University of Alberta

Assessment and Mapping of Fire Severity on Rangeland in the Fescue Grass Ecoregion of southwestern Alberta Using Resource Satellite Data, Field Observations, and Digital Terrain Models

By

Janna P. Wowk ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

in

Water and Land Resources

Department of Renewable Resources

Edmonton, Alberta

Fall 2000

0-612-59902-7

University of Alberta

Library Release Form

Name of Author: Janna P. Wowk

Title of Thesis: Assessment and Mapping of Fire Severity on Rangeland in the Fescue Grass Ecoregion of southwestern Alberta Using Resource Satellite Data, Field Observations, and Digital Terrain Models.

Degree: Master of Science

Year this Degree Granted: 2000

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Date: 29 September 2000

ABSTRACT

In December 1997, a 22,000 hectare wildfire spread through native foothills rough fescue grassland and forested grazing lease land in the strongly rolling topography of the Porcupine Hills southwest of Granum, Alberta. A study was initiated in the spring of 1998 to investigate the extent to which post-fire land cover, as determined using LANDSAT Thematic Mapper image data, could be used to indicate fire severity, and the extent to which fire severity was related to topographic variability. A post-fire land cover map was developed based on the normalized difference vegetation index. Field data and this map were used to create a fire severity map, which was combined with selected topographic variables derived from a digital elevation model. It was possible to map levels of fire severity using post-fire land cover; however, the presence of high amounts of green vegetative cover was not always indicative of low fire severity. Slope azimuth, elevation, and the interactive effects of slope azimuth and slope magnitude explained a greater proportion of variability in fire severity than slope magnitude alone. Prevailing wind direction, available fuel, and historical livestock grazing likely influenced the observed patterns of fire severity.

A thousand mile walk begins with a single step.
Chinese Proverb

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Assessment and Mapping of Fire Severity on Rangeland in the Fescue Grass Ecoregion of southwestern Alberta Using Resource Satellite Data, Field Observations, and Digital Terrain Models submitted by Janna P. Wowk in partial fulfillment of the requirements for the degree of Master of Science in Water and Land Resources.

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This thesis is dedicated in loving memory to my Baba, Mrs. Sadie Wowk, who passed her love of learning onto me.

ACKNOWLEDGEMENTS

I thank my supervisor, Dr. Peter Crown, who not only taught me about research and helped me grow as a scientist, but who also taught me about professional integrity and ethics, and helped me grow as a person. His endless support, words of encouragement, and calm rationale helped make this become a reality. I am fortunate to have had the opportunity to work with him.

I thank my supervisory committee members, Dr. Edward Bork and Mr. Tim Martin, for their advice and guidance. Their input and involvement into the project is sincerely appreciated. I also thank my external examiner, Dr. Anne Naeth, for her helpful suggestions and comments.

Thank you also to the staff and graduate students in the department for their support and friendship throughout the course of my studies. Special thanks are extended to Mr. Rick Pelletier for his advice and assistance with GIS, and to Dr. Emmanuel Mapfumo for his assistance with statistical analyses.

Sincerest appreciation is extended to Mr. Roy Penniket, without whom my field season would not have gone as smoothly or as successfully. He provided valuable advice and assistance. He opened his heart and his home, and for this I will always be grateful. Thank you also to Cate for being such a wonderful field assistant and companion.

I thank my family and friends for their patience and encouragement during the course of my studies. Their support is gratefully acknowledged.

I thank Mark, whose endless support and encouragement helped me realize my goal. He is my biggest fan, and I love him. Thank you for your patience and understanding.

The support of the Alberta Agricultural Research Institute, the University of Alberta, the Alberta Cattle Commission, Norwest Laboratories, and Alberta Agriculture, Food and Rural Development is gratefully acknowledged.

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CHAPTER 1 Introduction

1.1 Background

On December 14, 1997, a 22,000 hectare wildfire of anthropogenic origin swept across the Porcupine Hills southwest of Granum, Alberta, Canada. The fire travelled a total distance of 31.5 km in approximately four hours, extending northeast from the ignition point in the Porcupine Hills. Conditions for the fire were highly volatile due to the combined effects of the extended warm, dry weather leading up to the fire, lack of snow cover, and mean hourly wind speeds of 35.5 km/hr (Environment Canada 1999). This resulted in an intense fire that consumed native grassland, forested grazing lease land, deeded ranchland, and cropland.

Approximately 18,000 hectares of the area that burned were native foothills rough fescue *(Festuca campestris* Rydb.)[1] communities. This had a significant negative impact on livestock producers in the affected area, because of the importance of these native plant communities for species providing long-term productivity and use for winter grazing (Willms *et al.* 1993). Although grasslands evolved under a natural fire regime with an estimated fire return interval of 5-10 years (Wright and Bailey 1982), foothills rough fescue plant communities are likely less tolerant of infrequent, high intensity wildfires occurring due to high fuel loads (Bork *et al.* 2000). Miller and Findley (1994) reported that the amount of litter material within or around a living plant might be greater following long periods of fire exclusion. Under conditions of high fuel loading fire effects on vegetation might be more severe, because of higher temperatures and increased residence time.

1.1.1 The Importance of Native Grasslands

Native grasslands are an important rangeland resource to the agricultural sector of the province in that they provide a sustainable source of forage for the livestock industry.

[1] Remaining nomenclature follows Moss (1994).

Rangelands, in general, also provide a resource for carbon sequestration (Svejcar *et al.* 1997), watershed management (Frasier *et al.* 1998), wildlife (Jones and Manning 1996), and recreation (Dormaar and Willms 1990). Thus, conservation management of these unique areas is important to all Albertans.

In 1990, native grasslands occupied approximately 6.5 million hectares in Alberta (Dormaar and Willms 1990). Unfortunately, this number is declining due to the conversion of these rangelands to cropland, hayland, or "improved" pasture. This, coupled with pressures for wildlife habitat and recreational use, has placed increased importance for effective rangeland management and conservation.

1.2 Project Outline

Concerns raised within the farming and ranching community over the condition of the burned native grasslands and their ability to recover prompted a study to assess the extent and rate of vegetation recovery following the fire. Researchers at the University of Alberta, Alberta Agriculture, Food and Rural Development, and Agriculture and Agri-Food Canada are conducting this study (Bork *et al.* 2000). At the same time, the Conservation and Development Branch of Alberta Agriculture, Food and Rural Development initiated the Southwest Alberta Burn Area Project. The purpose of this preliminary study was to map pre-fire land cover using satellite imagery. Alberta Agriculture, Food and Rural Development personnel at the Lethbridge Research Station were also involved in studies of the fire's effect on insect populations, in particular, grasshoppers. In addition, a smaller scale study was initiated in the spring of 1998 by a Granum area consultant to document vegetation recovery and pattern throughout the fire area using sequential ground photographs from specific point locations. However, the task remained to add the additional perspective of extending the fire severity information across the fire area.

1.2.1 Objectives

This study was initiated in the spring of 1998 to quantify and evaluate the areal extent of land cover, and relate this to various fire severity classes and topographic variability using post-fire satellite data, field observations, and digital elevation and terrain models (DEM and DTMs). Specific objectives of the study were:

1. To determine the extent to which post-fire land cover could be used to indicate the level of fire severity.
2. To determine the extent to which fire severity was related to selected topographic variables: slope azimuth, slope magnitude, elevation, and slope azimuth-magnitude class combinations.

1.2.2 Hypotheses

The following hypotheses were developed:

H_1: Land cover, as indicated by the normalized difference vegetation index, (NDVI) relates to fire severity.

H_2: Fire severity will correlate with prevailing wind direction, if wind direction has a greater influence on fire behaviour than slope azimuth alone.

H_3: Fire severity will be greater on south- and southwest-facing slopes, if slope azimuth alone is the overriding factor influencing fire behaviour.

H_4: Fire severity will be greater as slope magnitude increases.

H_5: Fire severity will be greater at midslopes relative to lower and upper slopes.

H_6: Fire severity relates more to slope azimuth-magnitude class combinations than either slope azimuth or slope magnitude alone.

1.3 Rationale

The importance of increasing our understanding of large-scale ecosystem disturbances such as fire through the use of remote sensing and geographical information system (GIS) technologies, "...assumes added significance when potential implications of global climate change are considered." (Turner *et al.* 1997). Balling *et al.* (1992a, b) concluded that the variation in area burned in Yellowstone National Park was related to the increased aridity observed in the region since 1895. According to Romme and Turner (1991 as cited by Turner *et al.* 1997) and Gardner *et al.* (1996 as cited by Turner *et al.* 1997), fire frequency may increase in Yellowstone if the future climate becomes warmer and drier. In 1988, Van Wagner reported that there had been a marked increase in the annual extent of wildfires in Canada since the late 1970s; however, whether this was related to global climate change was not known (Turner *et al.* 1997). Davison (1996) reported similar findings to that of Van Wagner (1988). He presented an overview of wildland fuel management programs in the context of ecosystems and the sustainability of rangeland resources, and concluded that existing data clearly indicated wildland fires were increasing in frequency, size, and intensity. Davison (1996) further concluded that the occurrence, frequency, size, and intensity of a fire are largely dependent on rangeland management practices that influence fuel load properties. Given the unusually dry conditions in southern Alberta over the last three years combined with grazing management practices that result in high litter loads, it is quite possible that fire frequency may increase in this region. Following the Granum Fire there were a number of major and minor grassland fires, thus it becomes important to increase our understanding of ecological patterns and processes associated with large- and small-scale fires.

Fire has a significant effect on the reflectance properties of land cover due to vegetation removal, soil exposure, and soil color alteration, which makes the analysis of fire severity by spectral data possible (White *et al.* 1996). Jakubauskas *et al.* (1990) reported that the potential flexibility afforded by a GIS would allow for additional data sets from preceding or succeeding dates to be added, creating a database for the study of long-term change within a given study area. Thus, remote sensing and GIS techniques are useful tools for mapping the extent and pattern of fire, as well as understanding vegetative response and recovery as it relates to fire severity (Jakubauskas *et al.* 1990, White *et al.* 1996).

Pixel reflectance values provide a unique record of a fire event, which can be used to map the fire boundary and determine the area of the fire, to assess fire severity, and to monitor and evaluate post-fire vegetation regeneration (Milne 1986, White *et al.* 1996). Pre-fire satellite data can also provide valuable information, because it is an important prerequisite to understanding and interpreting vegetation recovery, and in establishing an index of fire severity (Milne 1986). Milne (1986) suggested that attempts to establish a meaningful fire severity index from satellite data required additional consideration of topographic effects.

GISs, which allow digital satellite data to be combined with digital elevation and terrain data, are useful in assessing fire severity on a landscape-level. Digital elevation models and derivative topographic surfaces, termed DTMs, are commonly used as sources of topographic information (Giles and Franklin 1996) for landscape modeling (Moore *et al.* 1991). Digital terrain data augmented by digital satellite data can be used to develop models of pre-fire vegetation distribution (Milne 1986) and post-fire vegetation recovery. Together these two models, combined with ignition point location and prevailing wind direction, would provide a means by which various fire severity classes could be assessed at a landscape-level.

The approach and analysis techniques developed for this particular research project will be of benefit to both livestock producers and rangeland scientists. A database, to include: a DEM, DTMs, satellite imagery, and distribution models of fire severity, will be in place for use with field observations and data collected over the next few years to continue to monitor the impacts of this and other grassland fires. This will provide a practical tool for livestock producers and rangeland scientists to locate problematic areas (i.e., moderate to high fire severity areas) and subsequently implement effective rangeland management practices that will facilitate faster recovery of the grassland.

1.4 Study Area

The fire area is located immediately west of highway #2 near Granum, Alberta and has the following approximate coordinates: 49°40' to 49°53' North Latitude and 113°30' to 113°55' West Longitude (Figure 1.1). This area traverses three ecoregions: the Montane Ecoregion, the Fescue Grass Ecoregion, and the Mixed Grass Ecoregion (Strong and Leggat 1992). The largest portion of the fire occurred within the Fescue Grass Ecoregion, which is also the main area of interest for the study, thus it will be the only one of the three ecoregions described.

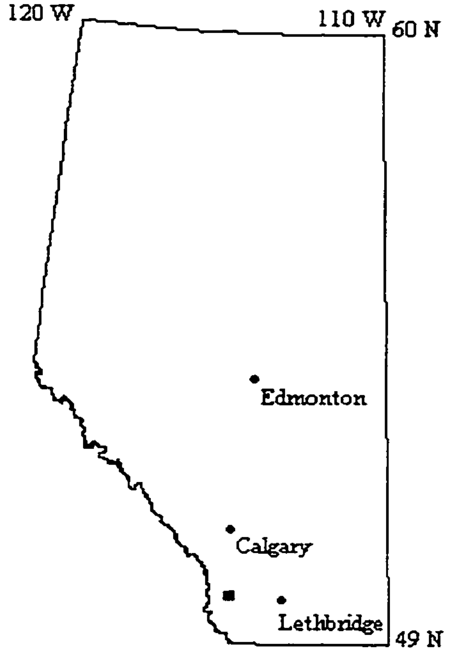

Figure 1.1 Sketch map of Alberta with the general location of the study area indicated by the black box between Calgary and Lethbridge.

The climate of the Fescue Grass Ecoregion is moist sub-humid without a marked deficiency of precipitation (Sanderson 1948). Mean annual precipitation totals 445 mm with most of it falling during the summer months (Strong and Leggat 1992). Due to the proximity of this ecoregion to the Rocky Mountains and the increased elevations associated with this proximity, summers tend to be cool and winters tend to be warm (Strong and Leggat 1992). Mean annual temperature is 5°C with January means of −10°C and July means of 18°C (Naeth 1988). There are approximately 230 growing days with a short frost-free period of 25 days (Naeth 1988).

The topography is best described as gently rolling to hilly, with elevations ranging from 1050 to 1650 m above mean sea level (AMSL). The study area is located in the Porcupine Hills District, which falls into the Porcupine Hills Upland Section comprising part of the Southern Alberta Uplands Region. (Pettapiece 1986).

Most of the region is covered by glacial deposits of Pleistocene age (Moss 1944, 1955). Both cordilleran and continental glaciers advanced over the area leaving morainal material, till, and boulder clay deposits (Moss 1944). Bedrock consists mainly of tertiary sandstone, shale, and coal seams (Allan 1943 as cited in Moss 1955, Green 1972 as cited in Pettapiece 1986). Rock outcrops are common along many hillsides.

The Fescue Grass Ecoregion lies west of the Mixed Grass Ecoregion and immediately east of both the Montane and Aspen Parkland ecoregions in the southwestern portion of Alberta (Strong and Leggat 1992). The Fescue Grass Ecoregion is represented by a very diverse and species-rich flora, which includes a number of different native and non-native grasses, forbs, shrubs, and trees. Native vegetation in the area is dominated by foothills rough fescue with Parry oat grass (*Danthonia parryi* Scribn.) as the co-dominant grass species (Moss 1944, 1955, Moss and Campbell 1947, Looman 1969). Foothills rough fescue is the dominant species in undisturbed and lightly grazed areas, whereas Parry oat grass forms a disclimax under heavy utilization (Willms *et al.* 1985) and an edaphic subclimax on exposed sites (Moss 1955, Moss and Campbell 1947). Subdominant grasses include: Idaho fescue (*Festuca idahoensis* Elmer), bluebunch wheat grass (*Agropyron spicatum* [Pursh] Scribn. & Smith), intermediate oat grass (*Danthonia californica* Boland), slender wheat grass (*Agropyron trachycaulum* [Link] Malte), and hooker's oat grass (*Helictotrichon hookeri* [Scribn.] Henr.) (Wright and Bailey 1982). Timothy (*Phleum pratense* L.), Kentucky bluegrass (*Poa pratensis* L.), and smooth brome (*Bromus inermis* Leyss.) are now common exotic species in valley bottoms and on lower slopes (Wright and Bailey 1982) as a result of grazing (Willms *et al.* 1985). Common forbs and shrubs found in this ecoregion are listed in Table 1.1.

Table 1.1 Species list of forbs and shrubs.

Common Name	Latin Name
common yarrow	*Achillea millefolium* L.
pussy-toes	*Antennaria parvifolia* Nutt.
smooth aster	*Aster laevis* L.
milk vetch	*Astragalus* spp. L.
balsam-root	*Balsamorhiza sagittata* [Pursh] Nutt.
sticky purple geranium	*Geranium viscosissimum* Fisch. & Mey.
American hedysarum	*Hedysarum alpinum* L.
blazing star	*Liatris punctata* Hook.
puccoon	*Lithospermum ruderale* Lehm.
perennial lupine	*Lupinus argenteus* Pursh
pea vine	*Lathyrus* spp. L.
death camas	*Zigadenus venenosus* S. Wats
prairie crocus	*Anemone patens* L.
prairie smoke	*Geum triflorum* Pursh
shrubby cinquefoil	*Potentilla fruticosa* L.
wolf willow	*Elaeagnus commutata* Bernh. *ex* Rydb.
western snowberry	*Symphoricarpos occidentalis* Hook.
willow	*Salix* spp. L.
roses	*Rosa* spp. L.
fringed sage	*Artemisia frigida* Willd.
saskatoon	*Amelanchier alnifolia* Nutt.

Modified after Wright and Bailey (1982).

Aspen (*Populus tremuloides* Michx.) form groves in sheltered areas such as on north- and east-facing slopes and in slough depressions (Moss 1944, 1955), while balsam poplar (*Populus balsamifera* L.) occupy the flats and margins of rivers (Moss 1932, 1944). White spruce (*Picea glauca* [Moench] Voss), lodgepole pine (*Pinus contorta* Loudon), limber pine (*Pinus flexilis* James), and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) are common tree species found throughout the area on dry, rocky ridges (Moss 1944, 1955). These deciduous and coniferous tree species are invading the grassland due to the cessation of wildfires (Moss 1944, Moss and Campbell 1947, Wright and Bailey 1982).

Black Chernozemic soils developed on moderately to strongly calcareous, often thin, morainal deposits occur in the study area. These soils are relatively shallow and in some locations underlying bedrock is within 50 cm of the surface. Rock outcrops occur on some steeply sloping and ridged areas. There are three dominant soil units in the study area: the Beazer soil unit, the Dunvargon soil unit, and the Parsons soil unit. The Beazer soil unit is generally found on south- and west-facing slopes where soil conditions are relatively dry. Soils with thicker (greater than 15 cm) Ah horizons occupy north- and east-facing slopes and are represented by the Dunvargon soil unit. The Parsons soil unit represents Rego Black Chernozemic soils, which are dominant on some steeply sloping areas where soil development is controlled by the unstable surface conditions. (Kocaoglu *et al.* 1977).

1.5 Structure of the Thesis

A brief review of literature on fire behaviour and pattern specific to grasslands, and the historical and present applications of remote sensing and GISs for examining these patterns, is included in Chapter 2. Chapter 3 outlines the methods used in the study. Results of the study to determine if post-fire land cover could be used to indicate fire severity, and the extent to which fire severity was related to selected topographic variables, are included in Chapter 4. A synthesis of the conclusions and suggestions for further research can be found in Chapter 5.

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CHAPTER 2 Literature Review

Rangeland is defined as uncultivated grasslands, shrublands, or forested lands with a herbaceous and/or shrubby understory producing forage for grazing or browsing animals (Vallentine 1990). "Rangelands include natural grasslands, savannas, shrublands, most deserts, tundra, alpine communities, coastal and freshwater marshes, wet meadows, and grazed forest." (Tueller 1982). Grasslands, then, can be defined as a type of rangeland dominated by herbaceous vegetation, particularly grasses or grass-like species, and include those areas which support an open overstory of scattered shrubs and trees (Vogl 1974).

2.1 The Origin of Grasslands

Grasslands developed in response to a number of environmental factors, primarily climate and fire (Cooper 1961, Anderson 1964, Wells 1970, Nelson and England 1971, Vogl 1974). Anderson (1964) wrote that it is response to climate, which determines the type of vegetation that will finally dominate. This is certainly true of grasslands. Grassland herbaceous monocots possess a wide range of tolerance for extreme changes in climate enabling them to dominate diverse habitats; however, the same cannot be said for woody angiosperms (Vogl 1974). Many of the environmental extremes common to grasslands hamper the growth of woody vegetation, thereby allowing the unrestricted establishment and subsequent development of the better-adapted grassland species. Thus, climatic extremes likely helped to promote the establishment and expansion of monocots at the expense of woody species, which survive best under more stable environmental conditions.

Fire was also a factor in the development and maintenance of grasslands (Cooper 1961, Anderson 1964, Wells 1970, Nelson and England 1971, Vogl 1974). The establishment of large, uninterrupted grasslands was conducive to the free spread of large fire events (Wells 1970), thus grasslands developed in an environment that included fire. Fire tends to favour grass species over woody species (Anderson and Bailey 1980), because grasses are better adapted to fire than woody vegetation (Cooper 1961). The reason for this difference lies in their morphology (Cooper 1961). The growing point of monocots lies at or beneath the ground surface, reasonably protecting them from the effects of fire. Contrary to this, the living tissue of shrubs and trees is elevated above the surface of the ground, thereby exposing them to the full effects of fire. Thus, frequent fire events likely restricted the growth of woody vegetation. In 1932, Moss observed that burning effectively stopped tree advance in the Aspen Parkland Ecoregion of Alberta.

The combined effects of climate and fire are responsible for the origin and maintenance of grasslands, and therefore are an important part of grassland ecology (Daubenmire 1968, Nelson and England 1971). Grasslands developed in an environment that included fire, which acted as a natural selective force in the subsequent development of most grassland species (Vogl 1974) and their associated plant communities. Physiography has also been cited as an important factor in the establishment and maintenance of grasslands (Wells 1970).

2.2 Grassland Fire Behaviour

In 1966, Countryman introduced the concept of the fire environment. He defined the fire environment as a complex of topography, weather, and fuel components that influence or modify the establishment, growth, and behaviour of fire. Fire behaviour is affected by the state of each of these three environmental components and their interactions with each other, and with the fire itself.

Fire behaviour is not static, but varies widely in space and time (Countryman 1966). Weather is the most variable of the components, changing quickly in both space and time. Fuel also varies in space and time, while topography changes in space only. These components are closely interrelated, thus the current state of one component is dependent on the state of the others. In addition, a change in one component can initiate a chain of reactions that can affect the other components.

2.2.1 Topography

Topography includes: slope azimuth, slope magnitude, elevation, and how these components are configured (Miller 1994, Pyne *et al.* 1996). Variations in topography can cause changes in fire behaviour, because it affects how local fuel sources and weather conditions change (Countryman 1966, Miller 1994, Pyne *et al.* 1996). Topography modifies general weather patterns, producing microclimates that affect the distribution of vegetation communities and hence potential fuel type and condition.

The directional orientation of a slope is termed slope azimuth. Slope azimuth is important through its control over microclimatic factors that determine the initial temperature and moisture content of the combustible material (Fons *et al.* 1960 as cited by Chandler *et al.* 1963, Countryman 1966, Daubenmire 1968). Thus, slope azimuth is important in determining how exposed fuels will burn. Since solar radiation intensity is greatest when slope is perpendicular to the angle of the sun, fuel moisture changes with time of day and year (Countryman 1966, Chandler *et al.* 1983, Pyne *et al.* 1996). For instance, an east-facing slope begins to warm early in the day and reaches its maximum surface temperature sooner than both south- and west-facing slopes (Countryman 1966, Pyne *et al.* 1996). This differential heating of slope azimuths affects the likelihood of fire start and spread. Generally, south- and southwest-facing slopes are more favourable for fire start and spread in the Northern Hemisphere (Pyne *et al.* 1996), as they receive more sunshine, and therefore have lower humidities and higher fuel temperatures.

Fuel temperature and moisture content are also affected by slope magnitude through its direct effect on rate of spread (Chandler *et al.* 1963, Daubenmire 1968). The flames of a fire burning upslope are positioned closer to the fuels ahead of the fire, which dries and preheats the fuels at an increased rate (Miller 1994). A number of studies have considered the effect of slope magnitude on rate of fire spread. McArthur (1962 as cited by Chandler *et al.* 1983) reported that rate of spread doubled for every 10° increase in slope, while results from a study conducted by Chandler *et al.* (1963) suggested that rate of spread doubled for every 15° increase in slope up to 30°, and every 10° thereafter.

Daubenmire (1968) presented an overview of grassland fire ecology and reported that fire spreads up a 10° slope twice as fast as on level ground and four times as fast up a 20° slope. Thus, any time a fire moves from level ground to a steep hillside, rate of spread increases (Chandler *et al.* 1983).

Elevation, like slope azimuth and slope magnitude, influences fire behaviour through its effect on fuel availability (Pyne *et al.* 1996). There can be significant differences in general climate as described by temperature and relative humidity between valley bottoms, midslope positions, and upper slope positions. For instance, at midslope there is a relatively warm area referred to as the thermal belt. This area tends to have the least variation in daily temperature, the lowest average relative humidity, and the highest average temperature. Thus, midslope positions are likely more favourable for fire start and spread.

Heating by the sun is not uniform across a landscape due to differences in slope azimuth in relation to latitude, slope magnitude, and elevation. As a result, some areas become much warmer than others do and this changes throughout the day. This variation in local heat distribution creates variability in local weather.

2.2.2 Weather

Weather conditions leading up to, and those prevailing during a fire, determine fuel temperature and moisture content (i.e., available fuel), soil moisture, and wind speed (Daubenmire 1968). The ease of ignition and the amount of heating required to raise fuel to ignition temperature depend on initial fuel temperature (Miller 1994) and moisture content (Pyne *et al.* 1996). The most important effect of temperature is its influence on relative humidity, and therefore on fuel moisture content (Miller 1994). Thus, the temperature of fuels is an important factor controlling their susceptibility to burning and rate of burn (Chandler *et al.* 1983). Wright and Klemmedson (1965) studied the effects of season of burning, intensity of burn, and plant size on four bunchgrass species in an area southeast of Boise, Idaho. Results indicated that season of burn was the primary determinant of fire injury to the bunchgrasses studied during June and July. This seasonal response correlated with higher air temperatures and lower relative humidities, which created higher initial temperatures in the plant material.

Wind, like temperature, also affects fuel temperature and moisture content (Chandler *et al.* 1983, Pyne *et al.* 1996). It is the most important and variable of the weather components affecting fire behaviour (Chandler *et al.* 1983, Pyne *et al.* 1996), and has been reported to have the most influence on fire behaviour in fuel types characterized by fine fuels such as grasslands (Miller 1994). According to Chandler *et al.* (1983), wind aids in drying fuel through increased evaporation of fuel moisture. It also assists and increases rate of combustion by providing a constant supply of oxygen (Wright 1971), by preheating fuels through the tilting of flames toward unburned fuel, and by assisting the ignition of spot fires (Morton 1964). Chandler *et al.* (1983) also reported that rate of fire spread doubled for every four meters per second (i.e., 14.4 km/hour) increase in wind velocity in loosely compacted forest litter. Grass fires increase their rate of spread faster than this (Chandler *et al.* 1983). Results from a study conducted by Wright (1971) indicated that in some instances burning temperatures of plants were increased or hastened by gusty winds. Similarly, Cheney *et al.* (1993) conducted a study on fire spread in grasslands and determined that wind speed had the greatest effect on rate of spread. It is important to note that this experiment was conducted on a flat, open floodplain, thus topography was not a factor.

Wind and slope magnitude affect rate of spread in much the same manner; they expose potential fuel to additional convective and radiant heat (Pyne *et al.* 1996). The interaction between wind and slope magnitude depends on the relative force and direction of influence of each (Pyne *et al.* 1996). If the wind is blowing upslope, there is a cumulative effect and the head fire moves upslope; however, if the wind is blowing downslope, the head fire travels downslope. Given the right wind conditions it is possible for a fast-spreading fire to move downslope.

2.2.3 Fuel

Fuel is a critical component in the fire environment, because it affects ease of ignition, fire size and intensity, and rate of spread (Pyne *et al.* 1996). A number of studies have considered the effect of fuel load on some of these fire parameters. Davis (1949) determined that fuel load had a significant effect on fire spread and intensity. He reported that a greater fuel load resulted in a faster rate of spread and higher fire intensity. Conversely, Cheney *et al.* (1993) determined that fuel load did not influence fire spread. These results likely reflect the complexity of interacting variables common in fire studies. In 1971, Wright reported that a bunchgrass with a high density of fine fuels maintained the heat longer within the bunch than did one with relatively coarse stems and lower fuel loading. Similarly, Engle *et al.* (1993) reported that large bunchgrasses had higher levels of damage relative to small bunchgrasses due to the presence of higher fuel accumulations, prolonged fire duration, and deeper heat penetration into the plant tissue. Research conducted by Conrad and Poulton (1966) provided indirect evidence that lower fuel loads resulted in a lower level of heating of living plant material.

Fuel moisture content also affects fire spread rate and intensity, as well as fuel consumption, plant mortality, and smoke production (Pyne *et al.* 1996). Fuel moisture is a function of biological processes (i.e., plant phenology), fuel size, arrangement and composition, and location (Pyne *et al.* 1996). In a study conducted by Cheney *et al.* (1993), rate of fire spread was affected by dead fuel moisture content.

Although the properties of individual fuels have a direct influence on ignition and combustion, fire behaviour depends primarily on fuelbed characteristics (Chandler *et al.* 1983). A fuelbed is an association of both living and dead plant material of various shapes and sizes, thus it is difficult to characterize. Important factors to consider when describing a fuelbed include: size distribution, compactness, continuity, and fuel loading. The difficulty associated with characterizing a fuelbed is that individual fuel characteristics change with changes in weather and management (i.e., livestock grazing).

2.2.4 Fire

Fire behaviour is generally determined by topography, weather, and fuel; however, in some instances the fire itself influences the immediate environment, and therefore fire behaviour (Pyne *et al.* 1996). For example, heat from a fire can change or produce local winds, contribute to atmospheric instability, and cause cumulus cloud formation. According to Vogl (1974), large grassland fires are known to "...generate extensive convection columns that can result in the development of cumulus clouds that sometimes build to thunderstorm dimensions, generating lightning, thunder, and rain." Thus, the fire itself can induce important changes in local weather that can significantly alter fire behaviour.

Because fire behaviour is constantly changing in response to changes in the local environment, fires typically create a mosaic of burned and unburned patches across the affected landscape. As a result, fire does not affect all components of the ecosystem in the same manner or to the same degree. The manner and degree to which an area has been altered or the successional processes disrupted by fire is termed fire severity (DeBano *et al.* 1998). Fire severity is essentially a product of fire intensity and residence time and is generally classified as low, moderate, or high; however, because fire severity is both resource- and site-specific, classification must be developed locally (DeBano *et al.* 1998). Generally, fire severity can be determined by how severely litter has been removed and bare soil exposed (Wells *et al.* 1979 as cited by Chandler *et al.* 1983), because as fire severity increases there is a decrease in litter with a corresponding increase in exposed bare soil (Bork *et al.* 2000). A reduction in litter cover and an increase in exposed bare soil can result in increased moisture loss and soil erosion, which can impede post-fire recovery.

Broadscale disturbances such as fire are processes that alter landscape structure and pattern, resulting in the creation of patch mosaics. The spatial and temporal distribution of burned and unburned patches creates a variety of microhabitats, which increase landscape heterogeneity. This heterogeneity provides an ideal opportunity for the investigation of spatial patterns using remote sensing technology.

2.3 A Review of Remote Sensing Systems

Remote sensing provides the opportunity to inventory surface resources of the earth in a systematic and repetitive manner (Sabins 1997), thus remote sensing "...can contribute information for a variety of rangeland resource management applications." (Tueller 1989). Lillesand and Kiefer (1994) defined remote sensing as the "...science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation." Numerous satellite systems have been used to acquire remotely sensed data, and Table 2.1 lists some of the satellites presently available and generally used by range managers and range scientists (Lillesand and Kiefer 1994, Jensen 1996, Sabins 1997).

Advanced Very High Resolution Radiometer (AVHRR) images are well suited for studying generalized vegetation distribution on a continental or global scale at high temporal resolution. However, due to the low spatial resolution of this imaging system, detailed vegetation mapping at larger scales is not practical (Izaurralde and Crown 1990, Wade *et al.* 1994, Cihlar *et al.* 1997). Conversely, SPOT (Systeme Probatoire d'Observation de la Terre) images have relatively high spatial resolution, but low temporal resolution. This makes SPOT images more suitable for mapping at larger scales, but less suitable for capturing ephemeral events such as flooding or wildfires. An additional disadvantage of SPOT is that it does not cover the mid-infrared (1.3 to 3 μm) region of the spectrum that is recorded by LANDSAT Thematic Mapper (TM) Bands 5 and 7, which are sensitive to vegetation and soil moisture contents.

LANDSAT Multispectral Scanner (MSS) imagery also has lower spectral resolution compared to LANDSAT TM imagery, making it less suitable for subtle vegetation

Table 2.1 Characteristics of satellite imaging systems commonly used for range management applications.

Satellite System	Total Spectral Range	Spectral Bands	Spatial Resolution	Temporal Resolution
NOAA-AVHRR	0.58-12.5 μm	1: 0.58-0.68 μm	1100 m	daily
		2: 0.725-1.10 μm	1100 m	daily
		3: 3.55-3.93 μm	1100 m	twice daily
		4: 10.3-11.3 μm	1100 m	twice daily
		5: 11.5-12.5 μm	1100 m	twice daily
SPOT-XS	0.50-0.89 μm	1: 0.50-0.59 μm	20 m	variable
		2: 0.61-0.68 μm	20 m	variable
		3: 0.79-0.89 μm	20 m	variable
LANDSAT MSS	0.50-1.10, and 10.4-12.6 μm	4: 0.50-0.60 μm	79 m	18 days
		5: 0.60-0.70 μm	79 m	18 days
		6: 0.70-0.80 μm	79 m	18 days
		7: 0.80-1.10 μm	79 m	18 days
		8: 10.4-12.6 μm	79 m	18 days
LANDSAT-5 TM	0.45-2.35, and 10.4-12.5 μm	1: 0.45-0.52 μm	30 m	16 days
		2: 0.52-0.60 μm	30 m	16 days
		3: 0.63-0.69 μm	30 m	16 days
		4: 0.76-0.90 μm	30 m	16 days
		5: 1.55-1.75 μm	30 m	16 days
		7: 2.08-2.35 μm	30 m	16 days
		6: 10.4-12.5 μm	120 m	16 days

discrimination. Tucker (1978) conducted a study comparing satellite sensor bands for vegetation monitoring and concluded that significant improvements resulting from optimal spectral resolution alone could be expected from TM data over MSS data. In addition, LANDSAT MSS data has lower spatial resolution compared to LANDSAT TM data. The increased spectral and spatial resolutions of TM data are well suited for more detailed mapping and assessment of rangeland resources (Lauer 1985, Haas 1992); however, MSS imagery is more suitable for large area analyses such as geologic mapping. Detailed land cover mapping is difficult with MSS imagery, because so many pixels of the original data are mixed pixels. In contrast, the area containing mixed pixels in LANDSAT TM imagery is smaller due to increased spatial resolution, resulting in a potential for increased interpretation accuracy. Increased classification accuracy afforded by TM data is due not only to the addition of two mid-infrared bands (Bands 5 and 7), but also to improved radiometric resolution (Williams *et al.* 1984, Toll 1985). A disadvantage of both LANDSAT MSS and TM data is reduced temporal resolution, making it sometimes difficult to capture short-lived events. Tueller (1979) indicated that the 18 day interval of MSS imagery might be too coarse for some rangeland applications such as range readiness determination and vegetation maturity.

Additional remote sensing devices with potential rangeland management applications include: microwave systems, video systems, and high spectral resolution systems (Tueller 1989, Lillesand and Kiefer 1994). There are several different radar imaging systems, each with advantages and disadvantages for rangeland applications. In general, radar has the potential to measure and monitor land cover characteristics such as soil moisture, vegetation cover, and snow cover, as well as specific terrain features. Radar data can be used in conjunction with other forms of remote sensing data as supplemental information for rangeland monitoring; however, the cost of these systems can be a limiting factor. Conversely, video imaging systems offer several advantages for rangeland management due to their relatively low cost and real-time display. Video applications for range management include mapping rangeland vegetation and distinguishing among plant species (Everitt and Nixon 1985). One disadvantage of airborne video imaging systems is their relatively low spatial resolution at higher altitudes. As with radar, there are a number of different high spectral resolution systems suited for range management applications, which include mapping plant species-level data and phenological conditions (Palylyk and Crown 1999). Potential drawbacks to using high spectral resolution systems are the cost of acquiring and processing data, and storage capacity.

2.4 Applications of Satellite Data to Rangeland Management

Given the expanse and remoteness of rangelands, and the diversity and intensity of pressures upon them such as intensive agriculture, recreation, and urban development, remote sensing has proven to be a valuable rangeland management tool. Remote sensing technology has contributed information for a variety of rangeland resource management applications including: mapping of vegetation distribution, condition and productivity, mapping of rangeland soils distribution, watershed management, evaluation of wildlife habitat, evaluation and monitoring of grazing management (Tueller 1989), mapping the extent and pattern of fire, and monitoring post-fire vegetation recovery (Milne 1986, Jakubauskas *et al.* 1990, White *et al.* 1996). The most relevant to this study are mapping the extent and pattern of fire, and mapping vegetation condition and recovery as it relates to fire severity.

2.4.1 Wildfire Mapping

Remotely sensed data has proved useful in mapping the extent and pattern of wildfires, because of the significant change in reflectance values in MSS Bands 5 (visible red) and 7 (near-infrared) following a fire (Milne 1986, Jakubauskas *et al.* 1990). Research conducted by Jakubauskas *et al.* (1990) and Kasischke *et al.* (1993 as cited by Sabins 1997) has demonstrated the usefulness of band ratioing in detecting fire boundaries. Jakubauskas *et al.* (1990) used an MSS 7/5 ratio to successfully delineate fire area. Similarly, Kasischke *et al.* (1993 as cited by Sabins 1997) used NDVI[2] images computed

[2] $NDVI_{AVHRR}$ = (Ch2-Ch1)/(Ch2+Ch1), or $NDVI_{MSS}$ = (Band7-Band5)/(Band7+Band5)

from AVHRR data. They reported that the NDVI-derived images detected 89.5% of burned areas greater than 2000 hectares.

Mapping fire severity is also possible using satellite data. Jakubauskas *et al.* (1990) indicated that the effect of fire reduced reflectance in MSS Band 7 in direct relation to fire intensity. This is an important concept, because fire severity is a function of the intensity of a fire (Milne 1986). Higher reflectances in MSS Band 7 and lower reflectances in MSS Band 5 can be used as an indication of a less intense fire, and therefore lower fire severity (Milne 1986).

White *et al.* (1996) conducted a study demonstrating the use of remote sensing for mapping fire severity by evaluating spectral change as it related to vegetation response. They determined that a simple TM Band 7 (mid-infrared) classification was very sensitive to the characteristics of fire severity in a variety of communities, and that NDVI and ΔNDVI data were also good indicators of fire severity. In summary, White *et al.* (1996) concluded that reasonable maps of fire severity could be produced with accurate results from remotely sensed data; however, the process required understanding of the spectral data that were most relevant to the landcover associated with fire severity. Jakubauskas *et al.* (1990) were also able to successfully map levels of fire severity by way of "...exploiting the near-reversal of the standard vegetation reflectance spectral curve caused by the destruction of forest vegetation...".

2.4.2 Post-fire Vegetation Recovery

Milne (1986) reported that post-fire vegetation recovery could be investigated using LANDSAT MSS satellite imagery by "...monitoring the changes that occur in the spectral reflectance properties of individual pixels." As photosynthetically active vegetation begins to colonize the bare soil surface, reflectance values in Band 5 decrease while in Band 7 reflectance increases (Milne 1986). Thus, the ratio between Bands 5 and 7 increases with time as the vegetative cover becomes more complete.

Jakubauskas *et al.* (1990) used LANDSAT MSS and TM imagery to map the extent and nature of vegetation change following a forest fire and linked the observed changes to differences in fire severity. Their results showed that vegetation change was highest in severely burned areas and lowest in lightly burned areas. Similarly, results from a study conducted by White *et al.* (1996) suggested that changes in reflectance over multiple years showed the relationship between fire severity and vegetation response, as low fire severity areas had lower changes in reflectance relative to high fire severity areas. Thus, revegetation patterns are affected by variations in fire severity, and as a result, spatial patterns of spectral response differ with varying levels of fire severity.

2.5 Vegetation Indices

Several mathematical models exist that are used to predict or assess vegetation amount and condition from remotely sensed data; as mentioned above, these models are referred to as vegetation indices (Jensen 1996). For the information obtained from vegetation indices to be meaningfully interpreted and processed, knowledge of the typical spectral reflectance characteristics for healthy green vegetation, stressed or senescent vegetation, and dry bare soil is important. Most vegetation indices are based on the premise that there are significant differences in the shape of these three curves (Jensen 1996).

For healthy green vegetation there are significant changes in reflectance and absorptance of electromagnetic radiation from the visible (TM Bands 1, 2, and 3) to the near- (TM Band 4) and mid-infrared (TM Bands 5 and 7) regions of the spectrum (Tueller 1989). In the visible part of the spectrum the relatively high absorption of energy by healthy green vegetation is due to the presence of plant pigments, primarily chlorophylls (Tucker 1978, 1979, Lillesand and Kiefer 1994, Jensen 1996). Chlorophyll strongly absorbs energy in Bands 1 (visible blue) and 3 (visible red) (Colwell 1963, Tucker 1979, Lillesand and Kiefer 1994) while it reflects energy in Band 2 (visible green), thus accounting for the green color of leaves (Colwell 1963, Lillesand and Kiefer 1994). In the near-infrared part of the spectrum healthy green vegetation reflects almost half of the incident energy between 0.7 and 1.3 μm (Lillesand and Kiefer 1994, Jensen 1996). This relatively high near-infrared reflectivity of green vegetation is caused by the internal cellular structure of the plant leaves (Colwell 1963, Lillesand and Kiefer 1994). Beyond 1.3 μm, energy is either absorbed or reflected with little or no transmittance (Lillesand and Kiefer 1994). The strong absorption of energy by green vegetation in the mid-infrared region of the spectrum at specific wavelengths of 1.4, 1.9, and 2.7 μm is due to the presence of water (Lillesand and Kiefer 1994).

Leaf reflectance is approximately inversely related to the total water present in a leaf throughout the mid-infrared spectral range (Lillesand and Kiefer 1994), and as a result, stressed or senescent vegetation has lower absorption and stronger reflection in this region. Plant stress or death can alter the reflectance in the near-infrared part of the spectrum between 0.7 and 1.3 μm (Colwell 1956 as cited by Colwell 1963, Lillesand and Kiefer 1994). Typically, stressed or senescent vegetation reflects less than green vegetation in the near-infrared spectral region, whereas in the visible spectrum stressed or senescent vegetation reflects a greater amount of energy than green vegetation (Jensen 1996). The radiance in Band 3 is inversely proportional to the amount of chlorophyll present in the plant canopy (Tucker 1979), thus a decrease or end in chlorophyll production results in less chlorophyll absorption in this band (Lillesand and Kiefer 1994).

Factors that influence soil reflectance occur over less specific spectral bands. Some of these factors include: soil moisture content, soil texture, surface roughness, presence of iron oxide, and organic matter content (Lillesand and Kiefer 1994). These factors are variable, complex, and interrelated, thus it is important to be familiar with the local conditions. Generally, dry bare soil has higher reflectance than green vegetation and lower reflectance than stressed or senescent vegetation in the visible spectral region, while in the near-infrared part of the spectrum dry bare soil generally has lower reflectance than both green vegetation and stressed or senescent vegetation (Jensen 1996).

2.6 Common Vegetation Indices

Various spectral vegetation indices have been developed to characterize vegetation canopies (Huete 1988). The most common of these are either ratio or orthogonal indices (Huete *et al.* 1985, Heilman and Boyd 1986). "The ratio indices use ratios of linear combinations of near-infrared and red wavelengths...", whereas orthogonal indices use the measured distance perpendicular (orthogonal) from a given spectral point to a "...principal axis representing soil spectral variations as a measure of vegetation density." (Heilman and Boyd 1986). The more commonly used ratio and orthogonal vegetation indices are listed in Table 2.2.

Table 2.2 Examples of commonly used vegetation indices, where RED represents the visible red band, NIR represents the near-infrared band, and a, b and L represent coefficients.

Name	Vegetation Index	Source
Ratio VI	RVI = NIR/RED or RED/NIR	Pearson & Miller (1972)
Normalized Difference VI	$NDVI = \frac{(NIR-RED)}{(NIR+RED)}$	Rouse *et al.* (1974)
Greenness VI	GVI(RED, NIR) = PVI	Kauth & Thomas (1976)
Difference VI	DVI = 2.4NIR-RED	Richardson & Wiegand (1977)
Perpendicular VI	$PVI = \frac{NIR-aRED-b}{SQRT(1+a^2)}$	Jackson *et al.* (1980)
Soil Adjusted VI	$SAVI = \frac{(1+L)(NIR-RED)}{(NIR+RED+L)}$	Huete (1988)
Transformed Soil Adjusted VI	$TSAVI = \frac{a(NIR-aRED-b)}{RED+aNIR-ab}$	Baret *et al.* (1989)
Soil Adjusted Ratio VI	$SAVI_2 = NIR/(RED+b/a)$	Major *et al.* (1990)

Modified after Richardson and Everitt (1990).

Every vegetation index developed has advantages and disadvantages associated with it. Soil background reflectance, density of vegetative cover, number of mixed pixels, and the atmosphere can all seriously affect vegetation indices. Thus, the choice of one vegetation index over another requires knowledge of the factors that affect the individual index.

2.6.1 Normalized Difference Vegetation Index

The NDVI was one of the first successful vegetation indices developed based on band ratioing (Jensen 1996) and is by far the most widely used (Bannari *et al.* 1995, Sabins 1997). Jensen (1996) stated, "NDVI-related vegetation indices have been used extensively to measure vegetation amount on a worldwide basis." Examples of vegetation parameters related to NDVI include: phenological change (Ashley and Rea 1975, Rouse *et al.* 1974 as cited by Tucker 1979), biomass estimation (Tucker 1979), percent ground cover as it relates to burned forested land (Kasischke *et al.* 1993 as cited by Sabins 1997), and photosynthetic activity as it relates to fire fuel mapping (McKinley *et al.* 1985).

Tucker (1979) defined NDVI as the difference between the near-infrared and visible red reflectances normalized over the sum of these reflectances. Values for NDVI range from one to negative one, with values of one indicating high concentrations of healthy green vegetation, and values less than or equal to zero indicating non-vegetated land features such as water, rock, snow, ice, or clouds (Sabins 1997). Lillesand and Kiefer (1994) briefly explained these NDVI values in terms of relative reflectivity. Vegetated areas generally yield high index values, because of the relatively high near-infrared reflectance and low visible reflectance. In contrast, clouds, water, and snow have a higher visible reflectance than near-infrared reflectance, and therefore yield negative index values. Rock and bare soil have similar reflectances in both bands and yield an index value near zero.

In addition to the benefits of NDVI's wide applications, it also helps to compensate for changing illumination conditions (Ashley and Rea 1975, Baret and Guyot 1991, Lillesand and Kiefer 1994, Sabins 1997), variations in topography (slope azimuth and slope magnitude), and other extraneous factors (Lillesand and Kiefer 1994). According to

Pinter *et al.* (1983), ratio-based indices are relatively independent of illumination intensity. Similarly, Lillesand and Kiefer (1994) stated, "A major advantage of ratio images is that they convey the spectral or color characteristics of image features, regardless of variations in scene illumination conditions." An additional advantage of the NDVI is that it "...largely removes radiometric variations due to hilly topography..." characteristic of the Fescue Grass Ecoregion of Alberta (Thomson *et al.* 1984). However, in spite of the above conclusions there are factors that have been reported to influence NDVI observations. Among these factors are atmospheric effects (Huete 1988, Lillesand and Kiefer 1994) and soil substrate differences (Huete 1988, Baret and Guyot 1991).

Two relatively new vegetation indices specific to the NDVI were developed to reduce variations introduced by atmospheric effects. Kaufman and Tanre (1992) developed a new version of the NDVI called the Atmospherically Resistant Vegetation Index (ARVI). An atmospheric self-correcting factor, which depends on aerosol types, is used to correct for atmospheric effects between 0.60 and 0.70 μm. The ARVI is four times less sensitive to atmospheric effects than NDVI (Kaufman and Tanre 1992); however, the resistance of the ARVI to atmospheric effects depends on how well the self-correcting factor has been determined (Bannari *et al.* 1995). Pinty and Verstraete (1992 as cited by Bannari *et al.* 1995) developed the Global Environment Monitoring Index (GEMI), which minimizes the relative influence of atmospheric effects while conserving a large range comparable to the NDVI for dense vegetative cover (Pinty and Verstraete 1992 as cited by Bannari *et al.* 1995). Unfortunately, the GEMI is not well suited for sparse or moderately dense vegetation, because it is highly affected by soil color and brightness (Bannari *et al.* 1994 and Plummer *et al.* 1994 as cited by Bannari *et al.* 1995). It is important to note that the development of atmospherically corrected versions of the NDVI may not be that important, because according to Miller *et al.* (1983 as cited by McKinley *et al.* 1985), the effect of daily variance of incoming solar radiation caused by atmospheric conditions is reduced by the summation of the infrared and visible red bands. This allows the NDVI to be compared from date to date and site to site.

Several studies have considered the sensitivity of vegetation indices to soil background variations. Huete *et al.* (1985) reported that, for a given amount of vegetation, darker soil substrates resulted in higher index values when the NDVI was used to measure vegetation. Similarly, Huete (1988) reported that NDVI was seriously affected by soil variations and that any adjustment, like that used in the SAVI, would improve remotely sensed vegetation interpretations. However, he also reported that the use of the SAVI might result in a lowered vegetation index signal, particularly in studies involving a single soil type. He further stated that it was only when data were compared across different soil types that the NDVI suffered from soil problems, which the SAVI was capable of minimizing. Heilman and Boyd (1986) also reported that soil background affected NDVI to varying degrees; however, they assumed that all exposed soil was sunlit, so the results represented a worst-case scenario. They further suggested, "... even if soil-specific calibrations and soil lines are used, the accuracy of any estimates of rangeland vegetation density derived from the indices may vary with the soil background." Similarly, Huete (1988) reported that both ratio (RVI and NDVI) and orthogonal (PVI and GVI) indices were unable to provide an adequate description of the spectral behaviour of vegetation when vegetation was sparse. The PVI, which was developed based on the bare soil line theory, is supposed to take into account the effect of bare soils, but research has shown that it is not independent from soil brightness (Huete *et al.* 1985, Major *et al.* 1990, Baret and Guyot 1991, Cyr 1993 as cited by Bannari *et al.* 1995). This is not surprising, since changes in soil surface conditions cause variations in the slope and origin of the bare soil line (Huete *et al.* 1984 as cited by Bannari *et al.* 1995). Thus, for the index to be insensitive to soil type and condition it is necessary to calculate a bare soil line from numerous samples and use the mean (Bannari *et al.* 1995).

It is important to further note that complex vegetation indices such as the SAVI require the development of coefficients suitable to the conditions of the study area. Because the nature of soil-vegetation interactions varies with canopy closure, the ideal coefficient does not remain constant (Huete 1988). Research conducted by Qi (1993 as cited by Bannari *et al.* 1995) and Qi *et al.* (1994) has shown that the adjustment factor or coefficient is not constant, but rather a function that varies inversely with vegetative cover, thus prior knowledge of vegetation densities is required. The Modified Soil Adjusted Vegetation Index (MSAVI) developed by Qi *et al.* (1994) replaces the constant soil adjustment factor in the SAVI with a self-adjusting factor. Their study showed an increase in the vegetation dynamic response by the MSAVI, as well as a lowered sensitivity to soil background spatial and temporal variations; however, the MSAVI was validated using ground- and aircraft-based radiometric measurements only. In addition, the sensitivities to other external factors such as sensor viewing angles, atmospheric conditions, and solar illumination were not tested, thus it was not known whether these effects were accounted for in the MSAVI. Vegetation indices such as the SAVI, TSAVI, and MSAVI can be very computationally demanding.

The development of predictive relations between remotely obtained data and the quantitative and qualitative evaluation of vegetation has been of interest to rangeland managers (Everitt *et al.* 1990), because remote sensing offers a favourable alternative to traditional ground reconnaissance monitoring methods (West and Smith 1997). Because rangelands cover vast areas of complex and diverse environments, remote sensing of spectral characteristics provides a potentially cost effective means of surveying these areas. Visible and near-infrared multispectral satellite images provide the most useful data for examining vegetation patterns and corresponding ecological processes at both a regional and global scale (Saltz *et al.* 1999). Vegetation indices, then, play a significant role in monitoring vegetation cover.

2.7 Geographical Information Systems

Guptill (1989) defined a GIS as "...a system of computer hardware and software designed to allow users to collect, manage, and analyze large volumes of spatially referenced data and associated attributes." GISs evolved as a means of assembling, storing, and analyzing diverse spatial data, with the geographic location of the data serving as the basis for the information systems (Tomlinson *et al.* 1976 and Calkins and Tomlinson 1977 as cited by Stow and Estes 1981). The structure of GISs was developed around locational identifiers and the methods needed to encode data for input storage and manipulation (Stow and Estes 1981). "The functional components of a GIS are grouped into five categories: user interface, system/database management, database creation/data entry, data manipulation and analysis, and display and product generation." (Guptill 1989). Two common approaches used to represent the locational component of geographic information in most GISs are raster and vector data structures (Ehlers and Greenlee 1991, Lillesand and Kiefer 1994).

A raster system is organized as a grid cell structure in which each cell is uniform in size and dimension and has associated with it a spatial location and attribute data (Palylyk 1991). Thus, the location of geographic objects or attributes is defined by the row and column position of the cell or cells occupied (Lillesand and Kiefer 1994). The value stored for each cell indicates the type of object or attribute that is found at that location for the entire cell (Lillesand and Kiefer 1994). In a vector data system, graphic data are represented as points, lines, or polygons with associated information stored in an attribute database (Palylyk 1991). Features are encoded by determining the coordinates of their vertices, and topological coding is used to keep track of the spatial relationships between points, lines, and polygons (Lillesand and Kiefer 1994).

Raster and vector data systems each have advantages and disadvantages (Lillesand and Kiefer 1994). Raster systems have a simple data structure, they perform such operations as overlay analysis with increased computational efficiency (Ehlers and Greenlee 1991), and they effectively represent features having high spatial variability. However, data storage, spatial resolution of data, and accurate representation of topological relationships among spatial features can be a problem with raster data systems. In contrast, vector data systems produce lower volumes of data, they have improved spatial resolution, and they maintain topological relationships making network analysis more efficient. Disadvantages of vector data systems include a more complex data structure and increased computation time for such operations as overlay analysis.

There has been debate as to which data structure is the most effective in terms of storage efficiency, processing efficiency, and representation of spatial relationships (Ehlers and Greenlee 1991). The "...nature of the application, the kinds of data and information, and the distribution of the queries." all affect which data system is employed. Thus, there is no clear answer to this debate, as the most appropriate system changes with every situation. Fortunately, most GISs today support conversion between raster and vector formats, as well as the simultaneous integration of both data structures (Lillesand and Kiefer 1994). Both raster and vector data structures were used in this study, because digital remote sensing images are collected in a raster format, and vector data structures are typically employed in the digitizing and topology-producing processes (Ehlers and Greenlee 1991).

2.7.1 Integration of Remote Sensing and Ancillary Data within Geographical Information Systems

"One of the most important benefits of a GIS is the ability to spatially interrelate multiple types of information stemming from a range of sources." (Lillesand and Kiefer 1994). An important form of data merger employed in digital image processing is the registration of image data with ancillary data. Ancillary data may be choroplethic maps of various land attributes such as soil type and land cover, or maps of terrain characteristics such as slope azimuth, slope magnitude, and elevation (Hutchinson 1982). The basic logic behind data merging is that classification accuracy based on both image and ancillary data will be an improvement over a classification based on either image or ancillary data alone (Chavez 1986, Bolstad and Lillesand 1992).

DEM generation is one of the most successful areas of integration (Ehlers *et al.* 1989). A DEM is defined as a digital representation of elevation, whereas a DTM is defined as a digital representation of terrain relief (Allam 1978) such as slope azimuth, slope magnitude, and slope length. DEMs and DTMs are ordered arrays of numbers that represent the spatial distribution of elevation and other terrain characteristics (Doyle 1978) across the landscape. These spatial distributions are represented by an XY horizontal coordinate system and Z represents the recorded elevation or terrain characteristic.

Integration of elevation and other terrain information with digital satellite imagery has been reported to increase classification accuracy (Doyle 1978, Hutchinson 1982, Palylyk and Crown 1984), particularly in hilly or mountainous regions (Lee *et al.* 1988, Frank 1988, Palylyk and Crown 1999). Species that have similar spectral characteristics may occupy different elevations, slope azimuths, and slope magnitudes, thus topographic information can serve as a way in which to discriminate between spectrally similar classes on an image (Lillesand and Kiefer 1994). For example, Lee *et al.* (1988) combined TM data with topographic information derived from a DEM to determine soil characteristics of hilly terrain. Results demonstrated the importance of topographic data in the differentiation of soils in hilly topography. Frank (1988) also combined TM data with topographic data, as well as topoclimatic data, to map dominant vegetation communities in mountainous terrain. TM transformations, elevation, slope azimuth, and a slope azimuth-magnitude index were useful in distinguishing among alpine and subalpine vegetation types, but not forest type vegetation in the montane zone. Similarly, Palylyk and Crown (1999) integrated high resolution *casi* digital imagery, field data, and DEMs within a GIS to identify and map rangeland vegetation communities in hilly topography for change detection studies.

Because GIS technology allows scientists to process and interrelate many more kinds of data with greater speed and accuracy than was previously feasible, there is potential to greatly improve research-related tasks such as data manipulation and modelling. Thus, the integration of remote sensing and GIS technologies provides a potentially powerful tool for range scientists. The advantages of integrating these two technologies are numerous and include: computer-based storage and analyses of large volumes of data, archival database management, spatial analyses and modelling, and automated cartographic production (Palylyk 1991). The integration of remote sensing and GIS for mapping, inventory, and monitoring of rangelands has been demonstrated for a number of range-related applications. These include: land-use management and resource allocation

(Johnston 1987), grazing distribution and forage utilization (Brock and Owensby 2000, Guenther *et al.* 2000), vegetation change detection (Jakubauskas *et al.* 1990, Yool *et al.* 1997), and fire severity mapping (Jakubauskas *et al.* 1990). The most relevant to this study is fire severity mapping.

Remote sensing and GIS play a vital role in assessing fire damage, planning rehabilitation efforts, and monitoring recovery of the range (Sabins 1997). Jakubauskas *et al.* (1990) used pre- and post-fire digital satellite images within a GIS to map vegetation change and related the changes to differences in fire severity. They reported that using the GIS to analyze the digital data by means of matrix operations was useful in identifying the type and amount of vegetation change, as well as those areas that did not change. In addition, the GIS limited change analysis to the affected area only by masking out unaffected vegetation through the use of overlay operations.

The large volume of data generated by satellites cannot be used to its fullest potential if the information cannot be accessed and analyzed in an orderly and timely fashion (Jakubauskas *et al.* 1990). "Geographical information systems (GIS) provide a means by which this information can be organized, integrated with ancillary data, and analyzed..." (Jakubauskas *et al.* 1990) for rangeland monitoring and management. Because satellite technology provides repetitive coverage of land surface and a GIS provides a basis for retrieval, storage, and manipulation of a variety of land-related information (Palylyk 1991), the integration of both remote sensing and GIS technologies will facilitate more efficient mapping, inventory, and monitoring of rangelands.

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CHAPTER 3 Materials and Methods

In the first step of this project, appropriate satellite image data were acquired and analyzed to produce a land cover map with associated fire severity characteristics. Field data were then collected and the initial map was refined to produce a fire severity map. Finally, the fire severity classes were related to landscape attributes of slope azimuth and magnitude, and elevation through the incorporation of DTMs and a DEM, respectively.

3.1 Data Acquisition and Processing

Post-fire LANDSAT-5 TM digital data of Bands 3, 4, and 5 (Table 2.1) were acquired for May 20, 1998. A spring image was acquired, because spectral differences in land cover characteristics are at a maximum during this time of year. The Conservation and Development Branch, Alberta Agriculture, Food and Rural Development, provided pre-fire digital data of Bands 3, 4, and 5 for September 22, 1997, as well as a 25 x 25 m DEM of the affected area. In addition, black and white 1:60,000 aerial photographs from 1996 were purchased.

All digital image analysis procedures were completed using ARC/INFO[1] version 7.1.2 (ESRI 1997) geographical information system, in the Spatial Information Systems Laboratory, Department of Renewable Resources, University of Alberta. This was to ensure that data and methods were compatible with resources readily available throughout Alberta Agriculture, Food and Rural Development, who provided much of the initial data. In the following, keywords that link to the ARC/INFO Online Help are italicized the first time they appear.

The pre-fire digital data were previously geometrically corrected and *resampled* to 25 m using a *bilinear resampling algorithm.* Bilinear interpolation determines the new value of a cell based on a weighted distance average of the four nearest input cells, thus it will cause some smoothing of the data. The post-fire digital data were geometrically corrected to achieve image registration with the pre-fire digital data using the same resampling algorithm and pixel size. The geometric rectification (*warping*) process involved establishing fifteen control points between the post-fire image and the pre-fire image, then using these control points in a first order polynomial, forward transformation. This performed an affine transformation, which fit a flat plane to the control points in a normal direction along each point adjusting the from-point to the to-point. The root mean square errors (RMSE) in both the x and y directions were 15.12 and 18.46 m, respectively, giving sub-pixel accuracy. The geometrically corrected image data were used without further radiometric processing.

3.2 Mapping of Land Cover Using NDVI

A post-fire satellite color composite image was created by assigning red, green, and blue to Bands 4, 5, and 3, respectively. These bands were then combined using an *equal area stretch*. An equal area stretch spreads the cell values in a grid along the range of values from 0 to 255, then redistributes the data so that an equal number of cells are assigned to each of the 256 possible output values. Thus, an equal area stretch "...changes both the distribution of the cell values and the number of cells assigned to each value."

In addition to the three reflective TM image bands and the color composite image, a post-fire NDVI grid was also computed. NDVI makes use of the difference between the visible red and near-infrared reflectance that is at a maximum for high amounts of photosynthetically active biomass and at a minimum for low amounts of green biomass (Richardson and Everitt 1992). The popularity of this particular index lies in its usefulness for differentiating highly vegetated areas from rock and bare soil, clouds, water, and snow. NDVI was calculated as follows:

$$NDVI_{TM} = \frac{(Band4-Band3)}{(Band4+Band3)}$$

[1] The mention of trade names is for information only and does not imply endorsement.

Theoretically, NDVI results in a new image band where the values range from negative one to one. Adding one to the ratio to avoid negative values and multiplying the result by 100 stretched the range of values resulting in a grid of NDVI values where:

$$NDVI = [(Band4-Band3)/(Band4+Band3) + 1] * 100$$

The post-fire satellite color composite image was examined and ten distinctly different colors within the apparent fire boundary were identified: red, dark blue, light blue, dark green, bright green, cyan, pale cyan, yellow, white, and black. Using the *cellvalue* command, gray level values were recorded at five different sites within each color for each of the three reflective TM image bands (Bands 3, 4, and 5), as well as for the post-fire NDVI grid. The five NDVI values recorded for each of the colors were examined and ranges assigned to each. These ranges were used to *reclassify* the post-fire NDVI grid resulting in a post-fire land cover map.

Following the creation of the post-fire land cover map, land cover classes were determined for each of the colors identified in the post-fire color composite image based on a study of the gray level values for each of the three spectral bands and for NDVI (Table 3.1). Only five of the fifteen cover classes identified were tested in the field. The remaining classes were either identified as non-grassland cover components (i.e., cropland, forested land, water, etc.) or were assumed to have been relatively unaffected by the fire (i.e., bare soil and rock outcrops). Healthy green, upland vegetation and healthy green, riparian vegetation were treated as one class. The five land cover classes tested in the field were hypothesized to represent varying levels of fire severity on grasslands.

3.3 Field Data

Field data were collected using a stratified random sampling method. The experimental design was as follows:

a. Level of fire severity was the treatment with four treatments evaluated: A, B, C, and D (Table 3.1).

Table 3.1 Interpretive key for the post-fire (May 20, 1998) color enhanced image.

Interpreted Cover Type	Satellite Image Color Rendition	Geometric Configuration
Cropland		
Bare Soil (summerfallow)	light blue	rectangular, square, or irregular shaped fields
Low Residue	cyan	rectangular, square, or irregular shaped fields
Moderate-High Residue	pale cyan-white	rectangular, square, or irregular shaped fields
Irrigated Crops	red	circular, or irregular shaped fields
Grassland		
Bare Soil and Rock Outcrops	light blue	irregular shaped areas
Partially to Completely Consumed Thatch (A)	bright green	irregular shaped fields associated with shadows
Charred and Partially Consumed Thatch (B)	dark green	irregular shaped fields associated with shadows
Scorched or Charred Thatch (C)	yellow	irregular shaped fields associated with shadows
Healthy Green, Upland Vegetation (D)	red	irregular shaped fields associated with shadows
Healthy Green, Riparian Vegetation (D)	red	curvilinear drainage channels
Forested Land	black	irregular shaped areas
Miscellaneous		
Water	dark blue	irregular, circular, or curvilinear shapes
Roads	light blue	linear features
Shadow	black	irregular shapes

b. Each site was considered a replication with approximately ten replications per treatment.

c. Although every pixel within each replicated treatment could be considered an experimental unit, only one was tested per replication.

Field data were collected one year after satellite image acquisition, because time was required for image analysis and resources for field work were not immediately available. Justice and Townshend (1981) suggested that it might be advantageous to collect ground data after imaging, because "...preliminary analysis of the imagery improves sampling design, through scene stratification." The idea is that ground sampling will be more efficient if the study area is areally stratified and time taken to sample each type of area. They further suggested that ground data should be collected as quickly as possible following image acquisition; however, it was important to collect ground data during the same time of year as image acquisition, thus field data were collected in the spring of 1999. The difficulty associated with studying natural disturbances such as fire is that they are unplanned, making it difficult to study their effects with a well-balanced design (Turner *et al.* 1997).

Once the post-fire land cover map was created, approximately ten different sites (between nine and eleven sites were sampled) for each of the four treatments were located on the land cover map using 1:60,000 black and white aerial photographs according to the following guidelines:

a. Sites had to be no smaller than a 4 x 4 pixel area to avoid crossing treatment boundaries when sampling.

b. Sites had to be relatively accessible in the field.

c. Sites had to be spaced across the study area to ensure adequate representation of the entire study area.

It was not possible to sample an equal number of sites per treatment due to logistical difficulties encountered in the field.

At each field site a visual assessment was performed across an estimated 25 x 25 m area for the following data: % bare soil, % thatch, % litter, and % total live vegetative cover.

In addition, % rock was recorded for rocks greater than or equal to 10 cm in diameter, or if there were more than five rocks/m^2 greater than or equal to 5 cm in diameter. Thatch is a colloquial term used by some range scientists when referring to the organic horizon as defined by the Soil Classification Working Group (1998). Litter refers to all dead plant material not incorporated into mineral soil and occurring above the mineral soil and organic horizons.

Prior to field data collection, a pilot study was conducted to determine the optimum sampling area. Conducting a pilot study is a commonly used method in the analysis and classification of vegetation, because it not only aids in establishing the minimal sampling area, but also provides a general idea of the landscape and it's covering of vegetation. However, due to the variability in the data collected an appropriate sampling area could not be determined. In addition to this variability, it was important that the sampling area be compatible with the spatial resolution of the digital satellite imagery and DEM (25 x 25 m). One of the principal factors controlling the size of a sampling area is resolution of the imagery (Justice and Townshend 1981). A brief description of the pilot study can be found in Appendix A.

3.4 Mapping of Fire Severity

Following field data collection, each field site was assigned a fire severity level (i.e., high, moderate, and low) based on field data and site-specific descriptions of the levels of fire severity (Table 3.2), subjective field observations, and anecdotal evidence relating to range management (Penniket pers. comm.). This was necessary, in part, because field sampling was conducted approximately one year after image acquisition. These results were summarized by describing the relationships between the initial land cover classes (Table 3.1 - A, B, C, and D) and identified levels of fire severity using a method similar to a contingency table. Each of the cover classes was assigned a severity class based on the results from the contingency table. In addition, contingency table results and field data were used to summarize the cover components (i.e., bare soil, thatch, litter, and total live vegetative cover) for the identified levels of fire severity, as well as for each land cover class tested in the field. Following this, a fire severity map was created.

Table 3.2 Site-specific descriptions of the identified levels of fire severity.

Level of Fire Severity	Description
High	all litter was consumed; most to all thatch and woody debris were consumed; high amounts of exposed bare soil; bare soil may have been altered (e.g., burned or oxidized)
Moderate	litter was mostly consumed; thatch was partially consumed; woody debris was mostly consumed; moderate amounts of exposed bare soil; bare soil was not altered
Low	some unburned coarse litter fragments were visible; most to all thatch was intact; woody debris was partially consumed or charred; very little exposed bare soil; bare soil was not altered

Using the cellvalue command, gray level values were recorded at ten different additional sites within each of the four colors corresponding to the land cover classes of interest (i.e., A, B, C, and D) for each of the three reflective TM image bands, as well as for the NDVI grid. This resulted in fifteen values in total for each treatment (i.e., A, B, C, and D). The same procedure was followed for cropland with low amounts of residue, cropland with moderate to high amounts of residue, and bare soil and rock outcrops. These values, combined with contingency table results and field notes, were evaluated to create a fire severity map. The fifteen NDVI values recorded for each of the four treatments and three land cover classes were tested for normality using the "proc univariate" statement in SAS (SAS Institute Inc. 1988). Ranges were subsequently determined based on ($\mu \pm 1\sigma$). If the values were not normally distributed, a study of the values and the histogram for NDVI was performed to determine a suitable range. The final ranges of values were rounded to the nearest ten for simplicity. These ranges were then used to reclassify the NDVI grid producing the fire severity map; however, several additional steps were required as discussed below.

The ranges of gray level values identified for irrigated cropland and water were verified by recording additional gray level values and creating test grids of both land cover classes. Irrigated cropland occupied the highest range of NDVI values and water the lowest, thus it was desirable to know whether any other land features occurred beyond these ranges. The ranges were then modified accordingly.

Several areas covered by shadow occurred throughout the color composite image due to the combined effects of hilly topography, solar azimuth, and solar altitude at the time of image acquisition. As a result, these areas could not be accurately interpreted from the image, because shadow has a significant effect on canopy reflectance (Colwell 1974, Tueller 1979). Thus, a *hillshade* grid was created from the DEM using the same solar azimuth and altitude as that at the time of the post-fire LANDSAT-5 TM digital data. Following this, a map of all possible shadowed areas was produced by reclassifying the *hillshade* grid and then combined, using Boolean logic[2], with a slope azimuth grid created from the DEM. This was done to verify whether the areas were in fact shadow before combining the grid with the fire severity map. Following this, the fire severity map was *clipped* to fit the study area boundaries using a modified version of the fire boundary provided by the Conservation and Development Branch, Alberta Agriculture, Food and Rural Development.

Once the fire severity map was created, it was necessary to determine if any of the post-fire bare soil areas coincided with any pre-fire bare soil areas. This was an important task, because if a post-fire bare soil area was also bare soil prior to the fire, then it could not be considered a high fire severity area. A map of coincident pre- and post-fire bare soil was created through a series of steps as follows:

1. A map of pre-fire bare soil was created by reclassifying Band 4, then corrected for water and shadows using appropriate reclass maps and Boolean logic.

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[2] Boolean logic uses Boolean algebra, which Krzanowski *et al.* (1996) defined as a "Finite or infinite set of elements with the three defined operations of negation, addition and multiplication. These operations correspond to the set operations of complementation, union and intersection."

2. A map of post-fire bare soil was created by reclassifying Band 3, then corrected for cropland with moderate to high amounts of residue, scorched or charred thatch, water, and shadows using appropriate reclass maps and Boolean logic.
3. The pre-fire bare soil map and the post-fire bare soil map were combined using Boolean logic. This map also represented areas of rock outcrop.

The ranges of values used to reclassify individual band data were determined following the same procedure used to reclassify the NDVI grid. Gray level values were tested for normality and ranges determined based on ($\mu \pm 1\sigma$). If the values were not normally distributed, a study of the values and the histogram for each individual band was performed to determine a suitable range and the final ranges rounded to the nearest ten.

The map of coincident pre- and post-fire bare soil had a small amount of error associated with it, because none of the post-fire satellite bands available could effectively mask out bare soil (and rock outcrops) alone. The most appropriate post-fire satellite band was, as mentioned above, Band 3; however, the range of Band 3 values for bare soil overlapped with low crop residue areas, thus introducing some error. Because of this error, a series of test grids were produced to check if the fire severity map and associated data would be significantly affected by not accounting for coincident pre- and post-fire bare soil areas in the fire severity map. Maps of each of the four fire severity classes were created by reclassifying the NDVI grid according to the specified range of values for each and correcting for shadow. These four maps were then combined with the map of coincident pre- and post-fire bare soil using Boolean logic. The new data generated from these maps were compared with the original data using the Kolmogorov-Smirnov Test (Zar 1984) in SAS. The Kolmogorov-Smirnov Test is a non-parametric goodness of fit test that analyzes whether two samples may reasonably be assumed to come from the same distribution (Vogt 1993).

3.5 Fire Severity and Selected Landscape Characteristics

Maps of each of the four fire severity classes were combined with both a slope azimuth and slope magnitude grid created from the DEM, as well as the DEM itself (i.e., elevation data). Slope azimuth and slope magnitude were derived from the DEM using complex mathematical equations. The slope magnitude of each cell was determined by making each cell the central point of a 3 x 3 grid where an equation was fit to the 3 x 3 grid and the maximum rate of change in value was calculated. Slope azimuth was calculated for the direction of maximum rate of change from each cell to its neighbors. These processes continued until slope magnitude and slope azimuth values were calculated for the entire grid, resulting in two DTMs. Slope magnitude was given in percent and slope azimuth in degrees. Following this, it was necessary to convert all three grids from *floating point data* to *integer data* and *build* value attribute tables for each. This was an important step, because grids with floating point data have no value attribute tables associated with them, and the information contained within these tables was required for the analysis of the relationship between fire severity and landscape characteristics.

Once the four fire severity class maps were combined with the two DTMs and the DEM, text files were created for each. These files were then imported into Excel[3] as space-delimited text files. Following this, preference data were calculated for each severity class for each topographic variable and plotted. The preference graphs were plotted using a graphics software package called Origin[4]. The slope azimuth and elevation data were smoothed using adjacent averaging.

Evaluation of preferences was done using a procedure modified from grazing management studies (Gillen *et al.* 1984, Walker *et al.* 1989). The basic principle is to determine the preference a specific animal species has for the habitats on offer in the study area. In this case, the proportion of pixels occurring at each slope azimuth, slope

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[3] Microsoft Corporation. 2000. Microsoft Excel 2000. Redmond, WA.
[4] Microcal™ Software, Inc. 1997. Origin™ version 5. Northampton, MA.

magnitude, and elevation for each severity class was compared to the total proportion of pixels for that same severity class. For example:

[total Class A/(total Class A + total Class B + total Class C + total Class D)] - [Class A @ 0% slope/(Class A @ 0% slope + Class B @ 0% slope + Class C @ 0% slope + Class D @ 0% slope)].

The preference will either be positive or negative and will range between one and negative one. An index value greater than zero indicates a positive fire severity preference for a particular slope azimuth, slope magnitude, or elevation, whereas a value less than zero implies a negative preference for a particular slope azimuth, slope magnitude, or elevation. An index value of zero indicates no preference. The statistical method used to compare the preference distributions of each of the severity classes was the Kolmogorov-Smirnov Test (Zar 1984).

Regression analysis was not used to compare the preference distributions of each of the severity classes, because slope azimuth is cyclic in nature (Stohr and West 1985). For example, 360° is the same as 0°; however, in a linear statistical analysis such as regression these two values would be considered end members, and therefore 360° apart. Stohr and West (1985) overcame this problem by dividing azimuths into two hemispheres with a symmetrical relationship between them. They then used a dummy variable to identify the hemisphere to which the slope azimuth belonged. In this way, slope azimuth was indicated by the use of two variables, the first to indicate the angle difference measured from north and the second to show whether that azimuth was clockwise or counterclockwise. Another, and much simpler, approach would be to divide slope azimuth into classes; however, this method results in a loss of data.

The interactive effects of slope azimuth and slope magnitude on fire severity were also studied. To study these effects, slope azimuth-magnitude data had to be retrieved for every pixel within the four severity classes. Using the *gridascii* command, ASCII files of slope azimuth, slope magnitude, and the fire severity map were created and then merged into a tab-delimited text table. Following this, the slope azimuth data, which ranged from 0 to 359°, were divided into 24 uniform classes of 15° intervals. The slope magnitude data, which ranged from 0 to 54%, were divided into 11 uniform classes of 5% intervals. These data were categorized, because the data set would have been far too large to analyze (i.e., 360 x 55). Using the tab-delimited text table, a 24 x 11 space-delimited matrix table was created for each severity class and then imported into Excel. Preference data were calculated as described above; however, these preference graphs were plotted in Excel.

Multiple regression analysis (Zar 1984) was used to test whether the interactive effects of slope azimuth and slope magnitude influenced fire severity across the study area by examining the preference distributions of each severity class. In other words, it was tested whether the variability in fire severity could be explained or predicted by the interactive effects of slope azimuth and slope magnitude.

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CHAPTER 4 Results and Discussion

4.1 Land Cover Map

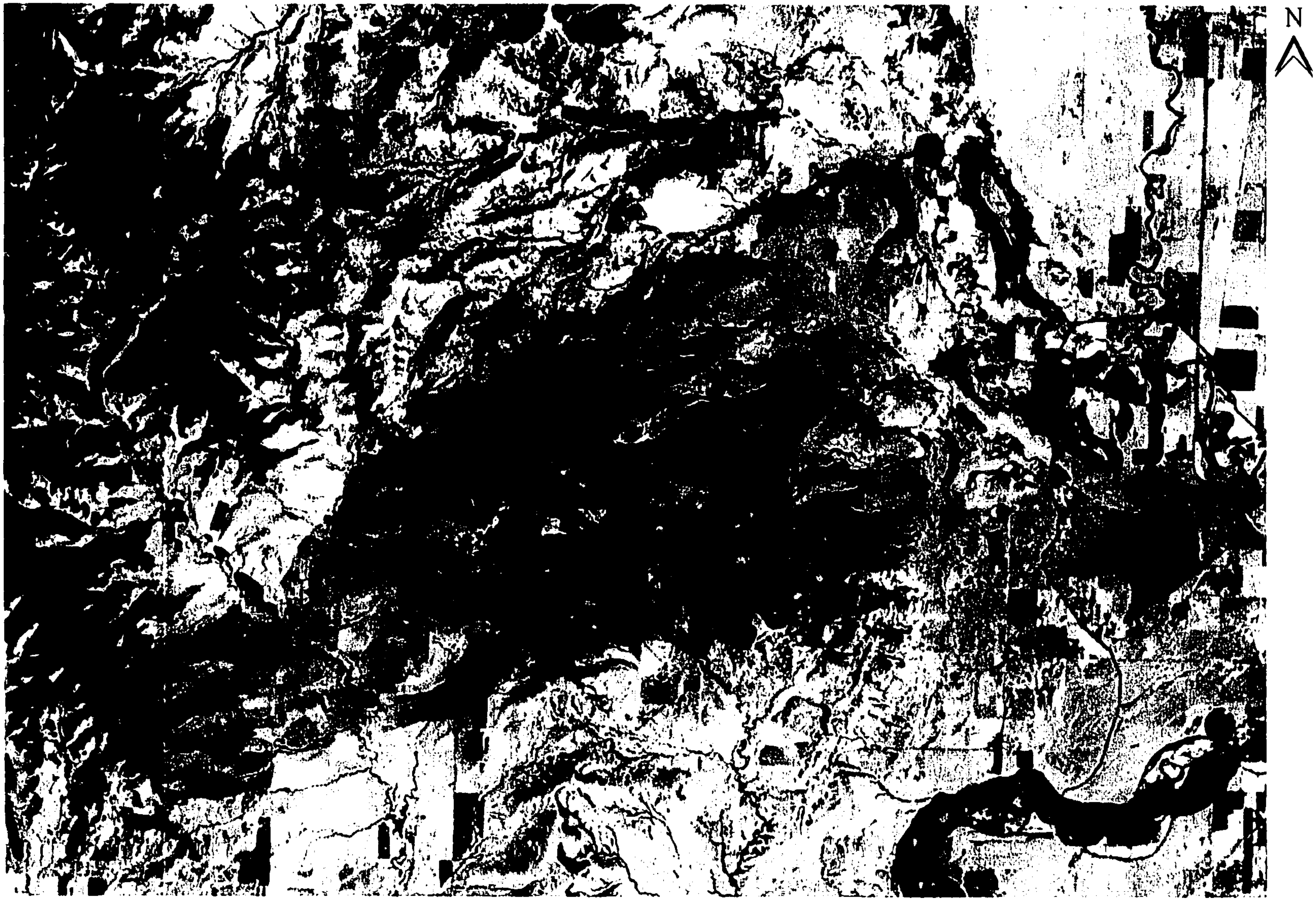
Classes of land cover interpreted from the post-fire color composite image were generally represented by unique color presentations (Plate 4.1); however, there was confusion between some of the initial land cover classes based on the ranges of NDVI values (Table 4.1). Croplands with low, moderate, and high amounts of crop residue were difficult to separate from each other using NDVI, as were bare soil from rock outcrops and shallow water (Plate 4.2). The reason for this was similarity in ratio values between classes. The identification of these individual classes was not the objective of this study. The land cover map is presented as Plate 4.3.

Table 4.1 Initial land cover classes with associated NDVI range of values and map color presentation.

Initial Land Cover Classes	NDVI Range	Map Color
Unknown	0-70	white
Bare Soil, Rock Outcrops and Shallow Water	70-90	blue
Cropland with Low to High Residue Levels	90-100	cyan
Partially to Completely Consumed Thatch (A)	100-110	red
Charred and Partially Consumed Thatch (B)	110-120	orange
Scorched or Charred Thatch (C)	120-130	yellow
Healthy Green Vegetation (D)	130-255	green

4.2 Fire Severity Map

The contingency table approach was useful in illustrating the degree of consistency between each of the initial land cover classes tested in the field and identified levels of fire severity (Table 4.2). Each cover class was associated with more than one level of fire severity; however, Classes B and C were dominantly one severity. Class B represented moderate fire severity, while Class C represented low fire severity. Class A represented



Approximate Scale 1:150,000

Plate 4.1 Post-fire color composite LANDSAT-5 TM image. Bands 4, 5, and 3 as red, green, and blue, respectively. Interpretive key presented in Table 3.1.

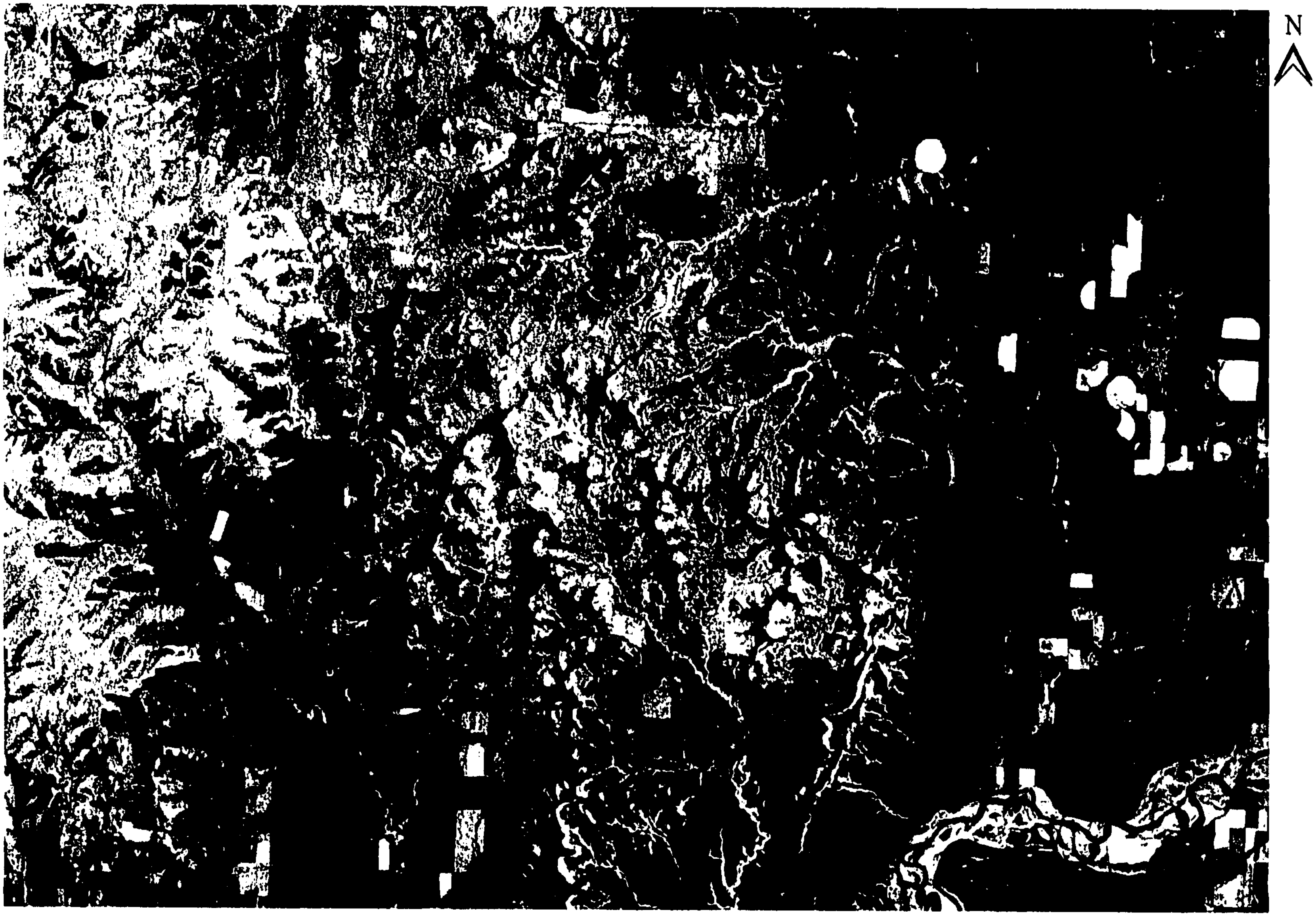


Plate 4.2 Post-fire NDVI grid. White areas represent healthy green vegetation, while black areas represent varying levels of exposed bare soil and water.

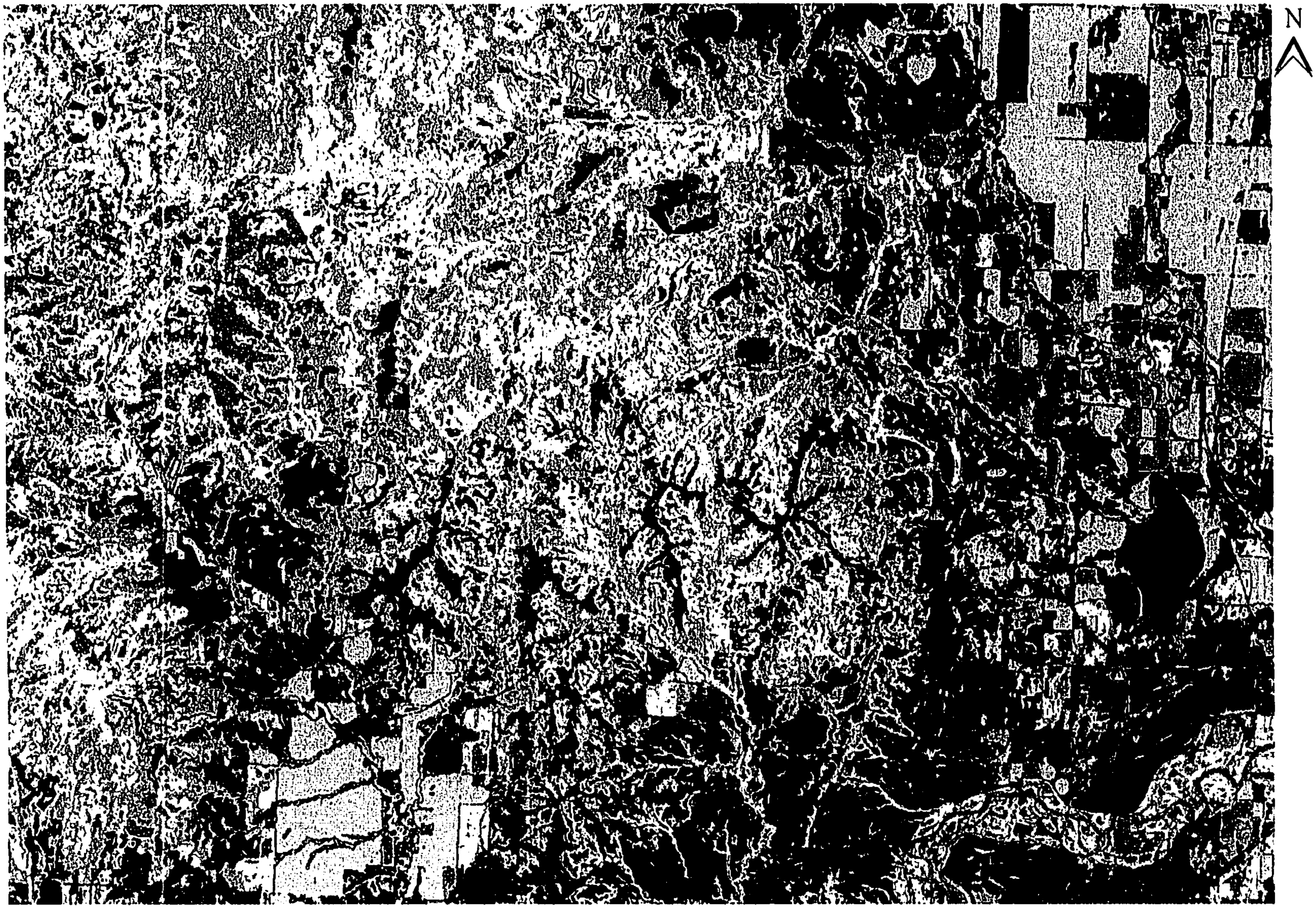


Plate 4.3 Post-fire land cover map. Legend presented in Table 4.1.

moderate to high fire severity rather than high fire severity, because 27% of Class A sites were moderate fire severity. This was considered to be an important proportion of Class A, and therefore could not be considered to represent high fire severity alone. Class D represented a broad range of fire effects, and was therefore classed as variable fire severity. Although the sites for Class D were different based on field data, they were spectrally similar. Factors such as target mixture and atmospheric effects may have contributed to the high omission error associated with Class D.

Table 4.2 Contingency table relating initial land cover classes to fire severity.

	Initial Land Cover Classes						
Fire Severity	A	B	C	D	**Total**	#Committed	%Commission
# of Sites	11	9	9	10			
High	7	2	0	3	**12**	5	42
Moderate	3	6	1	4	**14**	8	57
Low	1	1	8	3	**13**	2	15
Total	**11**	**9**	**9**	**10**			
# Correct	7	6	8	3			
# Omitted	4	3	1	7			
% Correct	64	67	89	30			
% Omission	36	33	11	70			

The summary of cover components confirmed that as fire severity increased, bare soil and thatch increased, while litter and total live vegetative cover decreased (Table 4.3). In general, sites classed as high fire severity were characterized by relatively high amounts of bare soil and thatch, and relatively low amounts of litter and total live vegetative cover. In contrast, relatively low amounts of bare soil and thatch, and relatively high amounts of litter and total live vegetative cover characterized sites classed as low fire severity. Moderate fire severity sites were characterized by higher amounts of bare soil and thatch than low fire severity sites, and higher amounts of litter and total live vegetative cover than high fire severity sites.

Table 4.3 Summary of cover components for sites classed as high (n=12), moderate (n=14), and low (n=13) fire severity given as mean (standard deviation) based on field data collected in June 1999.

Cover Components (%)	Fire Severity* High	Moderate	Low
Bare Soil	16.0 (11.0)	2.0 (3.0)	1.0 (2.0)
Thatch	13.0 (16.0)	16.0 (11.0)	5.0 (5.0)
Litter	7.0 (6.0)	10.0 (4.0)	23.0 (11.0)
Live Vegetation	63.0 (17.0)	68.0 (14.0)	70.0 (11.0)

* Derived from data in Tables B.1-B.4, Appendix B.

Favourable growing conditions during 1998 (Bork *et al.* 2000), combined with complete rest from domestic livestock grazing, resulted in increased rates of vegetation recovery. This was beneficial for high and moderate fire severity sites (Table 4.3). Vegetation regrowth on some low fire severity areas was likely impeded in the spring of 1999 due to high amounts of litter. Thus, these low fire severity areas should have been grazed late in 1998 (i.e., fall) to reduce litter accumulations.

Based on the summary of cover components alone, Class B was more representative of moderate fire severity compared to the other three classes (Tables 4.3 and 4.4). The summary of cover components for moderate fire severity and Class B were not synonymous, however, because of errors in the land cover map (i.e., misclassification) (Table 4.2). The same could be said for Class C. Based on cover components alone, Class C was relatively representative of low fire severity; however, the summary of cover components was not identical between the two due to misclassification. These results support the data presented in Table 4.2. According to Tables 4.3 and 4.4, Class A was relatively more representative of high fire severity than the other three classes. It should be noted, however, that Class A included some moderate fire severity sites (Table 4.2), because the determination of fire severity was based not only on bare soil, thatch, litter, and total live vegetative cover, but also on subjective field observations and anecdotal evidence relating to range management. Class D was less representative of a single fire severity class compared to the other classes due to the broad range of fire effects represented within Class D.

Table 4.4 Summary of cover components for the initial land cover classes given as mean (standard deviation) based on field data collected in June 1999.

	Initial Land Cover Classes*			
Cover Components (%)	A	B	C	D
Bare Soil	13.0 (12.0)	7.0 (9.0)	2.0 (2.0)	2.0 (6.0)
Thatch	20.5 (12.0)	15.0 (11.0)	8.0 (9.0)	1.0 (3.0)
Litter	8.0 (6.0)	13.0 (8.0)	18.0 (12.0)	16.0 (12.0)
Live Vegetation	56.0 (11.0)	61.0 (5.0)	71.0 (13.0)	81.0 (12.0)

* Derived from data in Tables B.1-B.4, Appendix B.

Results from the contingency table, field notes, and additional gray level values recorded from the post-fire NDVI grid were used to produce the revised criteria listed in Table 4.5. These ranges of values were employed for the mapping of fire severity, where Class A represented moderate to high fire severity, Class B represented moderate fire severity, Class C represented low fire severity, and Class D represented variable fire severity. The original ranges of values (based on the five gray level values) indicated that there was confusion between some of the cover classes. By recording an additional ten gray level values and assigning ranges based on ($\mu \pm 1\sigma$) (Table 4.6) some of the cover classes became more easily separated; however, this resulted in confusion between cropland with low to high residue levels, and bare soil and rock outcrops (Table 4.5). Using Band 4, it was possible to separate cropland with moderate to high amounts of residue from bare soil and rock outcrops, but it was not possible using any of the available image bands to separate cropland with low amounts of residue from the latter due to spectral similarity between bare soil, rock outcrops, and low residue cropland (Table 4.6).

Table 4.5 Revised land cover classes with associated NDVI range of values and map color presentation.

Revised Land Cover Classes	Original Range	New Range*	Map Color
Water	70-80	0-80	blue
Bare Soil and Rock Outcrops	70-90	80-100	cyan
Cropland with Low to High Residue Levels	90-100	90-100	cyan
Partially to Completely Consumed Thatch (A)	100-110	100-110	red
Charred and Partially Consumed Thatch (B)	110-120	110-120	orange
Scorched/Charred Thatch (C)	120-130	120-130	yellow
Healthy Green Vegetation (D)	130-255	130-155	green
Irrigated Cropland[5]	130-255	155-255	white
Shadow			black

* Derived from data in Table 4.6.

Table 4.6 Mean (standard deviation) of 15 point data for Bands 3 and 4, and NDVI used to create the fire severity map.

Revised Land Cover Classes	Band 3	Band 4	NDVI
Bare Soil and Rock Outcrops	79.0 (15.0)	66.0 (6.5)	92.0 (10.0)
Low Residue Cropland	81.0 (4.0)	72.0 (3.0)	94.0 (1.0)
Moderate to High Residue Cropland	98.0 (4.0)	87.0 (4.0)	94.0 (2.0)
Partially to Completely Consumed Thatch	60.0 (5.0)	68.0 (6.0)	106.0 (3.0)
Charred and Partially Consumed Thatch	49.0 (5.0)	66.0 (4.0)	114.0 (6.0)
Scorched/Charred Thatch	65.0 (4.0)	96.0 (5.0)	119.0 (4.0)
Healthy Green Vegetation	41.0 (5.0)	110.0 (14.0)	146.0 (8.0)

The process of creating the fire severity class map involved the production of several test grids. Test grids created for water and irrigated cropland showed that no other land features occurred in the study area beyond the ranges of NDVI values determined for these two cover classes. As a result, the ranges of values were extended (Table 4.5). Additional gray level values were recorded for both of these cover classes to aid in the creation of the test grids and determination of new ranges.

[5] None of the sites for treatment D fell into these areas.

A hillshade grid was created from the DEM using the same solar azimuth (~142.0°) and altitude (~56.0°) as that at the time of the post-fire LANDSAT-5 TM digital data (Plate 4.4). Following this, a map of all possible shadowed areas was produced from the hillshade grid and analyzed in Excel. Given that the solar azimuth was approximately equal to southeast, shadowed areas were expected to fall across northwest-facing slopes as illustrated in Figure 4.1. Any deviations from northwest-facing slopes (i.e., north-facing slopes) were likely a function of both solar altitude and ground geometry. As a result, north- and northwest-facing slopes were under-sampled. The fire severity map is presented as Plate 4.5.

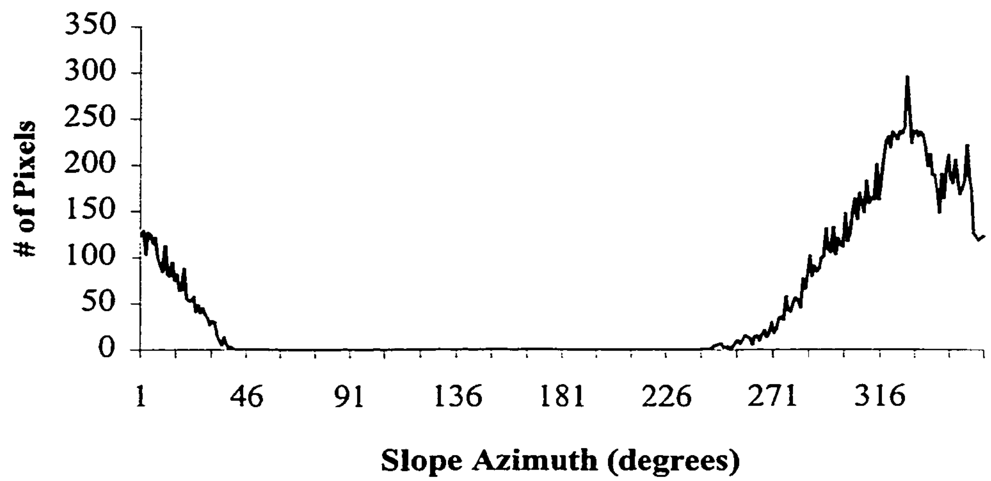
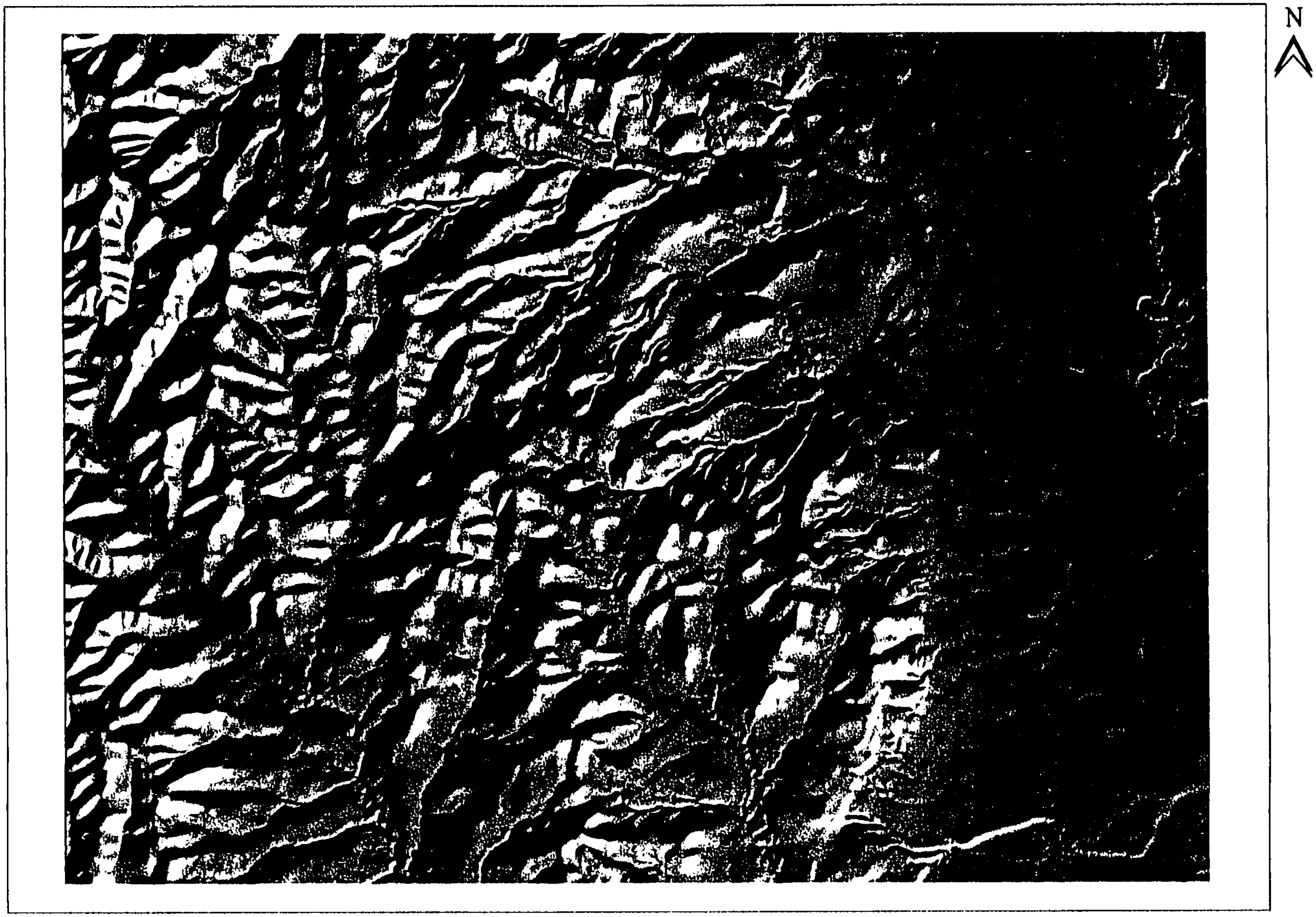


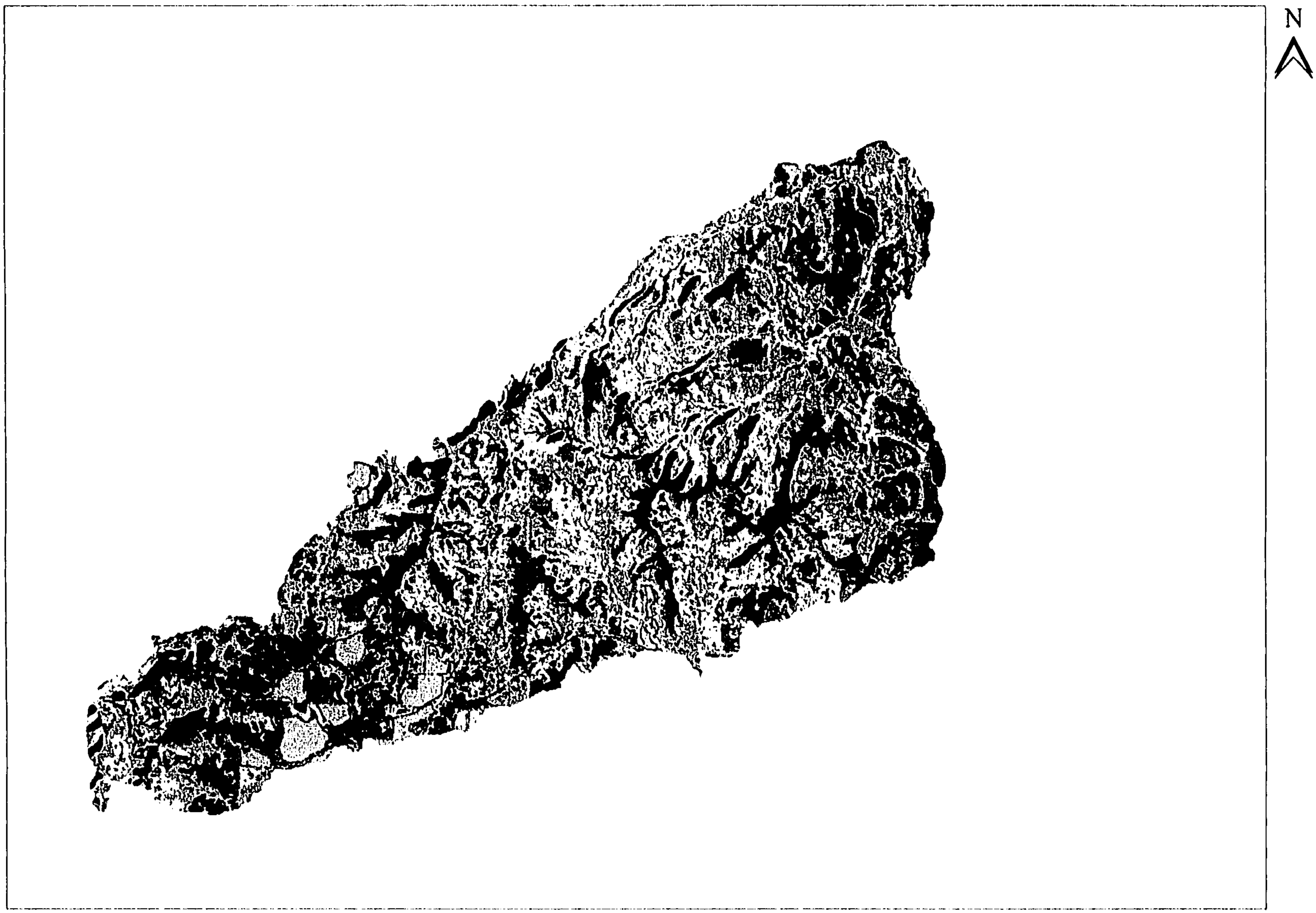
Figure 4.1 Shadowed areas that occurred within the study area based on the solar azimuth (~142.0°) and solar altitude (~56.0°) as that at the time of the post-fire LANDSAT-5 TM digital data, where 315° is equal to northwest. Shadowed areas occupied approximately 6% of the study area.

Test grids of each severity class accounting for coincident pre- and post-fire bare soil were created. Upon examination of these grids only Classes A and B were affected; however, Class B was affected by only one pixel, and therefore no analyses were performed for this class. Class A was affected by 2670 pixels (Plate 4.6), which was approximately 4% of the area for Class A. Preference data were calculated for the bare soil-corrected Class A (Class A-BS) data set for slope azimuth, slope magnitude, and elevation and compared to the original Class A preference data. Based on P-values, the



Approximate Scale 1:150,000

Plate 4.4 Hillshade grid created with the same solar azimuth (~142.0 degrees) and solar altitude (~56.0 degrees) as that at the time of the post-fire LANDSAT-5 TM digital data. Black areas represent areas in shadow.



Approximate Scale 1:150,000

Plate 4.5 Fire severity map. Legend presented in Table 4.5. Outline boundary registers with area boundary in Plate 4.1.

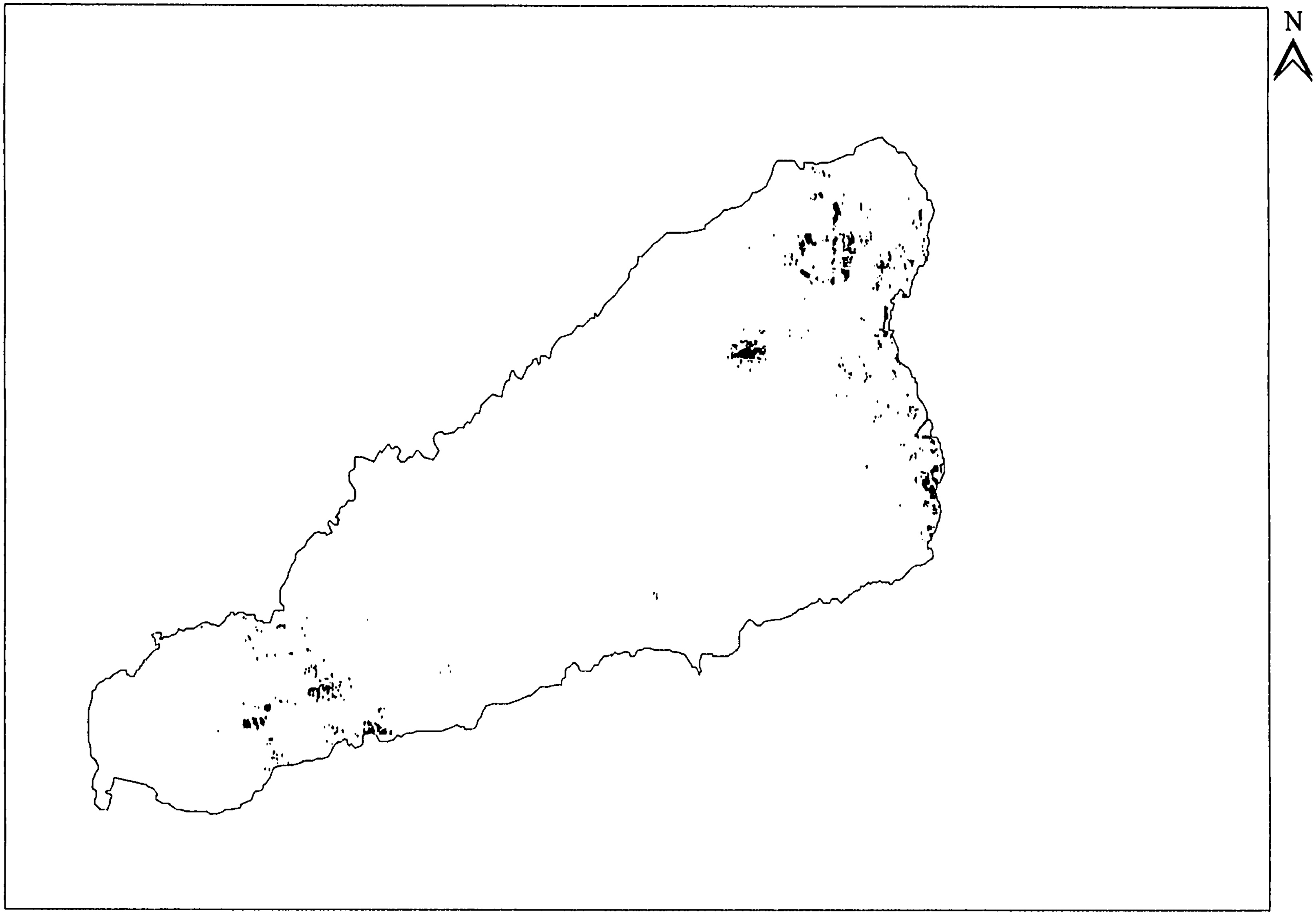


Plate 4.6 Map of coincident pre- and post-fire bare soil areas for moderate to high fire severity areas (Class A). Outline boundary registers with area boundary in Plate 4.1.

two sets of data could reasonably be assumed to have come from the same distribution and were identical for elevation (Table 4.7). As a result, the original data set was used for the remainder of the analyses.

Table 4.7 K-S Test results for the comparison of the original Class A data set with the bare soil-corrected Class A data set for slope azimuth, slope magnitude, and elevation.

Topographic Variable	P-values
Slope Azimuth	0.9999
Slope Magnitude	0.9986
Elevation	1.0000

4.3 Fire Severity and Selected Landscape Characteristics

4.3.1 Slope Azimuth

"The direction a slope faces is important through its control over microclimatic factors that determine the initial temperature of the combustible material and moisture conditions." (Daubenmire 1968). Given that surface temperature increases as slope azimuth changes from north to east to west to south (Holechek *et al.* 1998), south- to west-facing slopes should be associated with higher fire severities (i.e., Class A), and north- to east-facing slopes should be associated with lower fire severities (i.e., Class C). Moderate to high fire severity areas (i.e., Class A) had a relatively strong positive preference for southwest-, west-, and northwest-facing slopes (Figure 4.2), whereas low fire severity areas (i.e., Class C) had a negative preference for those same slope azimuths. In addition, Class C had a relatively strong positive preference for northeast- to southeast-facing slopes, while Class A had a negative preference for those same slope azimuths. These effects may also have been related to the prevailing wind direction (~southwest) at the time of the fire. The higher fire severities associated with southwest- and west-facing slopes may have been due to the flames being pushed into these slope azimuths,

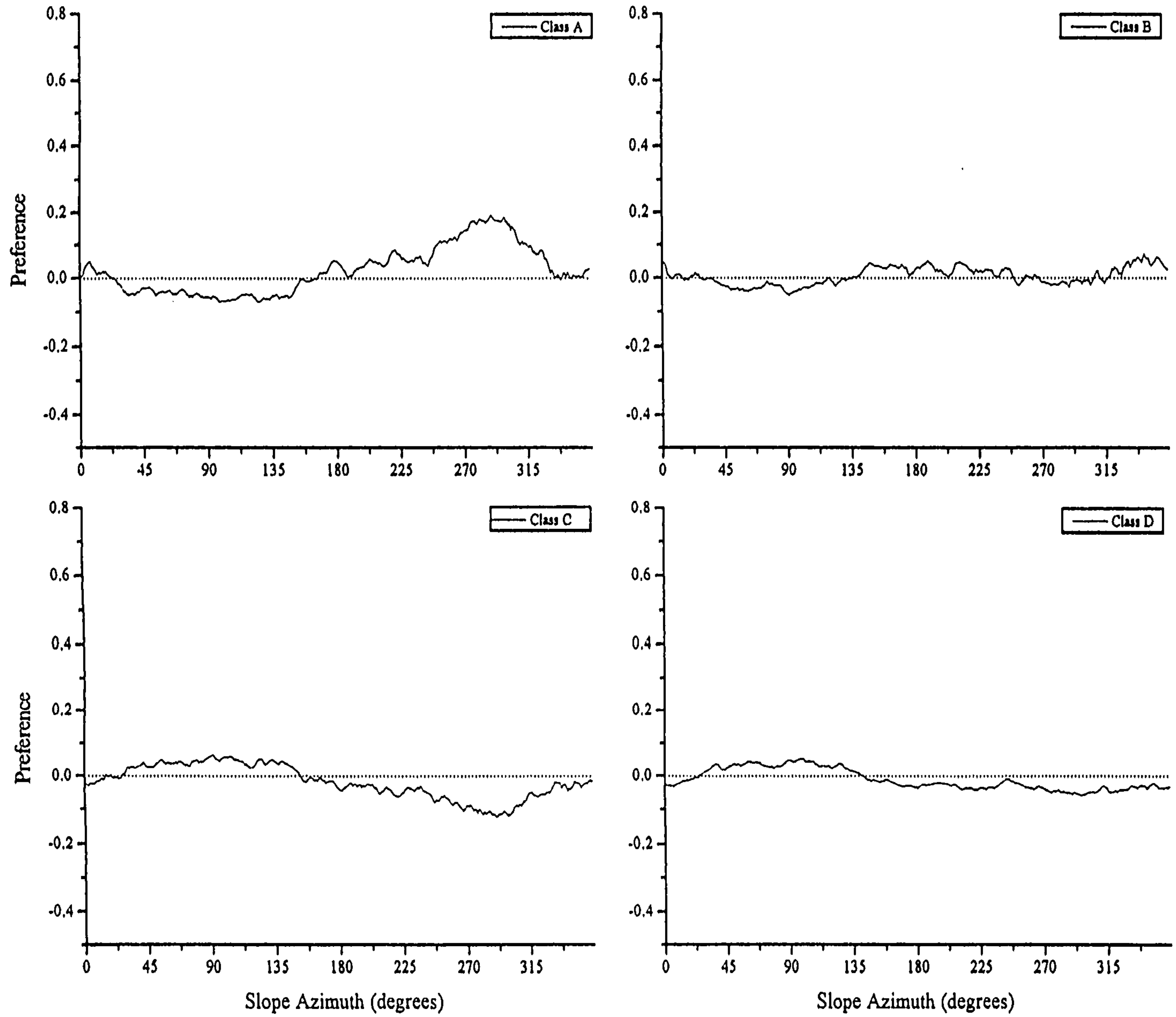


Figure 4.2 Preference graphs showing relationships between fire severity Classes A, B, C, and D and slope azimuth (smoothed data).

whereas the flames would have been pushed away from northeast- and east-facing slopes resulting in lower fire severities.

Classes A and B had a slight positive preference for north-facing slopes, while Classes C and D had a negative preference for that same slope azimuth. North-facing slopes are not as dry as south-facing slopes, and thus often support increased woody vegetation growth. A higher residence time, which is the "...amount of time that it takes the flaming front of the fire to pass a particular point." (Miller 1994), is usually associated with woody vegetation. This can result in higher fire severities (i.e., Classes A and B). Bentley and Fenner (1958) reported that woody fuels burned hotter than grass fuels. Similarly, Bailey and Anderson (1980) reported that higher fire temperatures were associated with woody fuels, and attributed this to a high density of standing live and dead western snowberry stems.

4.3.2 Slope Magnitude

There were different general patterns of slope magnitude preference data for severity Classes A and B compared to C and D (Figure 4.3). Classes A and B had strong negative preferences for steep slopes, while Classes C and D had strong positive preferences for steep slopes. Class A had a slightly stronger preference for low slopes compared to the other three classes, while Class C had a greater negative preference for low slopes.

Although forage use decreases as slope magnitude increases, because of avoidance of steep slopes by cattle (Mueggler 1965, Cook 1966, Pinchak *et al.* 1991), higher fire severities (i.e., Class A) were associated with lower slopes. As slope magnitude increases vegetation productivity decreases per unit of precipitation, because less water enters the soil and more runs off as overland flow (Holechek *et al.* 1998). Thus, steep slopes are associated with decreased litter accumulations compared to low slopes. The greater the accumulation of available fuel (i.e., litter and live or dormant vegetation), the higher the level of damage (Conrad and Poulton 1966).

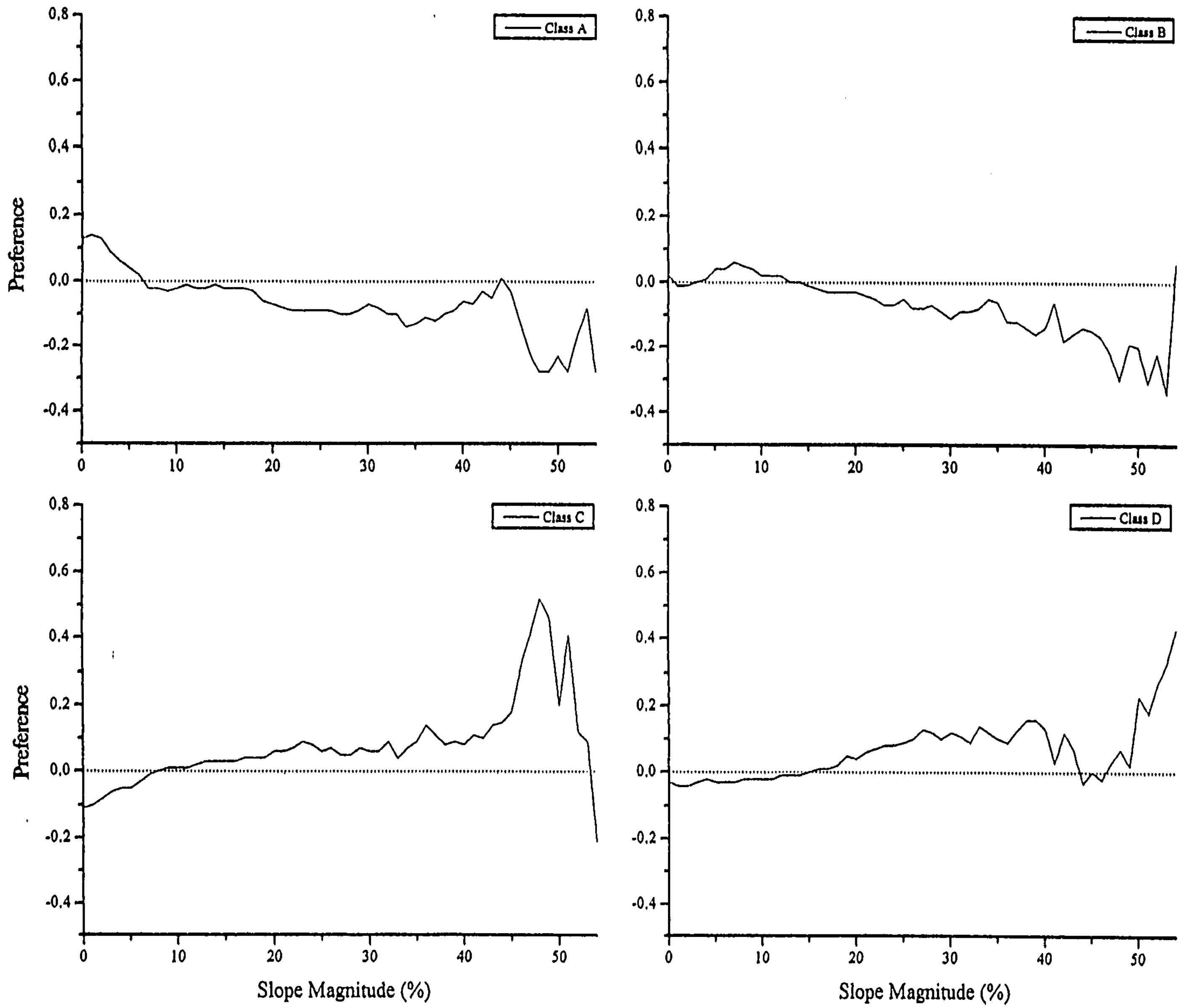


Figure 4.3 Preference graphs showing relationships between fire severity Classes A, B, C, and D and slope magnitude.

4.3.3 Elevation

Classes A and B had a positive preference for valley bottoms, while Classes C and D had a negative preference for that same slope position (Figure 4.4). Valley bottoms typically produce more forage than midslopes and upper slopes, because of increased moisture levels. Thus even with grazing, valley bottoms may have relatively higher litter accumulations (Holechek *et al.* 1998), which have been associated with higher levels of fire damage (Conrad and Poulton 1966). Classes A, B, and C had strong positive and negative preferences for specific elevations; however, Class D did not appear to have strong preferences for any particular elevation relative to the other three classes. This was likely because this severity class represented a broad range of fire effects.

The range in elevation within the study area is likely not large enough, compared to mountainous areas, to affect significant climate differences among valley bottoms, midslopes, and upper slopes, thus there did not appear to be a thermal belt effect. However, microtopography may have been masking these effects. Slope azimuth and slope magnitude change with elevation and these changes influence local solar radiation, and therefore fuel availability. The interactions between these three topographic variables were numerous and difficult to interpret, thus the preference graphs for elevation showed no distinct pattern and were irregular.

A greater proportion of variability in fire severity was explained by slope azimuth and elevation compared to slope magnitude, but only for Class A versus Class B and Class C versus Class D (Table 4.8). Classes A and B, and C and D preferred similar slope magnitudes, but not similar slope azimuths or elevations.

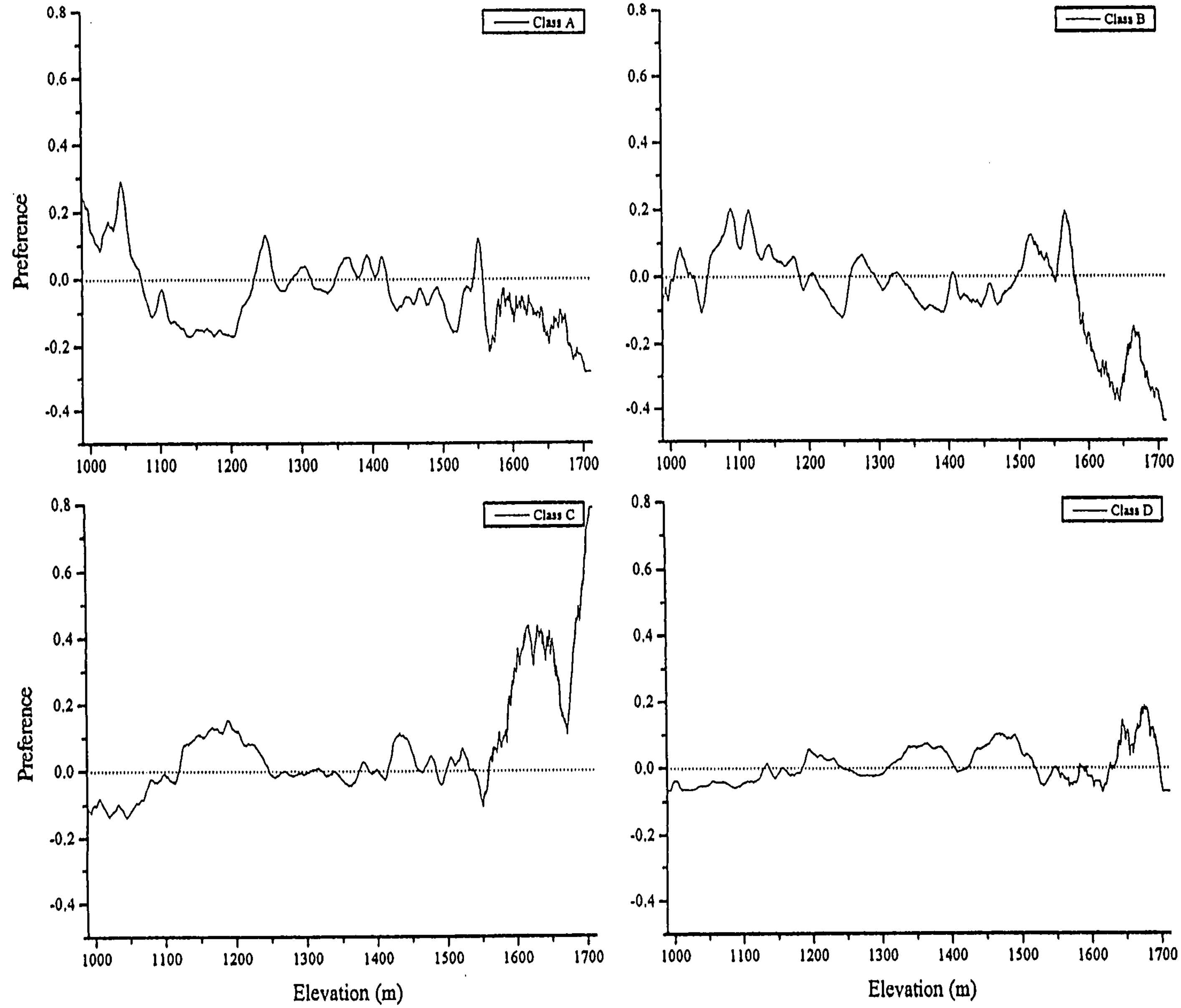


Figure 4.4 Preference graphs showing relationships between fire severity Classes A, B, C, and D and elevation (smoothed data).

Table 4.8 K-S Test results among fire severity classes for slope azimuth, slope magnitude, and elevation preference data.

Fire Severity Classes	Slope Azimuth	P-values Slope Magnitude	Elevation
A vs. B	0.0001	0.7646	0.0001
A vs. C	0.0001	0.0001	0.0001
A vs. D	0.0001	0.0001	0.0001
B vs. C	0.0001	0.0001	0.0001
B vs. D	0.0001	0.0001	0.0001
C vs. D	0.0001	0.4531	0.0001

4.3.4 Slope Azimuth-Magnitude Interactions

As stated previously, fire behaviour is the manner in which fire reacts to environmental components, which include: available fuel, weather, and topography (Countryman 1966). It is not static, but varies in both time and space in relation to changes in these environmental components. Available fuel and local weather change rapidly in time and space as fire progresses, while topography changes greatly in space. Thus, there are many interacting factors affecting fire behaviour, and therefore fire severity.

The interactive effects of the 24 slope azimuth classes and 11 slope magnitude classes resulted in complex patterns that were difficult to interpret (Figures 4.5-4.8 and Tables B.5-B.8, Appendix B). The cardinal direction of north was between classes A24 and A1, east was between classes A6 and A7, south was between classes A12 and A13, and west was between classes A18 and A19.

The difficulty associated with studying natural disturbances such as fire is that there are many interacting factors that affect the resultant landscape patterns of which topography is only one. Slope azimuth and slope magnitude influence fuel availability through their control over microclimatic factors (Countryman 1966, Miller 1994, Pyne *et al.* 1996). Topography also influences grazing distribution (Mueggler 1965, Cook 1966, Pinchak *et*

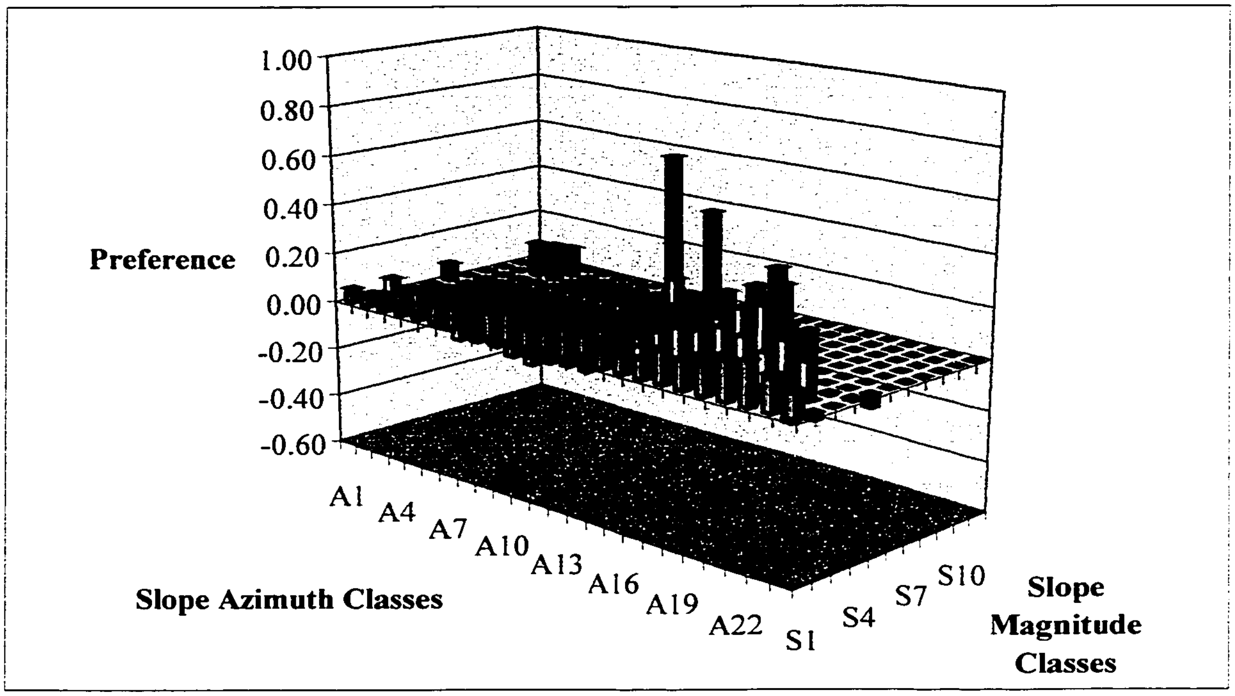


Figure 4.5 A preference graph showing the interactive effects of slope azimuth and slope magnitude classes for moderate to high fire severity areas (Class A).

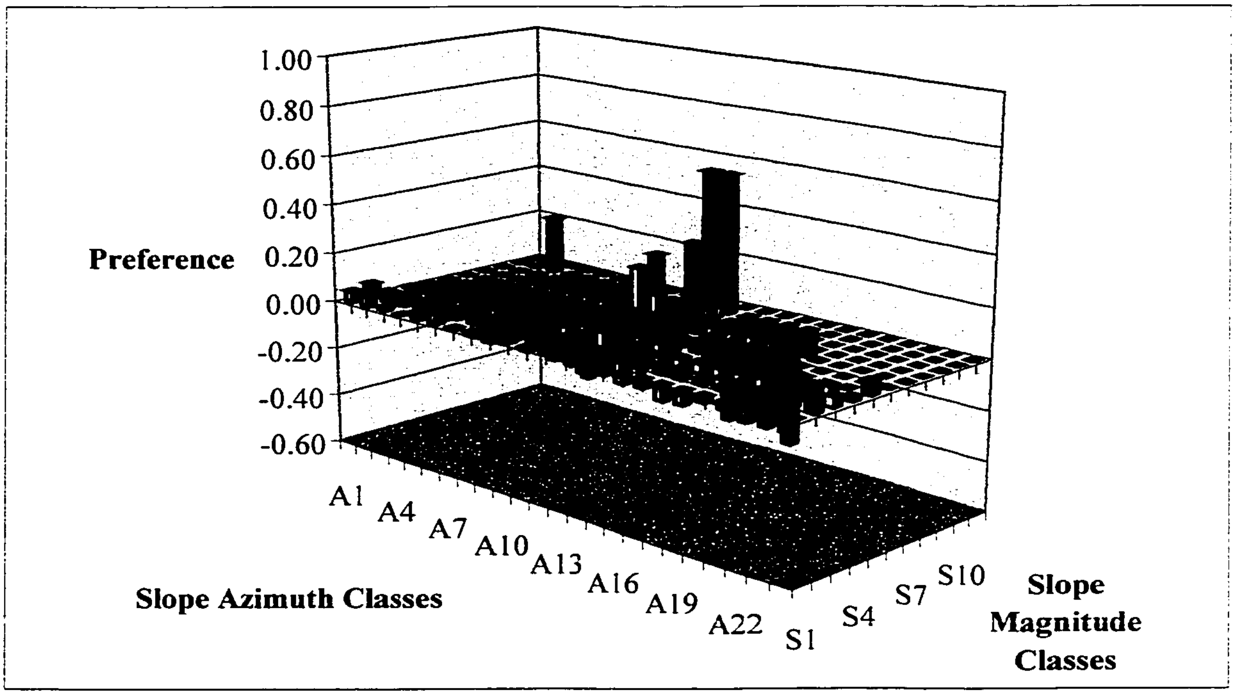


Figure 4.6 A preference graph showing the interactive effects of slope azimuth and slope magnitude classes for moderate fire severity areas (Class B).

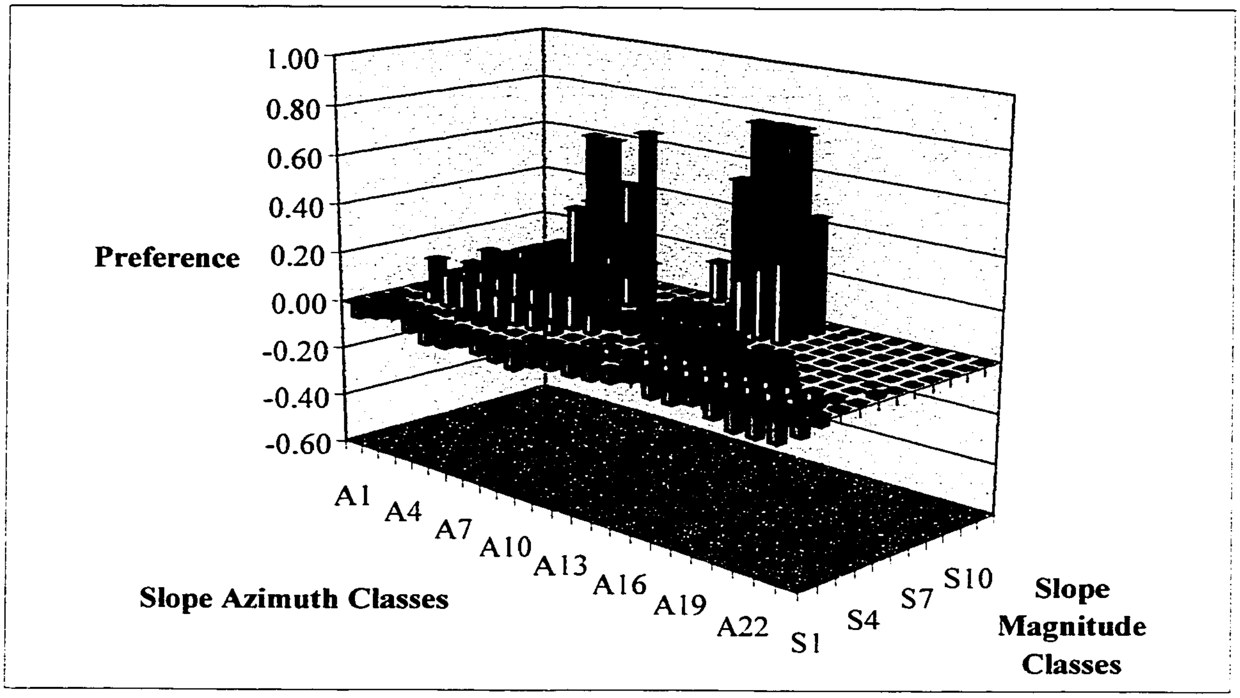


Figure 4.7 A preference graph showing the interactive effects of slope azimuth and slope magnitude classes for low fire severity areas (Class C).

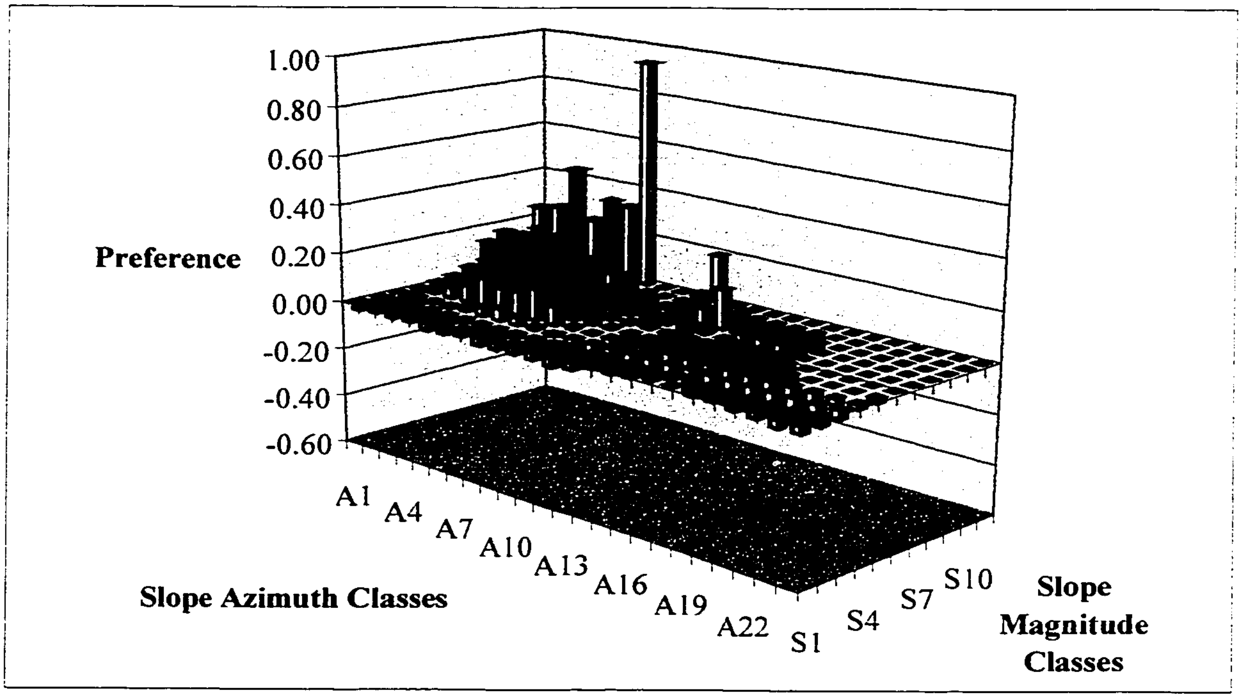


Figure 4.8 A preference graph showing the interactive effects of slope azimuth and slope magnitude classes for variable fire severity areas (Class D).

al. 1991), and therefore fuel loading. Like topography, weather conditions leading up to, and those prevailing during a fire, determine fuel availability (Daubenmire 1968). In addition, wind and slope magnitude interact, and this interaction is dependent on the relative force and direction of influence of each (Pyne *et al.* 1996).

Historical livestock grazing effects may have also influenced NDVI values and the resulting fire severity classification. Livestock preferentially graze valley bottoms in the Fescue Grass Ecoregion (Willms 1988), changing species composition from native bunchgrasses to rhizomatous exotic grass species (Willms *et al.* 1985). Heavy, continued grazing pressure results in a decrease in vegetative cover and litter, with a corresponding increase in bare soil. This would decrease NDVI accordingly.

Class A displayed a uniform preference for lower slopes across all slope azimuths, which then declined with increasing slope magnitude for slopes facing northeast to south (Figure 4.5). This pattern likely represents a combination of the cumulative effects of historical livestock grazing and lower vegetation productivity associated with increasing slope (Holechek *et al.* 1998). Evidence of this possible grazing effect may also be interpreted from the distinct preference of Class A for elevations below 1100 m AMSL (Figure 4.4), where livestock would typically congregate.

Although there appeared to be a grazing influence, there was also evidence of a fire effect in Class A. The increasing positive preference for southwest- to northwest-facing slopes (Figure 4.5) generally coincided with the prevailing wind direction (~southwest) at the time of ignition. Thus, the overall patterns for Class A likely represent the cumulative effects of fire and historical livestock grazing.

Class B preferentially occurred on south-facing slopes, but only at very steep slope magnitudes (Figure 4.6). This pattern may have been due to the drier microclimate associated with these areas, which could have resulted in less fuel accumulating through time, or to the relatively rapid movement of flames over these areas from wind compression on steep slopes. The latter process would have reduced fire residence time to the point where damage to the vegetation was decreased. The combined effects of lower fuel loading and reduced residence time resulted in a lower level of fire severity (i.e., moderate fire severity) relative to Class A.

In contrast to Classes A and B, Class C occurred on very steep, southwest-facing slopes and northeast- to east-facing slopes (Figure 4.7). These latter areas were also dominated by Class D (Figure 4.8), and thus occurred together (Plate 4.5). The apparent low fire severity on northeast- to east-facing slopes may have been the result of more moist and cooler microclimate effects. The preference of Class C for greater slope magnitudes facing southwest may have resulted from the presence of rock outcrops and drier, more exposed sites having reduced fuel accumulations. In addition, wind effects may have been stronger on these steep, southwest-facing slopes resulting in lower residence times.

The regression model (preference = slope azimuth, slope magnitude) was significant for all classes of fire severity, that is, the interactive effects of slope azimuth and slope magnitude influenced fire severity across the study area (Table 4.9). Due to the nature of the data (replication data), the R-square values were low. Taking the mean Y (slope magnitude) at every X (slope azimuth) and re-running the regression analysis was not recommended, because information would have been lost (Freund 1971 as cited by Zar 1984).

Table 4.9 Regression analysis results for slope azimuth-magnitude preference data.

Fire Severity Classes	P-values	R-square	RMSE
A	0.0001	0.1956	0.1223
B	0.0001	0.1015	0.1214
C	0.0001	0.1187	0.1572
D	0.0001	0.1826	0.0958

In general, there were significant influences on fire severity, as mapped in this study, exerted by specific topographic variables and the interactions between them; however, there were many other interacting factors that affected fire behaviour, and therefore fire severity. Under natural conditions, then, it was difficult to explain patterns of fire severity, because of these many interacting factors. Thus, patterns of fire severity were the result of more than just the interactive effects of slope azimuth and slope magnitude.

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CHAPTER 5 Synthesis

5.1 Summary and Conclusions

The purpose of this study was to quantify and evaluate the areal extent of land cover, and relate this to various fire severity classes and topographic variability using post-fire satellite data, field observations, and a DEM and DTMs. Specific objectives were to determine the extent to which post-fire land cover could be used to indicate the level of fire severity, and to determine the extent to which fire severity was related to selected topographic variables including: slope azimuth, slope magnitude, elevation, and slope azimuth-magnitude class combinations.

A post-fire LANDSAT-5 TM image (May 20, 1998) was acquired and then analyzed to produce a land cover map using NDVI. Field data were subsequently collected and the initial land cover map was refined to produce a fire severity map. It was possible to map levels of fire severity using post-fire land cover in the Fescue Grass Ecoregion of southwestern Alberta (Hypothesis 1); however, there were some provisos. The presence of high amounts of healthy green vegetative cover (i.e., Class D) was not always indicative of low fire severity as might be assumed, because vegetation recovery was a function of many extraneous factors such as post-fire climatic conditions (Chandler *et al.* 1983, Miller and Findley 1994) and post-fire grazing management (Stinson 1994). The remaining three land cover classes (i.e., Classes A, B, and C) correlated well with the assigned fire severity classes.

Following the completion of the fire severity map, the four fire severity classes were related to landscape attributes of slope azimuth and magnitude, and elevation through the incorporation of DTMs and a DEM, respectively. The effects of these specific topographic variables influenced fire severity across native foothills rough fescue plant communities in southwestern Alberta. Fire severity was, in part, related to slope azimuth, slope magnitude, and elevation, with significant interactions between slope azimuth and magnitude in some situations. On a statistical basis, a greater proportion of variability in fire severity was explained by slope azimuth, elevation, and the interactive effects of slope azimuth and slope magnitude than slope magnitude alone.

The complexities of fire behaviour made it difficult to determine whether prevailing wind direction or slope azimuth had the greater influence on fire severity. It was not known if southwest- and west-facing slopes burned more severely due to surface temperature (i.e., solar azimuth effect) or wind direction, because the prevailing wind direction at the time of the fire was approximately southwest. It is reasonable to conclude that both affect fire severity; however, the effects of both may have been modified by other factors influencing fire behaviour, as the highest preference for Class A was not for south- or southwest-facing slopes (Hypotheses 2 and 3).

The direction a slope faces influences the amount of solar radiation received by that slope (Holechek *et al.* 1998), and as such, influences the type of vegetative cover present. Higher fire severity areas (i.e., Class A) were not always and only associated with south- and southwest-facing slopes, but also with west-, northwest-, and north-facing slopes (Hypothesis 3). Not only did fuel condition (i.e., temperature and moisture content) affect fire severity, but also fuel type (i.e., woody vegetation versus grass-like vegetation) and fuel accumulation.

Steeper slopes were not always associated with higher fire severities (i.e., Class A) (Hypothesis 4). For this particular fire, the effects of slope magnitude on severity were relatively complex. Slope magnitude may have affected fire severity through its effect on vegetation productivity (i.e., fuel accumulation) or by its influence on fire behaviour (i.e., residence time). Livestock grazing distribution may have also contributed to the observed preferences for slope magnitude.

The effects of elevation on fire severity were difficult to interpret due to microtopography; however, valley bottoms appeared to be associated with higher fire severities (i.e., Class A) (Hypothesis 5). Again, livestock grazing may have contributed to this observed preference. The range in elevation within the study area is likely not large enough, compared to mountainous areas, to affect significant climate differences between valley bottoms, midslopes, and upper slopes, thus there did not appear to be a thermal belt effect.

Factors affecting fire severity influence one another, thus it was desirable to study the interactive effects of slope azimuth and slope magnitude. The interactive effects of these two topographical variables significantly influenced fire severity across foothills rough fescue grasslands in southwestern Alberta, but no more than slope azimuth alone (Hypothesis 6). Thus, slope azimuth was as important in determining the resultant landscape pattern following the fire as were the interactive effects of slope azimuth and slope magnitude.

The DEM was not only useful in studying the effects of topography on fire severity, but also in mapping shadowed areas across the study area. It was important to map shadowed areas, because shadow affects canopy reflectance (Colwell 1974, Tueller 1979), and therefore should be excluded from subsequent image analyses. Thus, the use of a DEM in mapping fire severity across grasslands with variable topography was important.

Overall, this study demonstrated the utility of integrating LANDSAT-5 TM digital data and a DEM and DTMs to study the relationship between fire severity and topography across foothills rough fescue grasslands in southwestern Alberta. An NDVI-derived map proved to be useful and relatively accurate in mapping fire severity, and when combined with DEM-derived maps (DTMs) of slope azimuth and slope magnitude, as well as the DEM itself, the study of the relationship between fire severity and topography was possible. This study also demonstrated that natural disturbances such as fire are difficult to study, because: (1) they are unplanned (Turner *et al.* 1997) and (2) there are many extraneous factors affecting response and recovery of the affected community. Because there are so many interacting factors affecting fire behaviour, and therefore fire severity, it was difficult to study each of the known factors independently. In addition, the time lapsed between image acquisition and field data collection may have presented some difficulties in mapping fire severity. Some of these difficulties were met by basing the fire severity classification on additional subjective field observations and anecdotal evidence relating to range management, and not just on bare soil, thatch, litter, and total live vegetation.

5.2 Suggestions for Further Research

Several aspects of this study have potential as the basis for future research. These are outlined in the following:

- To map species-level data and link this information to fire severity across the affected landscape, it would be useful to obtain high spatial and spectral resolution data (e.g., *casi* digital imagery) along with high resolution DTMs.

- Recording historical grazing management practices since the last major fire event in this study area, combined with fuel load data within a GIS, would provide one with appropriate information required to investigate the influence of livestock grazing on patterns of fire severity across hilly topography.

- Given that the recovery of a fire-stressed vegetation community typically does not occur within one, or even two, growing seasons, acquiring additional digital satellite imagery over the next several years would allow one to monitor the response and recovery of the foothills rough fescue plant community in southwestern Alberta.

- One could expand on the above by setting up exclosures across the affected area to investigate the relationship between yield and fire severity. This information could then be used to explore what relationships, if any, occur between yield and topography. In other words, does topography affect recovery in terms of yield.

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Appendix A Pilot Data Study

A technique similar to the optimum sampling area method was used to determine the minimal sampling area. Cain and Castro (1971) defined the minimal area of a community as "...the smallest area on which the community can develop its characteristic composition and structure." Using the modified method involves starting with an area considered to be the smallest quadrat size, estimating the abundance of each relevant variable, then doubling the size of the quadrat and estimating the abundance of each relevant variable again. This process continues until abundance stabilizes with increased sampling area. When the abundance-area curve is plotted, the area corresponding to the point where the running mean stabilizes in value constitutes the minimal sampling area.

Two community types were selected for sampling, a low fire severity site and a high fire severity site. These two sites were chosen based on field observations made by personnel at Alberta Agriculture, Food and Rural Development and the University of Alberta. At each site a representative unit was selected based on a visual assessment to determine a starting point for data collection. Anomalies such as small depressions or rock outcrops were avoided. It was more important to avoid a starting position where apparently atypical conditions would be encountered than it was to sample an area where typical conditions would be encountered (Cain and Castro 1971).

Three, 30 m transects were randomly positioned within the representative unit, and 0.5 m^2 quadrats were placed every 1 m along each transect giving a total of 15 quadrats per transect. A visual assessment was performed at each quadrat for the following data: % bare soil, % thatch, % litter, and % total live vegetative cover. In addition, % rock was recorded for rocks greater than or equal to 10 cm in diameter, or if there were more than 5 rocks/m^2 greater than or equal to 5 cm in diameter. If a site fell on a slope, sampling occurred across the slope, and not down, in order to maintain a proper estimation of slope gradient. Once the data were collected for each site, confidence intervals were calculated for each cover component for each site. Due to the variability in the data collected an acceptable confidence interval, and therefore sampling area, could not be determined. As a result, the above method was not used for sampling, rather an ocular assessment was performed across an estimated 25 x 25 m area within the representative unit at each site.

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APPENDIX B Raw Data Tables

Table B.1 Field data collected between June 5-14 for treatment A.

Site Number	% Bare Soil	% Thatch	% Litter	% Live Vegetation	% Rock	Fire Severity Classification*
A-05	30	20	2.5	45	2.5	H
A-11	20	10	5	60	5	H
A-12	25	10	15	50	0	H
A-14	0	20	10	65	5	M
A-16	15	10	10	65	0	H
A-22	30	25	0	45	0	H
A-23	5	15	15	65	0	M
A-27	0	50	0	40	10	H
A-28	0	10	15	75	0	L
A-37	10	30	10	55	0	H
A-38	5	25	5	55	10	M

*Based on field data, subjective field observations, and anecdotal evidence relating to range management.

Table B.2 Field data collected between June 5-14 for treatment B.

Site Number	% Bare Soil	% Thatch	% Litter	% Live Vegetation	% Rock	Fire Severity Classification*
B-06	0	30	10	60	0	M
B-07	25	0	10	65	0	H
B-09	20	0	15	65	0	H
B-10	5	25	5	60	5	M
B-26	0	5	30	65	0	L
B-31	5	15	10	65	5	M
B-33	0	25	5	50	25	M
B-39	5	17.5	17.5	60	0	M
B-40	5	20	15	60	0	M

*Based on field data, subjective field observations, and anecdotal evidence relating to range management.

Table B.3 Field data collected between June 5-14 for treatment C.

Site Number	% Bare Soil	% Thatch	% Litter	% Live Vegetation	% Rock	Fire Severity Classification*
C-01	0	30	5	55	10	M
C-04	0	10	10	80	0	L
C-13	3	7	45	45	0	L
C-18	0	0	30	70	0	L
C-21	0	0	15	85	0	L
C-24	5	10	15	70	0	L
C-29	5	5	15	75	0	L
C-34	0	0	15	85	0	L
C-35	5	10	15	70	0	L

*Based on field data, subjective field observations, and anecdotal evidence relating to range management.

Table B.4 Field data collected between June 5-14 for treatment D.

Site Number	% Bare Soil	% Thatch	% Litter	% Live Vegetation	% Rock	Fire Severity Classification*
D-02	20	0	0	80	0	H
D-03	0	10	30	60	0	L
D-08	0	0	10	90	0	H
D-17	0	0	15	85	0	M
D-19	0	0	10	90	0	M
D-20	0	0	10	90	0	M
D-25	0	0	25	75	0	L
D-30	0	0	10	90	0	H
D-32	0	0	10	90	0	M
D-36	0	0	40	60	0	L

*Based on field data, subjective field observations, and anecdotal evidence relating to range management.

Table B.5 Raw matrix data for the interaction of slope azimuth and magnitude for moderate to high fire severity areas (Class A). Slope azimuth classes in 15 degree increments from 0-359 degrees and slope magnitude classes in 5% increments from 0-54%.

Slope					Slope Azimuth							
Magnitude	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**	**A11**	**A12**
S1	637	786	967	1349	1708	1756	1823	1820	1417	1130	870	648
S2	720	855	899	1025	1064	921	977	1240	1108	1078	807	693
S3	741	704	626	492	395	413	455	422	516	647	692	691
S4	468	555	346	221	259	226	221	184	256	301	300	476
S5	201	259	163	165	144	116	132	112	150	124	193	213
S6	12	143	91	75	53	69	51	80	78	123	237	154
S7	0	15	84	25	8	14	17	31	38	67	126	142
S8	0	0	31	28	0	9	14	15	19	31	42	79
S9	0	0	8	21	0	5	3	11	6	15	63	18
S10	0	0	1	2	0	0	1	0	0	7	12	0
S11	0	0	0	0	0	0	0	0	0	0	3	1
Total	**2779**	**3317**	**3216**	**3403**	**3631**	**3529**	**3694**	**3915**	**3588**	**3523**	**3345**	**3115**

A13	**A14**	**A15**	**A16**	**A17**	**A18**	**A19**	**A20**	**A21**	**A22**	**A23**	**A24**	**Total**
603	604	553	490	531	561	441	354	366	382	436	521	**20753**
605	535	503	554	660	793	746	749	600	495	349	476	**18452**
459	467	482	437	465	523	698	717	688	532	516	549	**13327**
365	376	449	424	456	520	558	668	606	513	389	474	**9611**
264	280	239	219	286	356	277	82	0	0	0	47	**4022**
146	203	185	146	207	163	5	0	0	0	0	0	**2221**
93	71	77	77	92	26	0	0	0	0	0	0	**1003**
20	12	12	20	7	0	0	0	0	0	0	0	**339**
27	2	1	1	0	0	0	0	0	0	0	0	**181**
0	0	0	0	0	0	0	0	0	0	0	0	**23**
0	0	0	0	0	0	0	0	0	0	0	0	**4**
2582	**2550**	**2501**	**2368**	**2704**	**2942**	**2725**	**2570**	**2260**	**1922**	**1690**	**2067**	**69936**

Table B.6 Raw matrix data for the interaction of slope azimuth and magnitude for moderate fire severity areas (Class B). Slope azimuth classes in 15 degree increments from 0-359 degrees and slope magnitude classes in 5% increments from 0-54%.

Slope					Slope Azimuth							
Magnitude	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**	**A11**	**A12**
S1	907	1178	1304	1553	1967	2291	2054	1839	1376	1247	910	810
S2	1192	1346	1585	1655	1751	1712	2056	2411	2348	1953	1500	1148
S3	908	1085	1112	1021	1046	976	990	1270	1431	1545	1245	950
S4	738	789	780	661	616	628	659	724	813	1068	786	686
S5	325	550	466	345	354	356	438	473	496	558	599	512
S6	14	194	251	238	195	211	287	307	271	336	432	266
S7	0	43	129	119	80	85	135	148	122	183	173	133
S8	0	0	75	28	23	27	37	60	51	81	76	81
S9	0	0	5	4	4	15	16	12	20	42	42	58
S10	0	0	2	2	0	1	6	1	0	1	19	4
S11	0	0	0	0	0	0	0	0	0	0	7	2
Total	**4084**	**5185**	**5709**	**5626**	**6036**	**6302**	**6678**	**7245**	**6928**	**7014**	**5789**	**4650**

A13	**A14**	**A15**	**A16**	**A17**	**A18**	**A19**	**A20**	**A21**	**A22**	**A23**	**A24**	**Total**
659	597	610	551	592	511	426	369	341	338	453	600	**23483**
1113	848	923	949	989	1085	865	818	733	683	859	975	**31497**
822	759	721	597	708	704	597	688	692	823	874	925	**22489**
557	563	586	450	487	437	406	460	609	610	634	734	**15481**
412	324	303	287	310	333	244	44	0	0	0	97	**7826**
249	283	173	202	219	131	9	0	0	0	0	0	**4268**
97	150	69	68	66	14	0	0	0	0	0	0	**1814**
32	23	16	32	10	0	0	0	0	0	0	0	**652**
7	1	5	2	0	0	0	0	0	0	0	0	**233**
3	0	0	0	1	0	0	0	0	0	0	0	**40**
0	0	0	0	0	0	0	0	0	0	0	0	**9**
3951	**3548**	**3406**	**3138**	**3382**	**3215**	**2547**	**2379**	**2375**	**2454**	**2820**	**3331**	**107792**

Table B.7 Raw matrix data for the interaction of slope azimuth and magnitude for low fire severity areas (Class C). Slope aziumth classes in 15 degree increments from 0-359 degrees and slope magnitude classes in 5% increments from 0-54%.

Slope					Slope Azimuth							
Magnitude	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**	**A11**	**A12**
S1	271	400	514	497	461	548	672	558	395	301	303	266
S2	407	500	672	720	825	897	1050	1180	999	791	535	460
S3	418	512	647	853	826	784	792	867	904	819	541	390
S4	358	470	539	567	682	609	779	666	731	825	486	306
S5	274	370	346	405	446	426	501	493	567	626	307	251
S6	6	179	228	178	247	335	362	290	321	274	199	202
S7	0	37	152	105	138	160	173	140	134	72	88	69
S8	0	0	86	56	52	78	62	71	40	20	15	17
S9	0	0	3	15	19	48	19	29	16	8	5	4
S10	0	0	0	1	14	18	8	7	0	0	6	0
S11	0	0	0	0	0	8	0	0	0	0	10	0
Total	**1734**	**2468**	**3187**	**3397**	**3710**	**3911**	**4418**	**4301**	**4107**	**3736**	**2495**	**1965**

A13	**A14**	**A15**	**A16**	**A17**	**A18**	**A19**	**A20**	**A21**	**A22**	**A23**	**A24**	**Total**
218	223	238	254	209	192	181	118	90	90	114	216	**7329**
381	376	326	255	333	310	232	215	241	248	286	321	**12560**
295	303	229	223	254	218	148	136	214	308	361	399	**11441**
265	183	174	173	134	125	85	71	130	187	261	337	**9143**
176	118	90	104	76	40	28	8	0	0	0	44	**5696**
97	60	47	63	45	24	2	0	0	0	0	0	**3159**
38	47	28	42	14	3	0	0	0	0	0	0	**1440**
14	16	22	50	20	0	0	0	0	0	0	0	**619**
0	22	16	28	11	0	0	0	0	0	0	0	**243**
0	13	6	12	2	0	0	0	0	0	0	0	**87**
0	0	0	0	0	0	0	0	0	0	0	0	**18**
1484	**1361**	**1176**	**1204**	**1098**	**912**	**676**	**548**	**675**	**833**	**1022**	**1317**	**51735**

Table B.8 Raw matrix data for the interaction of slope azimuth and magnitude for variable fire severity areas (Class D). Slope azimuth classes in 15 degree increments from 0-359 degrees and slope magnitude classes in 5% increments from 0-54%.

Slope Magnitude	Slope Azimuth A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
S1	67	103	112	149	107	144	192	103	92	84	60	34
S2	84	104	191	187	190	212	219	246	260	174	113	95
S3	77	125	158	156	197	242	291	274	241	202	119	56
S4	94	170	208	230	358	285	334	386	303	183	112	63
S5	68	164	211	263	304	263	332	321	326	185	88	43
S6	2	83	210	242	200	241	256	239	234	153	72	52
S7	0	15	85	107	117	125	165	113	57	37	45	31
S8	0	0	62	75	54	25	73	33	11	1	14	2
S9	0	0	3	9	29	15	32	10	2	0	4	0
S10	0	0	0	0	3	3	2	0	0	0	5	0
S11	0	0	0	0	0	5	3	0	0	0	7	0
Total	**392**	**764**	**1240**	**1418**	**1559**	**1560**	**1899**	**1725**	**1526**	**1019**	**639**	**376**

A13	A14	A15	A16	A17	A18	A19	A20	A21	A22	A23	A24	Total
43	79	77	79	126	87	58	48	36	31	26	38	**1975**
83	54	45	72	107	79	57	28	51	44	46	58	**2799**
74	56	50	40	68	40	16	7	41	42	63	69	**2704**
62	55	28	16	48	16	8	2	14	17	58	81	**3131**
27	29	5	16	29	10	3	0	0	0	0	10	**2697**
14	20	3	8	5	0	0	0	0	0	0	0	**2034**
24	21	1	11	5	0	0	0	0	0	0	0	**959**
10	15	2	1	1	0	0	0	0	0	0	0	**379**
4	3	1	0	0	0	0	0	0	0	0	0	**112**
0	0	0	0	0	0	0	0	0	0	0	0	**13**
0	0	0	0	0	0	0	0	0	0	0	0	**15**
341	**332**	**212**	**243**	**389**	**232**	**142**	**85**	**142**	**134**	**193**	**256**	**16818**