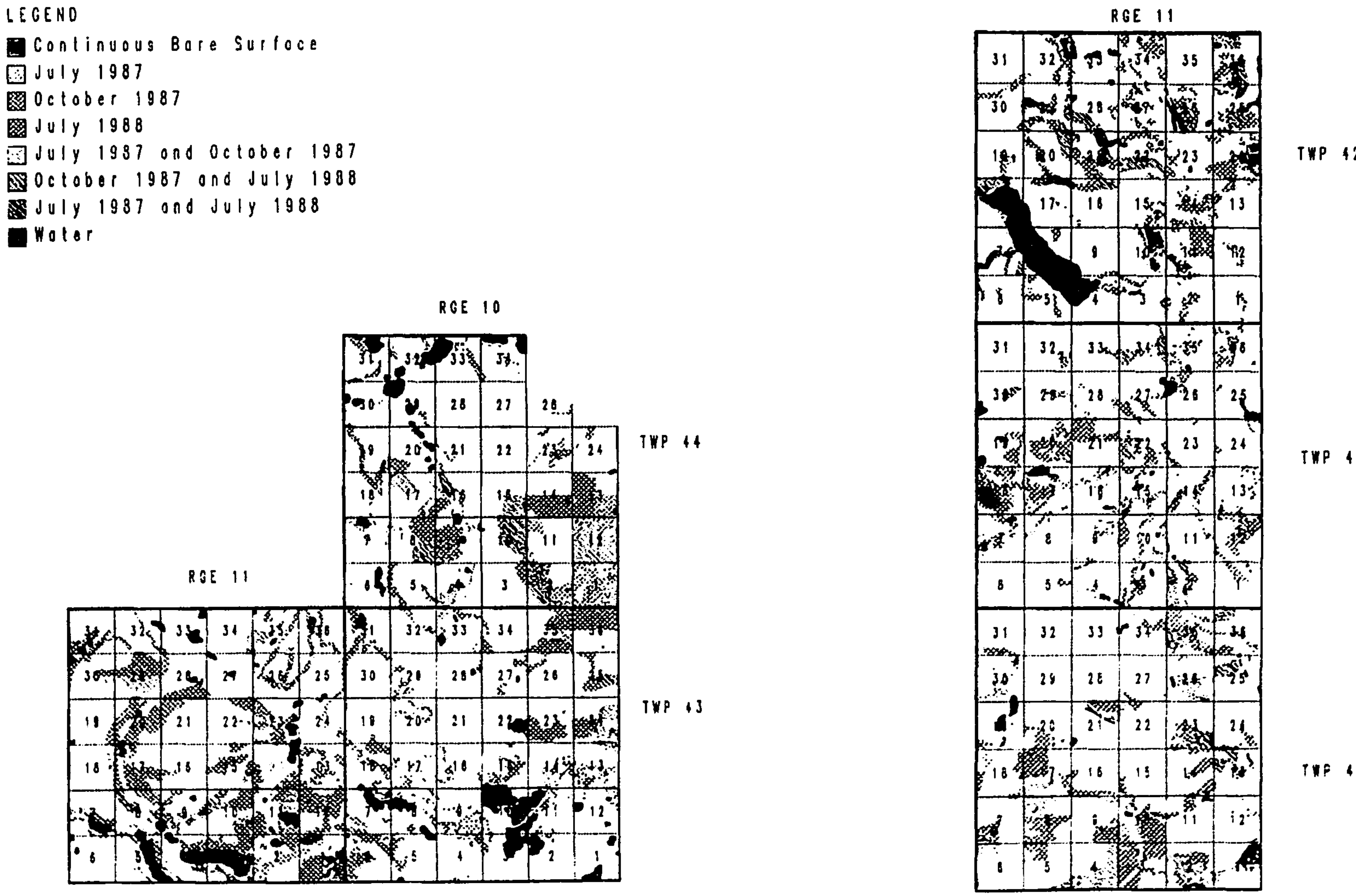

Plate 5.3. Cumulative Season Erosion Risk for Bare Soil Surfaces.

Table 5.6. Areal Summary of Cumulative Soil Erosion Risk.

Land Cover Sequence	Soil Erosion Risk Class		Study Area 1 Area (ha)	Study Area 2 Area (ha)
Continuous Bare Surface	6		22.1	38.2
	5		34.6	87.5
	4		0	0
	3		92.9	148.0
		Total:	149.6	273.7
Bare-Bare-Vegetated	6		26.6	16.0
	5		298.0	98.0
	4		0	0
	3		198.3	493.8
		Total:	522.9	607.8
Bare-Bare-Canola	6		11.4	9.7
	5		181.3	74.7
	4		0	0
	3		143.6	469.4
		Total:	336.3	553.8
Cereal-Bare-Bare	6		90.2	55.0
	5		24.6	164.8
	4		0	18.0
	3		242.0	417.1
		Total:	356.8	654.9
Canola-Bare-Bare	6		2.0	4.4
	5		37.3	84.9
	4		0	0
	3		169.2	27.8
		Total:	208.5	117.1
Bare-Fall Crop-Bare	6		1.5	0
	5		6.8	0
	4		0	0
	3		7.1	5.0
		Total:	15.4	5.0
Cereal-Stubble-Cereal	6		165.7	188.66
	5		628.7	98.64
	4		0	0
	3		408.9	998.54
		Total:	1203.3	1283.84
Cereal-Stubble-Bare	6		156.4	19.1
	5		581.0	3.6
	4		0	7.9
	3		802.9	515.2
		Total:	1540.3	548.8

Summary

Both single season and cumulative season soil erosion risk were examined through selective query of LANDSAT-derived theme files and digital soil survey information, using an ARC/INFO GIS. Tabular summaries and graphic products portrayed the extent and spatial distribution of soil erosion risk at a level of resolution that surpassed the soil erosion risk maps currently available for use in county-scale conservation planning.

The soils information was used to identify potential soil erosion risk on the basis of soil characteristics only, while LANDSAT data was used to determine risk on the basis of land cover. Analysis of integrated forms of these data, as spatio-temporal data bases, provided the most representative depiction of soil erosion risk on the basis of historical land management. The overlay of base map data on erosion risk graphics products enabled spatial referencing of erosion risk to the quarter-section level, which is appropriate for county-scale applications.

The advantages of using a GIS included the quantification of select combinations of soil erosion risk categories and land cover, the production of tabular summaries and geo-referenced map products, and the maintenance of a spatio-temporal data base that can be used for subsequent conservation-directed applications.

VI. SYNTHESIS

General Summary and Conclusions

The purpose of this dissertation was to explore and characterize the integration of LANDSAT TM and digital soil survey data in an ARC/INFO GIS for application to the inventory and monitoring of soil erosion risk in east-central Alberta. Additional objectives included the extraction of multitemporal land cover information from LANDSAT TM imagery, the integration of LANDSAT-derived theme files, digital soil survey data and base map data within a GIS, and the spatial and temporal analysis of soil erosion risk.

Three dates of LANDSAT-5 TM imagery (1987-07-02, 1987-10-06, 1988-07-20) were analyzed for extraction [illegible] oral land cover information. These dates were selected for their portrayal of maximum [illegible] riations of agricultural land cover types in the summer and autumn seasons, as ob [illegible] east-central Alberta. Image enhancement and classification techniques were e [illegible] derivation of land cover information suitable for integration within a GIS for use in erosion risk inventory and monitoring. Of these, simulated color infrared enhancements were useful for visual discrimination of agricultural cover types: cereal, canola, and fallow in the July imagery; fall crops, stubble and fallow in the October imagery. By comparison, principal components enhancements provided very colorful renditions of land cover, but were of limited utility for identification of specific cover classes due to the similarities in color rendition of physiognomically distinct types.

Of the classification methods examined, supervised and unsupervised methods were restricted in their utility due to the spectral variability of cover types caused by the heterogeneity of landscapes, surface features and soils of the study areas. In these areas, the spectral complexity of fields portrayed by satellite imagery is attributed to the presence of small ponds, native forest, and shrublands within fields, as well as the seasonal variations in field boundaries and crop rotations. The areas studied were quite different compared to regions of southern Alberta or Saskatchewan, where agricultural landscapes tend to be more homogeneous and field boundaries and crop rotations remain consistent from season to season. The application of conventional supervised and unsupervised classification methods, which are more suited to regions of spectrally homogeneous land cover, did not produce acceptable results for land cover mapping. As an alternative method, parallelepiped classification proved to be the most useful for derivation of land cover theme files, for all three dates of imagery. This procedure enabled the partitioning of cover types into multiple spectral classes to encompass their variability, interactive evaluation of intermediate classification results, and subsequent amalgamation of multiple classes into generalized land cover theme files.

The integration of these theme files within the GIS necessitated their conversion from raster-to-vector format. During this process, changes in the structure and information content of theme files were caused by the elimination of small polygons (<1.5 ha) for reduction of data volume and complexity. These changes involved commission of unclassified areas to existing land cover classes, and an overall reduction in the number of arcs and polygons defining each coverage. The elimination of small polygons was also necessary during development of integrated LANDSAT/soils coverages, as data volume and structure exceeded internal processing limitations of the GIS.

The processing of base map data involved the use of 8, 1:20,000 digital positional files for derivation of graphic overlays for the two study areas. Processing limitations of the GIS were also encountered due to the topological complexity of these data. The digital soil survey data required additional processing and editing of attribute data to achieve compliance with published maps. The use of digital data derived from various sources demonstrated the frequent need for additional processing of data in transfer between systems to ensure their utility within a host GIS. This included correction of discontinuities in graphics files, editing of attribute files, and raster-to-vector conversion.

Soils and land cover coverages were used independently in the analysis of erosion risk through production of tabular reports and graphics products based on single variables (i.e. soil erosion risk category or land cover). Integrated LANDSAT/soils coverages and their corresponding spatio-temporal data bases were used in the analysis of single season erosion risk, and temporal land cover sequences were used as the basis for analysis of cumulative season erosion risk. Resulting tabular reports and graphics products portrayed the areal extent and spatial distribution of erosion risk based on land cover and soil characteristics. These products provided much more detail compared to provincially-based maps of soil erosion potential, and therefore have considerable potential for use at the county-level where conservation management is targeted at existing and potential high risk areas. Knowledge of the areal extent and spatial distribution of soil erosion risk, coupled with the geo-referencing of individual fields, has considerable utility in design and implementation of conservation practices, as well as in identification of potential non-point source pollution.

In this study, the GIS provided a framework for geo-referencing of multiple sources of land information, an environment for spatial analysis, and a tool for the production of cartographic products and tabular summaries of seasonal and cumulative soil erosion risk. It also enabled the development of an archival system for the continued monitoring of land cover changes. The utility of the spatio-temporal data bases for inventory and monitoring can be further enhanced through addition of land ownership, assessment and productivity (yield) information, and through the development of a single parcel referencing system (e.g. quarter-section level). This would necessitate development of more complex attribute files, and may be better suited those GIS's utilizing a quadtree data structure.

Overall, this study demonstrated the utility of integrated LANDSAT and GIS technologies for county-level erosion risk inventory and monitoring. The operational use of GIS-based soil conservation planning will necessitate the automation of land-related information at the county-level, as well as the acceptance of GIS technology as a management tool. The use of LANDSAT data as a source of land cover information is likely to remain too costly for immediate use in conservation planning activities, but should not be overlooked as an important source of historical land cover information given that data archived for more than two years will likely be available at substantially reduced costs in the very near future.

Suggestions for Future Research

Several aspects of this study have potential as the basis for future research. These involve issues related to image analysis methods, integration procedures, and determination of soil erosion risk using integrated data. The techniques employed were based on ARIES-II and ARC/INFO software, and therefore could be explored using other software. Alternative image analysis methods for land cover information extraction may involve exploration of different classifiers, some of which are described in Chapter III. The evaluation of classifier performance for imagery of this geographic region would be an integral part of automating land cover information extraction for operational purposes.

Given the complexity of the study region, the pre-stratification of the LANDSAT data prior to classification according to field boundaries, or through the removal of boundary pixels through masking the imagery with base map data (e.g. transportation networks, hydrography), may hold potential for improvement of classification results. Alternatively, the incorporation of elevation data, in the form of digital elevation models (see for example Satterwhite 1984, Franklin 1987, Lee et al. 1988, Niemann 1988), may facilitate stratification during image classification, or in subsequent GIS-based analyses.

A relatively new area of research involves the application of artificial intelligence and expert systems to the classification of both remotely-sensed data (Argialas and Harlow 1990, Mehldau and Schowengerdt 1990) and soils information (McCracken and Cate 1986). These methods hold considerable potential for the improvement of computer-based classification and interpretation of land-related information. The application of neural networks (Caudill 1987; 1989) to landscape classification also holds promise for improvement in the analysis and interpretation of multi-source land information. Development of spatio-temporal data bases for GIS (Armstrong

1988, Langran 1990) also has potential for applications to analysis of temporal variations in soil erosion risk over large areas.

Another area of research related to the integration of remotely-sensed data within a GIS involves analysis of the changes in data structure and information content resulting from format conversion (i.e. raster-to-vector, or vector-to-raster). The concept of data reconstruction after format conversion, as suggested by Lam et al. (1987), is worthy of exploration for cases where the resolution of the original data may be altered as the result of format conversion. This is applicable to situations where soils data derived from reconnaissance level mapping are used in GIS-based spatial analysis of large areas. Additionally, the reduction of original LANDSAT data resolution through the resampling to larger pixels, or the elimination of land cover polygons smaller than the MLD of the soil survey information used, would be useful in determining the effects of generalization of these data. Standards for data generalization that consider both the original data scale and presentation scale of final products need to be developed.

A more fundamental research topic may involve the comparison of vector and raster GIS's for applications in soil erosion risk monitoring. While a raster-based system may eliminate the phenomenon of polygon fragmentation encountered in vector coverage overlay, the extent and effects of rasterization of vector data require exploration. The need for quantifying changes in vector-to-raster conversion, as well as raster-to-vector conversion, has been recently addressed by Lunetta et al. (1991).

Error analysis in GIS applications is also a relatively new area of research (Klinkenberg and Xiao 1990). As the popularity of GIS's for resource management increases, determination of product accuracies will require greater consideration. Methods for quantification of error at all stages of GIS processing and analysis are required, particularly when data from many sources, and of varying scales, survey intensity levels, resolutions, and inherent accuracies are combined for spatial analysis.

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APPENDIX I

GLOSSARY OF ACRONYMS AND TERMS

algorithm: a set of rules used in the computerized solution of a problem.

affine transformation: a geometric transformation of digital data which includes rotation, displacement, scaling and skewing.

arc: a line whose endpoints are defined by nodes.

ASCII: American Standard Code for Information Interchange. A seven-bit code widely used for exchanging alphanumeric data between computers.

attribute: descriptive information associated with a point, line, polygon or grid cell (e.g. sampling site number, road number, area, soil type).

boundary pixel: a pixel whose radiometric value is a composite of the reflectance characteristics of several different surface features.

build: an ARC/INFO software procedure for creating topology.

classification: in image analysis, the process of assigning individual pixels of a digital image to categories (spectral classes) on the basis of their radiometric values.

clipping: the process of extracting a subset of data located inside (or outside) user-defined boundaries.

coverage: a digital version of a map comprised of graphic and attribute files.

CPU: Central Processing Unit. The part of a computer where arithmetic and logical operations are performed.

cubic convolution: a cubic spline approximation to the theoretically perfect sinc(x) resampling function. It uses a 16-point (4x4) neighborhood of pixels as input to compute the value of the output pixel.

edit: the process of removing errors from, or modifying graphic or attribute data.

export: the process of formatting and transferring data from a computer system to storage media or to another computer.

geometric correction: for digital imagery, the removal of sensor, platform or scene induced errors and distortions such that the data conform to a desired projection. This involves the creation of a new digital image by resampling the input image.

hardcopy: a copy of a digital file (image, map, photograph) on permanent media.

hardware: physical components of a computer system including the actual computer, keyboard, display monitor and printer. For GIS, hardware may include a digitizer and a plotter.

import: the process of uploading data to a computer from storage media or another computer.

input: the data entered into a computer, or the process of entering data into a computer.

ISIF: Intergraph Standard Interchange Format. A data format used by Intergraph for data storage.

line: a basic unit of geographic information, defined by two or more x,y coordinates. A line can be represented by a single arc or by multiple arcs. Linear features (e.g. roads, rivers) in a vector GIS consist of line segments.

maximum likelihood: a method of classification based on probability theory for fitting a mathematical model to a set of data.

MLD: Minimum Legible Delineation. The minimum sized area that can be represented on a map given the mapping scale (e.g. on a 1:50,000 soil survey map, the MLD is 12.5 ha).

MSS: multispectral scanner sensor payload of LANDSAT-1, -2 and -3 that provided data at a 4 channel spectral resolution and an 80 m pixel resolution.

NOAA: a satellite system operated by the National Oceanic and Atmospheric Administration that provides spectral and thermal data at a 1 km pixel resolution at nadir.

node: a beginning point or an end point of an arc.

pixel: "picture element." The basic element in a digital image or grid cell data structure.

point: a geometric representation of a specific location (e.g. a sampling site or a well).

polygon: a closed boundary defined by contiguous arcs, which represents a region of uniform characteristics (e.g. a soil map unit or a water body).

quadtree: hierarchial data structure based upon the principle of recursive decomposition of space into mutually exclusive quarters or square tiles until the region is homogeneous or some specified level has been reached; the objective being to minimize data storage.

raster: a data structure based on regular grid cells, with each cell assigned a value describing a characteristic (e.g. land use, reflectance, elevation).

rasterization: the process of converting vector (line, polygon) data to a raster (grid cell) format.

relational database: a method for structuring data (often as tables), according to a relational scheme, in which the relationships between data are used for data access across several files.

resampling: in image analysis, the transformation of pixels to a desired projection and scale.

software: computer programs for the execution of specific tasks.

SIL: Survey Intensity Level, defined and controlled by the number of field inspections per map unit (e.g. a SIL=3 is typical for 1:50,000 scale mapping of soils, with a median MLD of 12.5 ha, and involves one field inspection per 20-200 ha).

sliver polygons: polygons created in the overlay of two vector graphic files, when boundaries are not in perfect registration. Sliver polygons are also considered **spurious polygons**.

spaghetti file: a data model for the storage of vector data in which points, lines and polygons are stored as simple lists of coordinates.

SPOT: Systeme Probatoire pour L'Observation de Terre. A satellite system operated by France that provides spectral data at 10 m and 20 m pixel resolutions.

spurious polygons: synonym for **sliver polygons**. These are often considered to be unimportant data, as they are formed as a result of boundary mismatch.

SVF: Single Variable Format. A precursory data format for raster data required in the raster-to-vector conversion process.

TM: Thematic Mapper. The seven channel spectral sensor payload on LANDSAT-4 and -5, that provides digital imagery at a spatial resolution of 30 m.

topology: the defined spatial relationships between objects in a spatial data base, which may include connectivity, contiguity, area and perimeter definition.

vector: a quantity having both magnitude and direction. In GIS, a vector is represented by a minimum of two sets of coordinates.

vectorization: the process of converting raster (grid cell) format data to vector format.

UTM: Universal Transverse Mercator. A grid system based on the Transverse Mercator Projection which is commonly used for topographic maps and geo-referencing of satellite imagery.

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APPENDIX II

SUMMARY OF EDITS TO DIGITAL SOIL SURVEY DATA FILES

Study Area 1: Source Data File: [ROMANARC.FLAG]SEDGP.E00:1

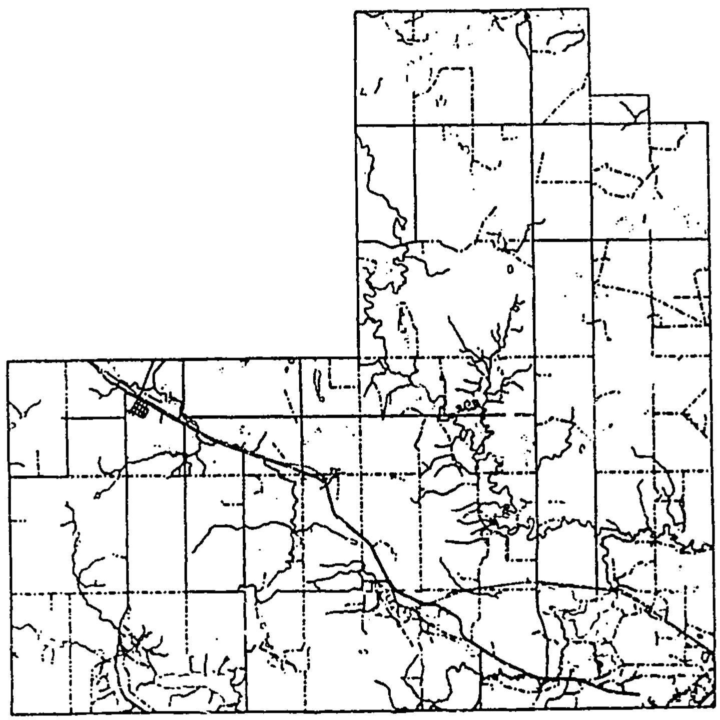
Original Record #	Map Unit (before editing)	Map Unit (after editing)
96	HNDC2/3	EOR2/3
99	FST9/3	HER5/3
100	FST9/3	HER5/3
124	EOR10/5	EOR6/4
142	- not labelled-	BEL1/3
145	HND1/4	EOR1/4
146	RB4	RB4 (not labelled on map)
151	HND4/4	EOR10/4
174	HNDC1/3	EOR1/3
189	HND6/4	EOR6/4
206	- not labelled -	REIR2/4-5
236	HND2/4	EOR10/5
248	HND4/5	EOR10/5

Study Area 2: Source Data File: [ROMANARC.FLAG]ALLIDDP.E00:1

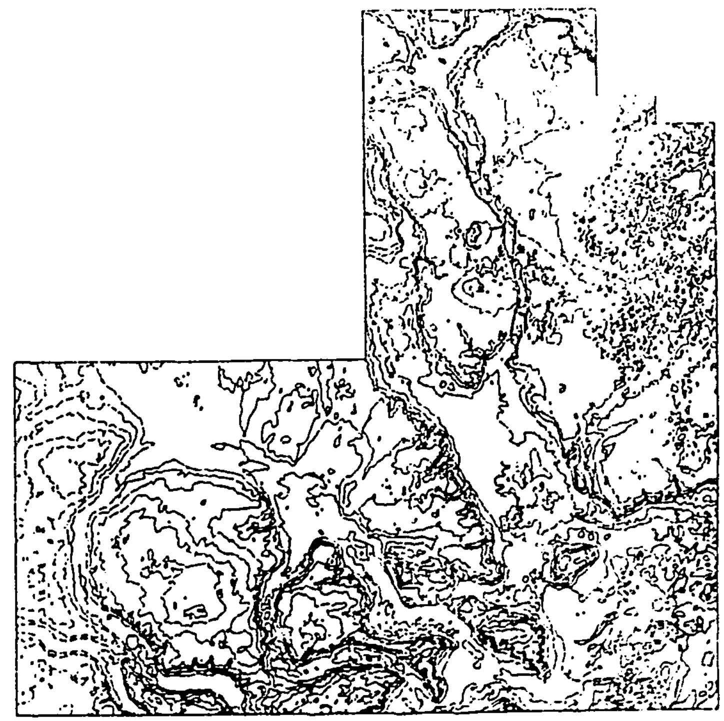
Original Record #	Map Unit (before editing)	Map Unit (after editing)
42	HND4/5	EOR10/5
45	HND3/3	EOR3/3
80	AMT1/4	REIR1/3
85	HNDC1/3	EOR1/3
88	MEDC1/3	IRROR1/3
102	HND1/4	EOR1/4
110	HGFM1/2	EOR1/4
165	FST7/3	HER4/3
181	HND1/3	EOR10/4
184	HND1/4	EOR1/4
214	MEWW1/3	REIR1/3
266	- not labelled -	EOR10/4

APPENDIX III

SELECTED BASE MAP GRAPHICS FOR STUDY AREAS



AREA 1: TRANSPORTATION NETWORKS AND HYDROGRAPHY.



CONTOURS.

3 of/de 3

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

1.0 1.1 1.25 1.4 1.6 1.8 2.0 2.2 2.5 2.8 3.2 3.6 4.0 4.5 5.0 5.6

END

27.04.92

FIN