AN ABSTRACT OF THE DISSERTATION OF

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Abstract approved: Signature redacted for privacy.
William J. Ripple

This investigation on fire mosaics addressed several aspects: (1) quantifying the role of terrain variables in fire-related mortality and historical mean fire return interval (MFRI), (2) comparing post-burn Landsat Thematic Mapper (TM) imagery, TM difference imagery, and aerial photo interpretation to map forest survival after wildfire, and (3) to describe and discuss wildfire effects on successional stage patterns and wildlife habitat.

The two study sites were located on the Willamette National Forest in the Oregon Cascades. The Warner Creek burn was the location of a 1991 wildfire covering 3669 ha; the Upper McKenzie site was the location of ecological and historical fire studies.

Historical MFRI, terrain, and vegetation data were input into a geographical information system. Random sampling was conducted on all layers, and was also used to ground truth forest survival, primarily with aerial photography. Relationships of terrain to forest survival and historical MFRI were analyzed with regression. Regression was also used to model forest survival with TM data. Error matrices were used to compare classified TM data and aerial photo interpretation in mapping survival.

At both sites, terrain variables accounted for more variation in forest survival (12-62%) or historical MFRI (4.8-21.9%) within individual physiographic areas, than across the respective study areas. Moreover, the significant topographic variables differed among individual physiographic areas.

Regressions of TM band transformations were used to evaluate forest survival. The TM difference imagery with stratification by pre-fire tasseled cap (TC) wetness explained 75% of the variation in live canopy ratio, and post-burn TM Structural Index (SI) accounted for 72%. Classification of the TM difference imagery with pre-fire TC wetness had an overall accuracy of 68%, that of the post-burn SI was 63%, and that from aerial photo interpretation was 56%.

Before the burn, landscape matrix was closed mature/old-growth. After the burn, the early seral/rock stage expanded, the open mature/old-growth stage was created, and the closed mature/old-growth was reduced and fragmented. Thus, overall habitat diversity and edge increased, but interior habitat decreased. Also, patches of early seral/rock were more variable in size and complex in shape than staggered setting clearcuts on public lands.

Analyzing Fire Mosaics in Temperate Coniferous Forests with GIS and Remote Sensing

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Dedicated in loving memory to my father, Walter

CHAPTER 1

INTRODUCTION

Preamble

To begin, I want to make a few remarks providing focus.

My dissertation involved the application of geographic information systems and remote sensing to fire ecology research. The setting was the temperate coniferous forest of the Pacific Northwest. My research was an observational study focusing on three facets in particular: the influence of terrain on fire effects, evaluation of methods for mapping fire-related mortality, and changes in landscape structure and patterns after wildfire.

First, while the literature in fire ecology and fire history was voluminous, no research had been done quantifying the influence of terrain variables on fire-caused mortality, or historical fire frequency. My research addressed this void.

Second, aerial photography has been the predominant means of mapping forest survival after wildfires. Although digital imagery has been available for the past two decades, such imagery has not been shown superior to aerial photo interpretation for mapping forest survival after wildfire. My research compared the effectiveness of several digital image processing techniques to aerial photo interpretation for mapping survival after fire.

Third, landscape ecology as a science has grown immensely in recent years (Forman 1995, Turner 1989). Measurements have been developed to study ecosystem patterns, interactions among landscape elements, and their changes over time. While fire effects have been studied, very little has been published on landscape patterns from wildfire. My final objective compared landscape patterns before and after an actual wildfire.

Study Sites

The study includes two separate sites. One is a 3669 ha burn at the Warner Creek site, which occurred in 1991; the other is the Upper McKenzie site, 11,608 ha, which includes the H.J. Andrews Experimental Forest (Figure 1.1). Both areas for this study are on the Willamette National Forest, within the west-central Cascades of Oregon.

The terrain is rugged, with elevations ranging from 800-1800 m above sea level at the Warner Creek site, and 500-1500 m at the Upper McKenzie site. The geology is primarily of volcanic origin, with characteristic broad valleys and steep slopes of previous alpine glaciers (Walker and Griggs 1981). The climate is maritime, with the Pacific Ocean moderating the extremes for winters and summers (Shumway 1981). Precipitation ranges from 120 to 160 cm, with most falling between October and March (Shumway 1981, Franklin and Dyrness 1973). Hot, dry, east winds in the summer are critical fire weather events (Schroeder and Buck 1970). Forests are within the western hemlock (*Tsuga heterophylla*) zone at lower elevations, and the Pacific silver fir (*Abies amabilis*) zone at higher elevations (Franklin and Dyrness 1973).

Conifers dominate the forest vegetation, which is unique for temperate climates (Franklin and Dyrness 1973, Waring and Franklin 1979). Coniferous forests can develop high leaf surface areas, with leaf area index ranging from 10 to 20 m^2/m^2, and photosynthesize during frost-free weather in the winter (Waring and Franklin 1979). The conifers can also maintain their height growth for well into maturity. Moreover, their great size enables the trees to store water during summer drought (Waring and Franklin 1979). Their needle-shaped leaves are very efficient for precipitating fog in winter (Shumway 1981), and for transpiration in summer (Waring and Schlesinger 1985). Deciduous hardwood species, on the other hand, are at a distinct disadvantage. Their growth is limited to summer, which is dry in the Pacific Northwest. Hardwoods are neither as long-lived nor do they grow in as

LOCATION MAP

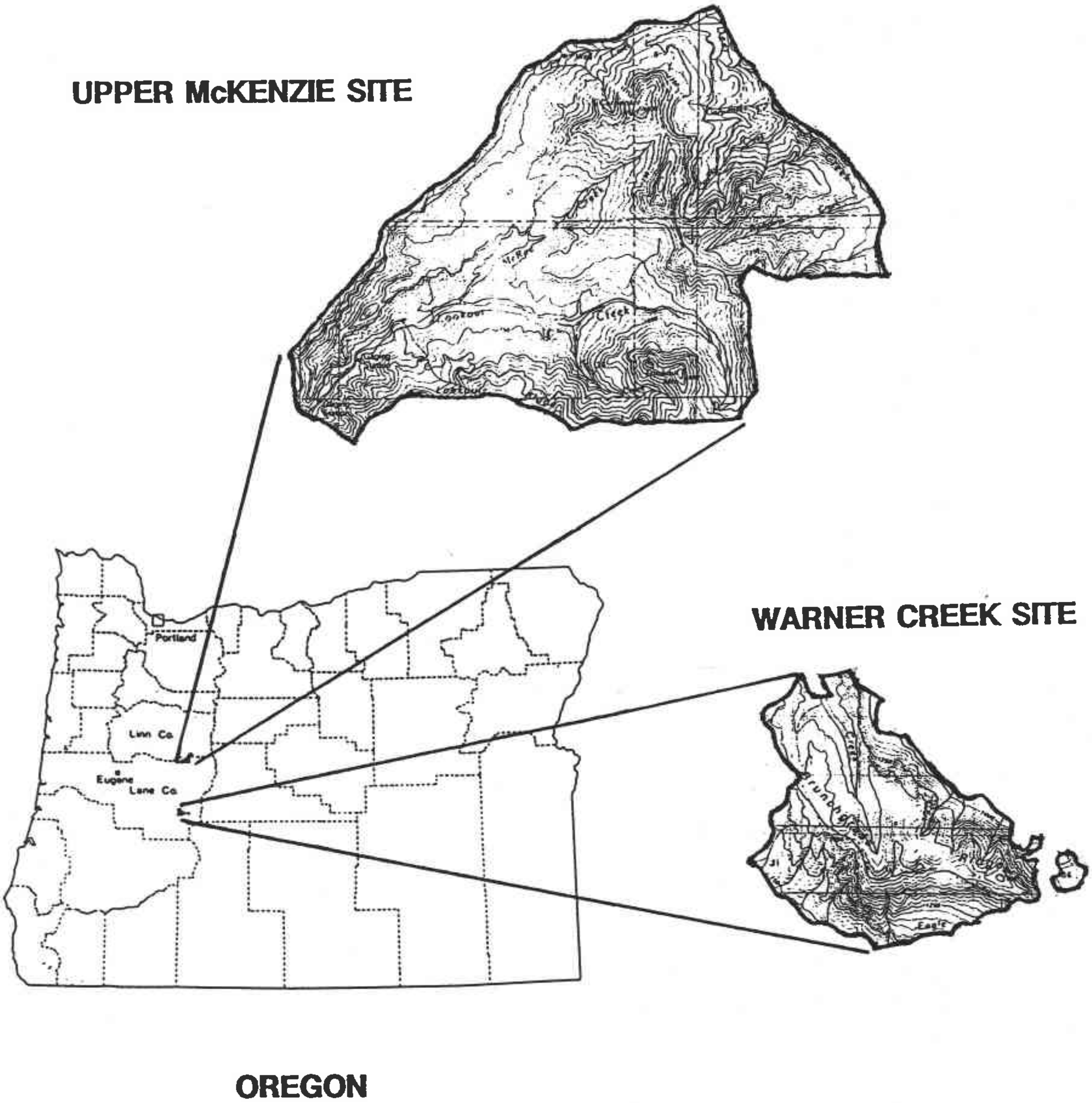

Figure 1.1. Approximate locations of the Warner Creek and Upper McKenzie sites in Oregon. Site enlargements adapted from US Geological Survey 30 x 60 minute maps, but not to original scale.

large as the conifers. Overall, Waring and Franklin (1979) concluded the current regional climate favors conifers over hardwoods.

All successional stages are represented (Brown 1985) on both study sites, particularly old-growth Douglas-fir (*Pseudotsuga menziesii*) forest. Old-growth forests consist of at least twenty Douglas-fir/ha older than 200 years, with multilayered canopies, and considerable coarse woody debris of at least 10 snags/ha and over 37 tons/ha of large logs (Old-growth Definition Task Group 1986). These trees can grow to great size, often 1-2 m in girth, and 60-80 m in height, and can live over a millennium (Waring and Franklin 1979).

Fire Ecology

Fire plays a significant role in vegetation patterns and dynamics throughout the world, including North America. Primary sources of ignition include lightning (Komarek 1966, 1968), and people (Kay 1995, Pyne 1982, Stewart 1963). Cold fronts producing thunderstorms and lightning are sources of ignition for fires across North America (Komarek 1964, 1966; Taylor 1969, 1971).

Schroeder *et al.* (1964) categorized 14 regions in the United States based on critical fire weather and fuels. Komarek (1968) generalized Schroeder's work into 7 fire bio-climatic regions throughout North America: eastern deciduous forest, southern pine forest, tropical evergreen forest, central grasslands, boreal forest, tundra, and the western mountain complex (Table 1.1).

The frequency, severity, and extent of fire defined its functional role in the dynamics of forest ecosystems: the fire regime (Agee 1990, 1993; Kilgore 1981). Mutch (1970) hypothesized that fire-dependent communities burned more readily because natural selection made them more flammable than other communities. Thus, the relationship between the fire regime and the forest ecosystem was reciprocal (Agee 1990, 1993; Kauffman 1990b), *i.e.*, changing the fire regime could alter the forest ecosystem, and *vice versa*.

Table 1.1. Descriptive summary of fire bio-climatic regions across North America (Komarek 1968).

Fire Bio-climatic Region	Vegetation	Citations
Eastern Deciduous Forest	Forest: *Acer spp.*, *Fagus spp.*, *Quercus spp.*, *Pinus strobus*, *P. taeda*, *P. rigida*, *P. virginiana*	Ahlgren and Ahlgren 1960 Little 1964, 1973, 1974 Wihelm 1973
Southern Pine Forest	Forest: *Pinus echinata*, *P. palustris*, *P. taeda*, *P. elliottii*, *P. clausa*, *P. serotina*, *Acer spp.*, *Quercus spp.*	Cypert 1973 Hermann *et al.* 1991 Komarek 1974 Landers 1991 Platt *et al.* 1991 Snyder 1991
Tropical Forest	Fire-adapted forest, savanna	Budowski 1966 Vogl 1969
Central Grasslands	Grass: *Andropogon spp.*, *Bouteloua spp.*, *Hilaria spp.*	Box 1967 Humphrey 1963 Jackson 1965 Komarek 1965 Smith and Owensby 1973 Wright 1973
Boreal Forest	Forest: *Picea glauca*, *P. mariana*, *Pinus banksiana*, *P. resinosa*, *P. strobus*, *Prunus spp.*, *Populus spp.*, *Quercus spp.*	Ahlgren and Ahlgren 1960 Ahlgren 1973, 1974 Heinselman 1971 Lynham and Stocks 1991 Rowe 1971 Van Wagner 1971
Tundra	Lichens (*Alectoria spp.*) and grass (*Hierochloe alpina*, *Eriophorum spp.*)	Cochrane and Rowe 1969 Komarek 1964 Wein and Bliss 1973
Western Mountain Complex	Forest: *Pinus contorta*, *P. ponderosa*, *Sequoiadendron giganteum*	Arno 1980 Biswell 1963, 1973 Franklin and Laven 1991 Hartesveldt and Harvey 1967 Kilgore and Briggs 1972 Lotan 1976 Roe *et al.* 1971 Weaver 1951, 1964, 1968

In particular, fire played a prominent role in shaping the forest ecosystems of the Pacific Northwest (Agee 1990, 1993; Walstad *et al.* 1990). In Oregon alone, Agee (1990, 1993) estimated that nearly 322,000 ha burned annually, based on forest inventory data from the early 1940s. Morris (1934) compiled an historic record of major fires for much of the first century of European settlement in western Oregon and Washington. Major fires burned in the Oregon Coast Range in 1849 and 1933, and throughout western Oregon and Washington in 1868 and 1902.

Anthropogenic use of fire has been superimposed on the natural occurrence of fire. Native Americans used fire to promote wildlife habitat, food sources, and to drive game for hunting throughout North America (Komarek 1965, Pyne 1982, Stewart 1963, Thompson and Smith 1971). This also has been documented in the Willamette Valley and elsewhere in Oregon (Boyd 1986, Morris 1934, Zybeck 1993). The Kalapuya of the Willamette Valley appeared to burn in late summer or early autumn (Boyd 1986).

European settlers did not follow the same pattern of burning, however, as that from natural ignition or aborigines. Fires from grazing and logging were set throughout the year, particularly in the spring and fall (Komarek 1965, Burke 1980). Effective fire suppression, however, began in 1911 with passage of the Weeks Act (Dana and Fairfax 1980), which established the federal policy of cooperating with the states in the protection of forests from fire.

Fire suppression has had profound effects, changing the natural fire regime and altering vegetation patterns. For example, in Oregon and Washington, fire suppression has permitted the invasion of oak (*Quercus* spp.) woodlands by ponderosa pine on the eastside, or by Douglas-fir on the westside (Agee 1994). Also, fire suppression has appeared the most likely factor for the expansion of western Juniper (*Juniperus occidentalis*) in eastside grasslands (Agee 1994, Kauffman 1990a).

Furthermore, fire suppression, combined with other management practices has created severe forest health problems in eastside forests of Oregon and Washington (Everett *et al.* 1994). In order to restore forest health, and fire to forests, an understanding of the historical fire regimes and consequent landscape structure and pattern is necessary (Arno and Ottmar 1994).

Fire History

Fire has been a predominant ecological disturbance factor in the forests of the Pacific Northwest, and its frequency has varied with climatic changes and other factors (Hansen 1947, Brubaker 1991). Using fossil pollen records, Cwynar (1987) found that the forests of the northern Cascades shifted from an open forest to a closed one dominated by Douglas-fir about 11,000 years ago. This vegetation shift was likely in response to climatic warming. Concomitantly, fire occurrence increased as shown by more charcoal deposits. Fire frequency gradually decreased 6500 years ago, shifting toward a wet-temperate climate as indicated by an increase in western redcedar (*Thuja plicata*) and western hemlock and a decrease in charcoal accumulation.

Agee (1990, 1993) described three general fire regimes for Pacific Northwest forests: high severity, moderate severity, and low severity. The high severity regime had infrequent fire (> 100 years apart) of high intensity that killed the overstory (Agee 1990, 1993; Kilgore 1981). The moderate severity regime was quite variable in fire frequency (25-100 years) and severity. Consequently, this regime created patchiness in the landscape with multi-aged stands (Agee 1990, 1993; Morrison and Swanson 1990). The low severity regime had frequent burning (< 25 years apart) with low intensity. Climatic factors of temperature and available moisture affected the ignition frequency, fire severity, species adaptations, and forest structure of the ecosystem (Kilgore 1981, Kauffman 1990b).

Several studies have been conducted to quantify the fire history in forests of the Pacific Northwest. Pickford *et al.* (1980) found that lightning fires (1916-1975 AD) accounted for 81% of the area burned in the Olympic National Park, primarily in the summer. According to Fahnestock (1976), lightning was the ignition source for 88% of the fires in the Pasayten Wilderness of Washington. In the west-central Cascades of Oregon, Burke (1980) studied historical US Forest Service records documenting fire occurrence from 1850 to 1977. She found that 60% of all fires were caused by lightning. In addition, lightning-caused fires tended to be small, and occurred primarily in July and August, coinciding with severe fire weather for the region. Anthropogenic fires, on the other hand, were larger and more widely distributed throughout the fire season.

Numerous investigators have quantified historical fire occurrence using dendrochronology to date fire scars. Hemstrom and Franklin (1982) found that fire was the primary disturbance factor of Mount Rainier National Park; the average fire rotation was 434 years. Teensma (1987) and Morrison and Swanson (1990) studied fire history in the west-central Cascades of Oregon. They found that infrequent catastrophic fires occurred with occasional underburning. Teensma (1987) determined the mean fire return interval to be 166 years for stand replacing and partial stand replacing fires, 114 years for all fires from 1435 to 1910. Since active fire suppression began (1911), Teensma (1987) found that the mean fire return interval increased to 587 years.

Through historical fire studies, investigators have found relationships of fire occurrence with terrain features. Fahnestock (1976), Pickford *et al.* (1980), and Teensma (1987) found that historical fire incidence was positively related to elevation. In addition, Teensma (1987) found that the mean fire return interval varied considerably by aspect and exposure to dry east winds as well.

Objectives

Despite extensive fire research, the literature lacks any quantification of how much variation in historical fire incidence can be explained by topography. Moreover, most empirical fire behavior models are based on weather and fuel conditions, with slope effects estimated as an empirical coefficient to fireline intensity (Rothermel 1972, 1983; Albini 1976). Such models do not directly account for differences due to elevation, aspect, or slope position.

My doctoral research involved two studies, terrain and remote sensing analyses of fire mosaics in the coniferous temperate forests of the west-central Cascades of Oregon. In the first study, I focused on the relationships of terrain variables to fire behavior. My objectives were as follows:

(1) To investigate the statistical relationships between forest survival and terrain variables on the Warner Creek Burn, using regression techniques. How much of the variation can terrain variables account in forest survival after a wildfire?

(2) To investigate the statistical relationships between historical fire occurrence and terrain variables on the Upper McKenzie Site, using regression techniques. How much of the variation can terrain variables account in historical fire occurrence?

Space-borne sensors have been used to observe the effects of forest fires and other disturbances for the past two decades. For example, Cablk *et al.* (1994) used Landsat Thematic Mapper (TM) imagery to estimate forest mortality following hurricane Hugo. Chuvieco and Congalton (1988) used TM to discriminate fire scars in Valencia, Spain, but had trouble separating lightly burned stands from non-burned stands since both were sparsely vegetated. This indicates the fact that techniques of image processing are not standardized for estimating fire effects. Indeed, many assessments after wildfire still rely on aerial photography, such as for the Warner Creek Burn (Bailey 1993).

Utilizing a geographic information system (GIS), the pattern of fire across a landscape could be studied. GIS technology has been used to study neighborhood effects in wildfire distribution (Chou *et al.* 1990, Wu 1991), evaluate fire hazard (Chuvieco and Congalton 1989), and plan fire suppression and land use activities (Chou 1992, Hamilton *et al.* 1989). However, changing landscape patterns from wildfires have only been analyzed in simulations (Romme 1982), not from actual burns.

For the second study, I evaluated the use of Landsat TM data for mapping forest survival, and studied changes in successional stages after a wildfire. My objectives were as follows:

(3) To evaluate the effectiveness of using Landsat TM imagery to mapping forest survival after a wildfire.

(4) To compare several techniques for mapping forest survival after a wildfire.

(5) To describe changes in successional stages and landscape patterns due to wildfire, and discuss their impacts on wildlife habitat.

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CHAPTER 2

THE ROLE OF TERRAIN IN FIRE MOSAICS OF TEMPERATE CONIFEROUS FORESTS

Abstract

This investigation focused on the role of terrain variables in fire-related mortality and historical mean fire return interval (MFRI). Two areas were studied on the Willamette National Forest of western Oregon. The Warner Creek site was the location of a 1991 wildfire (USDA Forest Service 1993); the Upper McKenzie site was the location of fire history and ecological studies (Teensma 1987).

Historical fire data for the Upper McKenzie site were input into a geographic information system (GIS), whereas forest survival at the Warner Creek Burn was interpreted from aerial photography. Terrain data for both sites were generated from digital elevation models (DEM), and from digitized stream, ridge, and vegetation layers. I randomly sampled all layers, and investigated the relationship of terrain to mortality and historical MFRI using regression analyses.

At both sites, terrain variables accounted for more variation in forest survival (12-62%) or historical MFRI (4.8-21.9%) within individual physiographic areas than across the respective study areas. Moreover, the significant topographic variables differed among individual physiographic areas for both sites, and included ridgeline proximity, elevation, stand age, and aspect.

Factors such as fire fighting, fuel loading, weather conditions, and neighborhood effects probably affected forest survival at Warner Creek along with terrain.

Introduction

Several studies have investigated the fire history of forests in the Pacific Northwest. Pickford *et al.* (1980) studied the fire history of the Olympic National Park (1916-1975 AD) and found that the incidence of fire increased with elevation, and in the drier eastside of the park. Fahnestock (1976) found that lightning fire ignitions were positively related to elevation in the Pasayten Wilderness of Washington. Hemstrom and Franklin (1982) studied the disturbance history of Mount Rainier National Park. Fire was the primary disturbance factor, with an average rotation of 434 years. All but two of the major fire episodes corresponded with reconstructed times of drought.

In the west-central Cascades of Oregon, Teensma (1987) and Morrison and Swanson (1990) studied historic fires. They used dendrochronology to date stand establishment and fire scars, and found a mixture of infrequent, catastrophic fires and more frequent underburning. Teensma (1987) determined the mean fire return interval (MFRI) to be 166 years for stand-replacing and partial stand-replacing fires. In addition, he found that the MFRI varied considerably among landscape positions by aspect, elevation, and exposure to dry east winds.

Fire behavior models have incorporated the interaction of fire spread with fuels, weather, and terrain (Albini 1976; Andrews 1986; Rothermel 1972, 1983, 1991). Slope effects were accounted for in fireline intensity (Rothermel 1972, 1983, 1991). Other terrain effects on fire intensity and spread were incorporated indirectly through fuel type and moisture (Anderson 1982, Andrews 1986, Andrews and Chase 1989, Burgan and Rothermel 1984, Rothermel *et al.* 1986). Turner and Romme (1994) suggested that predicting fine-scale crown fire behavior could be accomplished by linking mechanistic and probabilistic models.

Despite considerable research on fire ecology and history (Table 2.1), no one has quantified the effects of terrain variables on forest survival following wildfire, or on historical MFRI. The objectives of this study were to determine the following:

Table 2.1. Summary of expected qualitative relationships for terrain and vegetation variables to fire behavior and effects.

Variable	Relationship to Fire Effects*	Citation
Live Canopy Ratio	↑ fireline intensity => ↑ rate of spread or fuel consumption => ↓ forest survival	Alexander 1982 Rothermel and Deeming 1981
Stand Age	↑ fuel in young and old stands => ↓ forest survival	Agee and Huff 1987
Stand Type	↑ bark thickness => ↑ resistance to fire: Douglas-fir > true fir > western hemlock	Kauffman 1990 Kimmins 1987
Relative Elevation and Proximity to Ridgelines	High relative elevation or ↑ proximity to ridgelines exposes vegetation to wind; also ↑ elevation => ↑ true fir; both events => ↓ forest survival or ↑ fire frequency	Albini *et al.* 1982 Andrews 1986 Burgan and Rothermel 1984 Franklin and Dyrness 1973
Relative Elevation and Proximity to Streams	Low relative elevation or ↓ proximity to streams => ↑ fuel moisture; also ↓ elevation => Douglas-fir; both events => ↑ forest survival or ↓ fire frequency	Same references as Relative Elevation and Proximity to Ridgelines
Aspect	Southern aspect => ↑ incident sunlight => ↓ fuel moisture => ↓ forest survival or ↑ fire frequency; Eastern aspect => ↑ exposure to dry east winds => ↓ forest survival or ↑ fire frequency	Albini 1976 Rothermel 1983 Rothermel *et al.* 1986 Schroeder and Buck 1970
Slope	↑ slope => ↑ pre-heating of fuels => ↓ forest survival	Albini *et al.* 1982 Rothermel 1972
Physiographic Area	Fire behavior unique to each area due to terrain influence on weather, fuels, and moisture	Teensma 1987
Surface Roughness	↑ changes in slope and aspect might disrupt fireline intensity => ↑ forest survival	Same references as slope and aspect

* ↑ = increasing
↓ = decreasing
=> = leads to

(1) How much of the variation in forest survival after a wildfire can be explained by vegetation and terrain variables?

(2) How much variation in historical mean fire return interval can be explained by terrain variables?

Methods

Study Sites

Both study sites are within the Willamette National Forest. The physiography is rugged, and includes portions of the Western Cascades (elevations 500-1500 m) and the High Cascades (elevations over 1500 m) (Franklin and Dyrness 1973). The climate is maritime, moderated by the Pacific Ocean (Shumway 1981). Winters are wet and mild, with snow primarily in the high elevations (> 600 m); summers are relatively cool and dry. Occasional hot east winds during summer create severe fire weather conditions (Schroeder and Buck 1970). Precipitation (120-200 cm) occurs mostly between October and March (Franklin and Dyrness 1973). Conifers dominate the moist, temperate climate, and grow to great size and age (Waring and Franklin 1979, Franklin and Dyrness 1973).

The primary study site was the Warner Creek Burn, about 12 km east of the town of Oakridge, Oregon. The burn comprised 3669 ha, in which 30% of the stands were completely killed, 39% were partially killed, and the remaining 31% was underburned or escaped burning (Figure 2.1). According to the USDA Forest Service (1993), the variable fire intensity significantly altered the vertical structure and spatial patterns in the surviving forest stands.

The weather had been hot and dry since the spring of 1991, when the fire started on 10 October 1991. The fire began in the southeast corner of Bunchgrass Ridge, and initially spread west across

Figure 2.1. Map of live canopy ratio (defined p. 24) for the Warner Creek Burn from the best ratio difference imagery (Table 3.2), at 1:63,360.

Survival Class	Area (ha)	%
0-25% LCR	1116	30.4
26-50% LCR	736	20.1
51-75% LCR	691	18.8
76-100% LCR	1126	30.7

LCR = live canopy ratio

MAP FOR LIVE CANOPY RATIO (LCR)

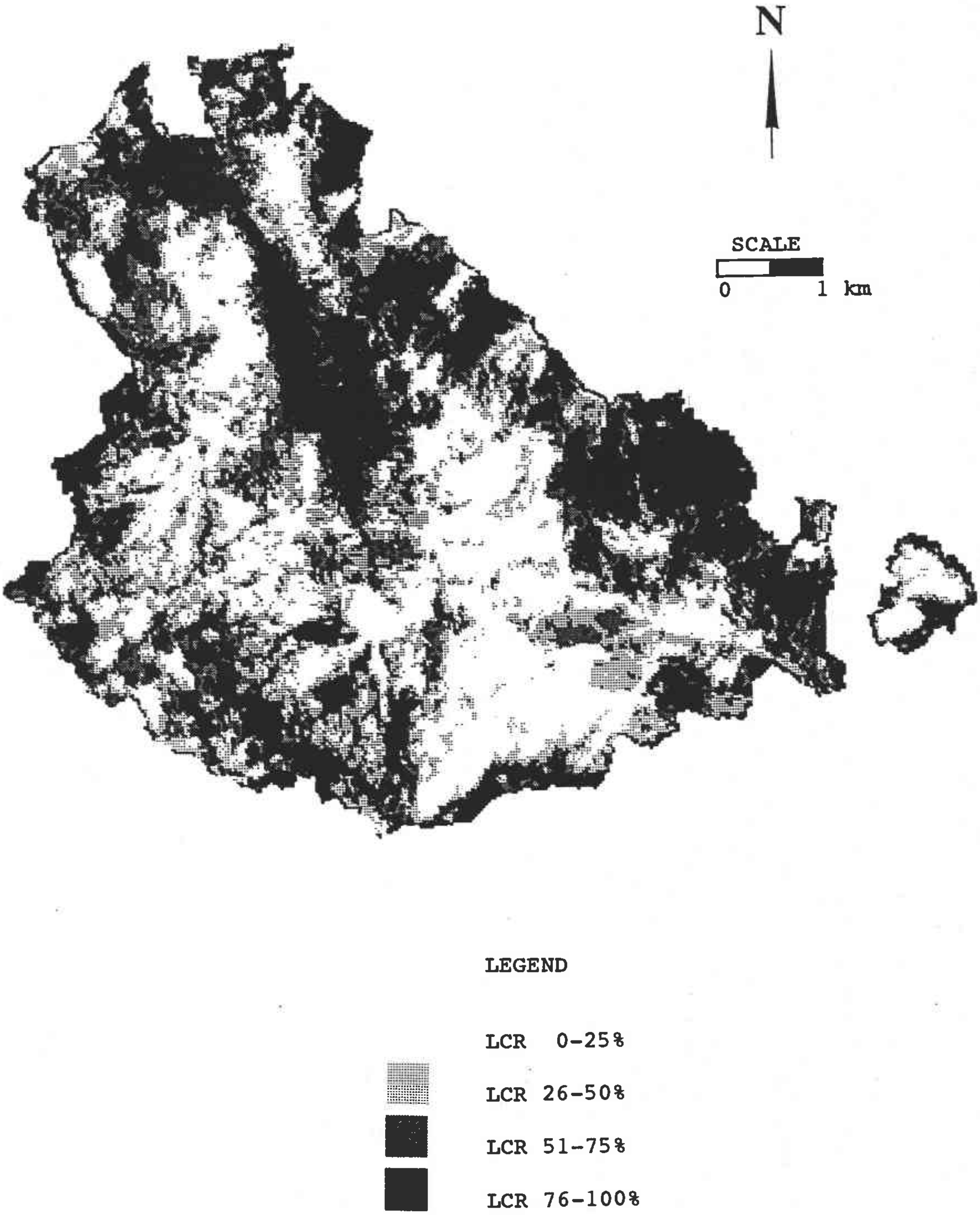

Figure 2.1:

Bunchgrass and north into the western edge of the Kelsey Creek basin (Walker and Rogers 1991). East winds channeled by the dissected terrain, spread the fire southward the next few days (McCulley 1996, per. comm.). According to Walker and Rogers (1991), on 15 October, southwest winds combined with upslope winds causing major fire runs and crowning, particularly across the southern face of Bunchgrass Ridge and into the Kelsey basin. Similar southwest winds on 16 October, accompanied by moist, marine air caused the fire to burn across most of the Kelsey basin and down the northwestern slope of Bunchgrass Ridge. A couple days later, a cool, moist inversion and the cliffs above Black Creek prevented the fire from spotting into that drainage. Cold fronts with showers extinguished the flames on 22-23 October.

US Forest Service (USFS) personnel from the Oakridge Ranger District provided maps of pre-fire stand age, forest type, and streams. These maps were digitized into the Earth Resources Data Analysis System (ERDAS 1990) GIS. A 7.5-minute, Level I DEM from the US Geological Survey (1987) was registered to the digitized maps and resampled to 25 m x 25 m pixel size with a root mean square error less than 0.01 pixels.

Forest survival was measured as a ratio of living canopy cover surviving the wildfire, to that before the burn, and called the live canopy ratio (LCR). I evaluated LCR with 1:13,000 color aerial photos of the Warner Creek Burn taken on September 1992 using a Delft stereoscope. LCR was photo interpreted for 196 randomly sampled points within a 75 m x 75 m area using a forest cover template (Paine 1981), and became the response variable.

The second study area was the Upper McKenzie site. The Upper McKenzie site was selected for its extensive fire history record (Teensma 1987). The 11,608 ha area including the H.J. Andrews Experimental Forest, was located about 2 km north of McKenzie Bridge, Oregon. Teensma (1987) developed a fire history of the area for the past 550 years. Fire polygons from Teensma (1987) were digitized into ERDAS (1990) and combined in an overlay analysis to generate a fire frequency layer. The overlay included fire events (1435-1839 AD) before European settlement changed the fire regime (Burke 1980).

The fire frequency layer was then filtered (median value within a circle of radius 2 pixels) to remove some of the extraneous pixels from the overlay analysis. This GIS layer for historical number of fires (Teensma 1987) was divided into the time interval (404 years) to obtain the response variable, historical MFRI (Figure 2.2). In the four centuries examined, every location within the study area had burned 2-14 times. The predominant historical MFRI for nearly 20% of the study area was 80.8 years.

Terrain Analysis

At the Warner Creek site, I analyzed the relationship between LCR and several terrain and vegetation variables: relative elevation, aspect, slope, proximity to ridgelines, proximity to perennial streams, surface roughness, stand age, forest type, and physiographic area. Elevation was determined directly from the DEM image. Aspect and slope of the terrain were derived from the DEM with the ERDAS (1990) TOPO module. I transformed the aspects twice using the function [Cosine $(X_{MAX}-X_{OBSERVED})+1$], with X_{MAX} and $X_{OBSERVED}$ in degrees, generating two continuous variables (0-2) for regression analysis (Beers *et al.* 1966). The transformation $X_{MAX}=180$ contrasted north (value 0) and south (value 2) aspects; the transformation $X_{MAX}=90$ contrasted west (value 0) and east (value 2) aspects.

As an intermediate step, the number of changes in aspect for aspect diversity in a 3 x 3 window was derived using the ERDAS (1990) GIS module. The aspect diversity layer was used as background to digitize the primary and secondary ridgelines on the computer monitor. Afterward, distance classes of 25 m increments from ridgelines were generated for a proximity to ridgeline layer.

Figure 2.2. Map of historical (1435-1839 AD) mean fire return interval on the Upper McKenzie site (derived from Teensma 1987), at 1:110,000.

Historical MFRI (years)	Area (ha)	%
202.0, 134.7, 101.0, & 80.8	5399	46.5
67.3, 57.7, & 50.5	4912	42.3
44.9, 40.4, & 36.7	1158	10.0
33.7, 31.1, 28.9, & 26.9	139	1.2

MFRI = mean fire return interval

HISTORICAL MEAN FIRE RETURN INTERVAL (MFRI)

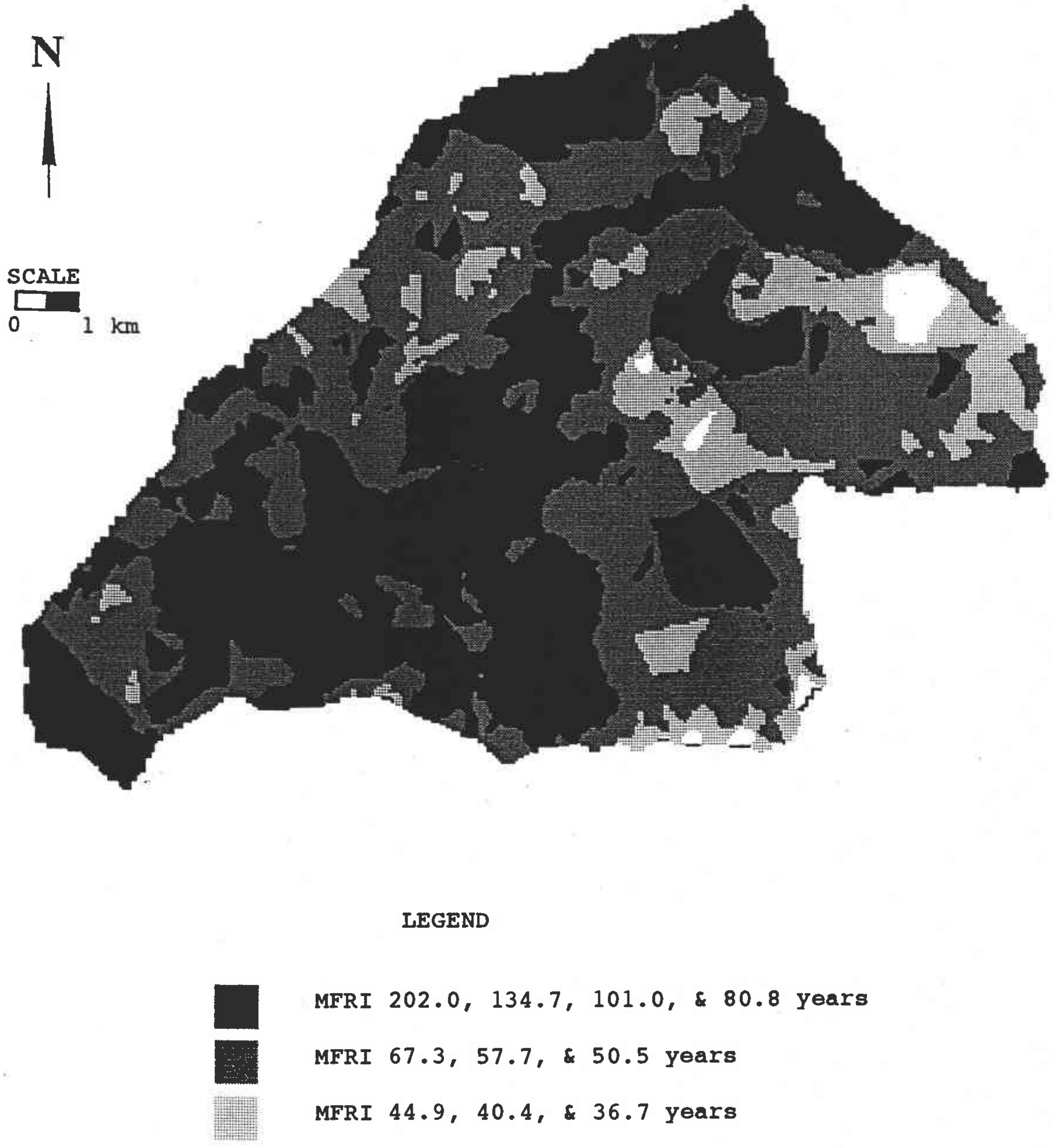

Figure 2.2:

Perennial streams were digitized into ERDAS (1990), and developed into distance classes for proximity to perennial streams, similar to those for ridgelines. Surface roughness was derived by adding the number of changes in slope classes (10-degree units) and aspect classes (9 orientations) for each pixel through an overlay analysis.

A USFS pre-fire vegetation map was digitized in ERDAS (1990). This map provided information on stand composition and age, and was generalized into two layers: forest type and stand age (0-550 years). Three forest type classes were analyzed: Douglas-fir (*Pseudotsuga menziesii*), true fir (*Abies* spp.), and true fir/mountain hemlock (*Abies* spp./*Tsuga mertensiana*).

The Warner Creek Burn was divided into four physiographic areas based on terrain (Figure 2.3). Teensma (1987) found a significant effect on historical MFRI due to physiographic area, so physiography was examined on the Warner Creek site in a similar manner. Bunchgrass Ridge and Kelsey Creek were used to delineate the physiographic areas.

Global positioning system (GPS) technology has been used to evaluate the accuracy of digital terrain maps (Adkins and Merry 1994, August *et al*. 1994). A preliminary evaluation was conducted to assess the accuracy of the DEM for the Warner Creek site with a GPS and 12 points. Through simple linear regression analysis, DEM-derived elevations were very significantly related to GPS-derived elevations ($P < 0.0001$, $r^2 = 0.996$). Aspect transformations from the DEM were significantly related to aspect transformations from field measurements ($P = 0.00005$, $r^2 = 0.821$). DEM-derived slope (degrees) was also significantly related to field measured slope, but explained less variation ($P = 0.002$, $r^2 = 0.632$). The DEM used for Warner Creek exhibited some striping, as found by Garbrecht and Starks (1995) in another Level I DEM. Filtering did not remove the striping, but the magnitude of systematic error was not considered great. The striping,

PHYSIOGRAPHIC AREAS IN WARNER CREEK SITE

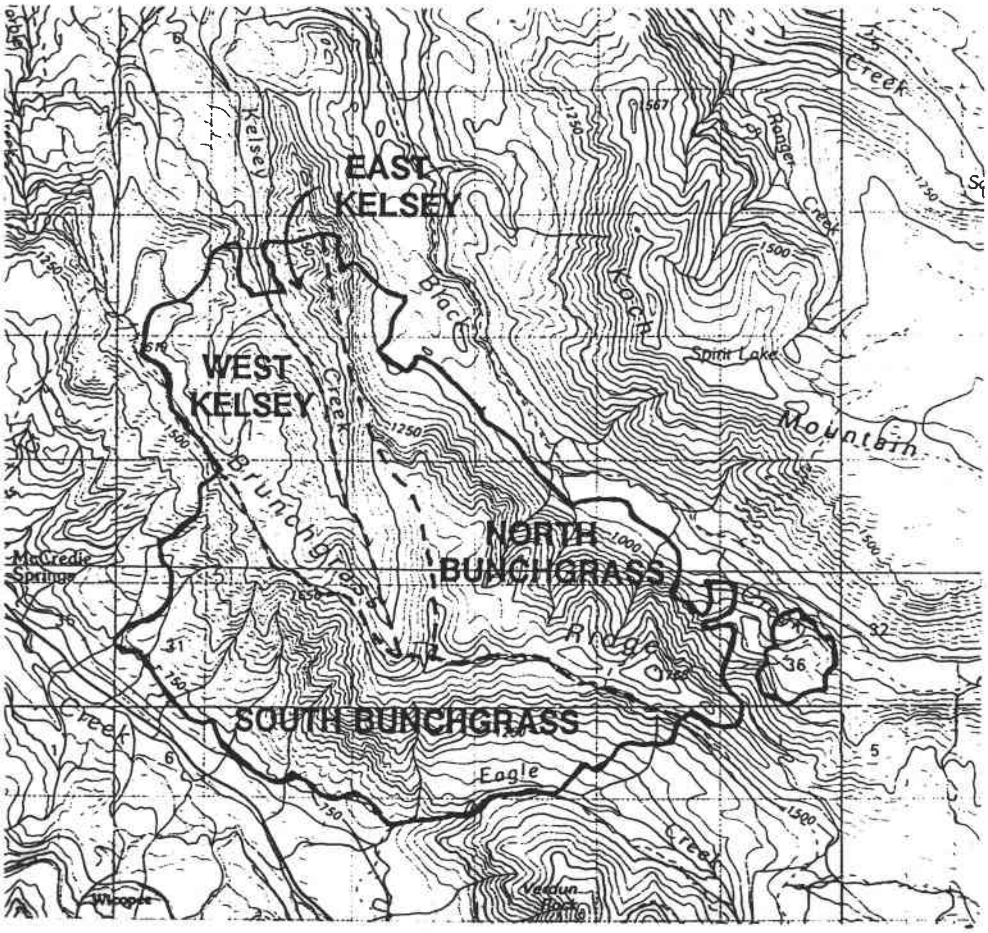

Figure 2.3. Delineation of physiographic areas within the Warner Creek site. Map from US Geological Survey (1983b) 30 x 60 minute quadrangle for Oakridge, Oregon, at 1:100,000.

however, probably contributed to the lower r^2 values for layers derived from the DEM, such as elevation, aspect, and slope.

The terrain variables for the Upper McKenzie site were developed from a DEM and a digitized stream layer as with the Warner Creek site. No vegetation variables, however, were included in the Upper McKenzie analyses. The four physiographic areas were Blue River, County Creek, North Lookout, and South Lookout (Figure 2.4, Teensma 1987).

Sampling and Analyses

For the Warner Creek Burn, 196 randomly generated coordinates were selected to lie within polygons at least one pixel from the boundary of any stand type. For every point, data were collected from each GIS layer. Regression analyses were conducted to describe the relationship of terrain and vegetation factors to LCR within each physiographic area, and across the entire site. Simple linear and multiple linear regression models were analyzed. Multiple linear models were developed by using the forward stepwise procedure (F-to-enter and F-to-leave = 4.0, Statistical Graphics Corp. 1992). Correlation analyses among explanatory variables were conducted to check independence. Multiple regression models were evaluated for autocorrelation with the Durbin-Watson statistic (Neter *et al.* 1989).

A similar methodology was followed for the Upper McKenzie site as well, but the pixel size for all GIS layers was 30 m x 30 m. A DEM and digitized stream layer were used to generate the terrain variables. Regression analyses were conducted to describe the relationship of terrain factors to historical MFRI within each physiographic area, and across the entire site.

Teensma's maps of historical fires, however, were subject to his data interpretation. Teensma (1987) showed the approximate location of his sample points on the Upper McKenzie site on a map, which was digitized into a GIS. The distribution of his sample points across the study site was clumped, and left some large gaps. Thus, my

PHYSIOGRAPHIC AREAS IN UPPER McKENZIE SITE

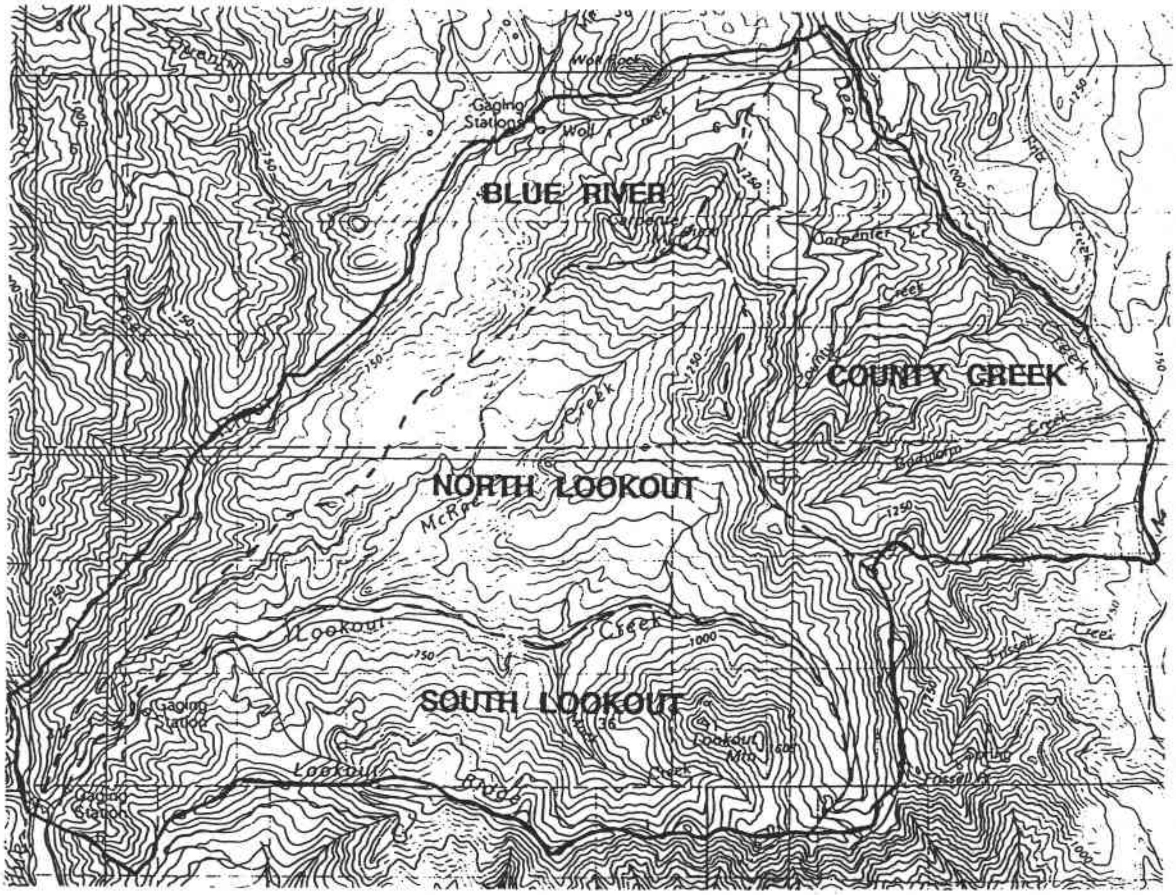

Figure 2.4. Delineation of physiographic areas within the Upper McKenzie site. Map from US Geological Survey (1983a) 30 x 60 minute quadrangle for McKenzie River, Oregon, reduced to 1:110,000.

sampling was restricted to the same relative domain in order to remove any interpretational bias of the historical fire records. A total of 250 points across the site were randomly chosen for regression analyses. Regression, correlation, and autocorrelation analyses were conducted as with the Warner Creek data.

Results

Warner Creek Site

Within each physiographic area, regressions accounted for 12-62% of the variation in LCR (Table 2.2). Correlation analyses among the vegetation and terrain variables indicated that a few were highly correlated, however these correlations varied among the physiographic areas (Appendices 2.1-5). Average LCR ranged from 45-73% among physiographic areas, in the following ascending order: West Kelsey, South Bunchgrass, North Bunchgrass, and East Kelsey.

Within the East Kelsey physiographic area, distance from primary and secondary ridgelines was positively and significantly ($P < 0.0001$) related to and accounted for 54.0% of the variation in LCR (Table 2.2). The East-West (EW) aspect transform was also positively and significantly ($P = 0.023$) related to and explained 22.2% of the variation in LCR. In addition, a multiple regression model included proximity to ridgelines and perennial streams ($P < 0.0001$), and accounted for 61.9% of the variation in LCR. The Durbin-Watson test was not significant for autocorrelation among explanatory variables.

For the West Kelsey physiographic area, elevation and slope were negatively and significantly ($P < 0.01$) related to LCR. Elevation accounted for 24.7% of the variation in LCR, and slope accounted for 21.8%. Also, a multiple regression model including elevation, North-South (NS) aspect transform, slope, and proximity to perennial streams ($P < 0.0001$) explained 56.3% of the variation in LCR; the Durbin-Watson test did not indicate autocorrelation.

Table 2.2. Significant regressions of live canopy ratio (%) on terrain and vegetation variables within each physiographic area of the Warner Creek Burn.

Physiographic Area	Explanatory Variable	Parameter Estimate	P-value	r^2
East Kelsey (n = 23)	Ridgeline Prox (intercept)	0.15017 (15.12)	0.00007 (0.2587)	0.540
	Aspect Tr EW (intercept)	125.846 (51.4)	0.02336 (0.0002)	0.222
	Stepwise model: Ridge Prox Stream Prox (intercept)	 0.23169 0.12930 (-42.86)	<0.0001	0.619
West Kelsey (n = 31)	Elevation (intercept)	-0.11021 (199.72)	0.00441 (0.0004)	0.247
	Slope, degrees (intercept)	-1.95989 (92.01)	0.00810 (<0.0001)	0.218
	Stepwise model: Elevation Aspect Tr NS Slope Stream Prox (intercept)	 -0.21587 -18.77981 -1.65405 0.07489 (358.11)	<0.0001	0.563
North Bunchgrass (n = 71)	Stand age (intercept)	0.30771 (3.977)	0.00009 (0.7926)	0.200
	Elevation (intercept)	-0.07557 (160.82)	0.00036 (<0.0001)	0.169
	Stream Prox (intercept)	-0.05395 (89.36)	0.00137 (<0.0001)	0.139
	Aspect Tr EW (intercept)	24.9819 (28.27)	0.00547 (0.0359)	0.106
	Ridgeline Prox (intercept)	0.02658 (42.89)	0.01710 (<0.0001)	0.080
	Slope, degrees (intercept)	0.89665 (37.82)	0.05107 (0.0080)	0.054
	Stepwise model: Stand age Elevation Aspect Tr EW (intercept)	 0.42822 -0.09473 19.23580 (75.88)	<0.0001	0.553
South Bunchgrass (n = 71)	Elevation (intercept)	-0.05276 (107.78)	0.00247 (<0.0001)	0.125
	Ridgeline Prox (intercept)	0.01927 (26.93)	0.02336 (0.0048)	0.072

n = sample size
Tr = transformation
EW = East-West
NS = North-South
Prox = proximity

Within the North Bunchgrass physiographic area, stand age, EW aspect transform, and proximity to ridgelines were positively and significantly ($P \leq 0.02$) related to LCR; whereas slope was marginally ($P = 0.051$) related to LCR. Elevation and proximity to perennial streams were negatively ($P \leq 0.001$) related to LCR. The highest coefficient of simple determination was for LCR on stand age ($r^2 = 0.200$). A multiple linear regression model that included stand age, elevation, and EW aspect transform accounted for 55.3% of the variation in LCR. Once again, the Durbin-Watson test for autocorrelation was negative.

In the South Bunchgrass physiographic area, elevation was negatively and significantly ($P = 0.0025$) related to LCR; whereas proximity to ridgelines was positively and significantly ($P = 0.0234$) related to LCR. The highest coefficient of simple determination was for LCR on elevation ($r^2 = 0.125$). With forward stepwise selection, no multiple linear regression model was superior to either simple linear regression model.

A pooled analysis across the entire Warner Creek study area was also conducted (Appendix 2.6). Elevation and proximity to streams were negatively and significantly ($P < 0.00001$) related to LCR; proximity to ridgelines and stand age were positively and significantly ($P < 0.01$) related to LCR. The highest coefficient of simple determination was for elevation ($r^2 = 0.108$).

Multiple regression models of categorical variables of forest type and physiographic area versus LCR were significant ($P < 0.01$) for the entire Warner Creek study area. LCR decreased in true fir and mountain hemlock, and forest type accounted for 8.2% of the variation in LCR; physiographic areas explained only 4.7% of the variation. The best fitting multiple regression of terrain and vegetation variables on LCR included stand age, elevation, EW aspect transformation, true fir type, East Kelsey and North Bunchgrass physiographic areas

($P < 0.0001$, $R^2 = 0.244$). The Durbin-Watson test did not indicate autocorrelation.

Upper McKenzie Site

Regression analyses for terrain variables on historical MFRI within each physiographic area were explored (Table 2.3). Models accounted for 4.8-21.9% of the variation in historical MFRI within any given physiographic area. Correlation analyses among terrain variables indicated that a few, particularly elevation, ridgeline proximity, and stream proximity were consistently and highly correlated (Appendices 2.7-11). Median historical MFRI among physiographic areas ranged from 57.7-80.8 years, in the following ascending order: South Lookout, North Lookout, Blue River, and County Creek.

In the Blue River physiographic area, the NS aspect transform was positively and significantly ($P = 0.0012$) related to historical

Table 2.3. Significant regressions of historical mean fire return interval on terrain variables within Blue River and North Lookout physiographic areas on the Upper McKenzie site. No significant regressions found on County Creek and South Lookout physiographic areas.

Physiographic Area	Explanatory Variable	Parameter Estimate	P-value	r^2
Blue River (n = 45)	Aspect Tr NS (intercept)	26.0048 (62.44)	0.00120 (<0.00001)	0.219
	Stream Prox (intercept)	-0.0236 (96.48)	0.03652 (<0.0001)	0.098
North Lookout (n = 75)	Ridgeline Prox (intercept)	0.00977 (65.20)	0.00117 (<0.00001)	0.135
	Elevation (intercept)	-0.0408 (122.3)	0.00164 (<0.00001)	0.128
	Surface Roughness (intercept)	5.3090 (60.55)	0.05759 (<0.00001)	0.048

n = sample size
Tr = transformation
EW = East-West
NS = North-South
Prox = proximity

MFRI; whereas proximity to perennial streams was negatively related ($P = 0.0365$) to historical MFRI. The simple linear model of historical MFRI on the NS aspect transform had the higher $r^2 = 0.219$.

For the North Lookout physiographic area, two variables were significantly ($P < 0.002$) related to historical MFRI: proximity of primary and secondary ridgelines, and elevation; surface roughness was marginally ($P = 0.0576$) significant. Historical MFRI was related positively to ridgeline proximity ($r^2 = 0.135$) and surface roughness ($r^2 = 0.048$), and negatively to elevation ($r^2 = 0.128$).

Based on a forward stepwise selection, no multiple regression model was superior to any simple linear model for either the Blue River or North Lookout physiographic areas. In addition, no single or combination of terrain variables were significantly related to historical MFRI in the County Creek and South Lookout physiographic areas.

Pooled regression analyses against terrain variables were conducted on the historical MFRI for the entire Upper McKenzie study area (Appendix 2.12). Elevation was negatively and significantly ($P = 0.0003$) related to historical MFRI, and surface roughness was positively related ($P = 0.0018$). The coefficients of simple determination were low, and elevation was the higher ($r^2 = 0.050$).

A multiple regression model of historical MFRI on physiographic areas was highly significant ($P < 0.0001$), accounting for 15.1% of the variation. From forward stepwise selection, another highly significant multiple regression model on historical MFRI included the County Creek and South Lookout areas, the NS aspect transformation, and proximity to perennial streams ($P < 0.0001$, $R^2 = 0.190$).

However, the Durbin-Watson test statistic indicated significant ($P = 0.05$) positive autocorrelation for both multiple regression models in the pooled analysis. As such, the estimators were still unbiased, but the significance levels and coefficients of multiple determination were inflated (Neter *et al.* 1989, Pindyk and Rubinfeld 1981).

Discussion

Warner Creek Site

Terrain and vegetation variables tended to account for more variation in LCR within each physiographic area (Table 2.2) than across the entire study area (Appendix 2.6). In the East Kelsey area, most forest mortality occurred closer to the main ridge; a large patch of unburned forest remained along Kelsey Creek. Interestingly, the ridgeline proximity was more effective in explaining LCR than elevation or proximity to streams. Although the ridgeline and stream proximity variables were correlated ($r = -0.76$), the stream layer was mapped with greater detail than ridgelines, so the correlation was not very high (Appendix 2.1). The variety of survival classes that occurred at similar elevations on the northern portion of the area lowered the correlation of LCR and elevation.

The significance of the EW aspect transformation in East Kelsey was confusing given the physics of fire behavior. The LCR should have declined with exposure to dry east winds (Schroeder and Buck 1970), but the East Kelsey area had a predominantly western aspect. These relationships seemed an artifact of the burning pattern in the area. Those areas with greatest LCR had northern, or northeastern aspects and lower slopes, whereas those areas that burned intensely had western or southwestern aspects and steeper slopes.

In the multiple regression model for East Kelsey, LCR was positively related to proximity to ridgelines and streams. The positive correlation of LCR to proximity to ridgelines agreed with the literature (Table 2.1); that LCR decreased with proximity to streams seemed counter intuitive. In the presence of ridgeline proximity, however, LCR also showed a positive relationship to stream proximity probably due to multicollinearity in the model (Appendix 2.1, Neter *et al.* 1989).

For the West Kelsey area, LCR was negatively correlated with elevation, corroborating the results of Pickford *et al.* (1980) and Teensma (1987). Many stands burned along the crest of Bunchgrass Ridge, whereas a large, unburned stand remained in the riparian zone. As for slope, LCR decreased with increasing slope in agreement with fire behavior modeling (Rothermel 1972, 1983, and 1991). The multiple regression model included four variables. Again, LCR was positively related to proximity to streams, indicating multicollinearity (Appendix 2.2, Neter *et al.* 1989). The R^2 might have been somewhat high due to the relatively large number of explanatory variables and small sample size.

Meanwhile, fire fighters had saved two young plantations at high elevations (Phenix 1996, per. comm.; USDA Forest Service 1993) in West Kelsey. By removing the samples from the two protected plantations, the r^2 for both elevation ($P = 0.0006$, $r^2 = 0.356$) and slope ($P = 0.0086$, $r^2 = 0.229$) were greater, while remaining negatively correlated to LCR. In addition, stand age became positively and significantly ($P = 0.0036$, $r^2 = 0.273$) related to LCR. The multiple regression model retained the same variables and was altered slightly ($P < 0.0001$, $R^2 = 0.594$).

In the North Bunchgrass area, the fire burned downslope on the northwestern face of Bunchgrass Ridge, and underburned most of the older stands (Walker and Rogers 1991). The young plantations, however, were completely killed due to their high, dry fine fuel content (Agee and Huff 1987, USDA Forest Service 1993). This explained the significant relationship of stand age. Slope was positively related to LCR, however, which contradicted models of fire behavior (Albini 1976, Andrews 1986, Rothermel 1972, 1983, and 1991). Most of the young plantations, which were killed, grew on the gentler toe slopes in the Black Creek drainage. The burning pattern also explained the positive relationship of the EW aspect transform to LCR, which contradicted expectations (Table 2.1); much of the older timber grew on northeastern and eastern aspects. The LCR was inversely related to perennial stream proximity, which was expected due to higher fuel moisture content near streams, as hypothesized by Ripple (1994). Also, the LCR was inversely related to elevation, which corroborated the historical work of Pickford *et al.* (1980) and Teensma (1987).

The multiple regression model on LCR in North Bunchgrass included three of these significant variables: stand age, elevation, and the EW aspect transform. The sign of the coefficients remained the same as in their respective simple linear regression models.

Within the South Bunchgrass area, neither elevation nor proximity to ridgelines accounted for much variation in LCR. Even though this area had mostly dry, southern and southwestern exposures, aspect was not significantly related to LCR. Apparently, under the extreme burning conditions of a crown fire (Van Wagner 1977) with strong winds channeled across the ridge face (Walker and Rogers 1991), terrain variables played a lesser role (Turner and Romme 1994).

Data from physiographic areas were pooled so the effects of terrain and vegetation variables on LCR could be investigated across the entire Warner Creek Burn. The smaller extent limited the range of variability in terrain variables, enhancing the detection of relationships with LCR. Ultimately, the importance of any single variable was specific to a given physiographic area. These findings indicated that terrain factors apparently operated more effectively within the smaller extent of physiographic areas, than across the entire study site.

Multi-scale effects might also explain the greater effectiveness of variables within physiographic areas than across the landscape, and the significance of physiographic areas to LCR. Terrain variables within a physiographic area might have interacted with weather variables, thereby affecting fire behavior in unique ways. For example, Baker (1989) found that both micro- and macro-scale processes influenced riparian vegetation in western Colorado. Therefore, improvement to modeling wildfire behavior should account for topographic effects at various scales.

Factors other than topography and stand type, such as fire fighting, neighborhood effects, fuel loads, and weather, probably played a role in wildfire behavior. Fire suppression efforts probably confounded relationships between fire intensity and topography. Fire fighters lit backfires in the North Bunchgrass and West Kelsey physiographic areas (Kreger 1996, Martin 1996, Phenix 1996, Robertson 1996, Sexton 1996, all per. comm.). They did not document the extent of the backfires, however. In addition, fire retardant drops from airplanes began the first day and continued until the fire was out (Bailey 1996, per. comm.). Thus, retardant drops occurred throughout the burn area.

The effects of suppression efforts on my results were probably mixed. Effects of protection efforts in the West Kelsey area had already been discussed. Fire fighters conducted little backfiring in the East Kelsey or South Bunchgrass areas (Bailey 1996, Sexton 1996, both per. comm.). Retardant drops in these areas might have lowered fireline intensity temporarily, but I think the effects were minimal on my results. Finally, fire suppression efforts in the North Bunchgrass area involved both lighting backfires and dropping fire retardant. Since the extent of backfiring was not recorded, fire fighting effects on my results were difficult to determine.

Neighborhood effects mean that the samples were not entirely independent, but spatially related. Although random sampling assured equal probability in choosing sample points, the movement of the fire was not random; areas closer to the conflagration had a greater chance of burning. Chou *et al.* (1990) found that spatial autocorrelation played a significant role in modeling fire distribution with logistic regression analysis. Chou (1992) used this principle to generate a probabilistic model of wildfire occurrence to develop fire management strategies; the model incorporated topography, vegetation, and weather with proximity to human transportation and habitation. Clarke *et al.* (1994) argued that fire behavior was fractal (that is, self-similar), and incorporated this self-affinity into a simulation model with weighted functions for fuel and topography. All these efforts accounted for neighborhood effects.

Upper McKenzie Site

Individual terrain variables also explained a greater amount of variation in historical MFRI within individual physiographic areas at this site.

Within the Blue River area, historical MFRI was negatively related to distance from perennial streams, as hypothesized by Ripple (1994). The positive relationship of the NS aspect transformation, however, were anomalous. Historical MFRI should have decreased with movement toward the southern aspect (Albini 1976, Andrews 1986, Andrews and Chase 1989, Rothermel 1972, 1983, 1991).

In the North Lookout area, historical MFRI was positively related to elevation, as Teensma (1987) and Pickford *et al.* (1980) found. Although Agee (1991) found fewer fires with increasing elevation, in the Siskiyou Mountains, lower elevation sites were dry, and higher elevation sites were moist. Since elevation and ridgeline proximity were negatively correlated (Appendix 2.9), one would have anticipated that historical MFRI was negatively related to ridgeline proximity.

Surface roughness was positively related to historical MFRI within the North Lookout area. Though not discussed in the literature *per se*, surface roughness was expected to disrupt fireline intensity with changes in aspect (which changed fuels and fuel moisture, Burgan and Rothermel 1984, Kimmins 1987) and slope (which affected pre-heating of fuels, Rothermel 1972 and 1983). As such, historical MFRI was expected to increase with increasing surface roughness. However, the positive correlation of surface roughness to historical MFRI might also have been an artifact of the data. There was a considerable amount of small scale striping in the DEM for the Upper McKenzie site, primarily in the North and South Lookout areas. The surface roughness variable added together the changes in slope and aspect, thereby accentuating the noise in the DEM data.

Surprisingly, historical MFRI was not significantly related to any terrain variable in the County Creek and South Lookout areas. Teensma (1987) believed that high historical MFRI was related to exposure to east winds in the County Creek area. The EW aspect transform, however, was a poor predictor of historical MFRI, and did not adequately account for the effect of exposure to dry east winds.

The analyses were repeated by pooling data to evaluate terrain effects on historical MFRI across the entire study site. Two terrain variables were related to historical MFRI, but the coefficients of determination were very low. Surprisingly, neither aspect transform was significant, in contrast to Teensma's (1987) results. Multiple regression models gave slightly better results than simple linear models.

Terrain variables were more effective explaining variation in historical MFRI within physiographic areas, rather than across the study site, in like manner to fire behavior at Warner Creek. Each physiographic area tended to limit the range of variability in certain terrain variables, thus increasing the likelihood of detecting patterns in historical MFRI. In addition, multi-scale effects might have been involved within physiographic areas. This might have accounted for the significance of physiographic areas to historical MFRI across the study site, but the lack of any clear terrain control within the County Creek area. Terrain features within each physiographic area might have interacted with climate and other factors influencing historical fire patterns in unique ways. Therefore, models for historical fire patterns should incorporate topographic controls particular to the landscape, and at multiple scales, to improve effectiveness.

Management Implications

Local topographic effects on fire behavior can be substantial, particularly in smaller physiographic areas, such as sub-drainage basins. Observational studies such as this one could identify the topographic variables meaningful for inclusion in probabilistic models. In so doing, prediction of fire behavior could be improved, as was done by Chou (1992) and Wu (1991).

Furthermore, the spatial variability of historical fire patterns necessitates changes in our forest management practices. For instance, topographic influences could be used to determine rotation length for a given site. Morrison and Swanson (1990) used historical fire analyses in the western Cascades to map fire severity patterns over particular time periods. Altogether, these studies could be used to determine the type of regeneration harvest to use, such as clearcut, shelterwood, or uneven-aged management.

Conclusions

Topographic and vegetation variables were significantly related to the LCR following the Warner Creek Burn. Terrain and vegetation variables accounted for more variation in LCR within individual physiographic areas, than across the entire site. In addition, the most prominent terrain variable for explaining variation in LCR was specific for each physiographic area.

The relationships of terrain variables to explain variation in historical MFRI at the Upper McKenzie site paralleled the findings at Warner Creek. Terrain variables accounted for a fair amount of variation in historical MFRI across the entire site. Within individual physiographic areas, however, terrain variables explained a much greater proportion of the variation in historical MFRI than across the Upper McKenzie site.

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CHAPTER 3

ASSESSING WILDFIRE EFFECTS WITH LANDSAT THEMATIC MAPPER DATA

Abstract

This investigation compared several types of remote sensing data to map forest survival after a wildfire: post-burn Landsat Thematic Mapper (TM) imagery, TM difference imagery, and aerial photo interpretation. In addition, landscape patterns were measured to describe the effects of the fire on successional stage patterns. Also, impacts of the fire on wildlife habitat were discussed.

The study site was located on the Willamette National Forest in the Oregon Cascades. The Warner Creek Burn occurred in October 1991 after a prolonged drought, and covered 3669 ha.

Regressions of TM band transformations were used to evaluate forest survival. The TM difference imagery with stratification by pre-fire tasseled cap (TC) wetness explained 75% ($P < 0.0001$) of the variation in live canopy ratio, and post-burn TM Structural Index (SI) accounted for 72% ($P < 0.0001$). Classification of the best TM difference imagery with pre-fire TC wetness had an overall accuracy of 68%, that of the post-burn SI was 63%, and that from the aerial photo interpretation was 56%. Both classified images had better user's accuracy in all categories, particularly for partially burned stands, than the photo interpreted survival map.

Pre-fire landscape patterns indicated a matrix of closed mature/old-growth stands comprising 77% of the area. After the burn, the early seral/rock stage expanded, the open mature/old-growth stage was created, the closed mature/old-growth stage was reduced and fragmented. Overall habitat diversity and edge increased after the burn, but interior habitat was dramatically reduced. In addition, patches of early seral/rock were much more variable in size and complex in shape than staggered setting clearcuts on public lands.

Introduction

Space-borne sensors have been used for the past two decades to observe the effects of forest fires. Landsat Thematic Mapper (TM) imagery was used to evaluate the effects of the Yellowstone fires of 1988 (Jeffery 1989). Helfert and Lulla (1990) used photographs from space shuttle flights between 1973-1988, finding a ten-fold increase in burning in the Amazon Basin. Pereira and Setzer (1993) analyzed spectral characteristics of fire scars in the Amazon with TM images. Chuvieco and Congalton (1988) used TM data to discriminate fire scars in Valencia, Spain, but had trouble separating lightly burned stands from unburned stands. They found that use of TM band ratios improved results. Garcia and Caselles (1991) used the TM thermal band, 6, with the normalized difference of bands 4 and 7 to detect burned areas in Valencia.

Landsat imagery has been analyzed within a geographic information system (GIS) to study patterns and detect changes in land cover (Hall *et al.* 1991, Jakubauskas *et al.* 1990, Lo and Shipman 1990, Spies *et al.* 1994). For example, Spies *et al.* (1994) used multidate classification of Landsat Multispectral Scanner data in a GIS to study changes in forested landscapes across ownerships in the Oregon Cascades. Baker (1992) and Romme (1982) conducted landscape analyses with a GIS from simulations of data based on historical fire research.

Digital image processing, however, has not been shown to be superior to aerial photo interpretation in mapping forest survival after fire. In addition, techniques for detecting fire damage in forests have not been standardized. Between 10-23 October 1991, a wildfire burned at Warner Creek in the Willamette National Forest, about 12 km east of Oakridge, Oregon. Major fire growth 14-16 October burned several thousand hectares despite fire suppression efforts (Walker and Rogers 1991); a total of 3669 ha of forest was burned. In addition, the effects of an actual fire on landscape patterns had not previously been reported. In this study, Landsat TM imagery was used to delineate the canopy cover of successional stages after the burn at Warner Creek.

The objectives of this investigation were as follows:

(1) To evaluate the effectiveness of post-burn Landsat TM imagery, Landsat difference imagery, and aerial photography in mapping forest survival after the Warner Creek Burn.

(2) To compare three different algorithms for calculating Landsat difference images.

(3) To investigate the usefulness of including ancillary data, or pre-burn imagery for vegetation stratification, in mapping forest survival after the Warner Creek Burn.

(4) To describe the effects of a severe wildfire on landscape patterns, and discuss potential impacts of the wildfire on wildlife habitats.

Methods

Study Site

The study site was located on the Warner Creek Burn in the Willamette National Forest. The 1991 burn was 3669 ha, about 12 km east of Oakridge, Oregon (Figure 3.1). The burn was within a habitat conservation area for the northern spotted owl (*Strix occidentalis caurina*).

The physiography is rugged, and the elevation ranges between 800-1800 m. The climate is maritime, with wet winters and dry summers (Shumway 1981). Average annual precipitation is 160 cm, with most falling between October and March. Conifers, particularly old-growth Douglas-fir (*Pseudotsuga menziesii*), dominate the habitat conservation area (Franklin and Dyrness 1973), the preferred habitat for the northern spotted owl (Carey *et al*. 1990, Forsman *et al*. 1984, Ripple *et al*. 1991b). Old-growth stands have at least 20 Douglas-fir/ha

Figure 3.1. USDA Forest Service (1993) map for the Warner Creek Burn in three survival classes at 1:63,360.

Class	Extent (ha)	%
Meadow/Rock	331	9.0
LCR < 40%	1299	35.4
LCR 40-89%	709	19.3
LCR > 89%	1330	36.3

LCR = live canopy ratio

US FOREST SERVICE SURVIVAL MAP

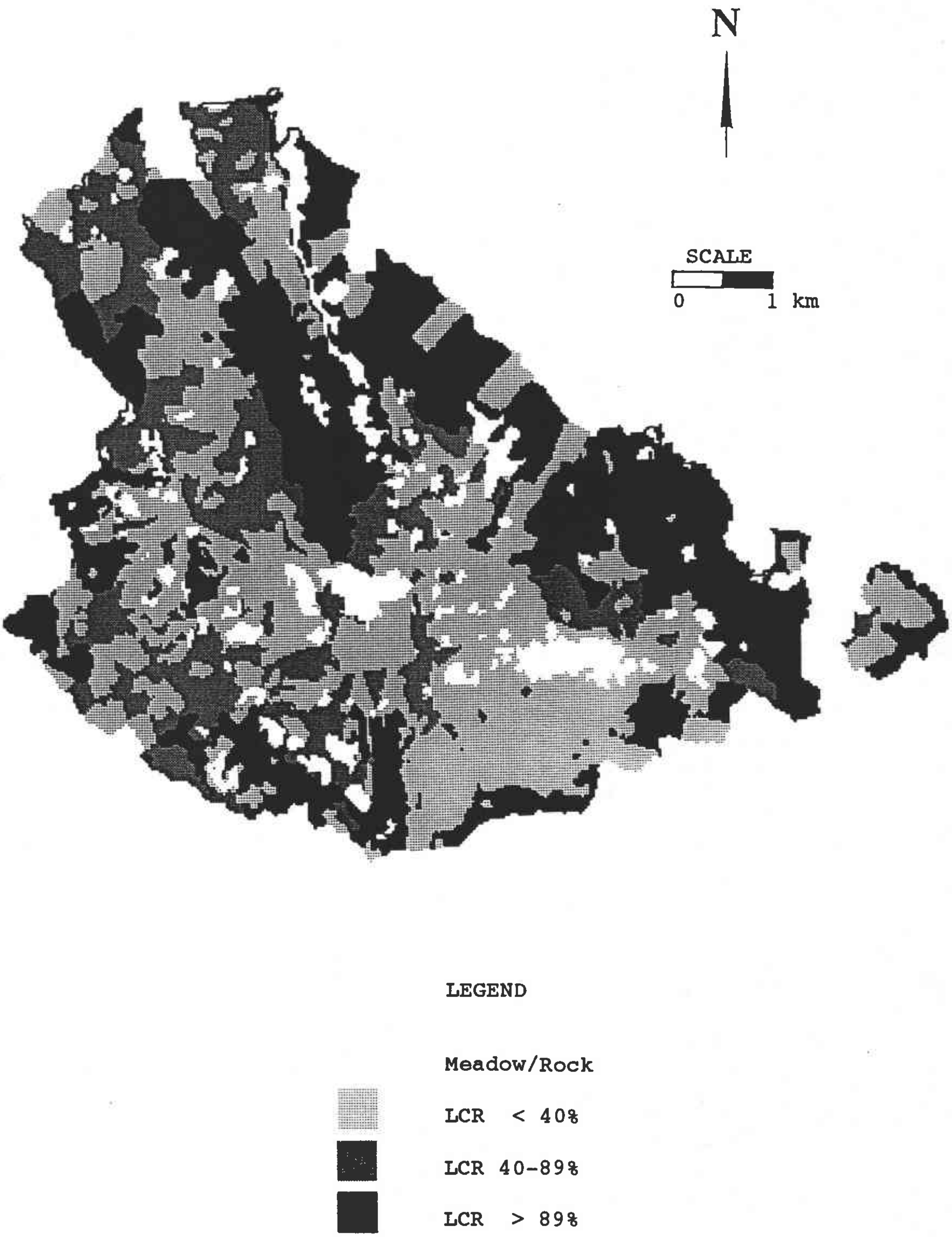


Figure 3.1:

older than 200 years, multilayered canopies, and considerable amounts of coarse woody debris with at least 10 snags/ha and over 37 tons/ha of large logs (Franklin *et al.* 1981, Old-growth Definition Task Group 1986, Spies and Franklin 1988). These old-growth characteristics are essential for ecosytem and riparian processes.

Before the fire, nine owl pairs resided within the burn perimeter (Steele 1993). However, most of the mature and old-growth Douglas-fir stands were killed or partially burned in the fire. Consequently, restoration of owl habitat was a significant issue in the Warner Fire Recovery Project (USDA Forest Service 1993).

Image Processing

Several methods of mapping forest survival were compared: single date post-burn TM imagery, difference images from pre-burn and post-burn TM imagery, and aerial photo interpretation. Regression analyses on forest survival were used to compare TM imagery. Inclusion of ancillary data on stand age and elevation, or pre-burn TM images were also evaluated.

Two TM images were used for this investigation, one taken before the wildfire and the other after. The pre-fire image was scene 5270918140, path 45, row 30 from 1 August 1991. The post-fire scene was 92325024-01, path 46, row 30 from 9 July 1992. Subscenes containing the 3669-ha burn area were used. The US Forest Service (USFS) provided maps on forest survival from 1:13,000, color, aerial photographs, pre-fire stand age and type, and a digital elevation model (DEM). Vegetation maps were digitized into the Earth Resources Data Analysis System (ERDAS 1990a).

Several steps were necessary to prepare the imagery for analysis. First, both dates of imagery were geo-referenced to a map and then registered together, to permit pixel-to-pixel analysis over time. Second, radiometric correction was made; the type depended on the comparison. For change detection with difference images, the post-fire TM data were radiometrically normalized to the pre-fire TM data. Thus, the sensor response to the post-fire scene was calibrated to the pre-fire levels. For classification using either date of TM data independently, radiometric corrections were made for atmospheric haze on each image. Third and last, spectral band ratios and other transformations were used to account for shadows from the rugged terrain at the Warner Creek site.

In order to use the ancillary data of stand age or elevation during image processing, the pre-fire image was rectified to US Geological Survey 7.5 minute topographic quadrangles by using a linear polynomial rectification with 61 ground control points (ERDAS 1990b). The image was resampled using the nearest neighbor algorithm to 25 m x 25 m pixels and a root mean square error (RMSE) less than 0.8 pixels.

Following the rectification, the post-fire image was registered to the pre-fire image to detect changes. The post-fire image was rectified with a quadratic transformation with 47 control points. The image was resampled using the nearest neighbor algorithm to 25 m x 25 m pixels and a RMSE under 0.37 pixels, as recommended by Jensen (1981).

At this point, both TM images were normalized to radiometrically appear as though viewed simultaneously. The technique used was a simple band-to-band regression analysis as described in Coppin and Bauer (1994), Eckhardt *et al.* (1990), and Vogelmann (1988). Co-locatable reference targets (features whose reflectance was not expected to change with time) were sampled from each image. Six targets were chosen: 2 lakes, 2 rock outcrops, 1 young Douglas-fir plantation, and 1 mature Douglas-fir plantation. Olsson (1993) found that inclusion of vegetation targets improved the normalization of change detection for such cover types. For each band-to-band regression, the intercept term corrected for differences in atmospheric path radiances, and the slope term for differences in sensor calibration, sun angle, Earth/sun distance, atmospheric attenuation, and phase angle, between dates (Eckhardt *et al.* 1990). Coefficients of simple determination for all bitemporal band pairs, except the thermal band 6, were between 0.981-0.997 (Appendix 3.1). The thermal band was excluded due to its lesser spatial resolution.

An analysis of variance on test targets including a lake, a rock outcrop, and a mature Douglas-fir plantation was conducted for all normalized bands to check results. Normalized bands were not significantly different in test targets for the rock outcrop and Douglas-fir plantation. Normalized bands 3,5, and 7 were not significantly different for the lake. However, normalized bands 1,2, and 4 were significantly different for the lake test target (99% confidence level) using the least significant difference (Miller 1981). The band means for the lake were as follows (pre-fire image to normalized post-fire image): 56.5 to 58.2 for band 1, 19.2 to 17.4, for band 2, and 10.9 to 7.0 for band 4.

For single date classification of imagery, the radiometrically normalized images were not used to avoid excessive data manipulation. Instead, a simple histogram adjustment was applied for atmospheric haze correction on bands 1 through 4 (Jensen 1996) on both TM images.

Finally, it was necessary to correct for topography since the reflectance of similar cover types can vary widely due to slope and aspect differences (Holben and Justice 1980, 1981; Jensen 1996; Lillesand and Kiefer 1994). Several TM band transformations were tested: 3/7, 5/2, (Lillesand and Kiefer 1994), the normalized difference vegetation index (NDVI) [(4-3)/(4+3)] (Tucker 1979), 4/2 (Coppin and Bauer 1994), 4/5 or the structural index (SI) (Fiorella and Ripple 1993a, Vogelmann 1988), 7/4 (Cablk *et al.* 1994, Vogelmann and Rock 1988), and the tasseled cap (TC) transformation for TM data (Crist *et al.* 1986). The TC transformation was based on the spectral soil line (Jackson 1983), and then transformed into the orthogonal TM reflective axes of brightness, greenness, and wetness (Crist and Cicone 1984a&b, Crist and Kauth 1986). In general, the principal TC axes describe planes of soil, vegetation, and moisture variation in soil and vegetation.

The band ratios were calculated from digital values (DV) as the quantity 162.34*Arctan($DV_{BAND\ A}/DV_{BAND\ B}$), which scaled the ratio over the 8-bit quantized range of 0-255 (Jensen 1996, Lillesand and Kiefer 1994). Each axis of the TC transformation was also scaled to an 8-bit quantized range (Fiorella 1995, per. comm.).

The selected transformations emphasized soil background, vegetation, and moisture conditions. Transformations 3/7 and TC brightness enhanced soil characteristics; 4/2, 5/2, NDVI, and TC greenness emphasized vegetation; 7/4, SI, and TC wetness revealed defoliation, as well as vegetation and soil moisture.

<u>Classification and Analyses</u>

Forest survival was measured in two ways: (1) the ratio of living canopy cover after versus that before the fire, and (2) live canopy cover surviving the burn. This permitted image development for each objective. Ground truthing was based on stereoscopic analysis of 1:13,000 scale color aerial photographs of the site taken September 1992, and field reconnaissance. Live canopy ratio (LCR) and post-burn forest canopy cover were estimated using a template of canopy cover (Paine 1981) with a Delft stereoscope. Although total pre-burn canopy cover was estimated from post-burn photography, LCR and post-burn canopy cover were very highly correlated ($P < 0.00001$, $r^2 = 0.926$).

Sample plots of 75 m x 75 m were randomly located across a registered image of the burn. The sample plot centers were at least 37.5 m from the borders of a stand (on the pre-burn type map). There were 169 samples for model development, and 57 for verification. Perennial grasses grew back by July 1992, however, and consequently showed greater reflectance than if detected immediately after the burn. In addition, rock outcrops probably showed little change between image dates; difference values might be confused with lightly underburned or non-burned forest stands. Thus, meadow and rock areas were not included in sampling for model development, or in the accuracy assessment. The meadow and rock areas were added to maps by an overlay procedure in ERDAS (1990a) from the pre-fire vegetation layer.

Four approaches were compared for image classification: (1) single date post-fire band transformations, (2) difference images for each band transformation, (3) inclusion of ancillary data, and (4) inclusion of pre-fire band transformations for stratification of forest stands (Franklin *et al.* 1995).

The difference images of band transformations were calculated by using three algorithms: (1) subtraction, $\{[(DV_{POST\text{-}BURN}-DV_{PRE\text{-}BURN})+1]*127\}$ (Jensen 1996), (2) a ratio, $162.34*\mathrm{Arctan}(DV_{POST\text{-}BURN}/DV_{PRE\text{-}BURN})$ (Jensen 1996), and (3) a standardized difference, $162.34*\mathrm{Arctan}[(DV_{POST\text{-}BURN}-DV_{PRE\text{-}BURN})/(DV_{POST\text{-}BURN}+DV_{PRE\text{-}BURN})]$ (Coppin and Bauer 1994). All algorithms were scaled to an 8-bit range.

The digital image data were analyzed by regressing the band transformations on LCR and post-burn canopy cover (Cablk *et al.* 1994, Vogelmann and Rock 1988). Models were developed by using the four approaches and three algorithms listed above. Regressions included simple and multiple linear models. The best fitting multiple linear models were developed by using the forward stepwise procedure (F-to-enter and F-to-leave = 4.0, Statistical Graphics Corp. 1992). The correlation among band transformations were conducted to check independence. Also, multiple regression models were evaluated for autocorrelation with the Durbin-Watson statistic (Neter *et al.* 1989).

Two regressions on LCR were used for classification. The USFS survival map and the classified imagery were divided into three survival categories: 0-39% LCR, 40-89% LCR, and ≥90% LCR. Error matrices were calculated (Lillesand and Keifer 1994, Story and Congalton 1986) to evaluate the USFS survival map and the two classified maps for accuracy. In addition, Kappa coefficients were calculated for each error matrix by using a multivariate discriminant function that evaluated the matrix accuracy after removing the effects of chance agreement (Cohen 1960, Congalton *et al.* 1983, Titus *et al.* 1984, Verbyla 1995). The Kappa coefficients and their respective pairwise comparisons were then tested for significance.

Finally, LCR was again regressed against post-burn TM band transformations and difference images, but without young plantations ($\leq$ 10 years). This was done to determine if removing very young ages would improve model performance and reduce classification confusion.

Landscape Patterns and Change Analysis

Landscape patterns were analyzed for three successional stage (Table 3.1) maps. The first was developed from the pre-fire GIS layer for stand type and age from the USFS. For the second, I correlated post-burn cover from ground truth against the USFS LCR ($P = 0.002$, $r^2 = 0.63$) in order to develop the appropriate successional stage parameters. Then post-fire canopy cover classes were overlaid with USFS pre-fire successional stages in ERDAS (1990a). The third was generated in a similar manner to the second by using the post-burn canopy cover from the classified Landsat difference images (Table 3.1) overlaid with USFS pre-burn successional stages. Both post-burn successional stage maps were filtered in ERDAS (1990a) with a majority algorithm and a 3 x 3 window to remove noise.

Landscape indices were calculated with FRAGSTATS (version 2.0, McGarigal and Marks 1995) on the successional stage maps. Changes in landscape structure before and after the wildfire were described. I also noted differences in the representation of landscape structure between the second and third successional stage maps. Several measures of landscape structure from FRAGSTATS were reported: area, number of patches, average patch size and its standard deviation, edge density, nearest neighbor distance and its standard deviation, area weighted average patch fractal, landscape diversity, and core area.

Table 3.1. Successional stages as adpated from Brown (1985).

SUCCESSIONAL STAGE	STAND STRUCTURAL CONDITIONS
Before the Wildfire	
Early Seral/Rock	Grasses, forbes, shrubs, and/or rock outcrops; Shrubs ≤ 3 m tall; Shrub cover <30%; Stand age < 25 years (≤ 10 years for plantations).
Sapling/Pole	Open sapling-pole trees > 3 m tall; DBH > 3 cm; Canopy cover 30-59%; Stand age 25-40 years (11-20 years for plantations). Closed sapling-pole trees 3-30 m tall; Canopy cover ≥ 60%; Understory minimal; Stand age 40-79 years (21-79 years for plantations).
Open Mature/ Old-growth	Like Closed Mature/Old-growth, but canopy cover 30-59%.
Closed Mature/ Old-growth	Large, mature stands > 30 m tall; Stand age 80-200 years; DBH ≥ 53 cm; Canopy cover ≥ 60%. Old-growth stands have ≥ 20 trees/ha that are > 200 years; 60-80 m tall; 1-2 m DBH; Canopy cover ≥ 60%; Understory usually present; Coarse woody debris ≥ 37 tons/ha with ≥ 10 snags/ha.
After the Wildfire	
Early Seral/Rock	Grasses, forbes, shrubs, and/or *numerous snags*; Includes stands of any age in which fire killed ≥ 70% of the overstory, leaving < 30% canopy cover; Also includes rock outcrops and soil.
Sapling/Pole/Snags	Sapling-pole size trees and *many snags* present; Includes stands 25-80 years (11-80 years for plantations) in which fire killed < 70% of the overstory, leaving ≥ 30% canopy cover.
Open Mature/ Old-growth	Large, mature and old-growth stands (height > 30 m tall, DBH > 53 cm) and *many snags* present; Includes any stand > 80 years in which fire killed 41-70% of the overstory, leaving 30-59% canopy cover.
Closed Mature/ Old-growth	If fire burned these closed mature or old-growth stands, < 40% of the overstory was killed, but the understory was burned; Includes stands ≥ 80 years with canopy cover ≥ 60%.

DBH = diameter at breast height, 1.37 m.

The fractal dimension was a relative measure of edge complexity to patches (Goodchild 1980, Mandelbrot 1967); the simplest shapes approached one, and the most complex approached two. Landscape diversity was measured with two indices by Simpson (1949) for measuring species diversity in richness and evenness. In FRAGSTATS, Simpson's richness index measured the probability that two randomly chosen patches would be different types. The Simpson's evenness index measured the proportion of each patch type as compared to equal distribution among all patch types. The evenness index ranged from zero for no evenness, to one for perfect evenness in a landscape.

Characteristics of habitat for both edge and interior wildlife were derived using measures significant to the northern spotted owl in FRAGSTATS. Chen *et al.* (1992, 1993) reported edge effects between early and late seral stands of Douglas-fir forests extending well beyond 100 m. Johnson *et al.* (1991), however, found that the northern spotted owl preferred interior habitat beyond 90 m from an edge. Therefore, the core area for closed mature/old-growth successional stage was defined as that interior area greater than 100 m from the edge. The search radius for nearest neighbor calculations was 1930 m. Steele (1993) used this radius to approximate the home range for the northern spotted owl on the Oakridge Ranger District.

Results

Image Classification

The best simple linear regressions on LCR used the post-fire band transformations (Table 3.2). The post-burn SI was best, with a highly significant coefficient of determination for LCR ($P < 0.00001$, $r^2 = 0.716$). The post-burn SI was followed by the post-fire 7/4, NDVI, and TC wetness in accounting for variation in LCR.

Table 3.2. Regressions on live canopy ratio and post-burn canopy cover across the Warner Creek Burn (n = 169).

Regressions on Live Canopy Ratio (%)	**p-value**	**R^2**
$0.8786*(SI_{POST}) - 47.244$	<0.0001	0.716
$-.7034*(7/4_{POST}) + 107.678$	<0.0001	0.678
$1.2453*(NDVI_{POST}) - 194.099$	<0.0001	0.655
$1.2478*(\text{TC wetness}_{POST}) - 1.109$	<0.0001	0.649
$0.8632*(SI_{POST}) + 0.2124*(SI_{PRE}) - 79.327$	<0.0001	0.719
$0.8664*(SI_{POST}) + 0.2988*(\text{TC wetness}_{PRE}) - 76.274$	<0.0001	0.724
$0.8551*(SI_{POST}) - 0.0098*(\text{Elevation}) - 31.929$	<0.0001	0.716
$0.8758*(SI_{POST}) + 0.0465*(\text{Stand Age}) - 55.170$	<0.0001	0.723
$0.6248*(SI_{POST}) + 0.4332*(\text{TC wetness}_{POST}) - 37.203$	<0.0001	0.732
$0.8336*(SI_{SUBT}) - 0.5677*(\text{TC brightness}_{SUBT}) + 1.0175*(\text{TC wetness}_{PRE}) - 50.429$	<0.0001	0.748
$-0.4904*(7/4_{STDF}) + 1.4453*(NDVI_{STDF}) - 1.4464*(\text{TC brightness}_{STDF}) + 0.9698*(\text{TC wetness}_{PRE}) + 49.204$	<0.0001	0.753
$-0.3910*(7/4_{RATIO}) + 1.2524*(NDVI_{RATIO}) - 1.1862*(\text{TC brightness}_{RATIO}) + 0.9562*(\text{TC wetness}_{PRE}) + 29.639$	<0.0001	0.754
Regression on Post-burn Canopy Cover (%)		
$-0.4184(3/7_{RATIO}) + 0.5382*(SI_{RATIO}) - 0.4127*(7/4_{RATIO}) - 0.7112*(\text{TC brightness}_{RATIO}) + 0.9761*(\text{TC wetness}_{PRE}) + 90.792$	<0.0001	0.785

n = sample size
SI = structural index
TC = tasseled cap transformation for Landsat Thematic Mapper
POST = post-burn date for imagery
PRE = pre-burn date for imagery
SUBT = difference algorithm by subtraction
STDF = difference algorthim by standardized difference
RATIO = difference algorithm by ratio

The difference images also produced significant regressions on forest survival, but coefficients of determination were much lower (Table 3.3) than for the post-burn band transformations. Moreover, the results among the three algorithms used for calculating the difference images were very similar. Ancillary data on stand age or elevation significantly improved many regressions of post-burn band transformations (Table 3.2) or difference algorithms on LCR. The R^2,

Table 3.3. Coefficients of determination for regressions on live canopy ratio for each difference image and algorithm ($n = 169$, $P < 0.00001$ for each regression model).

Difference Image	r^2 Subtraction Algorithm	r^2 Ratio Algorithm	r^2 Standardized Difference Algorithm
3/7	0.503	0.505	0.503
4/5 (SI)	0.586	0.586	0.582
7/4	0.587	0.553	0.560
4/2	0.467	0.472	0.475
NDVI	0.514	0.527	0.527
5/2	0.465	0.433	0.432
TC wetness only	0.520	0.481	0.456
TC brightness, greenness, & wetness	0.567	0.608	0.594

n = sample size
SI = structural index
TC = tasseled cap transformation for thematic mapper
NDVI = normalized difference vegetation index

however, increased only slightly over respective models without the ancillary data.

Including spectral data on pre-fire cover, such as pre-burn SI or TC wetness, with difference bands improved the coefficients of multiple determination on LCR ($P < 0.0001$, $R^2 = 0.521$-0.725) than without such data. In addition, including pre-burn SI or TC wetness with post-burn band transformations slightly improved regressions on LCR (Table 3.2).

Two regression models were chosen to classify for LCR and compared to the USFS survival map (Figure 3.1). Based on simplicity and ease of application, the first model was the best simple linear regression of LCR on post-burn SI (Figure 3.2). The second model was the best multiple linear regression of LCR on the difference images for 7/4, NDVI, TC brightness in the ratio algorithm, and pre-fire TC wetness (Figure 3.3). Several of the band transformations were highly correlated (Appendices 3.2-5). Nevertheless, the stepwise procedure used the forward selection method, so variables were included only if they explained a significant portion of the variation (Ganio 1995, per. comm.; Neter *et al.* 1989). Furthermore, the Durbin-Watson test did not indicate significant autocorrelation in any of the multiple regression models.

The classified maps of LCR (Figures 3.2&3) appeared considerably different from the USFS map of LCR (Figure 3.1). The extent of partially killed stands (40-89% LCR) was much greater on both of the classified maps than on the USFS map, primarily at the expense of the underburned stands (≥90% LCR). In addition, the underburned stands were more fragmented on the classified survival maps than on the USFS map. Although, the extent and pattern of completely killed (0-39% LCR) stands were similar, fire fighters successfully protected two plantations in the northeastern quadrant (Phenix 1996, Figure 3.1), which appeared killed in the TM classified maps (Figures 3.2&3).

Error matrices (Lillesand and Kiefer 1994, Story and Congalton 1986) were calculated for the USFS survival maps and classified survival maps (Tables 3.4-6). Overall accuracy improved from the USFS map of LCR (56%), to the post-burn SI map of LCR (63%), and finally the classified difference map of LCR (68%). The Kappa coefficient was significantly better than zero for each map of LCR (Table 3.7). In addition, the classified difference map was substantially better than the USFS survival map, by 12% ($P = 0.1727$). Both classified survival maps were much better at predicting partially killed stands; both had higher producer's and user's accuracy than the USFS map for that class. Both classified survival maps were also better in predicting underburned stands than the USFS map.

However, when the youngest plantations were removed from the data set, regression models improved their performance in predicting LCR (Table 3.8). In addition, the overall accuracy of classification improved to 68% for post-burn SI (Appendix 3.6), and to 70% for the ratio difference imagery with stratification by pre-burn TC wetness (Appendix 3.7).

Figure 3.2. Classified post-burn Structural Index map (Table 3.2) for the Warner Creek Burn in three survival classes at 1:63,360.

Class	Extent (ha)	%
Meadow/Rock	331	9.0
LCR < 40%	1400	38.2
LCR 40-89%	1379	37.6
LCR > 89%	559	15.2

LCR = live canopy ratio

CLASSIFIED POST-BURN STRUCTURAL INDEX SURVIVAL MAP

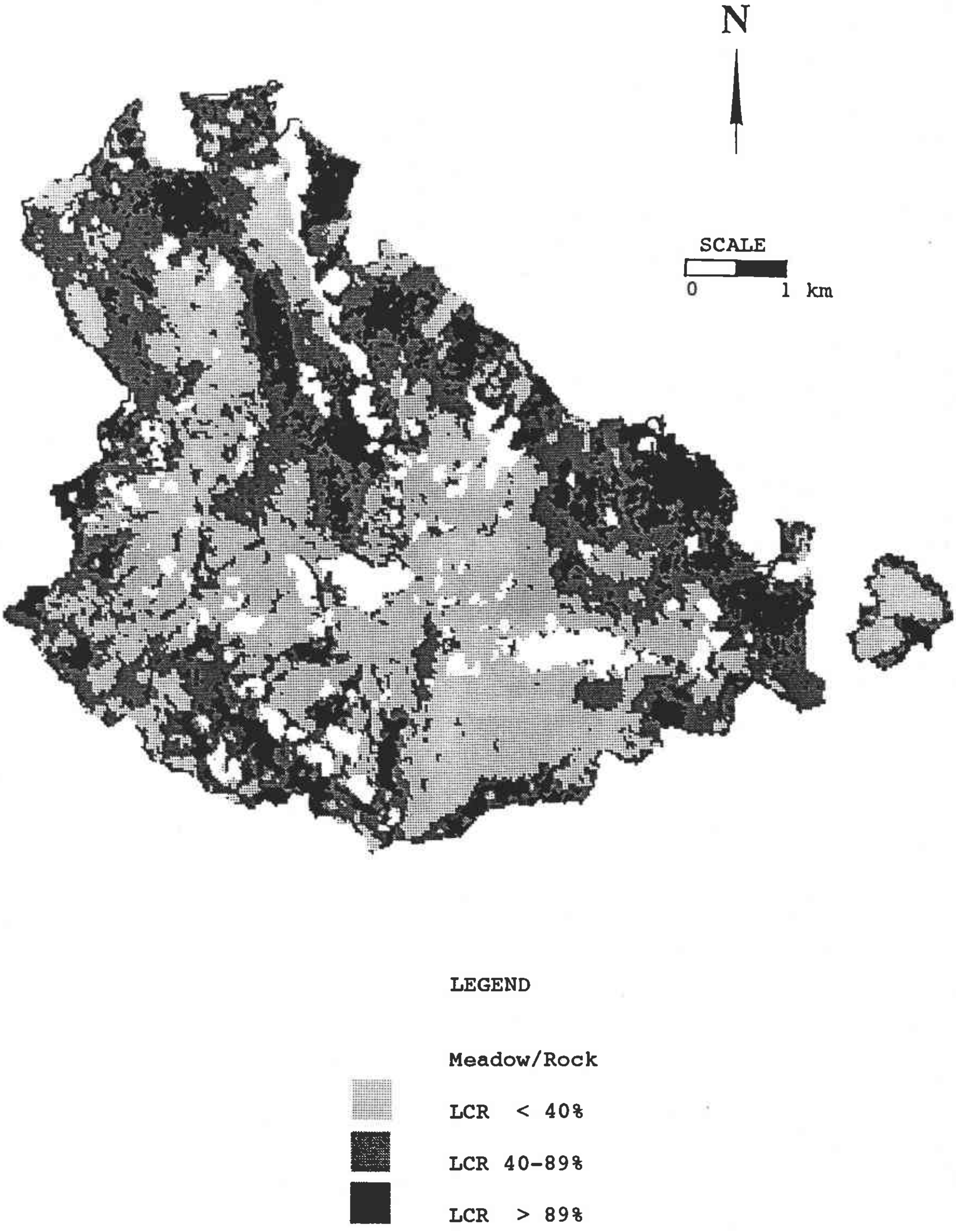


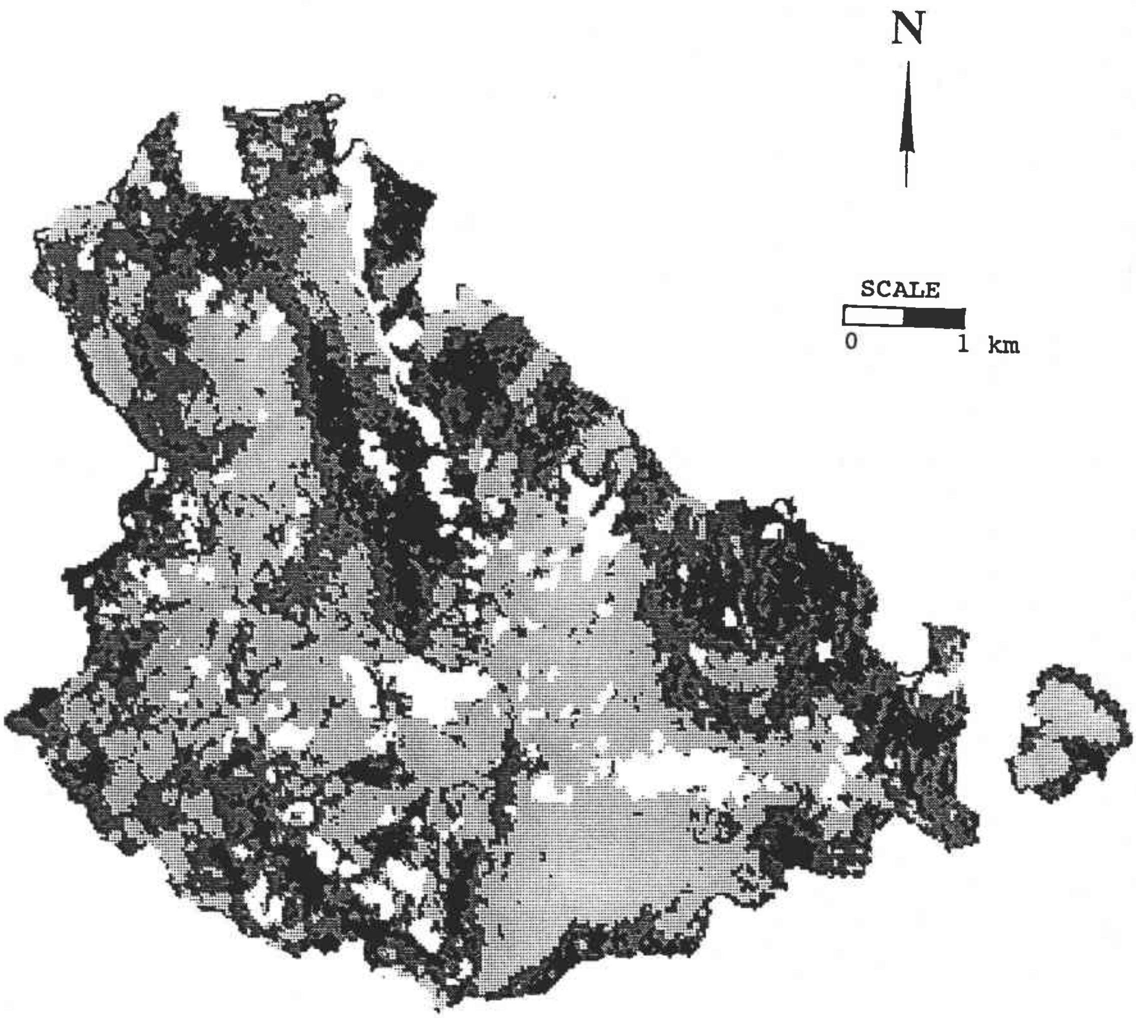
Figure 3.2:

Figure 3.3. Classified map for the Warner Creek Burn from Landsat TM ratio difference imagery with pre-burn tasseled cap wetness (Table 3.2) in three survival classes at 1:63,360.

Class	Extent (ha)	%
Meadow/Rock	331	9.0
LCR < 40%	1402	38.2
LCR 40-89%	1344	36.7
LCR > 89%	592	16.1

LCR = live canopy ratio

CLASSIFIED DIFFERENCE SURVIVAL MAP



LEGEND

Meadow/Rock

LCR < 40%

LCR 40-89%

LCR > 89%

Figure 3.3:

Table 3.4. Classification error matrix for USDA Forest Service (1993) survival map, based on live canopy ratio.

Classification Data	Reference Plots			Row Total
	0-39% LCR	40-89% LCR	≥ 90% LCR	
0-39% LCR	13	4	1	18
40-89% LCR	4	6	5	15
≥ 90% LCR	2	9	13	24
Column Total	19	19	19	57

Map Category	Producer's Accuracy (%)	Omission Error (%)	User's Accuracy (%)	Commission Error (%)
0-39% LCR	13/19 = 68	32	13/18 = 72	28
40-89% LCR	6/19 = 32	68	6/15 = 40	60
≥ 90% LCR	13/19 = 68	32	13/24 = 54	46
Overall Accuracy = (13+6+13)/57 = 56%				

LCR = live canopy ratio

Table 3.5. Classification error matrix for survival map, based on live canopy ratio, from the post-burn SI classification (Table 3.2).

Classification Data	Reference Plots			Row Total
	0-39% LCR	40-89% LCR	≥ 90% LCR	
0-39% LCR	13	2	0	15
40-89% LCR	6	14	10	30
≥ 90% LCR	0	3	9	12
Column Total	19	19	19	57

Map Category	Producer's Accuracy (%)	Omission Error (%)	User's Accuracy (%)	Commission Error (%)
0-39% LCR	13/19 = 68	32	13/15 = 87	13
40-89% LCR	14/19 = 74	26	14/30 = 47	53
≥ 90% LCR	9/19 = 47	53	9/12 = 75	25
Overall Accuracy = (13+14+9)/57 = 63%				

LCR = live canopy ratio

Table 3.6. Classification error matrix for survival map, based on live canopy ratio, from the classification of the ratio difference imagery with pre-burn TC wetness stratification (Table 3.2).

Classification Data	Reference Plots			Row Total
	0-39% LCR	40-89% LCR	≥ 90% LCR	
0-39% LCR	14	3	0	17
40-89% LCR	5	13	7	25
≥ 90% LCR	0	3	12	15
Column Total	19	19	19	57

Map Category	Producer's Accuracy (%)	Omission Error (%)	User's Accuracy (%)	Commission Error (%)
0-39% LCR	14/19 = 74	26	14/17 = 82	18
40-89% LCR	13/19 = 68	32	13/25 = 52	48
≥ 90% LCR	12/19 = 63	37	12/15 = 80	20
Overall Accuracy = (14+13+12)/57 = 68%				

LCR = live canopy ratio

Table 3.7. Kappa statistics for classification error matrices and tests for significance (Congalton *et al.* 1983, Titus *et al.* 1984).

Classification Error Matix	Kappa Coefficient	Z Test Statistic	p-value
A. USFS Survival Map	0.342	3.653	0.00026
B. Classified Survival Map from Post-burn SI	0.447	4.777	<0.00001
C. Classified Survival Map from Difference Imagery	0.526	5.620	<0.00001

Pairwise Comparisons of Error Matrices	Z Test Statistic	p-value
Difference between A and B	0.76558	0.4439
Difference between B and C	0.59318	0.5531
Difference between A and C	1.36365	0.1727

SI = structural index of Landsat TM
Difference imagery from best fit ratio algorithm with pre-burn tasseled cap wetness (Table 3.2)

Table 3.8. Regressions of live canopy ratio (%) on band transformations, without young plantations (≤ 10 years), across the Warner Creek Burn (n = 162).

Regressions on Live Canopy Ratio (%)	p-value	r^2
$0.8777*(SI_{POST}) - 45.971$	<0.0001	0.755
$-.7029*(7/4_{POST}) + 108.944$	<0.0001	0.716
$1.2567*(NDVI_{POST}) - 194.879$	<0.0001	0.705
$1.2858*(TC\ wetness_{POST}) - 3.409$	<0.0001	0.659
$0.8326*(SI_{SUBT}) - 0.4870*(TC\ brightness_{SUBT}) + 0.7865*(SI_{PRE}) - 81.527$	<0.0001	0.775
$-0.5845*(3/7_{RATIO}) + 0.8996*(SI_{RATIO}) - 0.4380*(SI_{RATIO}) - 1.0577*(TC\ brightness_{RATIO}) + 0.9333*(TC\ wetness_{PRE}) + 142.153$	<0.0001	0.782
$-0.6721*(3/7_{STDF}) + 0.6801*(SI_{STDF}) - 0.7052*(7/4_{STDF}) - 1.2607*(TC\ brightness_{STDF}) - 1.0513*(7/4_{PRE}) + 370.900$	<0.0001	0.783

n = sample size
SI = structural index
TC = tasseled cap transformation for Landsat Thematic Mapper
POST = post-burn date for imagery
PRE = pre-burn date for imagery
SUBT = difference algorithm by subtraction
STDF = difference algorthim by standardized difference
RATIO = difference algorithm by ratio

Landscape Patterns and Change Analysis

The wildfire increased the amount of coarse woody debris across the burn area in the forms of fallen, killed trees and standing snags. This condition was described in the successional stage classes (Table 3.1), and was most notable in those areas where fire completely or partially killed the stands. Although completely killed stands were considerably different from meadows and clearcuts due to snags, these stands were changed to the earliest seral stage.

Of the four successional stage classes, only the open mature/ old-growth class was created solely as a consequence of the wildfire (Figures 3.4-6). Early seral/rock (ESR) increased after the burn from 14% of the landscape, to 46% on the USFS map, or 54% on the classified map (Table 3.9). Conversely, closed mature/old-growth (CMOG) declined from 77% of the landscape before the burn to about 32% after the burn on the USFS map, or 23% on the classified map.

Figure 3.4. Pre-fire successional stage map from a US Forest Service timber type map for the Warner Creek Burn, at 1:63,360.

Sucessional Stage	**Extent (ha)**	**%**
Early Seral/Rock	522	14.2
Sapling/Pole	312	8.5
Open Mature/Old-growth	0	0
Closed Mature/Old-growth	2835	77.3

US FOREST SERVICE PRE-BURN SUCCESSIONAL STAGES

LEGEND

Early Seral/Rock

Sapling/Pole

Open Mature/Old-growth

Closed Mature/Old-growth

Figure 3.4:

Figure 3.5. Post-fire successional stage map for the Warner Creek Burn from an overlay of the US Forest Service survival and timber type maps, at 1:63,360.

Sucessional Stage	Extent (ha)	%
Early Seral/Rock	1697	46.2
Sapling/Pole/Snags	128	3.5
Open Mature/Old-growth	660	18.0
Closed Mature/Old-growth	1184	32.3

US FOREST SERVICE POST-BURN SUCCESSIONAL STAGES

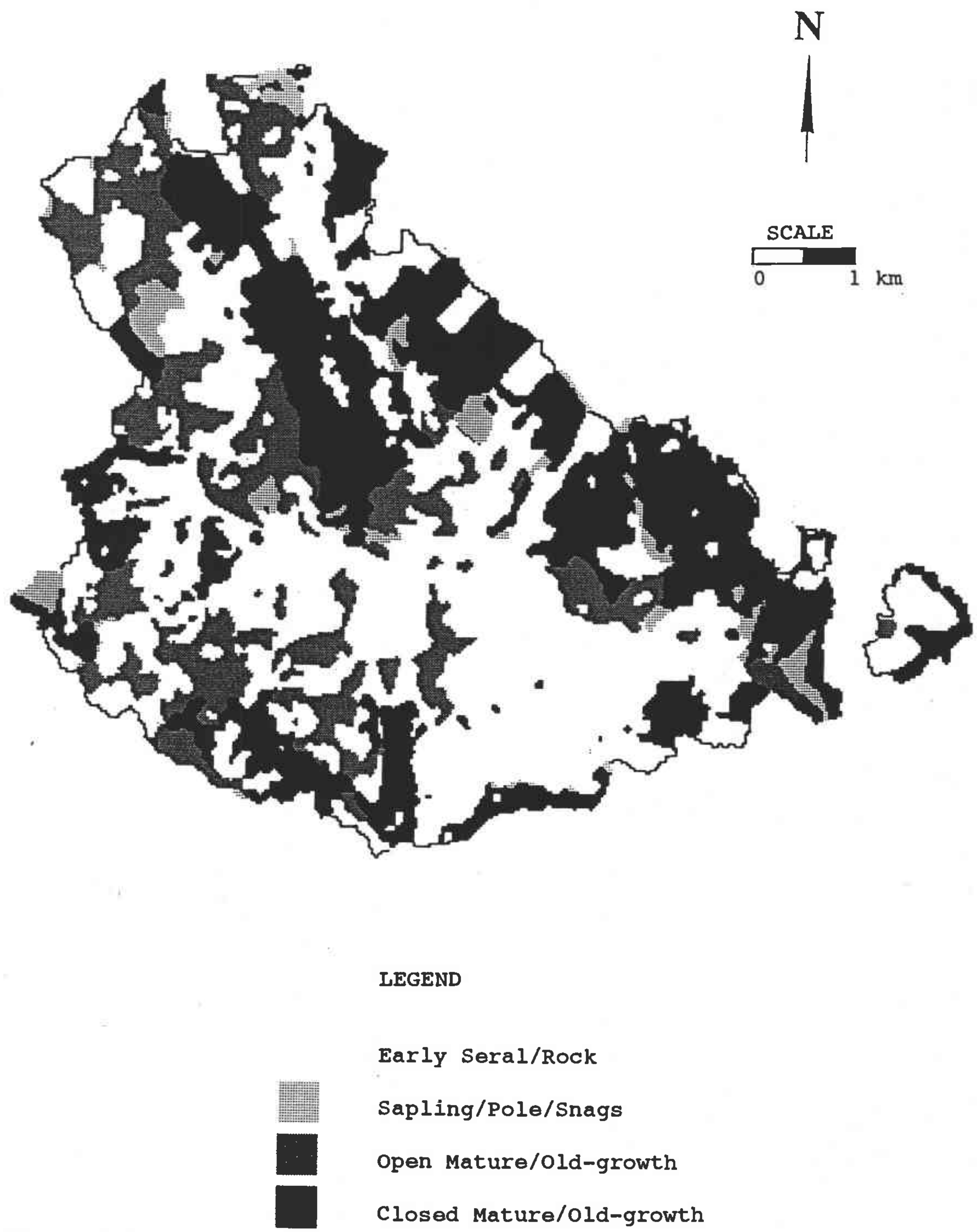


Figure 3.5:

Figure 3.6. Post-fire successional stage map for the Warner Creek Burn from an overlay of the classified difference map on canopy cover (Table 3.2) and pre-burn successional stages, at 1:63,360.

Sucessional Stage	Extent (ha)	%
Early Seral/Rock	1995	54.4
Sapling/Pole/Snags	141	3.8
Open Mature/Old-growth	704	19.2
Closed Mature/Old-growth	829	22.6

CLASSIFIED DIFFERENCE SUCCESSIONAL STAGE MAP

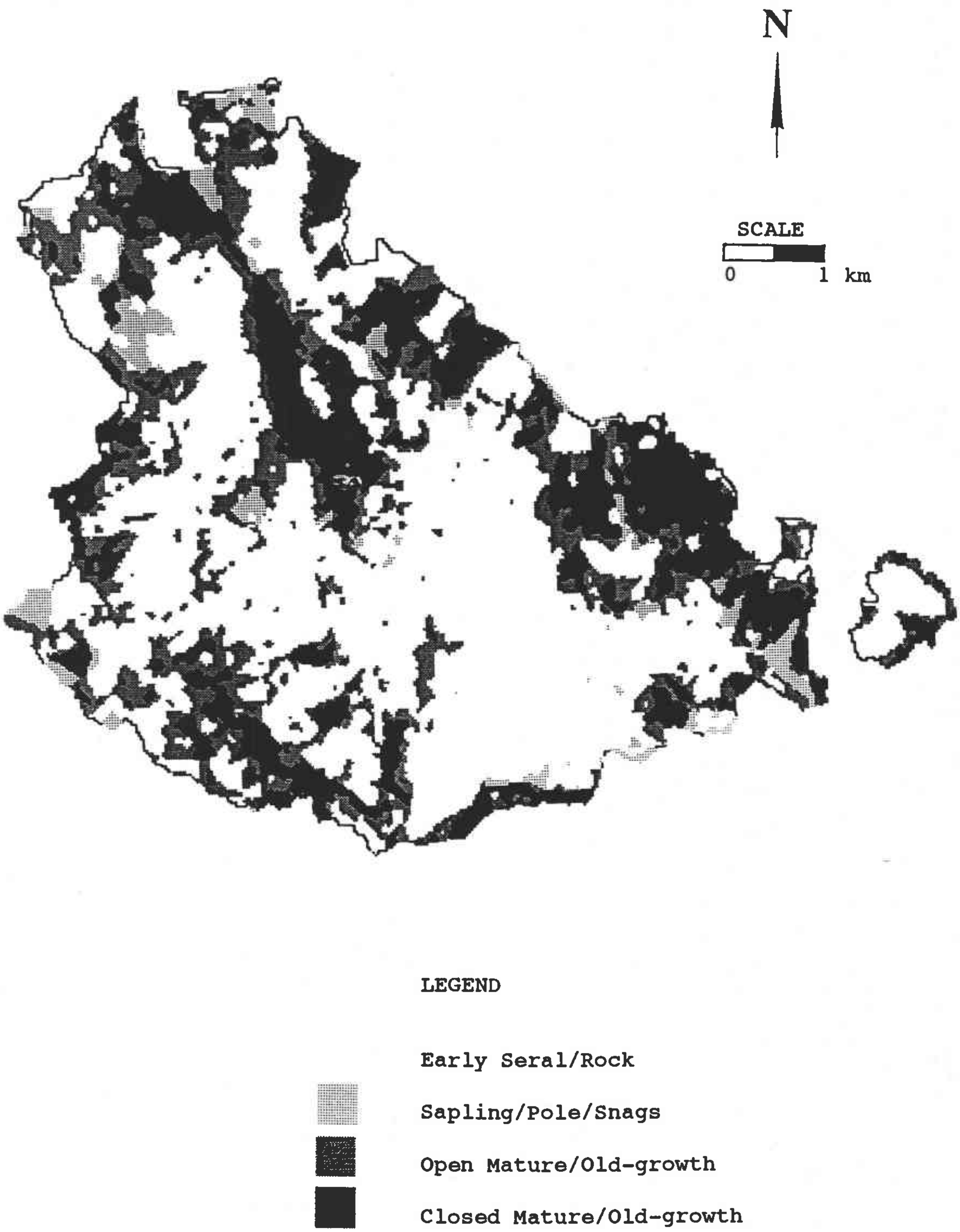


Figure 3.6:

Table 3.9. Landscape characteristics before and after the Warner Creek Burn using FRAGSTATS (McGarigal and Marks 1995).

Landscape Composition and Indices	Successional Stage Map		
	Pre-burn USFS Map	Post-burn USFS Map	Classified Map*
Early Seral/Rock (%)	14.2	46.3	54.4
Sapling/Pole/(Snags) (%)	8.5	3.5	3.8
Open Mature/Old-growth (%)	0	18.0	19.2
Closed Mature/Old-growth (%)	77.3	32.3	22.6
Edge Density (m/ha)	61.2	72.7	99.6
Simpson's Diversity Index	0.376	0.648	0.615
Simpson's Evenness Index	0.563	0.864	0.820

*Classified map from overlay of difference imagery on post-burn canopy cover (Table 3.2) with pre-burn successional stages.

Furthermore, the edge density increased across the landscape after the wildfire. In addition, the overall landscape diversity increased after the burn: Simpson's diversity index increased from 0.376 to about 0.6, and Simpson's evenness index from 0.563 to about 0.8.

Structure and pattern for ESR and CMOG were also examined (Table 3.10). Area for ESR increased dramatically after the burn. While the number of ESR patches declined after the burn, the average patch area increased. The heterogeneity of ESR patch size was enhanced by the fire as well. Also, the amount of ESR edge increased after the fire. Finally, ESR patch shape increased in complexity after the burn, as shown by a higher area weighted mean patch fractal.

The wildfire reduced the area of CMOG, increased the number of CMOG patches, and decreased their size. However, the patch size standard deviation decreased after the burn, as did the amount of edge. In addition, the wildfire simplified CMOG patch shape as shown by a lower area weighted mean patch fractal. Finally, the mean nearest neighbor distance between CMOG patches increased after the burn, as did the mean nearest neighbor standard deviation.

Table 3.10. Structure and pattern of early and late successional stages, before and after the Warner Creek Burn using FRAGSTATS (McGarigal and Marks 1995).

Class Indices	Successional Stage Map		
	Pre-burn USFS Map	Post-burn USFS Map	Classified Map*
Analysis on Early Seral/Rock			
Class Area (ha)	522	1697	1995
Number of Patches	151	70	95
Mean Patch Size (ha)	3.5	24.2	21.0
Patch Size Standard Deviation (ha)	7.9	146.7	157.9
Edge Density (m/ha)	37.8	53.0	55.3
Area Weighted Mean Patch Fractal	1.101	1.211	1.212
Analysis on Closed Mature/Old-growth			
Class Area (ha)	2835	1184	829
Number of Patches	16	40	120
Mean Patch Size (ha)	177.2	29.6	6.9
Patch Size Standard Deviation (ha)	661.8	70.2	26.9
Edge Density (m/ha)	53.7	38.8	44.3
Area Weighted Mean Patch Fractal	1.249	1.161	1.167
Mean Nearest Neighbor Distance** (m)	40.5	148.2	89.3
Nearest Neighbor Standard Deviation (m)	20.8	124.2	112.3
Total Core Area	1554	451	167
Number of Core Areas	21	24	26
Mean Core Area per Patch (ha)	97.1	11.3	1.4

*Classified map from overlay of difference imagery on post-burn canopy cover (Table 3.2) with pre-burn successional stages.
**FRAGSTATS calculated nearest neighbor distances from boundary cell midpoints, with cell dimensions of 25m x 25m.

Of greater significance than total area of CMOG was the impact of the burn on core area. Trends for core area of CMOG followed those for total area before and after the fire. The amount of core area decreased dramatically after the burn, as did mean core area per patch. Likewise, the number of core areas increased after the burn.

Finally, there were notable differences in most landscape and class indices between the post-burn USFS map and the classified map. The classified map showed greater detail in successional stages, which was reflected in calculations for landscape and class indices.

Discussion

Image Classification

The success of post-burn SI in predicting LCR on the Warner Creek Burn was consistent with previous work. Fiorella and Ripple (1993a) found that the SI was not affected by topography and was very useful in discriminating successional stages, particularly in delineating mature from old-growth forests. The TC wetness, however, was found insensitive to topography and closely related to stand structural attributes as well (Cohen and Spies 1992). Nevertheless, post-burn SI had a stronger linear relationship to LCR than post-burn TC wetness, and was simpler to calculate than TC wetness; the TC transformation required radiometric scaling to an 8-bit quantized range.

The post-burn band transformations (Table 3.2) were superior to difference images (Table 3.3) in delineating LCR with simple linear regression. Singh (1986) found that single date band regression was better at detecting forest cover changes than difference images, but the improvement was only slight. In addition, the similar results of algorithms for calculating difference images also corroborated the findings of Singh (1986).

It was surprising that single post-burn band transformations (SI, 7/4, NDVI TC wetness) predicted forest survival much better than any single difference image. For instance, Cablk *et al.* (1994) used the 7/4 difference image to predict forest damage with a coefficient of determination of 0.888 (n = 30). Perhaps misregistration errors in the rugged terrain were still too high despite the low RMSE for image registration (Townshend *et al.* 1992).

Inclusion of ancillary data, such as stand age or elevation, slightly improved the performance of regressions on forest survival. Congalton *et al.* (1993) successfully integrated ancillary GIS data with digital image processing to map old-growth forest cover in the Pacific Northwest.

Inclusion of pre-fire spectral transformations with the difference images and the post-burn band transformations, however, improved the R^2 of regressions substantially. Franklin *et al.* (1995) had similar results in detecting the forest mortality from western spruce budworm (*Choristoneura occidentalis*); including pre-infestation TC wetness in regression analyses aided stratification of the vegetation and improved change detection of forest mortality than without pre-infestation TC wetness.

Multiple linear regressions of difference transformations with pre-fire spectral transformations were best for determining forest survival. However, correlated band transformations were often included in the models. For instance, the best regression on LCR included the ratio difference in the terms of 7/4 and NDVI transformations (Appendix 3.4). Therefore, interpreting the contribution of individual band transformations on forest survival was difficult due to multicollinearity (Neter *et al.* 1989).

Nevertheless, Coppin and Bauer (1994) used redundant difference band transformations to detect land cover change, noting that no single difference transformation was sensitive to all land cover changes. Stenback and Congalton (1990) also used redundant Landsat TM band combinations in their attempt to classify understory characteristics.

Only three categories of LCR were chosen to enhance overall accuracy (Cohen *et al.* 1995). The overall accuracies of the classified survival maps were 63% from post-burn SI (Table 3.5), and 68% from ratio difference bands with pre-burn TC wetness (Table 3.6). These accuracies were comparable to that for Franklin and Raske (1994) for classifying spruce budworm (*Choristoneura fumiferana*) defoliation with an overall accuracy of 66%. Furthermore, the classified difference survival map provided a 12% improvement in accuracy over the USFS photo interpreted map.

Both classified survival maps markedly improved discrimination at all levels of forest survival, from a comparison of user's accuracy (Tables 3.4-6). The digital imagery distinguished intra-canopy variation better than the USFS photo interpreted map. The classified survival maps had a smaller mapping unit than the USFS map; the TM imagery had a minimum mapping unit of 0.06 ha (1 pixel), whereas the photo interpreted map had a minimum mapping unit of 1.2 ha (Bailey 1993).

The most frequent error for the classified survival maps occurred in the partially burned class (40-89% LCR). This class had a great deal of spectral variation, but fewer samples than the other forest survival classes.

Both classified survival maps also tended to classify all young plantations, even those that had not burned, as having low survival (0-39% LCR). In my data, pre-burn and post-burn SI also had low values in young plantations, regardless of their LCR values. Fiorella and Ripple (1993b) noted that SI was low at young ages and increased with stand age up to stand closure, then decreased with stand age from mature to old-growth. Even stratification of difference band transformations with pre-burn TC wetness did not correct the problem; pre-burn TC wetness followed a similar trend to stand age as SI.

Repeating the regression analyses without the youngest plantations improved the coefficients of determination (Table 3.8); the young plantations with low reflectance and high LCR appeared as outliers. In addition, classification accuracy for the prediction of

LCR on post-burn SI improved to match that of the more complex difference imagery with pre-burn stratification by TC wetness (Appendix 3.6). Classification accuracy using the more complex difference imagery with pre-burn stratification also improved without the youngest plantations (Appendix 3.7), but not as much as for the post-burn SI.

Although removing the youngest plantations improved the classification, their removal did not correct the underlying limitation. Both regression models still predicted young plantations as having low LCR, even if not. Fiorella and Ripple (1993b) noted that using the SI to evaluate plantation health was not reliable below stand age fifteen.

Improvements to the techniques I used here might include more extensive fieldwork to establish training sites on specific survival classes, much as did Cablk *et al.* (1994) to evaluate survival after hurricane Hugo, or Cohen *et al.* (1995) to map forest age classes. Using a maximum likelihood or similar classifier might better separate forest survival classes than using regression on LCR by exploiting the full multispectral nature of the imagery. Further stratification of the age classes in modeling, or increasing the number of samples for younger age classes, might improve overall accuracy, especially since post-burn SI reflectance varied with stand age.

Landscape Patterns and Change Analysis

The wildfire wrought dramatic changes in landscape patterns of successional stages (Table 3.9). The early seral/rock stage expanded greatly, primarily at the expense of closed mature/old-growth. Also, the fire created a new successional stage, the open mature/old-growth (OMOG), comprising 18-19% of the burned area. The creation of OMOG most likely enhanced the diversity of the landscape, as reflected in the higher Simpsons's Diversity Indices after the burn.

Furthermore, the fire dispersed the remaining CMOG stands into many more patches, with less interior habitat and more edge exposed to openings, exemplifying fragmentation (Li *et al.* 1993). Fragmenting the CMOG probably enhanced overall landscape evenness, as reflected in the higher Simpson's Evenness Indices after the burn. Meanwhile, the wildfire effects of expanding ESR, fragmenting CMOG, and creating OMOG stands increased the amount of edge across the landscape.

Core area more than 100 m from an edge decreased threefold or more after the burn (Table 3.10). Franklin and Forman (1987) predicted that no core area would remain after 50% of forest was removed with the checkerboard pattern of harvesting. At Warner Creek, some core area remained after the wildfire, despite a reduction of over 50% in CMOG area. One explanation was the differences in the definition of edge effects. Franklin and Forman (1987) defined edge effects to 160 m, but core area remained even when increasing the edge to 150 m. Another explanation for the discrepancy was the fact that the wildfire did not burn a large portion of the Kelsey Creek basin, which was primarily CMOG. Consequently, wildfire effects resembled that of harvesting with the maintenance of a forest reserve, as simulated by (Li *et al.* 1993).

Landscape structural variables have been shown as weakly related to wildlife species richness and abundance in the Pacific Northwest (Lehmkuhl *et al.* 1991, McGarigal and McComb 1995). The short-term effects of the wildfire enhanced the spatial diversity of habitats, as indicated by the diversity indices. In addition, the large amount of coarse woody debris and snags from the fire would have created a substantial amount of habitat diversity (Hunter 1990). The increased amount of ESR and edge density would have favored edge species (Witmer *et al.* 1985), such as black-tailed deer (*Odocoileus hemionus columbianus*) and Roosevelt elk (*Cervus elaphus roosevelti*). However, the diminished CMOG and its core area would have negatively affected interior species, such as the northern spotted owl and others

(Lehmkuhl and Ruggiero 1991). Indeed, one pair of spotted owls within the burn was known to have left by 1992 (USDA Forest Service 1993).

The variations between the two post-burn successional stage maps primarily reflected a difference in mapping scale between digital imagery and aerial photo interpretation, as discussed earlier. Indeed, Gustafson and Parker (1992) predicted similar trends in landscape structure between different grain sizes, or scales, as seen in landscape patterns between these two maps. They found that randomized pixels had a lower mean patch area and nearest neighbor distance, and higher fractal dimension and number of patches, than randomized clumps.

Thus, the classified Landsat map showed greater fragmentation in the CMOG successional stage than in the USFS successional stage map. These results were consistent with the pixel based classification of digital imagery.

Management Implications

Using TM data would enable foresters to assess the effects of larger wildfires more quickly and cheaply than interpretation of aerial photography. Although a single TM scene may cost $4000 (Roughgarden *et al.* 1991), its coverage would be equivalent to 5000 low-altitude aerial photographs (Jensen 1996). In addition, a single date classification of forest survival using TM data transformed to the post-burn SI ratio would be relatively simple, accurate, more detailed, and less subjective than aerial photo interpretation.

On the other hand, the technique of using difference imagery with stratification of vegetation by initial TC wetness, is also useful for change detection. Such a technique would enhance natural resource managers' abilities to monitor landscape changes for long-term environmental evaluations. For instance, monitoring would be useful to implementing ecosystem management (Forest Ecosystem Management Assessment Team 1993, Kaufmann *et al.* 1994, Slocombe 1993) on public lands, or in applying the Sustainable Forestry Initiative (Wallinger 1995) to private lands.

Meanwhile, the fire enhanced the structural diversity of patches across the landscape in several ways. First, Agee and Huff (1987) found that fuel loadings in natural stands followed a somewhat U-shaped curve over time. Thus, young natural stands would have had more residual coarse woody material than young plantations, where harvesting and prescribed burning would have removed much debris (Little 1990, Spies and Franklin 1988, Walstad and Seidel 1990). Second, the wildfire created many partially timbered stands and numerous snags, the OMOG class. Third, clearings after the burn were much more variable in size and more complex in shape than staggered setting clearcuts on portions of managed public forests (Ripple *et al.* 1991a). Across large landscapes of public ownership, however, landscape patterns were more variable than the checkerboard model due to reserves in wilderness and research natural areas (Spies *et al.* 1994). Nevertheless, future forest management on public lands still needs to incorporate more structural variability in managed landscapes in order to more closely approximate the natural variability of landscape structure.

Conclusions

The post-burn SI, and difference images from TM data when stratified with pre-fire TC wetness, were substantially better at classifying LCR than aerial photo interpretation as applied to the Warner Creek Burn. In addition, removing samples for the youngest plantations improved regression coefficients of determination and classification accuracy.

The algorithm used to calculate difference images, and inclusion of ancillary data, had little effect on model performance.

The wildfire expanded the early seral/rock stage greatly, and created the open mature/old-growth stage. However, the wildfire drastically reduced and fragmented the closed mature/old-growth stage. Overall, the fire enhanced landscape diversity and increased edge.

Moreover, analysis of landscape patterns after the fire suggested there was much greater spatial variability in fire-created clearings than in forest cutting patterns previously employed on public lands.

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CHAPTER 4

CONCLUSIONS

Topographic and vegetation variables were significantly related to the LCR following the Warner Creek Burn. Terrain and vegetation variables accounted for more variation in LCR within individual physiographic areas, than across the entire site. In addition, the most prominent terrain variable for explaining variation in LCR was specific for each physiographic area.

The relationships of terrain variables to explain variation in historical MFRI at the Upper McKenzie site paralleled the findings at Warner Creek. Terrain variables accounted for a fair amount of variation in historical MFRI across the entire site. Within individual physiographic areas, however, terrain variables explained a much greater proportion of the variation in historical MFRI than across the Upper McKenzie site.

Meanwhile, the Landsat TM post-burn SI and difference imagery when stratified with pre-fire TC wetness, were substantially better at classifying LCR than aerial photo interpretation as applied at the Warner Creek Burn. In addition, removing samples for the youngest plantations improved regression coefficients of determination and classification accuracy.

The algorithm used to calculate difference images, and inclusion of ancillary data, had little effect on regression model performance.

The wildfire expanded the early seral/rock stage greatly, and created the open mature/old-growth stage. However, the burn drastically reduced and fragmented the closed mature/old-growth stage. Overall, the fire enhanced landscape diversity and increased edge.

Moreover, analysis of landscape patterns after the burn suggested there was much greater spatial variability in clearings created by the fire than in forest cutting patterns used on public lands.

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APPENDICES

Appendix 2.1. Correlation matrix (%) of vegetation and terrain variables in the East Kelsey area (n = 23).

	Vegetation and Terrain Variables							
	Age	Elev	Slope	Asp NS	Asp EW	Surf Rn	Ridge	Stream
Age	100	6	-46*	-13	22	40	28	-33
Elev		100	37	-5	-7	-29	-48*	80****
Slope			100	26	-14	-87****	-54**	63**
Asp NS				100	26	-11	-1	5
Asp EW					100	14	56**	-31
Surf Rn						100	54**	-48*
Ridge							100	-76****
Stream								100

p-values: *≤0.05, **≤0.01, ***≤0.001, ****≤0.0001
n = sample size
AGE = stand age (years)
ELEV = elevation above sea level (m)
SLOPE = slope (degrees)
ASP NS = aspect transformation contrasting north and south
ASP EW = aspect transformation contrasting east and west
SURF RN = surface roughness
RIDGE = proximity to primary and secondary ridgelines (m)
STREAM = proximity to perennial steams (m)

Appendix 2.2. Correlation matrix (%) of vegetation and terrain variables in the West Kelsey area (n = 31).

	Vegetation and Terrain Variables							
	Age	Elev	Slope	Asp NS	Asp EW	Surf Rn	Ridge	Stream
Age	100	-60***	-26	-40*	-22	14	51**	-65****
Elev		100	15	3	-1	-4	-83****	77****
Slope			100	20	-7	-21	14	17
Asp NS				100	39*	-51**	6	16
Asp EW					100	-33	-4	4
Surf Rn						100	-12	-6
Ridge							100	-69****
Stream								100

p-values: *≤0.05, **≤0.01, ***≤0.001, ****≤0.0001
n = sample size
AGE = stand age (years)
ELEV = elevation above sea level (m)
SLOPE = slope (degrees)
ASP NS = aspect transformation contrasting north and south
ASP EW = aspect transformation contrasting east and west
SURF RN = surface roughness
RIDGE = proximity to primary and secondary ridgelines (m)
STREAM = proximity to perennial steams (m)

Appendix 2.3. Correlation matrix (%) of vegetation and terrain variables in the North Bunchgrass area (n = 71).

VEGETATION AND TERRAIN VARIABLES

	AGE	ELEV	SLOPE	ASP NS	ASP EW	SURF RN	RIDGE	STREAM
AGE	100	28*	28*	14	-12	-11	2	-13
ELEV		100	-1	-18	-29*	9	-66****	57****
SLOPE			100	-1	7	-39***	-6	-24*
ASP NS				100	26*	-7	14	-5
ASP EW					100	-8	3	-6
SURF RN						100	-9	19
RIDGE							100	-78****
STREAM								100

p-values: *≤0.05, **≤0.01, ***≤0.001, ****≤0.0001
n = sample size
AGE = stand age (years)
ELEV = elevation above sea level (m)
SLOPE = slope (degrees)
ASP NS = aspect transformation contrasting north and south
ASP EW = aspect transformation contrasting east and west
SURF RN = surface roughness
RIDGE = proximity to primary and secondary ridgelines (m)
STREAM = proximity to perennial steams (m)

Appendix 2.4. Correlation matrix (%) of vegetation and terrain variables in the South Bunchgrass area (n = 71).

VEGETATION AND TERRAIN VARIABLES

	AGE	ELEV	SLOPE	ASP NS	ASP EW	SURF RN	RIDGE	STREAM
Age	100	6	32**	-10	10	-1	-12	27*
Elev		100	36**	-6	12	-3	-94****	41***
Slope			100	-45****	-30*	-18	-50****	55****
Asp NS				100	61****	-11	11	-18
Asp EW					100	-9	-7	3
Surf Rn						100	-3	8
Ridge							100	-58****
Stream								100

p-values: *≤0.05, **≤0.01, ***≤0.001, ****≤0.0001
n = sample size
AGE = stand age (years)
ELEV = elevation above sea level (m)
SLOPE = slope (degrees)
ASP NS = aspect transformation contrasting north and south
ASP EW = aspect transformation contrasting east and west
SURF RN = surface roughness
RIDGE = proximity to primary and secondary ridgelines (m)
STREAM = proximity to perennial steams (m)

Appendix 2.5. Correlation matrix (%) of vegetation and terrain variables across the Warner Creek site (n = 196).

VEGETATION AND TERRAIN VARIABLES

	AGE	ELEV	SLOPE	ASP NS	ASP EW	SURF RN	RIDGE	STREAM
AGE	100	5	7	-12	-8	11	-4	-19**
ELEV		100	18*	-24***	9	-2	-80****	43****
SLOPE			100	-11	-5	-35****	-23**	16*
ASP NS				100	-27****	-5	22**	8
ASP EW					100	-16*	-3	7
SURF RN						100	-5	1
RIDGE							100	-44****
STREAM								100

p-values: *≤0.05, **≤0.01, ***≤0.001, ****≤0.0001
n = sample size
AGE = stand age (years)
ELEV = elevation above sea level (m)
SLOPE = slope (degrees)
ASP NS = aspect transformation contrasting north and south
ASP EW = aspect transformation contrasting east and west
SURF RN = surface roughness
RIDGE = proximity to primary and secondary ridgelines (m)
STREAM = proximity to perennial steams (m)

Appendix 2.6. Significant regressions of live canopy ratio (%) on vegetation and terrain variables across the entire Warner Creek Burn (n = 196).

Explanatory Variable	**Parameter Estimate**	**p-value**	**r^2**
Elevation (intercept)	-0.05690 (127.12)	<0.00001 (<0.00001)	0.108
Stream Proximity (intercept)	-0.04160 (76.01)	<0.00001 (<0.00001)	0.103
Ridgeline Proximity (intercept)	0.01694 (42.56)	0.00410 (<0.00001)	0.042
Stand Age (intercept)	0.09103 (37.47)	0.00658 (<0.00001)	0.037
Stand Types: True Fir True Fir/Mountain Hemlock (intercept)	 -42.0929 -19.8824 (59.88)	0.0001	0.082
Physiographic areas: North Bunchgrass East Kelsey West Kelsey (intercept)	 17.8732 27.2603 -0.3821 (45.48)	0.0064	0.047
Stepwise model: Stand Age Elevation Aspect Tr EW True Fir East Kelsey North Bunchgrass (intercept)	 0.0795 -0.0516 14.2219 -23.3749 31.9154 13.2143 (84.40)	<0.0001	0.244

n = sample size
Tr = transformation
EW = East-West
NS = North-South

Appendix 2.7. Correlation matrix (%) of terrain variables across the Blue River physiographic area (n = 45).

Terrain Variables	Elev	Slope	Asp NS	Asp EW	Surf Rn	Ridge	Stream
Elev	100	-24	-25	-19	-16	-82****	85****
Slope		100	10	-14	-29	30*	-8
Asp NS			100	22	-17	7	-19
Asp EW				100	20	20	-22
Surf Rn					100	25	-4
Ridge						100	-58****
Stream							100

p-values: *≤0.05, **≤0.01, ***≤0.001, ****≤0.0001
n = sample size
ELEV = elevation above sea level (m)
SLOPE = slope (degrees)
ASP NS = aspect transformation contrasting north and south
ASP EW = aspect transformation contrasting east and west
SURF RN = surface roughness
RIDGE = proximity to primary and secondary ridgelines (m)
STREAM = proximity to perennial steams (m)

Appendix 2.8. Correlation matrix (%) of terrain variables across the County Creek physiographic area (n = 71).

Terrain Variables	Elev	Slope	Asp NS	Asp EW	Surf Rn	Ridge	Stream
Elev	100	16	-23	-16	-13	-85****	89****
Slope		100	10	-26*	-26*	-37**	28*
Asp NS			100	32**	3	22	-18
Asp EW				100	16	32**	-7
Surf Rn					100	7	-21
Ridge						100	-78****
Stream							100

p-values: *≤0.05, **≤0.01, ***≤0.001, ****≤0.0001
n = sample size
ELEV = elevation above sea level (m)
SLOPE = slope (degrees)
ASP NS = aspect transformation contrasting north and south
ASP EW = aspect transformation contrasting east and west
SURF RN = surface roughness
RIDGE = proximity to primary and secondary ridgelines (m)
STREAM = proximity to perennial steams (m)

Appendix 2.9. Correlation matrix (%) of terrain variables across the North Lookout physiographic area (n = 75).

TERRAIN VARIABLES

	ELEV	SLOPE	ASP NS	ASP EW	SURF RN	RIDGE	STREAM
ELEV	100	3	7	-43****	-49****	-90****	84****
SLOPE		100	-5	10	-11	-3	-1
ASP NS			100	22	4	-8	-1
ASP EW				100	22	54****	-41***
SURF RN					100	38***	-54****
RIDGE						100	-75****
STREAM							100

p-values: *≤0.05, **≤0.01, ***≤0.001, ****≤0.0001
n = sample size
ELEV = elevation above sea level (m)
SLOPE = slope (degrees)
ASP NS = aspect transformation contrasting north and south
ASP EW = aspect transformation contrasting east and west
SURF RN = surface roughness
RIDGE = proximity to primary and secondary ridgelines (m)
STREAM = proximity to perennial steams (m)

Appendix 2.10. Correlation matrix (%) of terrain variables across the South Lookout physiographic area (n = 59).

TERRAIN VARIABLES

	ELEV	SLOPE	ASP NS	ASP EW	SURF RN	RIDGE	STREAM
ELEV	100	42***	6	17	-21	-90****	85****
SLOPE		100	-10	1	-37**	-28*	33*
ASP NS			100	-7	6	1	-5
ASP EW				100	-6	-9	4
SURF RN					100	12	-19
RIDGE						100	-74****
STREAM							100

p-values: *≤0.05, **≤0.01, ***≤0.001, ****≤0.0001
n = sample size
ELEV = elevation above sea level (m)
SLOPE = slope (degrees)
ASP NS = aspect transformation contrasting north and south
ASP EW = aspect transformation contrasting east and west
SURF RN = surface roughness
RIDGE = proximity to primary and secondary ridgelines (m)
STREAM = proximity to perennial steams (m)

Appendix 2.11. Correlation matrix (%) of terrain variables across the Upper McKenzie site (n = 250).

	TERRAIN VARIABLES						
	ELEV	SLOPE	ASP NS	ASP EW	SURF RN	RIDGE	STREAM
ELEV	100	9	1	-4	-29****	-84****	78****
SLOPE		100	-3	-1	-23***	-7	12
ASP NS			100	8	-5	8	3
ASP EW				100	8	10	-20**
SURF RN					100	21***	-25****
RIDGE						100	-62****
STREAM							100

p-values: *≤0.05, **≤0.01, ***≤0.001, ****≤0.0001
n = sample size
ELEV = elevation above sea level (m)
SLOPE = slope (degrees)
ASP NS = aspect transformation contrasting north and south
ASP EW = aspect transformation contrasting east and west
SURF RN = surface roughness
RIDGE = proximity to primary and secondary ridgelines (m)
STREAM = proximity to perennial steams (m)

Appendix 2.12. Significant regressions of historical MFRI on terrain variables across the entire Upper McKenzie site (n = 250).

Explanatory Variable	Parameter Estimate	p-value	r^2
Elevation (intercept)	-0.03429 (116.30)	0.00034 (<0.00001)	0.050
Surface Roughness (intercept)	5.7444 (60.79)	0.00182 (<0.00001)	0.038
Physiographic Areas: Blue River County Creek South Lookout (intercept)	 1.6535 -16.5112 28.1441 (81.36)	<0.0001	0.151
Stepwise model: County Creek South Lookout Aspect Tr NS Stream Proximity (intercept)	 -16.0588 33.3997 8.0569 -0.0101 (81.08)	<0.0001	0.190

n = sample size
Tr = transformation
EW = East-West
NS = North-South

Appendix 3.1. Band-to-band radiometric normalization using simple linear regression of pre-burn on post-burn TM data (n = 6).

TM Band	Wavelegnth (μm)	Slope	Intercept	r^2
1	0.45-0.52	1.6819	-20.164	0.981
2	0.52-0.60	1.5378	-5.068	0.983
3	0.63-0.69	1.7430	-4.165	0.994
4	0.76-0.90	1.4401	-8.288	0.997
5	1.55-1.75	1.4168	-3.129	0.996
7	2.08-2.35	1.4938	-0.408	0.995

n = sample size

Appendix 3.2. Correlation (%) for post-burn band transformations and ancillary data at Warner Creek site (n = 169).

POST-BURN TM BAND TRANSFORMATIONS AND ANCILLARY DATA

	3/7	SI	7/4	4/2	NDVI	5/2	TC WET	AGE	ELEV
3/7	100	65***	-67***	53***	49***	-68***	73***	21*	-29***
SI		100	-97***	91***	96***	-76***	87***	3	-40***
7/4			100	-94***	-97***	71***	-86***	-2	39***
4/2				100	94***	-49***	74***	-8	-32***
NDVI					100	-65***	79***	-5	-38***
5/2						100	-75***	-16	42***
TC WET							100	30***	-33***
AGE								100	-3
ELEV									100

p-values: $*\leq0.01$, $**\leq0.001$, $***\leq0.0001$
TM = Landsat Thematic Mapper data
SI = structural index (TM 4/5)
NDVI = normalized difference vegetation index (TM 4+3/4-3)
TC WET = tasseled cap transformation for wetness of TM data
AGE = stand age (years)
ELEV = elevation above sea level (m)

Appendix 3.3. Correlation (%) for difference by subtraction band transformations at the Warner Creek site (n = 169).

TM BAND TRANSFORMATIONS USING SUBTRACTION ALGORITHM

	3/7	SI	7/4	4/2	NDVI	5/2	TC BRT	TC GRN	TC WET
3/7	100	87***	-90***	76***	76***	-81***	-38***	60***	88***
SI		100	-97***	92***	95***	-84***	-20	79***	94***
7/4			100	-94***	-95***	77***	19	-80***	-93***
4/2				100	97***	-60***	4	84***	84***
NDVI					100	-68***	-3	87***	88***
5/2						100	51***	-39***	-75***
TC BRT							100	25**	-24*
TC GRN								100	82***
TC WET									100

p-values: *≤0.01, **≤0.001, ***≤0.0001
TM = Landsat Thematic Mapper data
SI = structural index (TM 4/5)
NDVI = normalized difference vegetation index (TM 4+3/4-3)
TC BRT = tasseled cap transformation for brightness of TM data
TC GRN = tasseled cap transformation for greenness of TM data
TC WET = tasseled cap transformation for wetness of TM data

Appendix 3.4. Correlation (%) for difference by ratio band transformations at the Warner Creek site (n = 169).

TM BAND TRANSFORMATIONS USING RATIO ALGORITHM

	3/7	SI	7/4	4/2	NDVI	5/2	TC BRT	TC GRN	TC WET
3/7	100	88***	-88***	77***	78***	-73***	-44***	74***	81***
SI		100	-93***	93***	96***	-79***	-30***	90***	84***
7/4			100	-86***	-90***	74***	21*	-87***	-79***
4/2				100	97***	-60***	-6	92***	72***
NDVI					100	-67***	-13	94***	77***
5/2						100	59***	-49***	-57***
TC BRT							100	6	-32***
TC GRN								100	79***
TC WET									100

p-values: *≤0.01, **≤0.001, ***≤0.0001
TM = Landsat Thematic Mapper
SI = structural index (TM 4/5)
NDVI = normalized difference vegetation index (TM 4+3/4-3)
TC BRT = tasseled cap transformation for brightness of TM data
TC GRN = tasseled cap transformation for greenness of TM data
TC WET = tasseled cap transformation for wetness of TM data

Appendix 3.5. Correlation (%) for standardized difference band transformations at the Warner Creek site (n = 169).

TM Band Transformations using Standardized Difference Algorithm

	3/7	SI	7/4	4/2	NDVI	5/2	TC BRT	TC GRN	TC WET
3/7	100	88***	-89***	77***	78***	-73***	-43***	74***	82***
SI		100	-94***	93***	96***	-79***	-29***	90***	86***
7/4			100	-87***	-91***	74***	21*	-88***	-81***
4/2				100	97***	-60***	-5	91***	75***
NDVI					100	-67***	-13	94***	80***
5/2						100	59***	-48***	-56***
TC BRT							100	6	-28**
TC GRN								100	84***
TC WET									100

p-values: *≤0.01, **≤0.001, ***≤0.0001
TM = Landsat Thematic Mapper data
SI = structural index (TM 4/5)
NDVI = normalized difference vegetation index (TM 4+3/4-3)
TC BRT = tasseled cap transformation for brightness of TM data
TC GRN = tasseled cap transformation for greenness of TM data
TC WET = tasseled cap transformation for wetness of TM data

Appendix 3.6. Classification error matrix for live canopy ratio, from the classification of the post-burn Structural Index (n = 162, Table 3.8).

Classification Data	Reference Plots			Row Total
	0-39% LCR	40-89% LCR	≥ 90% LCR	
0-39% LCR	13	2	0	15
40-89% LCR	6	14	7	27
≥ 90% LCR	0	3	12	15
Column Total	19	19	19	57

Map Category	Producer's Accuracy (%)	Omission Error (%)	User's Accuracy (%)	Commission Error (%)
0-39% LCR	13/19 = 68	32	13/15 = 87	13
40-89% LCR	14/19 = 74	26	14/27 = 52	48
≥ 90% LCR	12/19 = 63	37	12/15 = 80	20
Overall Accuracy = (13+14+12)/57 = 68%				

n = sample size
LCR = live canopy ratio

Appendix 3.7. Classification error matrix for live canopy ratio, from the classification of the ratio difference imagery with stratification using pre-burn tasseled cap wetness (n = 162, Table 3.8).

Classification Data	Reference Plots			Row Total
	0-39% LCR	40-89% LCR	≥ 90% LCR	
0-39% LCR	14	2	0	16
40-89% LCR	5	14	7	26
≥ 90% LCR	0	3	12	15
Column Total	19	19	19	57

Map Category	Producer's Accuracy (%)	Omission Error (%)	User's Accuracy (%)	Commission Error (%)
0-39% LCR	14/19 = 74	26	14/16 = 88	12
40-89% LCR	14/19 = 74	26	14/26 = 54	46
≥ 90% LCR	12/19 = 63	37	12/15 = 80	20
Overall Accuracy = (14+14+12)/57 = 70%				

n = sample size
LCR = live canopy ratio

CORRIGENDA

Analyzing Fire Mosaics in Temperate Coniferous Forests with GIS and Remote Sensing by John D. Kushla

p. 2, last line: delete "in"

p. 41, line 16: "were" should read "was"

p. 54, line 5: "ecosytem" is correctly spelled as "ecosystem"

p. 59, line 19: "(Table 3.1)" should read "(Table 3.2)"

p. 64, line 13: "northeastern" should read "northwestern", and

line 16: "USFS survival maps" should read "USFS survival map"

p. 71, Table 3.8, row 7: "$-0.4380*(SI_{RATIO})$" should read "$0.4380*(7/4_{RATIO})$"