Spatial and Temporal Patterns of Wildfire Occurrence and Susceptibility in Canada

By
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ABSTRACT

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Wildfire processes in Canada are expected to change as a result of climate change. Predictive modeling of wildfire occurrence and susceptibility requires knowledge of ignition expectations and landscape conditions leading to burn. This research examines and quantifies the spatial and temporal patterns of wildfire across Canada with focus on wildfire occurrence and national scale drivers of susceptibility. Baseline ignition expectations and trends are identified and used to create unique fire ignition regimes, assess anthropogenic influence on ignitions, and determine regions with anomalously high ignitions. The aspatial and spatial characteristics of land cover were characterized for pre- and post-fire landscapes. These included land cover composition, configuration, and abiotic covariates. Temporal trends in forest pattern following ignition are examined and national scale drivers of wildfire susceptibility determined. Fire ignition regimes and anomalous ignition regions provide spatially explicit outputs for exploring ignition expectation in Canada. Wildfire was identified to burn mainly in coniferous forests with little fragmentation. Fragmentation increased after wildfire and regeneration of pre-fire forest pattern took 20 years. Additionally, anthropogenic proximity positively influenced ignition expectation, ignition trend, and wildfire susceptibility. This research provides broad scale methods to assess wildfire occurrence and susceptibility across Canada and

will facilitate understanding of changing wildfire processes in the future. Additionally, this research highlights the importance of anthropogenic activity on natural fire processes.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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CO-AUTHORSHIP STATEMENT

This thesis is the combination of two scientific manuscripts for which I am the lead author. The initial project structure, provided by Dr. Trisalyn Nelson and Dr. Michael Wulder, identified spatial-temporal analysis of the relationship between wildfire and land cover as a key research opportunity. For these two scientific journal articles I performed all research, data analysis, interpretation of results, and final manuscript preparation. Dr. Wulder and the Canadian Interagency Forest Fire Centre provided the data. Dr. Nelson and Dr. Wulder provided editorial comments and suggestions where required.

CHAPTER ONE

1.0 Introduction

1.1 Research Context

The summer of 2003 was considered to be the worst wildfire season in British Columbia in recent history. 2,500 fires burned over 265,000 ha of land, more than 330 homes were destroyed, 45,000 people were evacuated, and three firefighting pilots lost their lives (Filmon 2004). Damages were estimated at $700 million (Filmon 2004). An uncommonly hot and dry summer, fuel accumulation from previous wildfire suppression, and wide-spread mountain pine beetle infestation were considered to be catalysts for this anomalous fire season. Using 2003 as an example, we observe the immense impact of wildfire on humans and environment. Effective preparation and management is critical to mitigate such damages.

Wildfire has a central role in shaping the distribution of landscapes and ecosystems worldwide (Bond et al. 2004) and burns an average of two million ha of land in Canada every year (Stocks et al. 2002). Wildfire is a heterogeneous, ecological disturbance process that is controlled by climate and weather (Bessie and Johnson 1995; Flannigan and Harrington 1988), vegetation and landscape characteristics (Finney 2001; Romme 1982), and ignition sources (Malamud et al. 2005). In order to monitor changing dynamics of wildfire, reduce human risk and damage from wildfire, and maintain region-specific natural wildfire regimes, we must first understand historic spatial-temporal patterns of wildfire.

The interaction between abiotic and biotic factors and the wildfire process is complex, and fire regimes are changing as a result of increased human activity (Calef et al. 2008; Rollins et al. 2001) and climate change (Flannigan et al. 2005; Stocks et al. 1998). Models forecasting wildfire activity with anticipated climate change have indicated increases in fire occurrence (Wotton et al. 2002), fire severity (Flannigan et al. 2000), area burned (Flannigan et al. 2005), and lightning activity (Price and Rind 1994). Similarly, humans impact wildfire regimes by increasing (Syphard et al. 2007) or decreasing (Konoshima et al. 2010) the flammability of a landscape, actively suppressing fires in high value areas (Keeley et al. 1999), and maliciously or accidentally igniting fires (Yang et al. 2008).

Canada has multiple wildfire regimes that expect different ignition densities, area burned, and fire severity (Parisien et al. 2006; Agee 1997). Wildfire frequency is often inversely related to area burned (Stock et al. 2002), with some ecozones (e.g., Taiga Shield and Taiga Plains) exhibiting infrequent large fires while others (e.g., Montane Cordillera) exhibit frequent smaller fires. Ignitions and large wildfire susceptibility must be examined independently however; large fires may still occur in frequent ignition regions and numerous ignitions may occur where fires are notoriously large. For example, ten fires larger than 10,000 ha occurred in the Montane Cordillera in 2003, an anomalous weather year, when only three similar sized fires had previously occurred since 1980. By analyzing ignitions and burn susceptibility separately we can determine where fires are likely to ignite, and once they do, what they will likely burn.

Spatial studies of wildfire have typically used aspatial measures such as area burned, number of fires, or fire season length to summarize fire activity for a geographic region (e.g., Stocks et al. 2002; Bergeron 2001; Niklasson and Granstrom 2000; Weber and Stocks 1998). Most spatially explicit studies also have an extent that is relatively small (e.g., Yang et al. 2008; Tuia et al. 2008a; Jordan et al. 2008; Girardin and Mudelsee, 2008) and few examine all of Canada (e.g., Parisien et al. 2006; Flannigan et al. 2005; Stocks et al. 2002). Fire activity is heterogeneous, however, and cannot be explained only by aspatial measures (Flannigan et al. 2005; Whelan 1995). Spatial variation in landscape conditions, fire regimes, and human influence and suppression must be considered. It also must be examined at numerous extents to determine multi-scale drivers influencing wildfire. Fine spatial scale map based analysis is necessary to characterize fine scale drivers and variation of wildfire spatial pattern across Canada. The increasing availability of detailed and accurate spatial datasets of wildfire (Stocks et al. 2002) and landscape characteristics (Wulder et al. 2008a) enable us to answer such questions for large extents and fine scales.

In this thesis, temporal analysis of wildfire may be conceptualized in three ways: changing fire activity, changing landscapes as a result of fire, and landscape regeneration following fire. First, fire activity (e.g., number of fires and area burned) may change through time. Quantifying where this change is occurring and related magnitude allows expectations of fire to be appropriately adjusted. Secondly, the landscape resultant from fire may be examined in terms of forest composition and landscape pattern. Lastly, by analyzing how landscapes recover from wildfire (Goetz et al. 2006; Amiro et al. 2000), and knowing which landscapes are more likely to burn (Ryu et al. 2007), we may determine how long it will take until that landscape becomes fire-susceptible again. Quantifying change in landscape regeneration and susceptibility is important for effective fire preparation and management.

1.2 Research Goals and Objectives

The goal of this research is to examine and quantify the spatial and temporal patterns of wildfire across Canada. To accomplish this, I will separately examine wildfire occurrence and wildfire susceptibility. The combination of these two studies will provide insight into where fires are igniting and which landscapes burn once they do.

The first study will characterize the spatial and temporal pattern of fire ignition across Canada using ignition density estimates and temporal trajectories. I create and demonstrate the potential of an ignition expectation baseline for use in fire ecology and monitoring by completing the following three objectives:

1. To summarize spatial and temporal fire occurrence patterns by ecozone and identify new regions with similar historical space-time ignition patterns in Canada
2. To identify the relationship between fire ignition density and anthropogenic factors across Canada.
3. To map locations of unexpected space-time ignition densities in observed data.

Secondly, I analyze fire susceptibility in Canada by characterizing landscape characteristics pre- and post-fire and developing an understanding of drivers influencing wildfire occurrence. Four objectives will are addressed,

1. To quantify the composition of land cover in pre- and post-fire locations within Canada's forested ecozones.

2. To characterize spatial pattern of forests and abiotic variables (proximity to populated places, proximity to roads, and elevation) associated with pre-fire locations.
3. To quantify spatial pattern of forests following wildfire.
4. To create and evaluate drivers of wildlife through development of a national scale model of fire susceptibility.

CHAPTER TWO

2.0 Spatial and Temporal Patterns of Wildfire Ignition in Canada

2.1 Abstract

Climate change is anticipated to modify the distribution of wildfire occurrence in Canada. To monitor and understand changes in fire occurrence, a spatially explicit national measure of historic, current, and future wildfire ignition expectation is required, yet has not been developed. In this study I present a method for using spatial-temporal patterns of fire in Canada to identify baseline expectations and ignition trends at a 1km scale. The ignition baseline is used to demonstrate how: regions with homogenous space-time patterns vary within ecozones; space-time fire patterns may also be used to explore anthropogenic influences on ignition regimes; and unexpected fire patterns can be mapped. Kernel density estimates of wildfire ignitions were computed for each year between 1980 and 2006. Ignition density temporal trajectories were created for each 1km x 1km cell and time series metrics were calculated to describe expected ignition density, variability from expected density, and increasing or decreasing density trends. Temporal metrics were combined with k-means cluster analysis to generate five unique ignition regimes across Canada. The spatial distribution of fire regimes was compared across ecozones. Anthropogenic influence was assessed by comparing regimes with proximity to road and to populated places. Unexpected fire pattern was identified by comparing the expected fire ignition density (1980 – 2006) to the observed ignitions (2007) using an outlier based approach. Fire ignition densities decreased exponentially as distance to road or populated places increased and largest ignition trends occurred closest to both covariates. Fire ignition regime delineation was more dependent on human transportation

networks than human settlement. I identified locations where observed fire ignitions were unexpected given baseline trends. Our findings provide a unique approach to quantifying ignition expectation. I highlight the potential of this baseline for monitoring and fire-environment interaction research while offering a preliminary spatially explicit model of wildfire occurrence expectation in Canada.

2.2 Introduction

Forests are subject to a range of natural and anthropogenic disturbances. Wildfire is considered to be the dominant natural disturbance in boreal forests due to the possibility of complete stand replacement (Johnson 1992), and while variable approximately two million hectares of forest burn annually in Canada (Stocks et al. 2002). Fire is a driving factor for many ecological processes (Whelan, 1995), shapes landscape composition (Taylor and Skinner, 2003) and impacts carbon cycling (Kasischke et al. 1995).

Wildfire occurrence is influenced by four main factors: weather/climate (Flannigan and Harrington 1988), fuels (Romme 1982), ignition agents (Malamud et al. 2005), and humans (Rollins et al. 2001). Due to the spatially varying nature of factors influencing fire, fire ignition densities are also spatially heterogeneous. Spatial variability may be attributed to the vegetation heterogeneity (Larsen 1997), the temporal fire cycle (Parisien and Sirois 2003; Rollins et al. 2002), and/or vegetation and climate interactions (Bergeron et al. 2004). Spatial clustering has been found in both lightning caused fires (Podur et al. 2003; Diaz-Avalos et al. 2001) and in human caused fires (Yang et al. 2008; Cardille et al. 2001). Human activity can alter spatial pattern of wildfire in many anthropogenic regimes (Yang et al. 2007; Cardille et al. 2001), though the amount of impact may fluctuate with socioeconomic variables (Prestemon et al. 2002).

Temporal variations also occur in wildfire ignition densities. Ignitions per year can fluctuate in Canada with only 5,438 fires occurring in 2000 (Johnston 2000) to over 12,000 in 1989 (Stocks et al. 2002). Fire regimes are known to be extremely sensitive to climate (Flannigan and Harrington 1988), with Stocks et al. (2002) indicating that climate change impacts will be most significant in the boreal forest. Models have indicated expected increases in area burned (Flannigan et al. 2005), fire occurrence and severity (Flannigan et al. 2000; Stocks et al. 1998), fire season length (Wotton and Flannigan 1993), and lightning activity (Price and Rind 1994). Despite average trends, localized climate impacts are spatially dependent; for instance, Bergeron et al. (2004) has found locations where projected fire frequency is lower than historical numbers under increased atmospheric CO_2 scenarios. It is therefore important to quantify temporal pattern of ignitions at local spatial scales.

Aspatial studies of wildfire typically emphasize area burned, total number of fires, or fire season length summarized over study area (e.g., Westerling et al. 2006; Stocks et al. 2002; Bergeron 2001; Niklasson and Granstrom 2000; Weber and Stocks 1998; Bergeron 1991). Fire occurrence cannot be explained solely by aspatial measures (Flannigan et al. 2005; Weber and Flannigan 1997; Whelan 1995) and as fire datasets have become better developed and spatial data analysis is more accessible, spatial pattern characterization of fire occurrence has provided benefits (Yang et al. 2007; Tuia et al. 2008b; Parisien et al. 2006). However, these studies often summarize spatial pattern for a geographic region (e.g., an ecozone, province/state or country) or have a small spatial analysis extent. Conversely, a recent study by Krawchuk et al. (2009) examines forest fire distribution at global extents and a 100 km spatial resolution. There is a gap in fire research with few studies conducted at fine spatial scales, over larger areas, and through many time periods.

Fire managers in Canada utilize the outputs of the Canadian Forest Fire Danger Rating System (CFFDRS) for daily decision making on forest fire management (Stocks et al. 1989). Fire danger describes the overall static and dynamic factors in a fire environment that contribute to ignition ease, spread rate, difficultly of control, and fire impact (Wotton, 2009). The CFFDRS is comprised of four components: the Fire Weather Index System (FWI), the Fire Behaviour Prediction System (FBP), the Accessory Fuel Moisture System (AFMS), and the Fire Occurrence Prediction System (FOP). The FWI system (Van Wagner 1987) is used to evaluate fire weather conditions in a standardized forest type, providing a daily index based on temperature, relative humidity, wind speed and rainfall. The FBP system (Forestry Canada Fire Danger Group 1992) uses FWI outputs and location specific information to provide quantitative assessments of fire behavior in major Canadian fuel types. The AFMS allows for more specific temporal models of fuel moisture based on stand specific measures. The FOP system represents the expected fire occurrence in an area. There is no single, unified system for assessing fire occurrence probability across Canada and much of the prediction is based on FWI inputs, lightning and potential human activity, and the manager’s professional experience. For a more complete description of the CFFDRS and its constituent systems see Wotton (2009).

The FOP system does not currently have a standardized mechanism for assessing wildfire ignition probability across Canada (Wotton 2009). This CFFDRS component relies heavily on daily weather conditions, which are already reported in the FWI, and the manager's expertise. The development of an expected ignition baseline would assist fire managers in understanding the future fire activity potential in a management area. Many factors influence whether a fire will ignite but the realization of a fire pattern is susceptible to a certain amount of variation. In order to monitor change, it is important to know baseline spatial-temporal fire conditions at a fine spatial resolution and over a national spatial extent. Identifying and mapping unexpected fire pattern (which is outside the acceptable variation) would allow managers to determine where change is occurring. Further, ecological studies can be informed through knowledge of disturbance rates, with unusual rates over a region such as an ecozone or a particular location informing on habitat and possible changes to the nature of a given ecosystem (Duro et al. 2005).

The goal of this paper is to characterize the spatial and temporal pattern of wildfire ignition across Canada using ignition density estimates and temporal trajectories. I will demonstrate the potential of the ignition expectation baseline as a fire ecology research product and monitoring tool by completing three objectives:

1. Regime Delineation: Summarize spatial and temporal wildfire occurrence patterns by ecozone and identify new regions with similar historical space-time ignition patterns in Canada.

2. Wildfire Ecology: Identify the relationship between fire ignition density and anthropogenic factors across Canada.

3. Monitoring: Map locations of unexpected space-time ignition densities in observed data.

This study will focus on wildfire ignitions rather than area burned. While area burned is an important element of fire impact on forest systems, it greatly depends on human decision for suppression or non-suppression. This is exemplified by the often unsuppressed lightning fires in northern Canada which account for ~80% of national area burned (Stocks et al. 2002). Removing post-fire suppression from the analysis emphasizes the underlying ecological conditions leading to ignition.

2.3. Study Area and Data

2.3.1 Study Area

The extent of this study is 6,897,200 km^2 of forested ecozones of Canada (Figure 2.1). Ecozones are ecological regions that consist of similar biotic and abiotic factors such as topography, vegetation, and climate (Ecological Stratification Working Group 1995). The Boreal Shield and Taiga Shield were divided into east and west constituents due to their large size and differences in climate and fire occurrence (Amiro et al. 2001; Stocks et al. 2002; Parisien et al. 2006).

2.3.2 Wildfire Data

The National Fire Database (NFDB) is the most complete collection of Canadian wildfire data. The NFDB is compiled by the Canadian Forest Service from the 13 Canadian fire management agencies. For more information on the creation of the NFDB (previously referred to as the Large Fire Database) see Stocks (2002). From the NFDB, fires were mapped as points in a Geographic Information System (GIS). Each fire point represents the presumed ignition location of the fire and has attribute information including: start date, fire size, and cause.

The NFDB data completeness varies between agencies and years. While some records date back to 1918, others were not mapped prior to 1980. Due to considerations of completeness and consistency, plus changes in detection with satellite and airborne technology, this study focuses on fires between 1980 and 2006. There are more than 280,000 fires in the database, with 190,338 fires occurring within the study time range. Ignition data from 2007, a total of 4957 ignitions, are used for identifying unexpected ignition densities. Even with the more limited temporal window, considerations remain: there is a lack of suitable contributions to the NFDB for Manitoba, Nova Scotia, Newfoundland for 2000-2006; Northwest Territories for 2006; and Quebec for 2001-2006.

2.3.3 Anthropogenic Covariates

Two variables were used as assess anthropogenic influence on wildfire ignition: proximity to road and proximity to populated places. The proximity to roads provides, for each 1 km cell in the study area, Euclidean distance to nearest road of any size as specified by the 2008 road network file from Statistics Canada. The proximity to populated places coverage is similar but uses the distance to persistent night time light derived from the DMSP Operational Linescan System. This coverage represents 100% of populated places with a population above 5000, 96% of population above 500, and 65% of population 499 or less.

2.4. Methods

2.4.1 Kernel Density Estimation

The NFDB point data were converted to surfaces of ignition density using kernel density estimation. Kernel density estimators allow continuous estimation of a spatial point process and allow the calculation of ignition density rather than ignition counts (Silverman 1986). The ignition density $\lambda(z)$ at a particular location z in study area A can be estimated by

$$\lambda(z) = e(z)\sum_{i=1}^{n}\frac{1}{nh}k(\frac{z-z_i}{h}) \tag{1}$$

where k is a kernel function with unit variance and zero mean, h is the bandwidth, n is the number of events, and $e(z)$ is the edge correction factor. A normal kernel was used. Cell size was chosen to be 1 km so it was large enough to include a homogenous area of landscape, yet small enough to conserve general landscape pattern. Edge correction was completed by dividing the intensity estimate by the convolution of the normal kernel within the observation window.

There are numerous methods for identifying bandwidths. Least squares cross-validation is commonly used (Brooks and Marron, 1991; Bowman 1984), though some criticize the result as under-smoothed in situations with large sample sizes (Hemson et al. 2005). A variable bandwidth KDE may make ecological sense since homogenous landscape patch sizes vary across Canada, but multiple bandwidths are a challenge for inter-cell comparison. I decided to use a value of 50 km based on the possible average daily spread rate of fire (Alexander and Cruz 2006) and for generalization of similar landscapes.

A KDE surface of ignition density is created for each year. The majority of fires occur within the summer months, from June until September, but early and late fires will also be a product of the annual climatic and environmental characteristics. The temporal resolution reflects the natural fire cycle.

2.4.2 Temporal Trajectory

The yearly kernel density estimate surfaces provide an estimate of ignition density at each cell. Each cell has 27 years of ignition density information that may be examined as a temporal trajectory or time series. Each trajectory can be described by a number of metrics to summarize the ignition density temporal pattern (Figure 2.2), including: median, normalized inter-quartile range, and linear trend.

The median is the expected ignition density assuming no change in ignition trend. The median is a measure of central tendency and is preferred over the mean due to the left-skewed temporal trajectory distribution from high ignition density years. This is a simple yet effective measure of the expected ignition density for a cell.

The expected ignition density of a cell will be subject to natural variation from location specific climate, environmental, and anthropogenic changes. A standardized inter-quartile range was used to quantify this variation in a non-statistical manner. The inter-quartile range (IQR) is defined by

$$IQR = P_{0.75} - P_{0.25} \tag{3}$$

where $P_{0.75}$ and $P_{0.25}$ are the 75th and 25th percentiles of the time series, respectively. IQR is measure of variation that and is not influenced by outliers. A standardized IQR is created by

$$sIQR = \frac{IQR}{median} \tag{4}$$

Standardization allows for comparison between cells regardless of median amount since larger medians may inherently mean larger deviation.

The linear trend of the ignition density temporal trajectory was determined by ordinary least squares linear regression. Linear regression determines whether fire ignition trends are increasing, decreasing, or staying constant over the 27 year time period.

The resulting metrics will be analyzed using ecozones-specific frequency distributions to examine ecological differences in expected ignition densities, relative variation, or linear trend.

2.4.3 Cluster Analysis

To delineate regions with similar temporal fire ignition patterns, k-means cluster analysis was applied to the three temporal metrics: median, sIQR and linear regression slope. As an unsupervised classification method, k-means clustering is beneficial since it requires no initial labeling of classes and is suitable for exploratory data analysis. Each metric was scaled to have unit variance and thus equal influence in each dimension.

Five classes were chosen based on an appropriate reduction in the sum-of-square-error for all metrics. Sum-of-square-error will decrease as each new class is added, but the rate of decrease will change at the acceptable number of classes (Duda et al. 2000). Five classes optimized sum-of-square-error while maximizing interpretability. Selection of number of classes can be a subjective endeavor that may change depending on the focus of the project.

2.4.4 Anthropogenic Influence Assessment

While ignition regimes depend on many non-anthropogenic factors like climate and vegetation type, the proximity of a location to human activity may help explain the spatial distribution of regimes (Brosofske et al. 2007; Syphard et al. 2007). Human activity may be concentrated in human settlement (distance to populated places) or dispersed through transportation networks (distance to roads). It is important to assess how these two influential factors correlate to fire ignition patterns.

The temporal trajectory metrics were compared to the anthropogenic covariate coverages and analyzed by pixel. Frequency distributions of anthropogenic factors were developed for median ignition density and ignition trend at a national and regime scale. Median and inter-quartile range were used to describe the distributions due to their robust nature. The national distribution of the proximity covariates was used as an expected value.

2.4.5 Monitoring Unexpected Ignitions

Baseline expectations of wildfire ignition density are useful for assessing deviations from expected fire pattern. Assuming no trend in ignition density trajectory, subsequent year ignitions are expected to fall within a specific range of the baseline. Unexpectedly high fire ignition density was determined by:

$$ID_{unexpected} > P_{0.75} + 1.5 * IQR \qquad (5)$$

where $P_{0.75}$ is the 75th percentile and IQR is the inter-quartile range. This definition of unexpected ignition density was derived from Tukey's (1977) box and whisker outliers. Unexpectedly low ignition density values are rare due to the left skewed nature of the ignition density temporal trajectory, but are identified if they exist. Monitoring extent was limited since 2007 data was only available for select provinces/territories (Ontario, British Columbia, Alberta, Saskatchewan, and Yukon).

2.5. Results

2.5.1 Ignition Regime Delineation

Temporal trajectory metrics indicated that expected wildfire ignition density, relative density variation, and linear trend of ignition density varied across Canada (Figure 2.3). Expected ignition densities were highest in the south-central Montane Cordillera and north of Lake Huron in the central Boreal Shield. Ignition expectations were lowest in the northern, increasingly treeless, portions of Canada. Relative variation was highest in northern Canada and the Atlantic provinces, although reflecting opposed environmental and social conditions. The northern areas indicated have few trees or people, and the Atlantic locations with forests interspersed with roads and settlements. Ignition density trend varied across the country but tended to be neutral (no change) or slightly positive in more northern latitudes.

The broad and regional expectations are driven by ecological and climatic conditions and can be observed when the temporal trajectory metrics were separated by ecozone (Figure 2.4). The Montane Cordillera experienced the highest median number of expected ignition densities, 2.68 $x10^{-3}$ ignitions per km^2, as well as the largest IQR and outlier range in expected density. The Boreal Plains, Boreal Shield, and Pacific Maritime ecozones were second, third and fourth for expected densities, respectively, with similar IQRs and outlier ranges about half as large as the Montane Cordillera. Atlantic Maritime ignitions were notable as well, with a slightly smaller expected density and outlier range than the previous ecozones, but a similar variance of expected. All other ecozones experienced relatively low expected ignition densities.

Overall linear trends indicated that each ecozone has experienced a slight decrease in wildfire ignitions. Montane Cordillera has the lowest median trend with -5.01×10^{-5} ignitions per km^2 per year, largest IQR and largest outlier range. The Boreal Plains and Boreal Shield ecozones have similar ignition trend distributions with a median slightly below zero and IQRs of 4.12×10^{-5} and 3.03×10^{-5} ignitions per km^2 per year. The trends of the Pacific Maritime ecozone are skewed high with few positive and many negative trend locations. The remaining ecozones have expected trends near zero and little to no variation from that.

The relative variance metric, sIQR, is inherently large for regions with very small ignition density expectations such as the Hudson Plains, Taiga Shield and Taiga Cordillera. The relative variation in ecozones with medium to high expected density are a preferred application of the statistic and more relevant to management considerations. Despite large differences in expected density, Montane Cordillera, Pacific Maritime and Boreal Shield have similar relative variance distributions. The Boreal Plains have a small and comparatively consistent relative variance. The east-west differentiation in the Montane Cordillera is of particular interest as neither expected density nor linear trend exhibit this pattern.

The k-means classification produced five distinct regimes distributed across Canada (Figure 2.5). Expected ignition density was the largest contributor to regime delineation with linear trend as a secondary influence. Regimes were labelled by their ignition risk: 1. *Very Low*, 2. *Low*, 3. *Medium (with increasing linear trend)* or *Medium+*,

4. *Medium*, and 5. *High*. Temporal trajectory metric distributions for each regime are described in Figure 2.6. All regimes, with the exception of *Medium+*, have an overall neutral or negative linear trend.

The *Very Low* regime was located mostly throughout the northern forested ecozones of Canada and the Atlantic provinces. *Low* regime occurred through most of the south-central latitudes, roughly following the boreal forest and buffering the higher-expectation regimes. *Medium* and *Medium* + regimes were similar in density expectation but were differentiated by the ignition trend of the contained cells. These tended to occur within the southern ecozones. The *High* regime was found mainly in the south-central Montane Cordillera as well as patches throughout the Pacific Maritime, Boreal Shield, and Boreal Plains; these are also the areas with the highest ignition densities in Canada.

2.5.2 Assessment of Anthropogenic Influence

The distributions of temporal trajectory metrics by distance to road or distance to populated places are presented in Figure 2.7. The expected ignition density decreased exponentially as both distance to road and distance to populated places increased. The highest expected ignition densities were located in close proximity to roads and slightly further away from populated places. Locations furthest away from roads and populated places have very low expected number of ignitions. Maximum distance to roads were 80 km, 70 km, 62 km, and 36 km for the *Low*, *Med+*, *Med*, and *High* regimes, respectively. Maximum distances to populated places were 325 km, 194 km, 233 km, and 189 km, respectively. Linear trend of ignition density converged to zero as both covariates increased. Trends with the greatest magnitude occurred in locations close to roads and populated places.

Regime delineated covariate distribution characteristics (median and IQR) were compared to random using the national covariate distributions as expected. Median distance to road and median distance to populated place both decreased as ignition expectation increases (Table 2.1). *Very Low* areas occurred further away from both roads and populated places than the national expectation, though variation in distance to populated place was similar. All other regimes occurred closer to roads and populated places and have correspondingly smaller variance. Increasing ignition risk corresponded with increased proximity to covariate. Regime covariate distributions deviated from expected faster with distance to roads than populated places.

2.5.3 Monitoring Unexpected Ignition Densities

Unexpectedly high ignition densities in 2007 were identified in areas where data was available (Figure 2.8). Locations were identified in northern Ontario and northern Yukon, where the underlying ignition expectations were very low, and south western Alberta, where the underlying expectation was medium to high.

2.6 Discussion

Wildfire ignition in Canada is a spatially and temporally variable process. Summarization by ecozone is a useful way to examine the ecological impact on ignition expectation, variation, and trend. The likelihood of a fire igniting was highest in regions such as the south-central Montane Cordillera with a maximum of one ignition every 89.3 km^2 each year. Variability in ignition density may be dependent on elevation or terrain complexity as the eastern, higher elevation region of the ecozone exhibits higher relative variance. The interior plateau, a flat region within the western Montane Cordillera, had a smaller relative variance and therefore more consistent ignition expectation. The dry summers, fire-dependent conifers, and reduced fuel contiguity due to rugged topography (Parisien et al. 2006) may constitute the ecological risks for high ignition expectation under consistent external influences. Fire suppression and prevention has been effective in most of the Montane Cordillera as observed with the negative trends in ignition density. Unfortunately, this suppression has also been recognized as a cause for the increased homogeneity in forest structure and increased fuel loading in traditionally surface-fire dominated regimes (Brown 1983), effectively increasing the risk of a stand replacing fire. Anthropogenic risk for this ecozone can be explained by proximity to roads or populated places as fire ignition densities increased with proximity to both human covariates. This is consistent with results from Portugal (Catry et al. 2009), Spain (Romero-Calcerrada et al. 2008), Florida (Mercer and Presemon 2005), and the upper Midwest of United States (Cardille et al. 2001).

The Boreal Plains, Boreal Shield, and Pacific Maritime ecozones all experienced similar ignition density frequency distributions. Contrary to evidence that large fires with a short fire cycle occur in coniferous boreal forest (Payette et al. 1989) and smaller fires with a longer fire cycle occur in deciduous or mixedwood stands (Bergeron et al. 2001), no evident bias exists at this scale for the likelihood of ignition in conifer versus mixedwood stands, both which are interspersed throughout these ecozones. The heterogeneous deciduous and conifer dominated south eastern Boreal Shield experienced similar ignition density expectations as the coniferous south western Boreal Shield and eastern Boreal Plains. The Boreal Plains and Boreal Shield had high ignition rates surrounding the easily accessible lakes, likely indicating ignitions caused by human recreation. Similarly, the Pacific Maritime experienced high ignition density in south eastern Vancouver Island, exemplifying the impact of human presence on ignition density. Relative variance in expected density is low for all medium to high ignition density areas, indicating fairly consistent ignition rates in these ecozones.

Lowest ignition densities occurred in the northern ecozones where some areas have never experienced an ignition. Relative variation is high due to the low expected ignition density and linear trend is mostly zero. The cold climate and low levels of recreational activity partially explain the low number of ignitions, as does the more natural fire regime allowed in the area. The few fires in these remote locations pose little danger to communities and are rarely suppressed, resulting in 50% of the area burned in Canada (Stocks et al. 2002). This unaltered, natural fire regime allows for large fires to remove built up fuel and undergrowth, reducing the ignition susceptibility in the region and promoting a longer and more stable fire cycle. This is consistent with the modeled relationship between fire frequency and fire size in a natural regime, or "let burn" scenario, examined by Li and colleagues (1999). This stable fire cycle may be observed from the lack of trend in ignition density throughout these ecozones. As indicated from land cover (Wulder et al. 2008a) and related derived information on forest composition (amount of forest over a given unit area) (Wulder et al. 2008b), these areas are characterized by sparse forest cover, low vegetation ground cover, wetlands, and lakes.

An interesting relationship can be observed between ignition density expectation and linear trend of ignition density. In most locations a high ignition density was coupled with a negative trend in fire ignitions through time, possibly indicating the effectiveness of fire suppression or prevention efforts in ignition-prone areas. The locations with greatest positive ignition trends through time in the Boreal Plains and Boreal Shield occurred adjacent to regions with high ignitions and negative trend. While these areas often had less intensive ignitions, the positive trend indicates changing environmental or anthropogenic influence which may change the fire regime, and thus the ecology, of the region. These may be the most important areas to focus risk rating and monitoring efforts.

The delineation of wildfire regimes based on ignition expectations allows for identification of similar regions of space-time fire pattern across Canada. The five resultant groups are spatially distributed across the country. The *Very Low* ignition class is identified where expected: northern Canada, immediately bordering the prairies, and Pacific and Atlantic coastlines with little fuel or human activity. Driving factors in these regions may vary between high moisture (maritime coasts), low fuel availability (prairies), and low human activity (northern Canada). The *Low* regime roughly follows the July minimum temperature isoline of 10ºC throughout the Boreal Plains and Boreal Shield and up into the Taiga Plains. The Montane Cordillera, despite being outside this isoline, has a higher predisposition to ignitions due to its dry summers and coniferous stands. An isolated patch designated *Low* is located in the Boreal Cordillera near Whitehorse, Yukon Territory, and is best attributed to higher local levels of anthropogenic activity.

It is evident that the regime with fewest wildfire ignitions is occurring at the furthest distances from roads and populated places. These locations would be considered to be the most natural and have the least human influence. The *Very Low* regime may still occur near roads or human settlement, but climate, ecology, or human prevention ensures a negligible ignition risk. The *Low* regime also occurs at greater distances to road or populated places relative to the three highest regimes, though is absent at distances beyond 80 km from road and 325 km from populated places.

The *Medium*, *Medium+*, and *High* regimes are indicative of important areas to focus research and management attention. Again, these regimes encompass high-activity lakes in accessible regions. *Medium* and *High* ignition regimes occurred in many of the same areas with *Medium* often encircling the *High* regime. Both regimes occurred much closer to roads and populated places than the two lowest regimes, making it evident that greater numbers of ignitions occur in locations close to human activity. The Montane Cordillera contains the largest portion of contiguous *High* regime cells due to the conditions mentioned earlier, yet this regime exists in multiple ecozones despite the difference in underlying ecological composition. Factors impacting ignition may be different here, with ecology/management having greater influence in the Montane Cordillera while human activity is the main driver elsewhere. The *Medium* regime follows the same premise though expected ignitions are reduced.

The Linear trend of the ignition density also increases in magnitude, either positive or negative, as proximity to humans increases. The decrease in ignitions, possibly due to prevention or environmental change, is likely to occur close to humans given that distant locations are allowed to experience a more natural fire regime. Fire suppression and prevention efforts are most prevalent where civilian or corporate investments are at stake (Ward et al. 2001). Conversely, areas of increased ignitions are also occurring close to humans. The *Medium+* regime, similar in ignition expectation to the *Medium* or *Low* regime, spatially delineates this increasing ignition trend. While these locations do not have the immediate ignition susceptibility of the *High* regime, the increasing trend is indicative of changing ecological or anthropogenic conditions and should be considered for future forest management. This regime occurs closer to roads and populated places than would be implied from its ignition density, signifying the impact of human presence on not only expected ignition density but ignition density trend as well.

While the importance of both proximity to road and populated places on ignition density is evident, proximity to roads has greater relative change from the expected distribution in all regimes. This indicates that proximity to roads has a larger impact on regime delineation than proximity to populated places. The influence of human transportation network on ignitions has been discussed in the literature (Syphard et al. 2008; Stephens 2005) and is not surprising, considering humans disperse along transportation networks before accidentally igniting a fire. This provides further emphasis to include anthropogenic covariates, namely road proximity, into fire ignition models to compliment the ecologically established risk.

There is only a small area of unexpectedly high ignitions identified in 2007. This is consistent with the Canadian Forest Service overview of the fire season which was summarized as below average number of ignitions when compared to the previous ten and twenty years (Johnston 2007). The areas identified in northern Ontario and the Yukon occurred where expected ignition density is already very low, meaning that a few extra fires may increase the ignition density beyond what is expected. The unexpected area identified within the Southern Boreal Plains delineates abnormally high ignitions in South Western Alberta. That same region experienced hot dry weather during August of

2007 and an enacted fire ban (Johnston 2007). The detection of anomalous ignition densities facilitates the spatial delineation of unexpected ignitions; a requirement for the assessment of the cause of unusually high ignition densities.

2.7 Conclusions

The objective of this study was to quantify the spatial and temporal patterns of wildfire in Canada by identifying baseline ignition expectations and ignition trends. Distinct ignition-based regimes were spatially delineated and emphasize the variation in ignition density through space and time. Ignition density and ignition trend magnitude, both positive and negative, were positively influenced by increased proximity to human transportation network and human settlement. Unexpected or anomalous ignition densities were identified for 2007 and spatially defined. As a preliminary attempt to create a spatially explicit national measure of ignition expectation, this project has successfully quantified the space-time pattern of fire across Canada.

The ignition density and temporal trajectory metric approach provides spatially explicit, applicable information on ignition expectation baseline and forecasting using historic data. Future improvements to this model are easily implemented due to the flexibility of adding additional temporal trajectory metrics. Additionally, this method can be applied to any large point dataset to create a spatially continuous and temporally comparable measure. The results of this project address the necessity for a nation-wide fire ignition expectation model in Canada (Wotton, 2009) and demonstrate potential uses of the product.

Table 2.1 Anthropogenic covariate distribution characteristics by ignition regime. The expected distribution is from the complete national dataset. Regimes are compared the expected using median and inter-quartile range as descriptors.

	Road Median		Road IQR		Pop. Place Median		Pop. Place IQR	
	(m)	(% exp)	(m)	(% exp)	(m)	(% exp)	(m)	(% exp)
Expected	12040	(100%)	36044	(100%)	133300	(100%)	215830	(100%)
Very Low	27510	(228.4%)	52676	(146.1%)	245600	(184.2%)	226500	(104.9%)
Low	7000	(58.1%)	16046	(44.5%)	80230	(60.2%)	79730	(36.9%)
Medium+	1000	(8.3%)	4123	(11.4%)	46240	(34.7%)	47290	(21.9%)
Medium	2000	(16.6%)	6083	(16.9%)	57070	(42.8%)	51920	(24.1%)
High	1000	(8.3%)	2000	(5.5%)	39620	(29.7%)	32660	(15.1%)

Figure 2.1 Canadian forested ecozones (green) and fire ignition locations (black) from 1980 to 2006.

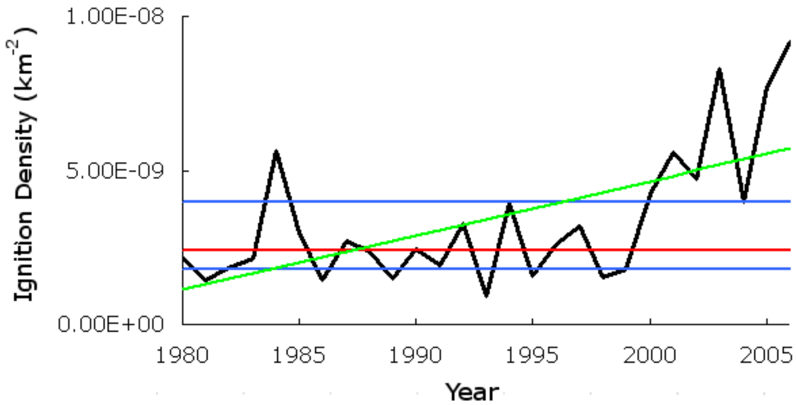

Figure 2.2 Ignition density temporal trajectory example with expected ignition density (median; red), amount of variation (inter-quartile range; blue), and trajectory trend (ordinary least squares linear regression slope; green).

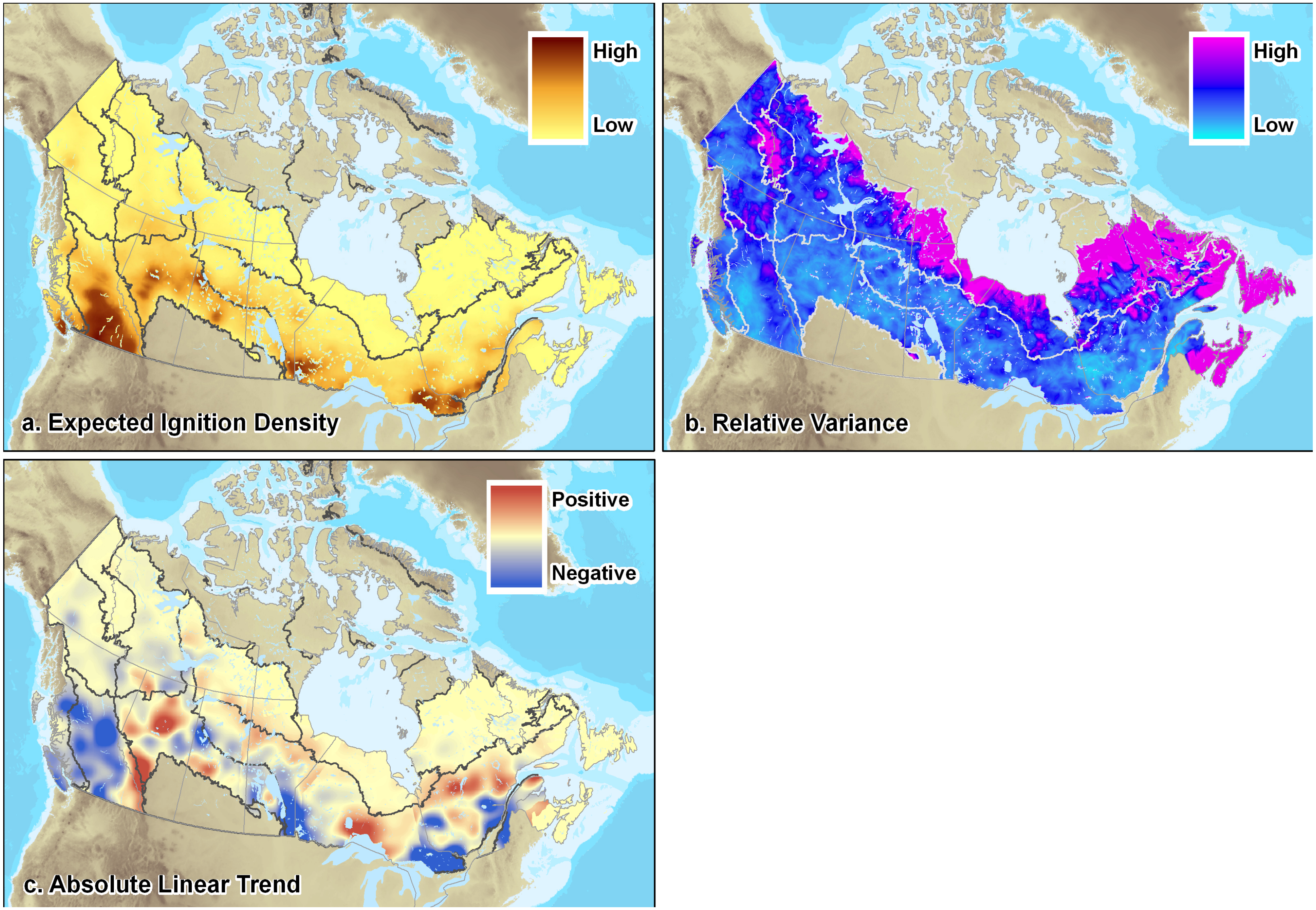

Figure 2.3 Temporal trajectory metrics of wildfire ignition density (a. expected ignition density - median; b. relative trajectory variation – standardized inter-quartile range; c. trajectory trend – ordinary least squares linear regression slope) across Canada

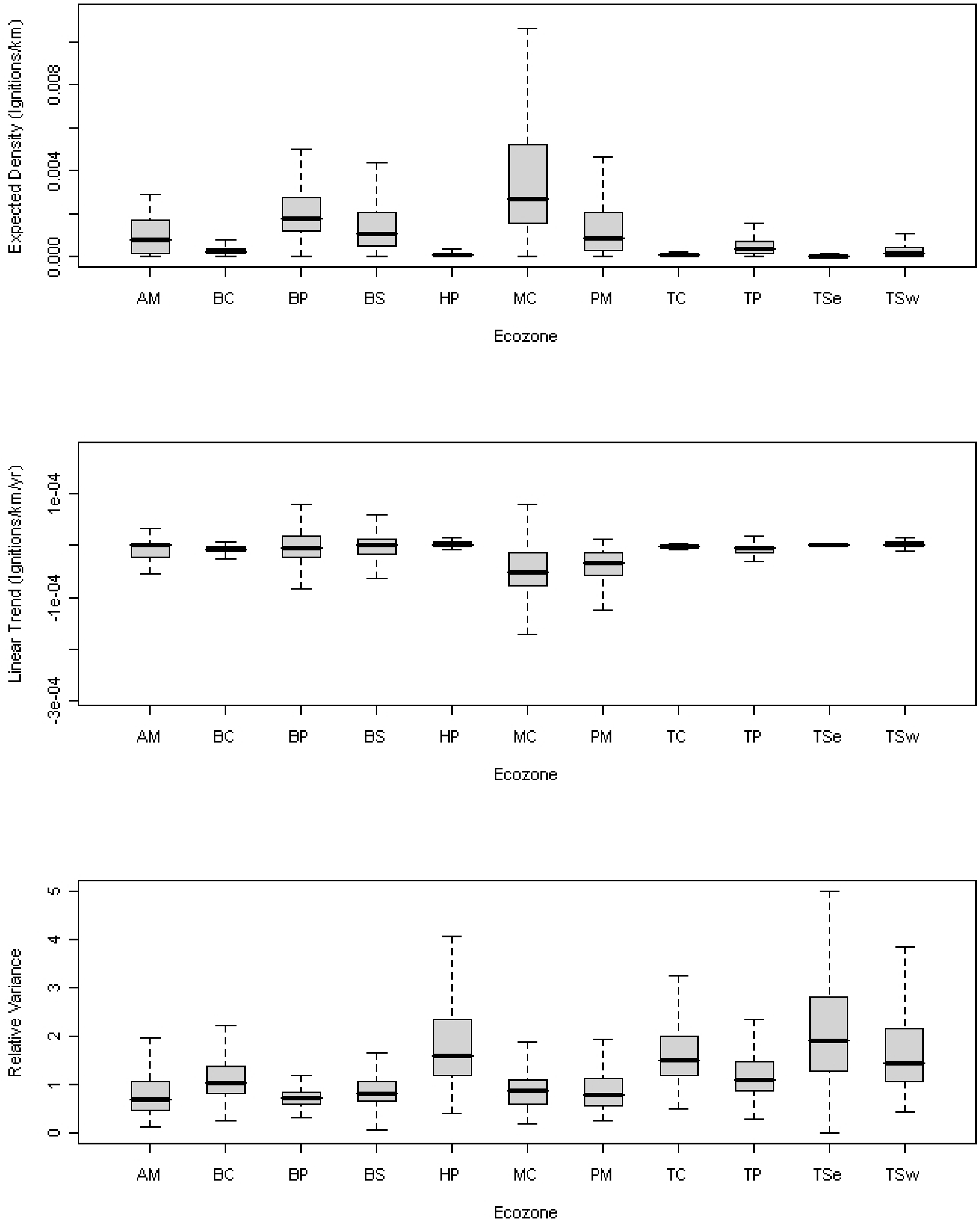

Figure 2.4 Ecozone separated box-and-whisker plot of temporal trajectory metric distributions. Median, 25th and 75th percentiles are represented in the box. The whisker denotes 1.5 * inter-quartile range or maximum/minimum data value, whichever is closer to the median.

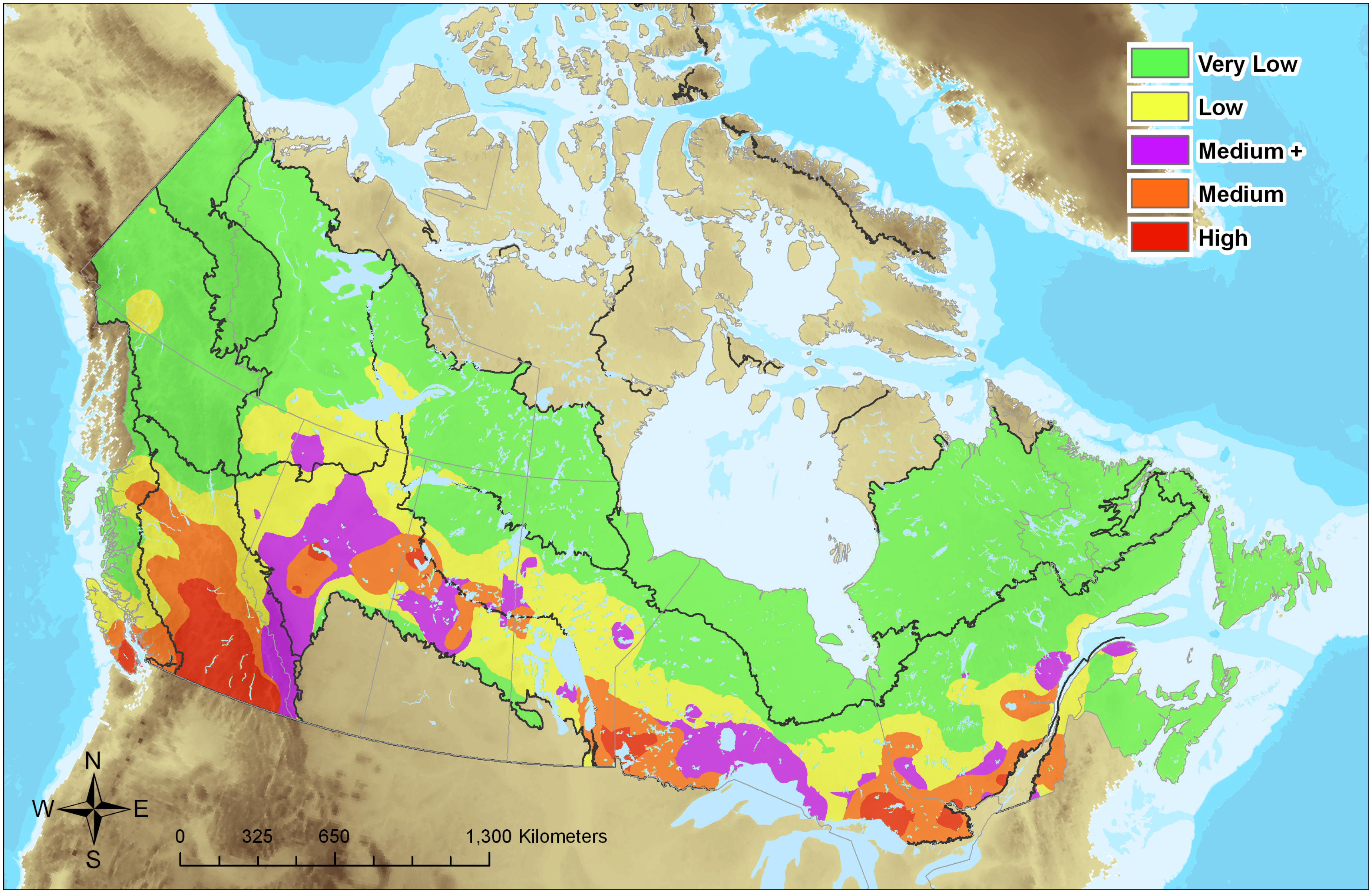

Figure 2.5 K-means delineated fire ignition regimes in the forested ecozones of Canada.

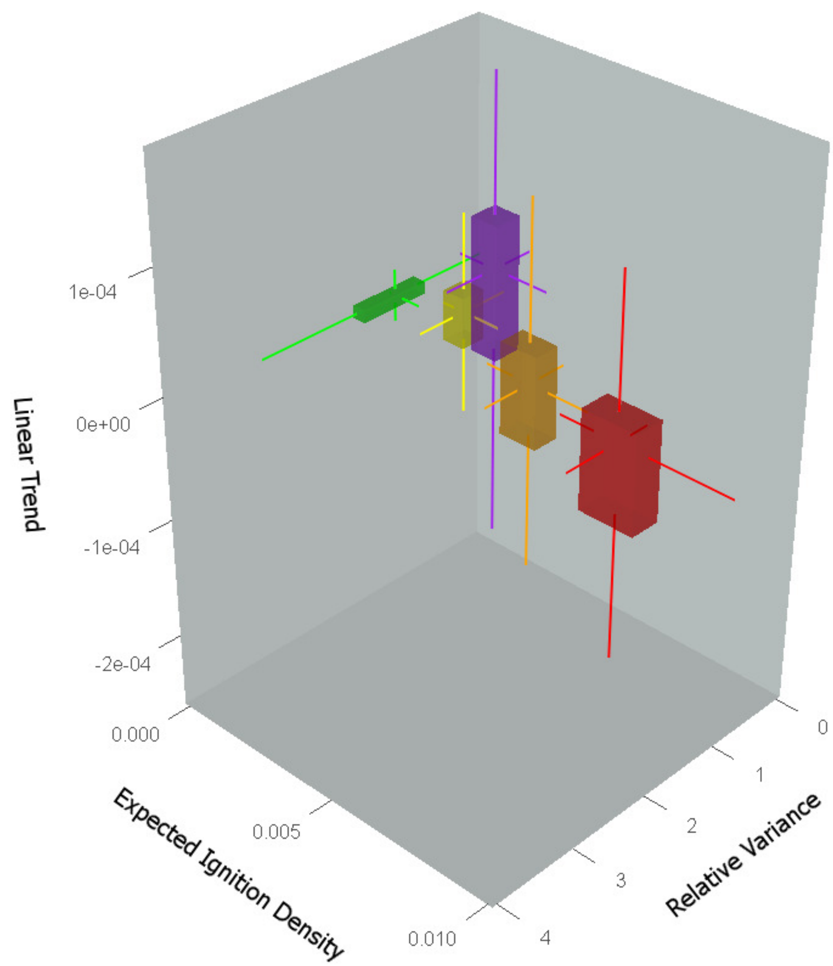

Figure 2.6 Three dimensional box-plot of the five delineated ignition regimes: green is very low, yellow is low, purple is medium with increasing trend, orange is medium, and red is high.

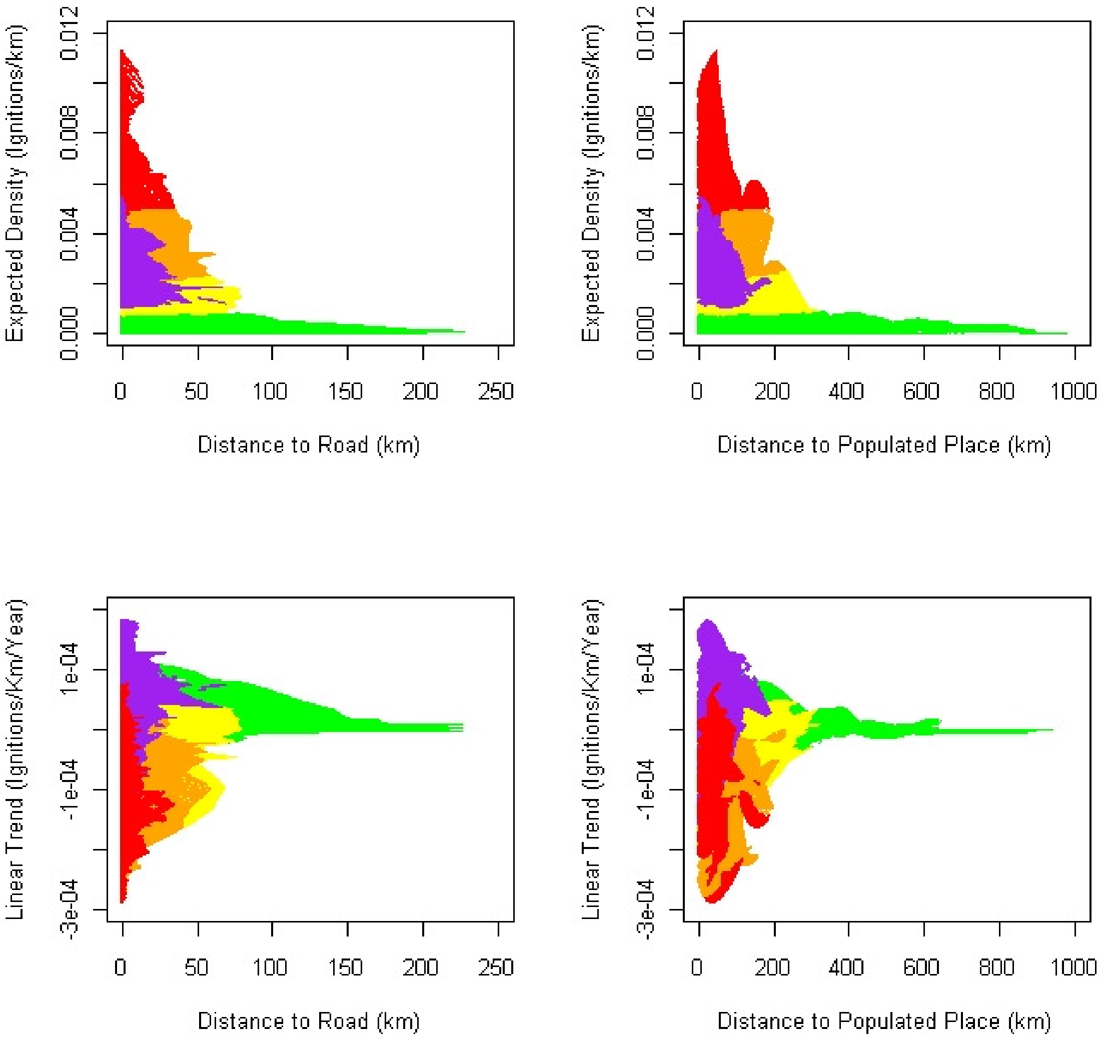

Figure 2.7 Temporal trajectory expected ignition density and linear trend plotted with two anthropogenic covariates: distance to road and distance to light (populated places). Points are color coded by the regime they belong to: green is very low, yellow is low, purple is medium with increasing trend, orange is medium, and red is high.

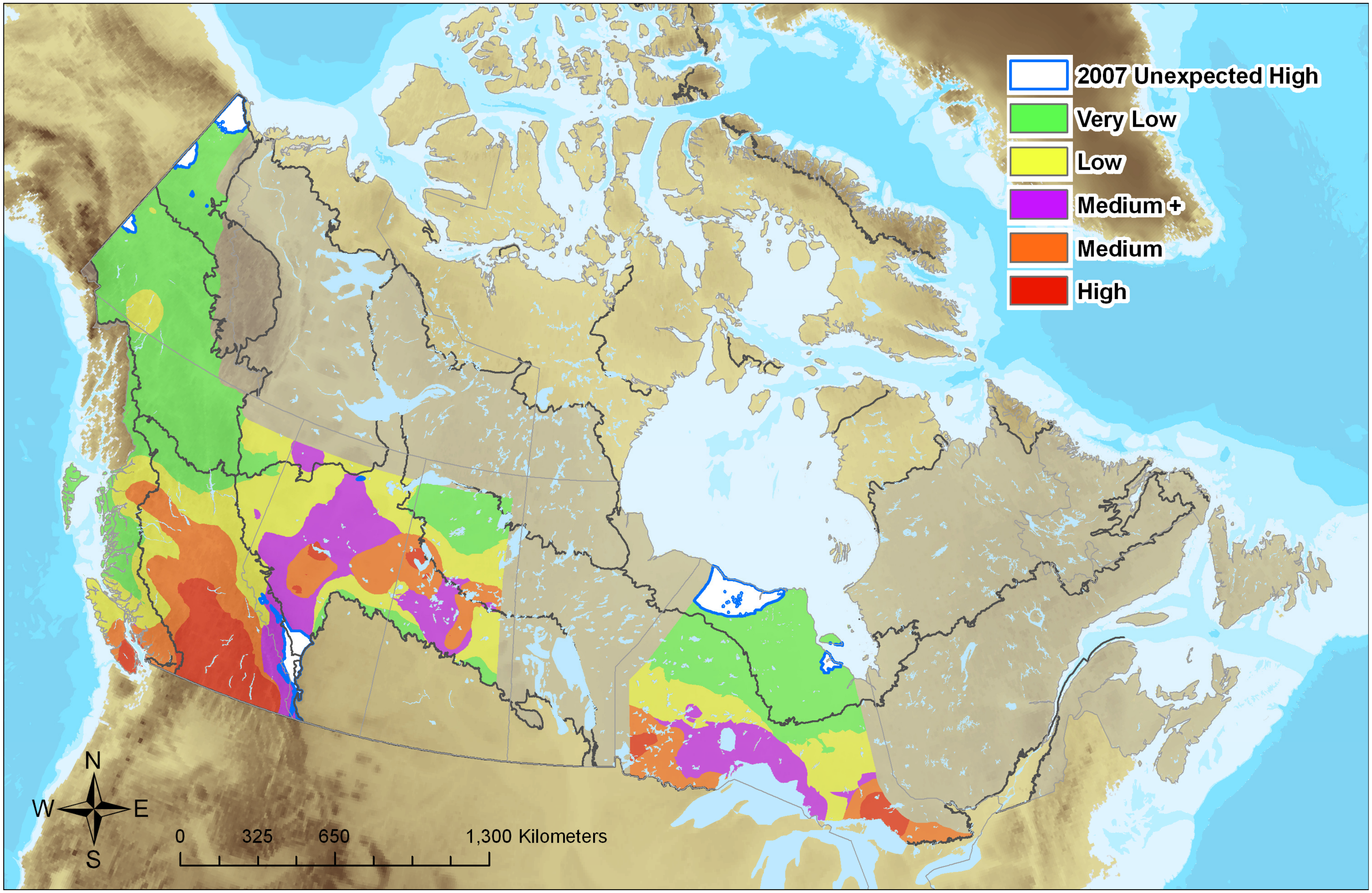

Figure 2.8 Unexpected high ignition density locations in Alberta, British Columbia, Saskatchewan, Ontario and the Yukon in 2007. Underlying ignition regime is indicated. Regions without 2007 ignition data available were removed from the analysis.

CHAPTER THREE

3.0 National Scale Drivers of Large Wildfire Susceptibility in Canada

3.1 Abstract

Wildfire processes are expected to change as a result of climate change. Predictive modeling of wildfire susceptibility in Canada requires knowledge of spatial and temporal patterns of forests present both before and after wildfire occurrence. In this research I aim to characterize landscape pattern pre- and post-fire at a national scale and identify drivers of national fire susceptibility. Pre- and post-fire distributions are created for land cover composition, four landscape pattern metrics, and four abiotic covariates. Temporal trends in forest pattern following wildfire were examined using 3-dimensional histograms. A large-area susceptibility model was derived using a decision tree classifying technique. The majority of large wildfires occur in coniferous forest with high forest cover, few forest patches, large mean forest patch area, and fragmentation-limited forest. Low to intermediate distances to populated places, road, and lakes experience unexpectedly high amounts of fire, as do lower elevations. Fire immediately impacts forest pattern, reducing cover, increasing number of patches, decreasing mean patch area, and increasingly fragmenting the forest. Regeneration to pre-fire forest pattern conditions occurs at approximately 20 years. The investigation of drivers of susceptibility indicated that non-sparse forests, elevation, and anthropogenic proximity were the national influencers of wildfire in Canada. Knowledge of space-time patterns of fire and identifying fire susceptible locations provides a baseline for future comparisons of response to climate.

3.2 Introduction

Wildfire is a dominant natural forest disturbance in Canada that burns approximately two million hectares of forest annually (Stocks et al. 2002). While short term effects of fire include changes to landscape pattern (Hayes and Robertson, 2009), wildlife habitat (Whelan et al. 2002; Emlen, 1970), soil (Giovannini et al. 2001), and air quality (Hardy et al. 2001), long term effects drive ecological processes (Whelan 1995), and impact carbon cycling (Kasischke et al. 1995). Wildfire regimes are changing due to a combination of climate change and fire suppression. Climate change has resulted in increased fire occurrence (Flannigan et al. 2000; Stocks et al. 1998) and area burned (Flannigan et al. 2005). In over managed forest areas, long-term fire suppression has been identified as resulting in unnatural fuel accumulations leading to larger, more severe, fires (Keeley et al. 1999). It is increasingly important to understand landscape scale patterns related to wildfire and to characterize fire susceptibility as a means of understanding how fire patterns are changing.

There are many factors impacting space-time patterns and likelihood of fire. Fire occurrence and spread can be attributed to weather and climate (Flannigan and Harrington 1988), landscape fuel conditions (Finney 2001; Romme 1982), ignition agents (Malamed et al. 2005), and human influence (Rollins et al. 2001). There is also a stochastic aspect to wildfire associated with variability in local weather conditions (e.g., surface moisture and wind speed (Bessie and Johnson, 1995)) and successful ignition events, both of which are difficult to predict. Despite fire clustering due to lightning strikes (Podur et al. 2003; Diaz-Avalos et al. 2001) and human caused ignitions (Yang et al. 2007; Cardille et al. 2001), predicting exact locations of ignitions is not possible.

Human impact on fire is a product of population presence and accessibility and assessing anthropogenic influence using proximity measures has been successful (Yang et al. 2007).

The relationship between landscape fuel condition (i.e., vegetation type and pattern) and wildfire processes is complex and cyclical (Turner and Romme, 1994). The spatial heterogeneity of landscape characteristics such as vegetation species, forest age, and landscape pattern (e.g., fragmentation) result, in part, from wildfire. Forest fire processes and susceptibility are also influenced by forest pattern (Rollins et al. 2002). The spatial arrangement of vegetation on the landscape relates to fire spread under ordinary weather conditions (Brown 1985). In landscapes where forest patches are highly connected or contiguous, it is possible that fire will propagate through the entire landscape (Turner and Romme, 1994). Conversely, increased patches of irregular shape reduce rate of fire spread through a landscape (Ryu et al. 2007).

When spatial processes cannot be measured explicitly, which is the case for large area forest processes, characterizing spatial patterns through time is a useful proxy. Spatial pattern can be quantified in terms of composition or configuration: composition metrics are used to measure a) number of classes or patch types in a landscape, b) proportion of each class in a landscape, or c) diversity of classes as described by evenness or richness (Gustafson 1998). Configuration metrics are used to quantify spatial pattern and feature arrangement in the landscape (Gustafson 1998). Both composition and configuration measures are critical for characterizing landscape pattern.

Characterizing the drivers of fire susceptibility of a landscape is crucial to fire management, protection of human resources, and maintaining a natural fire regime, and is a key step towards modeling susceptibility of forest to future fire. Modeling is an effective method for understanding the interaction between these drivers due to its low cost and broad applicability at numerous spatial scales (Keane et al. 2004). Products derived from remotely sensed products data can provide valuable information to these models, such as landscape composition and configuration, with wide-area coverage and fine spatial resolution. The development of national scale datasets for wildfire (Stocks et al. 2002) and land cover (Wulder et al. 2008a) and fragmentation (Wulder et al. 2008b) creates a unique opportunity to integrate and develop national scale models.

My goals for this research are 1. to characterize landscape characteristics pre- and post-fire at a national scale, and 2. to develop an understanding of drivers influencing wildfire occurrence through development of a national fire susceptibility model for Canada. I will meet these goals by completing four objectives:

1. To quantify the composition of land cover in pre- and post-fire locations within Canada's forested ecozones.
2. To characterize spatial pattern of forests and abiotic variables (proximity to populated place, proximity to roads, and elevation) associated with pre-fire locations.
3. To quantify spatial pattern of forests following wildfire.
4. To create and evaluate drivers of wildlife through development of a national scale model of fire susceptibility.

3.3 Study Area and Data

3.3.1 Study Area

The ten forested ecozones of Canada constitute 6,897,200 km^2 and define the extent for this study (Figure 1). An ecozone is defined as "an area of the earth's surface representative of large and very generalized ecological units characterized by interactive and adjusting abiotic and biotic factors" (Ecological Stratification Working Group, 1995). The majority of wildfires in Canada occur within the ten forested ecozones, often with individual ecozones exhibiting distinctive fire occurrence and area burned (Stocks et al. 2002). These large, sub-continental divisions enable meaningful summarization for regions of unique ecological and abiotic influence while allowing for comparisons with other ecozones-delineated studies.

3.3.2 Wildfire Data

The Canadian National Fire Database (NFDB) is a geographic collection of wildfires in Canada, aggregated by the Canadian Forest Service from the 13 provincial and territorial fire management agencies across the country. For information on the development of the NFDB see Stocks et al. (2002). The NFDB-polygon database consists of vector polygons that represent the fire perimeter as determined by satellite or aerial imagery, aerial observation, or ground mapping using global positioning system units. Information about the fire is often included such as start and end date, size, and cause. Only fires greater than 200 ha in size were included in the analysis (Figure 3.1).

The NFDB is not a complete inventory of all fires in Canada and completeness varies between agencies and years. Fire polygons were not available for all agencies until 1980 and availability wanes for some Maritime agencies post-2000, though most provinces contributed data until 2005, 2006 or 2007. Additionally, national detection of fires only became consistent after 1975 due to advances in aerial and satellite observation (Murphy et al. 2000). The temporal range of this study will encompass 1980 to 2007 to accommodate issues of completeness and consistency.

In this study I focus on fires with a burn area larger than 200 ha. Larger fires are more accurately mapped due to their size and longer duration, making fire data consistent post-1975 with the emergence of remotely sensed data. A 200 ha fire size has been the lower limit of the Large Fire Database used in numerous wildfire studies in Canada (Parisien et al. 2006; Stocks et al. 2002; Amiro et al. 2001). Additionally, large fires (greater than 200 ha) account for approximately 3% of ignitions but about 97% of area burned in Canada (Stocks et al. 2002), indicating the importance of such fires to changing landscape pattern and process.

3.3.3 Land Cover Data

Land cover information for Canada was obtained from the Earth Observation for Sustainable Development of forests (EOSD) product (Wulder et al. 2008a; Wulder et al. 2008b). Land cover conditions in the EOSD were collected circa year 2000 using over 480 Landsat-7 ETM+ scenes between the years of 1999 and 2002, with 90% of coverage occurring in the year 2000. Temporal change will be represented through regions of similar fire age where 2000 represents baseline conditions (i.e., fires from 1998 will represent conditions two years after fire). Forest pattern will be examined as post-fire (1980-1999; spatial regions where burn-altered landscape is observable in the EOSD) and pre-fire (2003-2007; spatial regions where wildfire has not occurred but will). 2003 was chosen as the pre-fire initial year as some post-2000 collected Landsat scenes contained a post-2000 fire, possibly introducing commission error. The large spatial extent, small spatial grain, and focused temporal period make the Landsat derived EOSD land cover product ideal for use as a baseline land cover assessment in Canada.

The EOSD hierarchical classification system of land cover type was developed to fit with the Canadian National Forest Inventory (Wulder and Nelson, 2003), and 23 unique classes were established for a map product with a spatial resolution of 0.0625ha (a 25 m by 25 m pixel). As the focus of this study is on the effect of fire on landscape pattern of forest, *other* classes (e.g., shadow, cloud) and *non-veg* classes (e.g., water, exposed land) were aggregated at the land base level, whilst *non-treed* classes (e.g., wetland shrub, shrub tall, bryoid) were aggregated at the land cover level. *Treed* classes were of utmost interest, and therefore classified at the vegetation type level (conifer, broadleaf, mixedwood) as well as the density class level (dense, sparse, open).

3.3.4 Abiotic Covariates

Abiotic factors with a temporally consistent influence on wildfire ignition and spread were included in the analysis. Anthropogenic influences included proximity to road and proximity to populated places while natural influences were measured using elevation. All abiotic datasets were summarized at a 1km grain corresponding to the forest pattern coverages. Proximity to road was created by calculating Euclidean distance to road of any size using the 2008 road network file from Statistics Canada. Proximity to populated places was created similarly, but using persistent night time light obtained from the DMSP Operational Linescan System instead.

3.4 Methods

3.4.1 Composition Distributions

To quantify the composition of land cover in pre- and post-fire locations across Canada, the frequency distribution of land cover composition in all of Canada's forested ecozones was determined and used as a baseline for comparison. Similar frequency distributions were created for pre- and post-fire composition. Percentage change in composition following fire was calculated for each landscape class to determine which types of landscape were burning and to characterize the resultant landscape nationally.

3.4.2 Configuration and Covariate Distributions

Several landscape pattern metrics were examined at a 1 km by 1km grain using a reclassification of land cover as forest, non-forest, and other as in Wulder et al. (2008a). Landscape pattern metrics are single, calculable values that are often used to describe the spatial pattern or content of a landscape (Frohn 1998). These metrics are useful due to their computational simplicity, ease of implementation, and broad scale applicability (Cardille and Turner 2002; McGarigal and Marks 1995). Wildfire influence on spatial pattern has been increasingly documented using landscape pattern metrics for small spatial extents (van Leeuwen et al. 2010; Montane et al. 2009; Ryu et al. 2007; Lloret et al. 2002), though no national scale studies exist. For this study I chose metrics that relate landscape pattern to process of fire (Li and Wu 2004; Levin 1992). Four landscape metrics were chosen for our study with possible pre and post fire importance: 1. proportion forest area, 2. number of forest patches, 3. mean forest patch area, and 4. proportion of all patches that are forest.

These four metrics provided important information on landscape composition and configuration and, despite overlap in some information provided, were selected for their biological relevance to wildfire spread and prevention, and vegetation re-growth. Proportion of forest area is an easily interpretable composition metric that describes the amount of a given cover type within a cell. It is a simple way to quantify pre and post-fire changes in amount of forest and may be used to characterize forest evenness or dominance (Botequilha Leitao et al. 2006). Number of forest patches and mean patch area can both be used to signify landscape heterogeneity, fragmentation, and contiguity while representing simple forest pattern descriptions. Forest fragmentation and complexity has been used to study spread (Ryu et al. 2007; Turner and Romme 1994), prevention (Finney 2001), and fire return interval (Roberts, 1996), and may have important implications for both pre- and post- fire landscapes. Finally, proportion of all patches that are forest provides additional information on the fragmentation of the forest in context of the landscape fragmentation (Wulder et al. 2008b). For example, a highly fragmented forest in a non-fragmented landscape can be differentiated from a highly fragmented forest in a highly fragmented landscape.

To characterize the nature of forest pattern and abiotic variables in locations that burned during the study, relative frequency distributions of landscape pattern metrics and abiotic covariates were generated for all forested ecozones. The relative distributions of the four landscape pattern metrics were generated for all locations and for locations that burned after 2003. Similarly, the relative distribution of abiotic covariates at all burned landscape locations was created to describe static influences on wildfire. Differences between relative distributions for all locations and burn locations were calculated and trends in forest pattern and covariates identified.

3.4.3 Forest Pattern Temporal Analysis

Forest spatial pattern following fire was also analyzed. Pre- and post-fire landscape conditions were separated by year of fire to examine how a burn alters forest pattern and vegetation re-growth. The temporal grain of one year reflects the natural fire cycle and allows inclusion of fires with no month or day information on ignition. Frequency distributions of landscape pattern metrics were created for locations with similar "time since fire" or "time until fire" characteristics. A 3-dimensional histogram facilitated the representation of a multi-dimensional relationship.

3.4.4 Decision Tree Model

The final objective was to create a national scale model identifying drivers of fire susceptibility. Determining the susceptibility to wildfire of a given landscape requires not only *a-priori* knowledge of biotic and abiotic conditions at fire locations but also the relative importance of each factor. For this study, I predicted locations of wildfire using landscape pattern metrics and abiotic covariates using a decision tree at the national level. Decision trees recursively partition large datasets to form a set of hierarchical rules that result in classes (Brieman et al. 1984). Decision trees are often used in a non-parametric exploratory manner to reduce the data volume, identify classes, and predict dependent variables based on a number of independent variables (Muthy, 1998). While the map of susceptibility is of interest, the use of a decision tree approach also allows for an exploration of the drivers of wildfire.

Pre-fire locations were identified and used as a *fire* class whilst non-burned locations were considered *non-fire.* Due to the absence of post 1999 fire data Nova Scotia, New Brunswick, and Newfoundland were excluded from the decision tree analysis. The number of burned pixels (n = 79,067) was much less than non burned pixels (n = 5,845,945), indicating a case of class imbalance. Imbalanced datasets may occur with environmental problems (i.e., detection of oil spills (Kubat et al. 1998)) and can result in the classifier having a bias towards the majority class (*non-fire* in this case), whereas the minority class (*fire*) is often the subject of study. Under-sampling of the majority class is suggested to overcome imbalance (Domingos, 1999), and can suit situations where the majority class contains data irrelevant to the classification process (Japkowicz and Stephen, 2002). The majority class was therefore under-sampled to 1.5 times the size of the minority class which maximized non-fire user accuracy and exhibited consistent high fire producer accuracy.

All four landscape pattern metrics and three abiotic covariates were used in the decision tree analysis along with ecozone and total count of fires in pixel. All pixels of class *fire* were included in the analysis to obtain the largest sample of pre-fire conditions. Pixels of class *non-fire* were subset using an ecozone-stratified random sample without replacement of size 1.5 times the minority class. This meant that ecozone non-fire pixels were represented at the same ratio of area burned; conditions in larger ecozones with less fire were not oversampled. All available data were subset into 70% training data for tree creation and 30% test data for tree validation. Monte Carlo simulations and resultant decision trees were completed to randomize which *fire* pixels occurred in training and test data and include a larger selection of the majority class. Twenty simulations were determined to be acceptable as all decision trees had similar leaf nodes. Final decision tree values were decided upon by using the simulation with highest *non-fire* user accuracy. Locations of fire susceptible cells were mapped.

The accuracy of the fire susceptibility model was evaluated. A confusion matrix was created to assess the decision tree accuracy for predicting fire location. User and producers error was calculated for both *fire* and *non-fire* classes and the Kappa coefficient (Cohen 1960) was used to assess overall accuracy. While overall accuracy is important, misclassification was anticipated to occur as forest with potential to burn has not yet. For this reason, high non-fire user accuracy may be more relevant in assessing model accuracy as it indicates lower non-fire commission error, or few fires accidentally classified as non-fire.

Model accuracy was also evaluated by ecozone using historic burn areas. Ecozone specific values of fire susceptible area and total area burned between 1980 and 2007 were standardized by total ecozone area. A Pearson correlation was used to assess relation between historic area burned and modeled susceptible area.

3.5 Results

3.5.1 Composition Distribution

Examination of landscape class composition in Canada (Figure 3.2) indicated that 44% of forested ecozones are forest class pixels and there is a fairly equal distribution of broadleaf, coniferous, mixedwood and wetland trees. Non-treed vegetation classes (i.e., shrubs, bryoids, wetland) compose a total fraction slightly less than the sum of treed classes. Non-vegetation classes and Other consist of 12.9% and 3.6% of the study area, respectively.

The fraction of forested ecozones pixels burned by large fires between 2003 and 2007 was 1.8%. Large forest fires predominately burn in forested pixels with coniferous forest as the principal class for fire (55.1% of burned pixels). Dense and open coniferous stands burned at a greater frequency than sparse given their natural distribution, but sparse conifer stands also exhibited a large fraction of pre-burn landscape. Broadleaf, mixedwood and wetland treed forests compose a small percentage of the area burned by large fires. Wildfires often occur in non-treed vegetation as well, either as grass or shrub-land fires or as collateral damage from forest-centric fires. Non-vegetation and other classes are still present in burn locations.

Between 1980 and 1999, 11.9% of forested ecozones pixels were burned by large forest fires. The post-fire land cover composition is similar to the typical distribution of classes in forested ecozones. The largest reduction in land cover class occurs within the coniferous classes (34% decrease) with open stands exhibiting the largest post-fire decrease followed by dense stands and sparse. Landscapes following burn tend to be higher in non-treed vegetation (22.2% increase) and non-vegetation classes than prior to fire. Few changes occur through the other forest classes.

3.5.2 Composition and Covariate Distribution

Relative frequency distributions and differences for all forested ecozones and pre-fire locations for landscape pattern metrics can be observed in Figure 3.3 and abiotic covariates in Figure 3.4. A greater difference in relative frequency indicates that fire is occurring in these landscape types at a higher rate than would be expected at random. The magnitude of difference may be an indicator of how preferential that landscape type is to fire (or *vice versa*), though it may also be a product of the greater percentage of fires within that landscape class. Consideration should be taken to acknowledge the total distribution of metrics and covariates across Canada.

Pixels with a higher percentage of forest cover are more often burning than those with less cover, though fires do occur through all landscapes regardless of percentage forest. Landscapes with fewer patches and small patch area were most frequently burned, though large patch areas appear more preferential to fire. Fire occurred relatively evenly through all landscapes regardless of forest to landscape fragmentation ratio, though burns preferentially occur where forest is less fragmented than the surrounding landscape.

The largest number of pixels burned occurred between 50 and 150 km away from populated places and within 12 km of a road. Burning preference is similar for all proximity metrics; fires occur with higher regularity at low to intermediate distances from populated places and roads. While fires are most frequent near to roads, occurrence is less than expected based on random. Similarly, fires burn most frequently at elevations between 290m and 580m with a negative preference in the lowest elevations: 1 – 280 m.

3.5.3 Forest Pattern Temporal Analysis

Landscape pattern metrics show distinct change and eventual return to pre-fire distributions after large fire events (Figure 3.5). All metrics demonstrated distributional changes immediately following fire (1999) when compared to pre-fire conditions (2001-2007). Percentage forest cover was high prior to burn. The distribution changes following burn and smaller values of forest cover are resultant, indicating that post-fire landscapes have relatively little forest cover. Number of patches increases following burn and mean forest patch area shifts from a bi-modal distribution with equal large and small patch landscapes to a small patch dominated landscape. The proportion of patches that are forest was found to have changed from a weak bi-modal distribution pre-fire to one of increased fragmentation compared to surrounding landscape.

All landscape pattern metrics for burn locations exhibited temporal trends toward pre-fire conditions. Percentage of forest increased across the landscape, number of forest patches decreased, mean forest patch area increased, and forests became less fragmented than the surrounding landscape. While the rate of change varied by metric, all distributions resembled pre-fire landscapes at 19 to 20 years after burn.

3.5.4 Decision Tree Model

The decision tree model for determining national scale drivers of fire susceptibility in Canada is presented in Figure 3.6. One landscape pattern metric (mean forest patch size) and three abiotic covariates (proximity to light, proximity to road, and elevation) were determined to be the best defining independent variables for burn locations. Patch area was determined to be most important and landscapes with a mean forest patch area of less than 0.64 ha were considered unlikely to burn. Next, pixels that were < 61km from populated places were excluded from the possible burn regions, as were landscapes above 1105 m. Finally, landscapes within 98 km of a road were considered possible burn locations.

The error matrix for the decision tree model is presented in Table 3.1. Total accuracy for the model is 61.3% with a Kappa coefficient of 0.268. There were low errors of commission for the *non-fire* class (20.1%) and low errors of omission for *fire* class

(17.86%). The largest misclassification occurred when *non-fire* pixels were incorrectly classified as *fire*.

Susceptible burn regions were mapped according to decision tree drivers (Figure 3.7). The mean patch area limits large sections in the western Boreal Cordillera, the Taiga Plains, and northern parts of the Taiga Shield, as well as scattered regions through all ecozones. The minimum distance to populated places created the hollow circles evident around the medium to large settlements in all regions. Maximum elevation limits removed large sections within the western, mountainous ecozones, but nothing within central or eastern Canada. Finally, the upper proximity to road limit removed northern patches in the Taiga Shield and Hudson Plains.

Driver related fire susceptible locations are found throughout the forested ecozones of Canada though the amount varies by ecozone. Ecozone-specific comparison of susceptible area and area burned (1980 – 2007), standardized by total ecozone area, are presented in Figure 3.8. Application of Pearson correlation indicates that there is a relationship between susceptible area and actual area burned by ecozone ($r = 0.752$). The decision tree model correlates best with area burned in the Taiga Plains, Boreal Shield (both large area susceptible, large area burned), and Montane Cordillera (low area susceptible, low area burned). The model correlates poorly with Hudson Plains and Pacific Maritime (high area susceptible, low area burned).

3.6 Discussion

Identifying landscape characteristics that precede large fire events aids understanding of conditions present at fire-prone locations. Large fires most often occur in coniferous forests of all densities due to increased proportion of coniferous forest in fire-dominated northern forested ecozones, non-suppression of large fires in northern ecozones (Ward et al. 2001), and importance of fire in the evolutionary history of certain conifers (Moore et al. 1999). Wildfire does not occur in Non-treed vegetation classes as often as in forest. Similarly, Non-vegetation and Other classes experience less area burned than the expected at random. Most non-forest burn is occurring as collateral damage within large forest fires. A small number of grassland-centric fires occur in Canada. While not included in our analysis scope, their importance is not overlooked (Bond and van Wilgen, 1996).

Compared to national trends, burns are more often associated with high percentage forest landscapes as wildfire requires fuel to burn and large fires require greater forest coverage. Similarly, a low number of forest patches and larger patch size enables large fires to propagate though a landscape easily (Turner and Romme, 1994). Under representation of wildfire in medium numbers of forest patches indicates that low patch number is critical for large fire occurrence. Forests with less fragmentation than the surrounding landscape are also preferentially selected for. These findings match the predisposition for fire in non-fragmented landscapes that has often been observed at regional spatial scales (Ryu et al. 2007).

Relationships between fire and anthropogenic covariates characterize settlement and transportation networks (i.e., accessibility) as important drivers of fire susceptibility.

Large fires occur more often than expected between 100 and 300 km away from populated places, likely due to increased pressure for suppression when close to human interests. Proximity to road is similar, with more fire than expected occurring between 12 and 72 km from roads, as fires close to roads are a priority to manage for suppression effort accessibility. The difference in magnitude between high-fire road and populated place proximities can be explained as roads are more wide-spread than populated places. By connecting populated locations, roads themselves do not correspond as well with highly protected human interests. The reduced occurrence of fire starting at 84 km to roads and 400 km to populated place is an artifact of reduced road network occurrence in low burn areas within the northern Taiga Shield and Hudson Plains. These are regions where natural drivers such as wetlands are controlling landscape fragmentation (Wulder et al. 2010) and decreasing fire susceptibility.

Large fires most often occur in elevations below 1000 m. Elevation likely influences fire frequency by controlling surface moisture and species composition, and fuel moisture has been demonstrated to increase with elevation (Hayes 1941). While the relationship between elevation and large fires will vary at a regional level, a 1000 m limit is similar to those found in other studies (1000 m in the Mediterranean, Diaz-Delgado et al. 2004; 1500 m in the Washington Cascades, Camp 1999; 800 m in Alaska, Kasischke et al. 2002). The limited occurrence of fire at low elevations can be explained in part by the increased wetland prevalence and decreased fire occurrence in the Hudson Plains.

Based on the decision tree model, mean forest patch area is the most influential factor on large fire susceptibility. Few large fires occur in forest patches smaller than 0.63 ha. Northern regions with sparse tree coverage, regions of high elevation, and regions where fire has recently occurred are determined to be less susceptible using this rule. The decision tree rules for proximity to populated place and elevation corroborate findings observed in the relative frequency distributions analysis. Reduced fire susceptibility with far distances to roads, though counter intuitive, is accounting for the lightly burned northern Taiga Shield and Hudson Plains without removing the heavily burned northern Taiga Plains and Taiga Cordillera. Considering similarities in fragmentation drivers in these ecozones (Wulder et al. 2010), this emphasizes the importance of roads on fire and may indicate an anthropogenic influence on fire activity in the Taiga Plains and Taiga Cordillera.

At the scale examined, forest pattern is less important than anthropogenic influence in driving large fire processes. The absence of forest pattern variables in our model of fire susceptibility drivers is perhaps not unexpected. This model has been created for a national extent to assess large scale drivers of wildfire, but the relationship between forest pattern and fire process varies spatially. There are numerous fire behavior regimes within Canada (Parisien et al. 2006; Stocks et al. 2002) and different landscapes that have adapted to each regime, influencing inter-fire landscape variation. Additionally, intra-fire variation may be resultant from collateral damage of large fires or extreme fire-weather causing burn of non-normal landscapes.

Anthropogenic influence appears to shape fire regimes at many spatial scales. Our drivers of fire susceptibility model has similarities with a study in the Ozarks Highlands Region of Kansas (Yang et al. 2008), an extent approximately 1.1% the size of our study area. Despite the differences in scale, both studies found human accessibility to be the primary driver of burn susceptibility and fire occurrence. Biotic and topographic factors were considered secondary descriptive elements though elevation was a greater descriptive factor in our model, likely due to larger study area.

While understanding conditions that lead to fire are important for modeling, management also requires knowledge of the response to forest fire. Large compositional changes occur after wildfire. The decrease in conifer forest composition associated with burn indicates that, in Canada, fire reduces the amount of coniferous forest in the short term. Conifer regeneration is expected given their co-evolution with fire, though regeneration times will vary by location (Shatford et al. 2007) and is dependent on fire severity (Key and Benson, 2005). The increase in Non-treed vegetation and Non-vegetation classes following burn demonstrate the importance of large fires in changing landscapes.

Many of the non-conifer forest classes (broadleaf, mixedwood, wetland) experience less than two percent change in amount of forest following burn. Wildfires do not occur as frequently in regions with non-coniferous forest. Natural fire regimes in these regions would likely involve fewer fires due to climatic controls. Increased anthropogenic-related ignitions or more severe fire weather, however, heightens fire risk and the overall impact on these species. While conifers may be evolutionarily adapted to high fire regimes, increased disturbance from fire could transform inexperienced environments (broadleaf and mixedwood) to non-treed or non-vegetation dominated regions (Ogden et al. 1998; D'Antonio and Vitousek, 1992).

Wildfire also changes landscape pattern. Wildfire increases fragmentation: percentage forest cover decreases, number of forest patches increases, mean forest patch area decreases, and forest to landscape patch ratio increases. The ability to accurately predict regeneration times for composition and configuration is essential for forest management, carbon modeling, and habitat analysis. Previous studies have examined regeneration compositionally as vegetation regeneration with normalized difference vegetation index (NDVI; Goetz et al. 2006) or net primary productivity (Amiro et al. 2000), and indicated regeneration time as five years or twenty to thirty years, respectively. Both of these measures take non-tree vegetation into account and reflect establishment of pioneer species and saplings. In this study, the regeneration of forest pattern to pre-fire levels took approximately 20 years. Forest cover increased, patches decreased in number, patch area increased, and forests became less fragmented. The twenty to thirty year period (Amiro et al. 2000) matches our response in percent forest cover. The short five year recovery period has been justified by accounting for spatial variability in burn severity (Goetz et al. 2006) which has demonstrated influence in vegetation recovery post-fire (Diaz-Delgado et al. 2003).

While national extent studies are important to understand the overarching, broad scale controls and results of wildfire, multiple fire behavior regimes exist within Canada (Parisien et al. 2006). Wildfire expectation and suppression requires region-specific analysis and fire management must be tailored to unique regions. The drivers of fire susceptibility model and map should be used as preliminary and exploratory tools. Local level susceptibility would include region specific expectations of fire behavior, anthropogenic influence, and ignitions, as well as temporally specific estimates of fuel moisture and fire weather (Wotton 2009).

The accuracy of the model, and thus the drivers of fire susceptibility, was considered accurate based on a producer accuracy of *fire* of 82%. The poor producer accuracy of *non-fire*, poor user accuracy of *fire*, and overall poor Kappa coefficient can be explained by the absence of future fire information. The model was especially accurate for the Taiga Plains and Montane Cordillera. Taiga Plains is an ecozone where large fires occur infrequently, whereas the Montane Cordillera experiences frequent, smaller fires. Conversely, the model performed less well the Hudson Plains and Pacific Maritime. Both Hudson Plains and Pacific Maritime have much less fire than the model anticipated, likely due to the amount of wetlands and amount of precipitation, respectively. The reduced susceptibility of mountainous, Cordillera ecozones compared to boreal forest ecozones is also evident, similar to findings by Parisien et al. (2006).

Fire severity is often related to extreme fire weather (Agee 1997) and can alter the degree of landscape change and regeneration. The influence of extreme weather is unaccounted for in this study due to the broad spatial and temporal scale which I examined drivers of fire susceptibility. With respect to climate change, however, it is important to understand where extreme fire weather is occurring, how frequently, and how it is changing. It is also important to examine how extreme fire weather and fire severity influence relate to drivers of susceptibility and post-fire landscape. Fine spatial scale models would benefit from the inclusion of weather.

3.7 Conclusions

The goals of this research were to characterize pre- and post-fire landscape conditions and determine drivers of national fire susceptibility in Canada. Fire burned predominantly in coniferous landscapes, decreasing coniferous classes after burn and increasing non-tree and non-vegetation classes. Landscape pattern metrics and abiotic covariates were used to demonstrate that large fire burns mostly in non-fragmented landscapes and at intermediate distances to anthropogenic influence. Fire immediately causes changes in landscape pattern and increases fragmentation, with regeneration to pre-fire landscape conditions takes approximately 20 years. Finally, a model of national scale drivers of susceptibility was created for Canada and identified non-sparse forest, anthropogenic proximity, and elevation as influential factors. Fire severity can influence all of these results, yet the NFDB does not currently contain accurate information on fire severity. Emphasis should be put on improving the estimation of fire severity from remote sensing techniques (Soverel et al. 2010).

Development of this national model of fire drivers provides a starting point for susceptibility modeling in Canada and emphasizes the influence of human activity on fire regimes. The distributions of land cover indicate that fire has broadly shaped the land cover composition, and that unnatural fires may negatively affect non-fire adapted forest. Additional insight has been given into landscape pattern regeneration after fire. This work provides a baseline for comparing future climatic influence on fire and landscape behavior. Future research should examine multi-scale implications, fire severity, and extreme fire weather impacts on landscape pattern and susceptibility.

Table 3.1 Error Matrix for accuracy assessment of the drivers of wildfire susceptibility decision tree.

Decision Tree Results

Reference Data	**No Fire**	**Fire**	**Producer Accuracy**	**Errors of Omission**
No Fire	16592	18454	*47.34%*	*52.66%*
Fire	4172	19193	*82.14%*	*17.86%*
User Accuracy	*79.90%*	*50.98%*		
Errors of Commission	*20.10%*	*49.02%*		

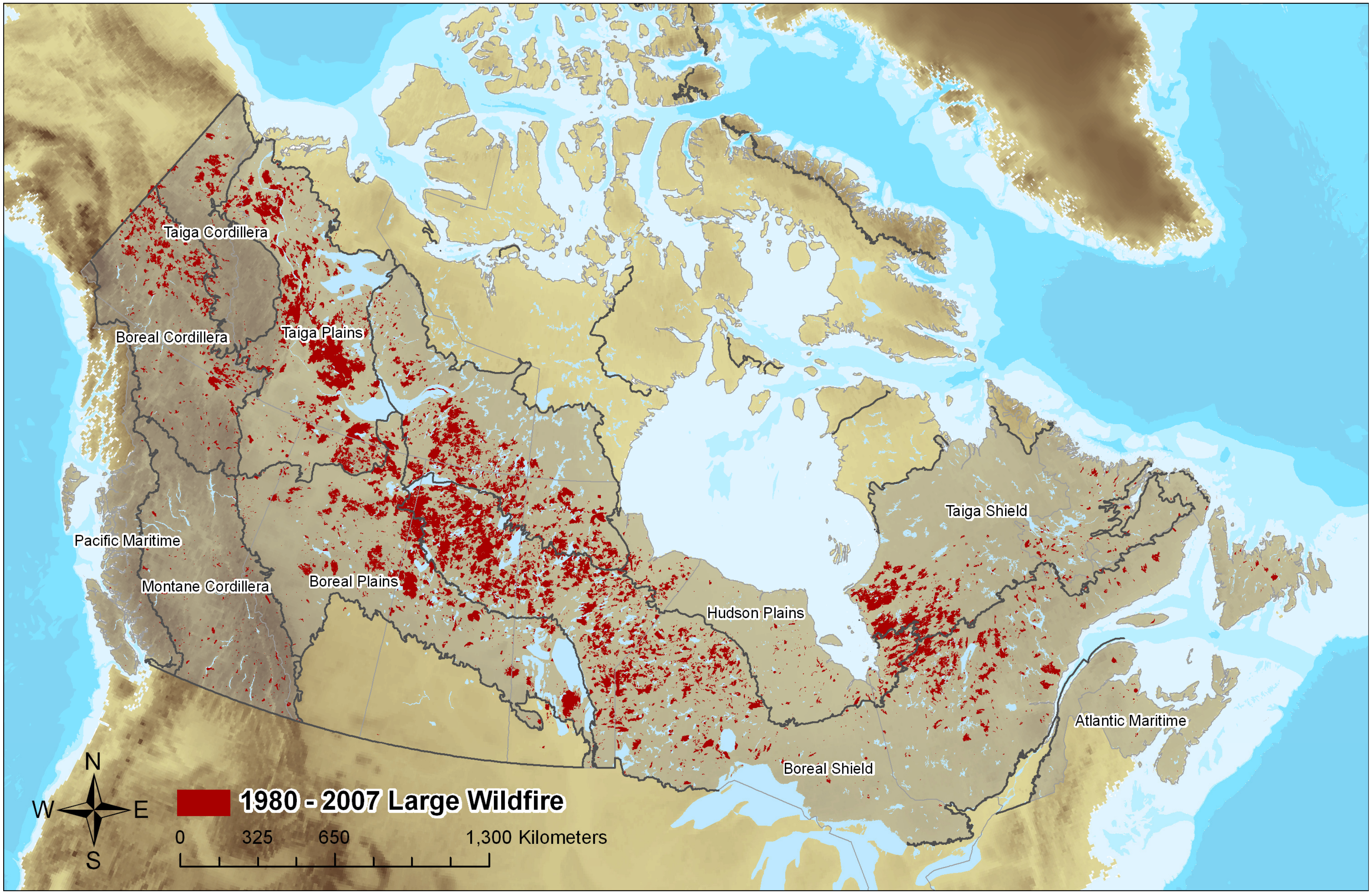

Figure 3.1 The ten Canadian forested ecozones and large wildfires (greater than 200 ha) between 1980 and 2007.

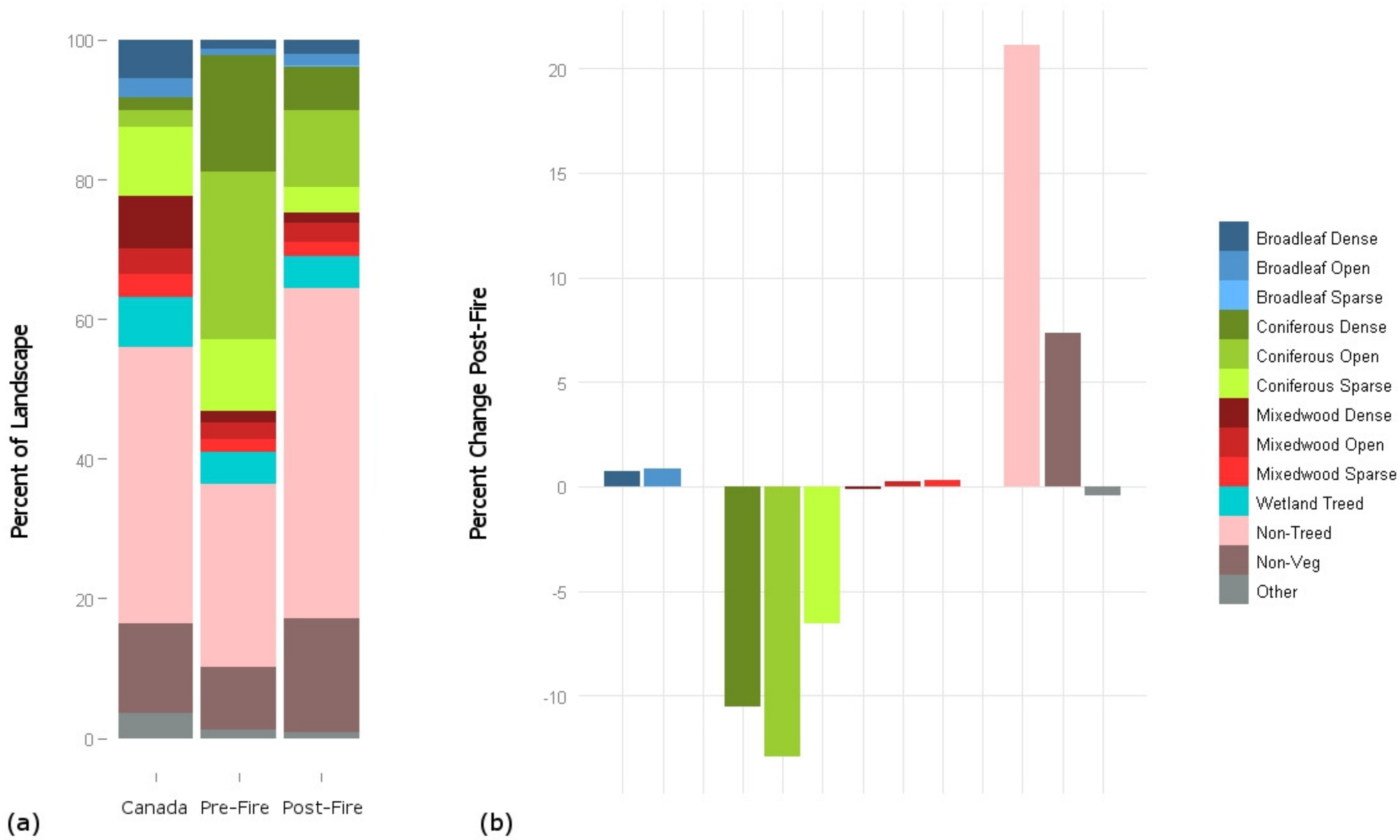

Figure 3.2 (a) Land cover composition distribution for all forest ecozones, pre-fire locations, and post-fire locations in Canada. (b) Post-fire percentage change by land cover composition class.

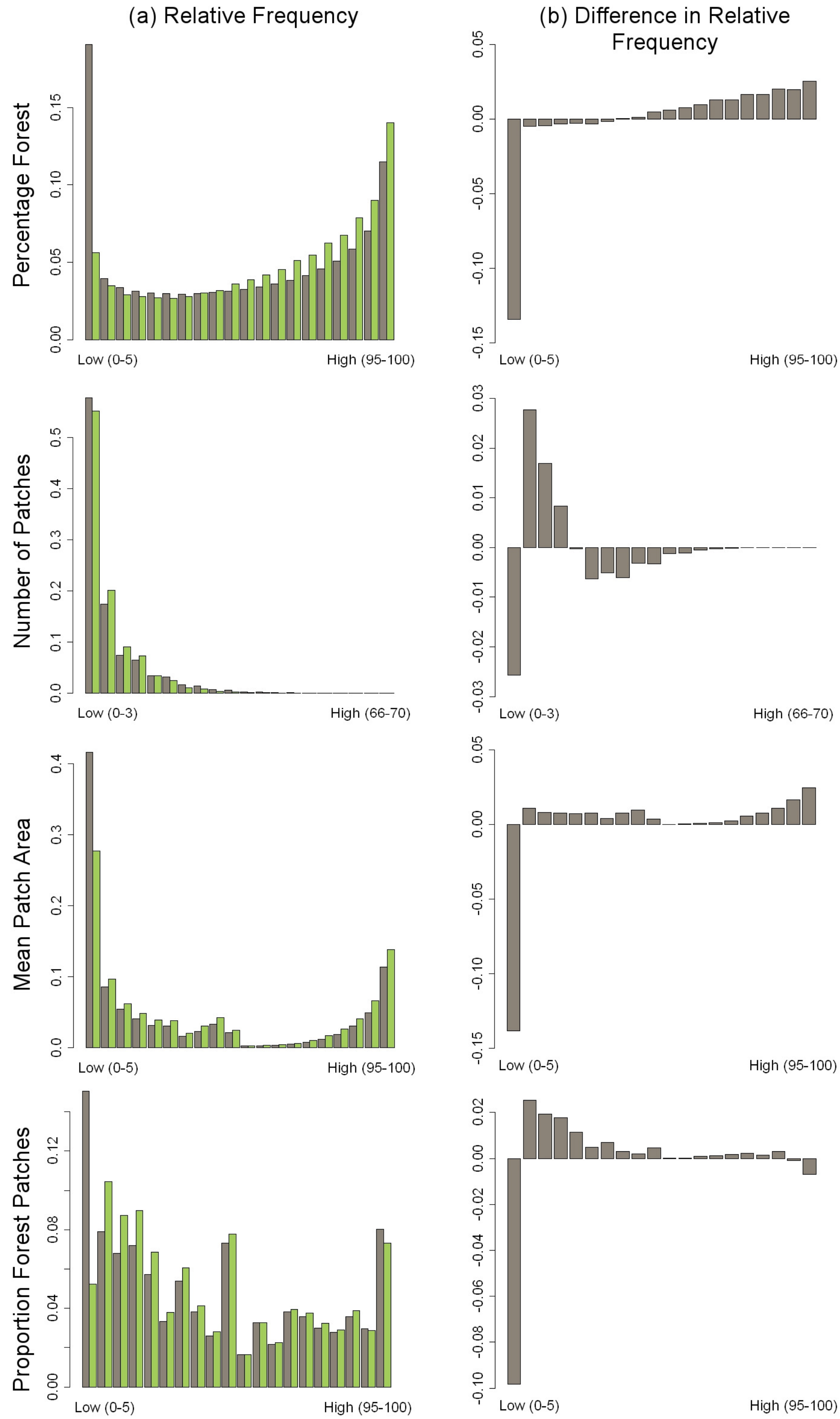

Figure 3.3 (a) Relative frequency distribution histograms for landscape pattern metrics in forested ecozones (grey) and pre-fire locations (green). (b) Relative frequency difference between forested ecozones and pre-fire locations for the same landscape metrics.

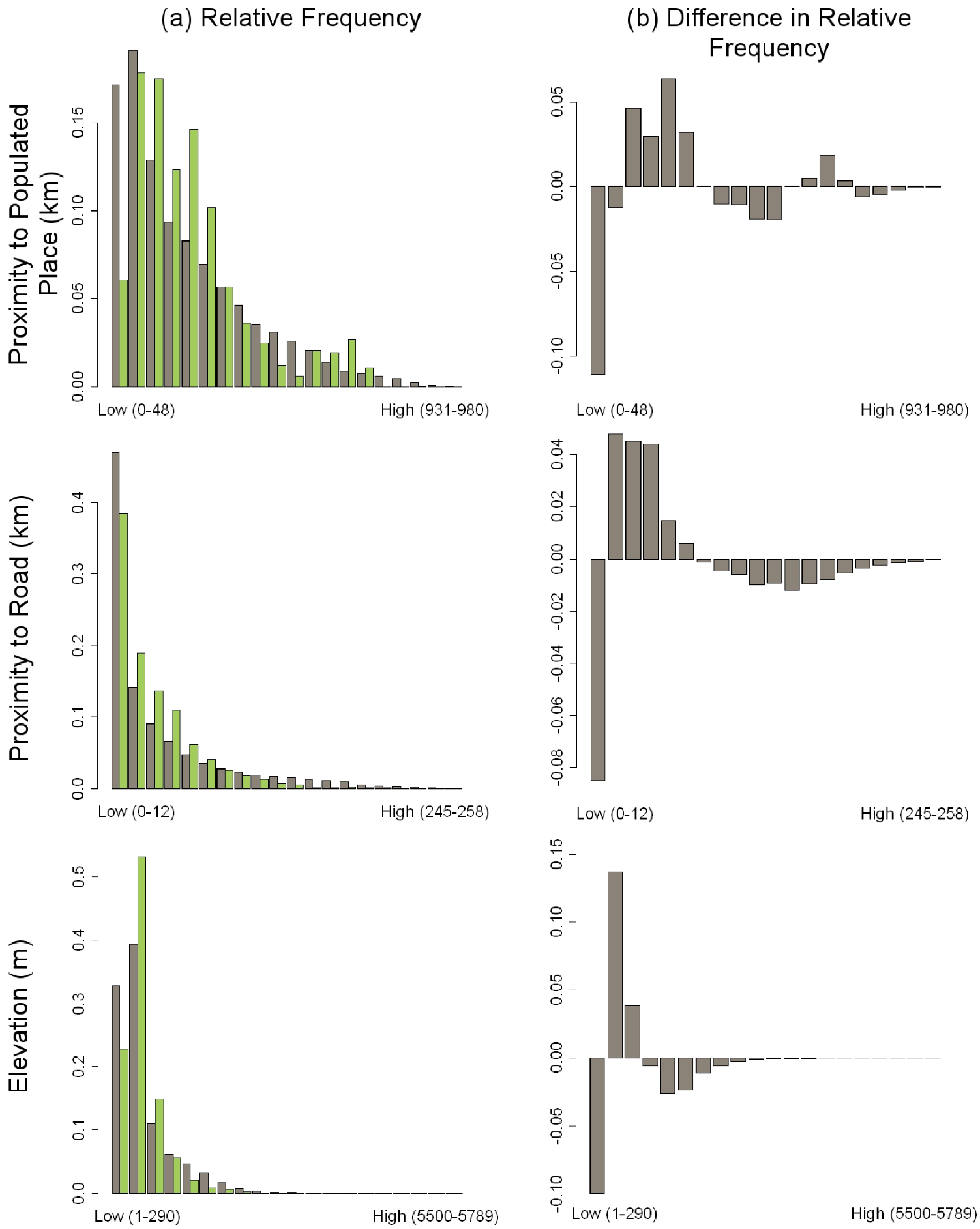

Figure 3.4 (a) Relative frequency distribution histograms for abiotic covariates in forested ecozones (grey) and pre-fire locations (green). (b) Relative frequency difference between forested ecozones and pre-fire locations for the same abiotic covariates.

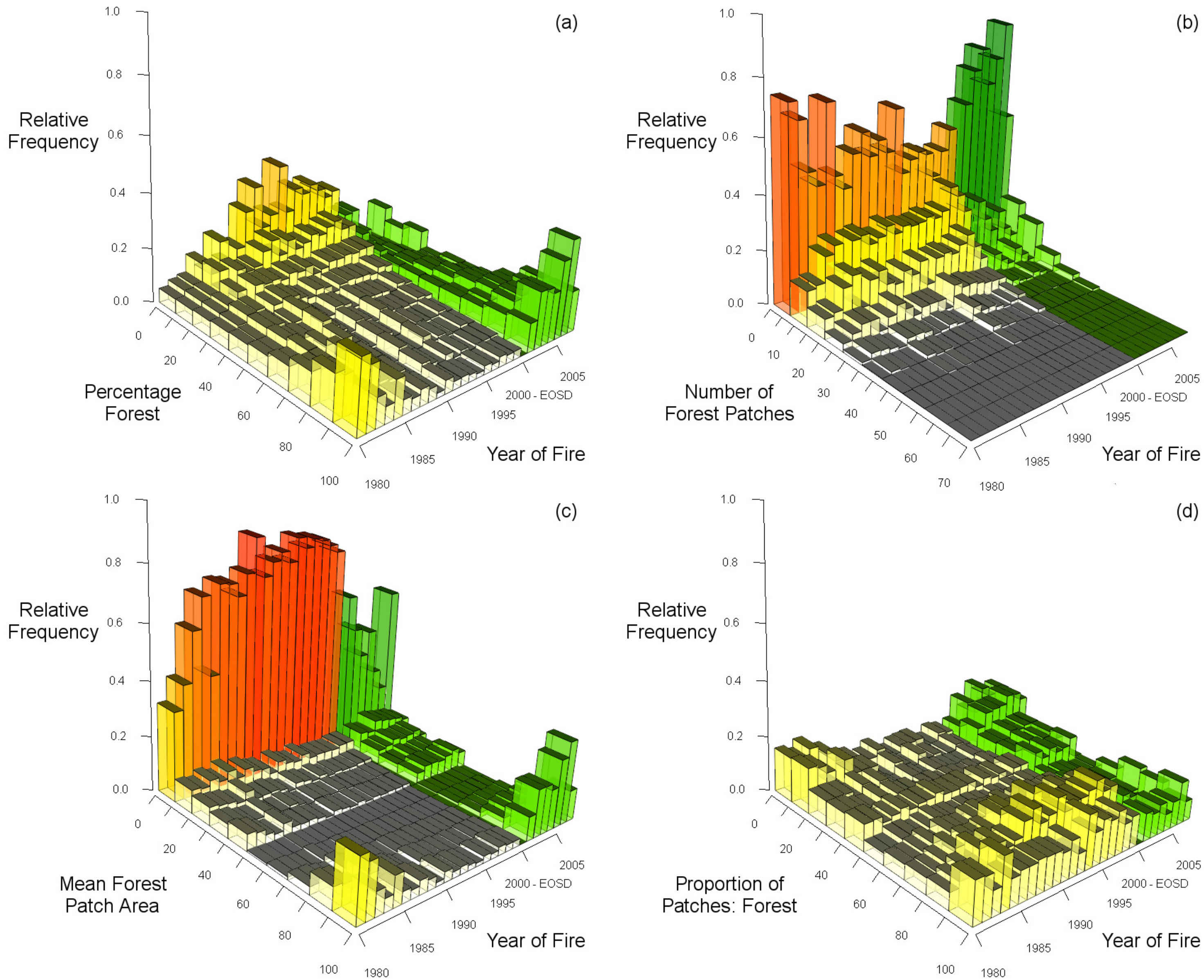

Figure 3.5 3-dimensional histograms of landscape pattern metric distribution by year of fire for (a) percentage forest cover, (b) number of forest patches, (c) mean forest patch area, and (d) proportion of all patches that are forest. Pre-fire conditions are indicated in green.

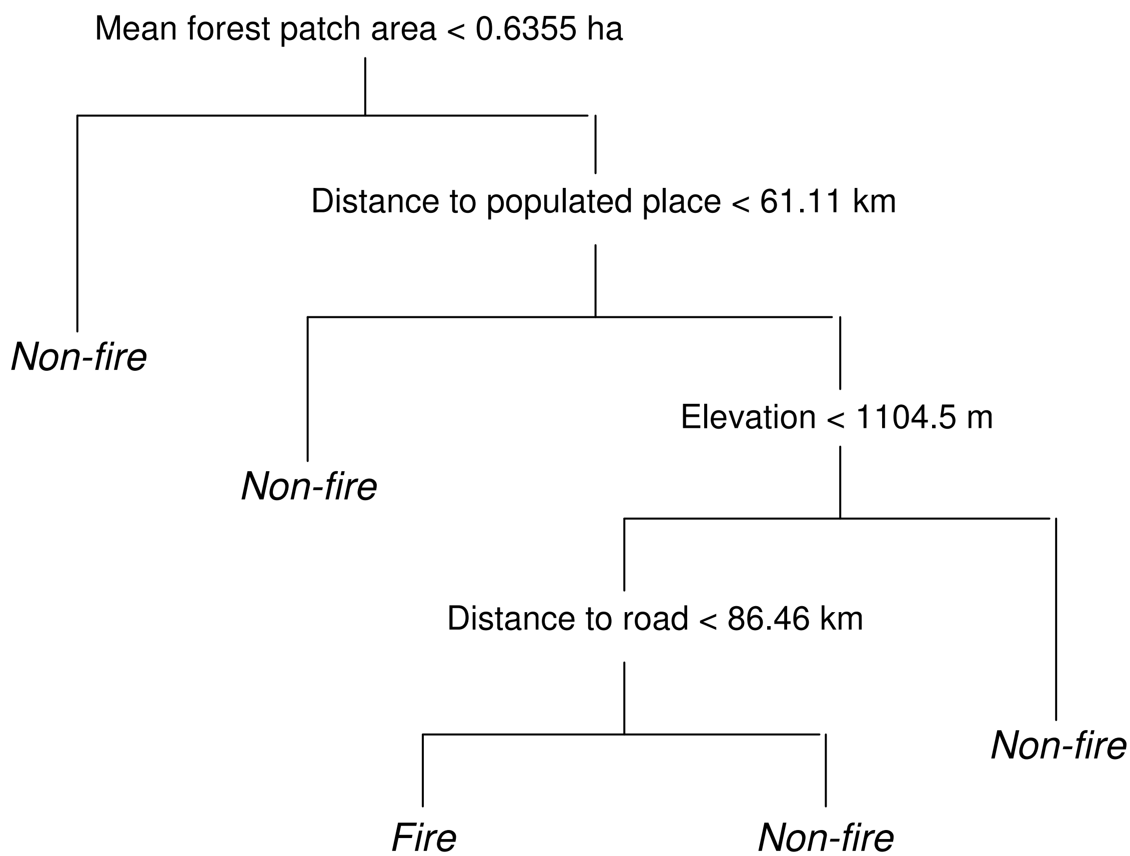

Figure 3.6 Decision tree model for identifying national drivers of large fire susceptibility in Canada. Decisions are made proceeding to the left if the statement is true.

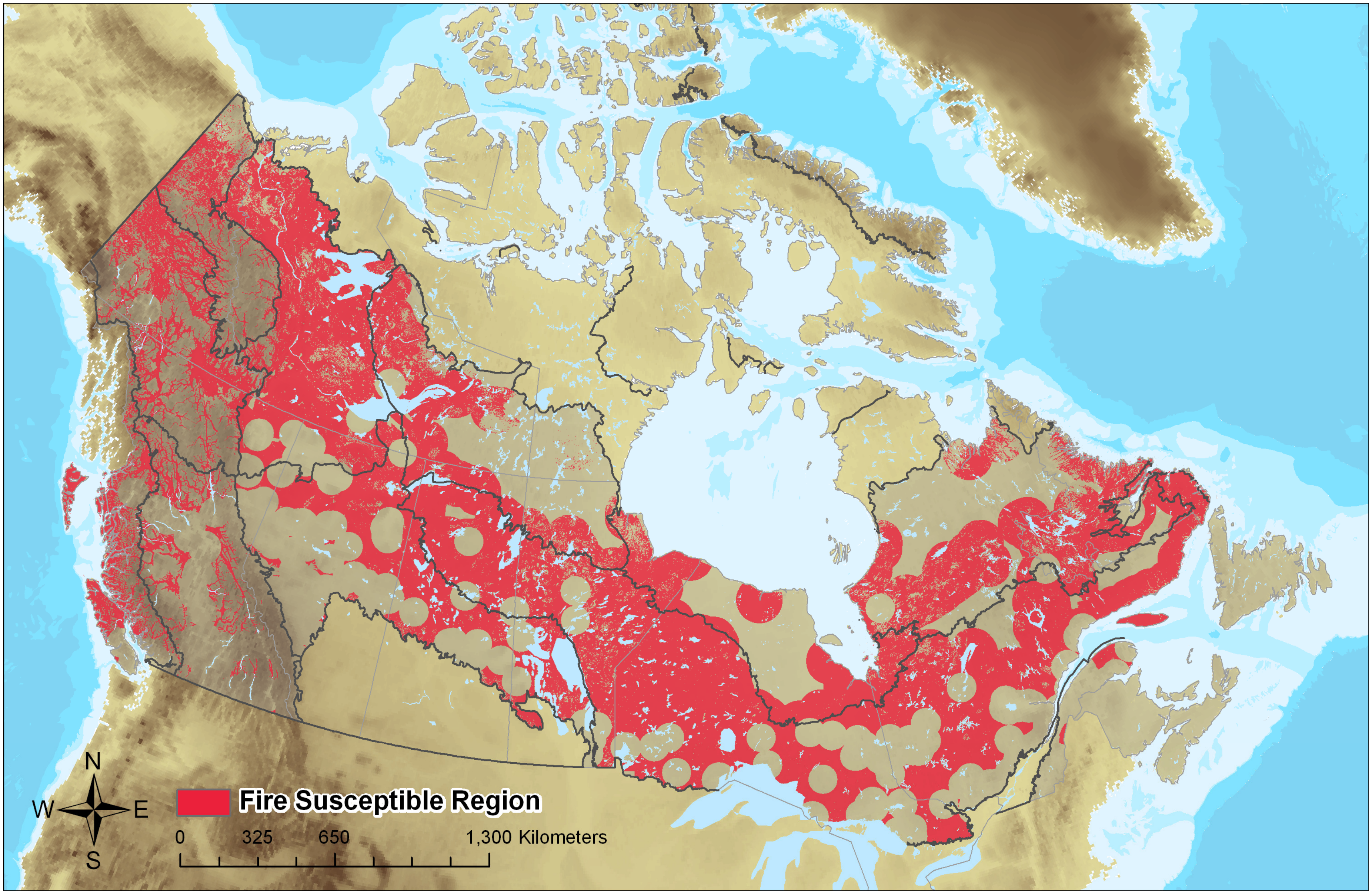

Figure 3.7 Susceptible large wildfire locations in Canada determined by decision tree derived national scale drivers. The circular pattern is a result of the minimum distance to populated place rule.

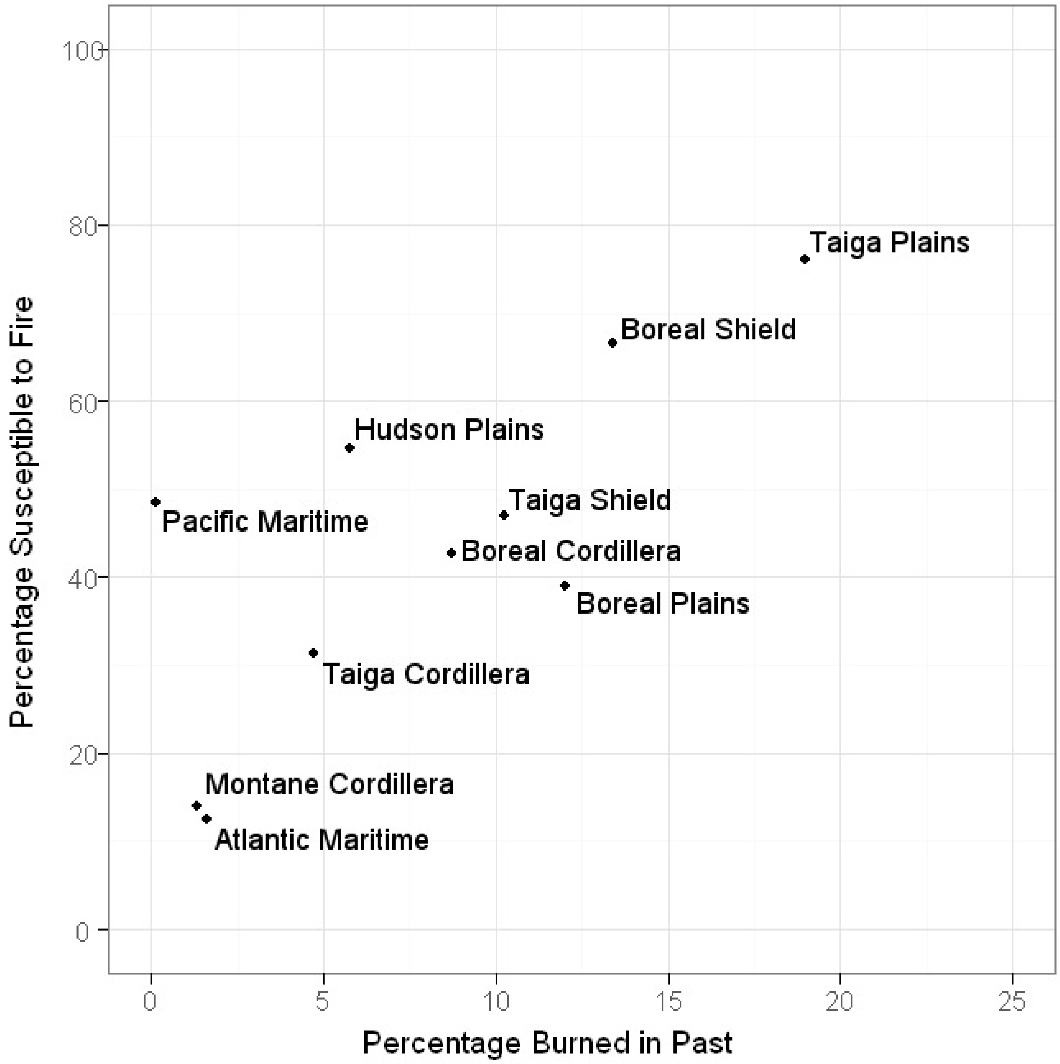

Figure 3.8 Ecozone-based comparison of area previously burned by large wildfires (between 1980 and 2007) and area susceptible to fire (determined by national scale drivers). Area is represented as percentage of total ecozone area.

CHAPTER FOUR

4.0 Conclusions

4.1 Discussion and Conclusions

A Firestorm 2003 Provincial Review was established to make recommendations for future management following the devastation of the 2003 fire season in British Columbia (Filmon 2004). Their summary of recommendations included suggestions of: 1. increasing knowledge of fuel reduction and treatment in human-forest interface areas and provincial parks, 2. amending land use plans to incorporate fire management considerations, 3. sharing knowledge with other jurisdictions with similar fire behavior, and 4. educating the public about preventing wildfire risk (Filmon 2004). This research can aid management and prevention of extreme fire damage by: 1. identifying optimal fuel treatment patterns for reducing fire susceptibility and risk, 2. suggesting land use plan changes by identifying landscape conditions prone to fire, 3. providing national-scale representation of similar fire regions, and 4. identifying human activity and education as a large and important aspect of fire prevention.

Wildfire activity is changing in Canada due to climate change (Flannigan et al. 2005; Stocks et al. 1998) and human activity (Calef et al. 2008; Rollins et al. 2001). In order to reduce human risk and damage, maintain natural fire regimes, and monitor changing forest and fire dynamics, we must first understand the spatial-temporal patterns of wildfire. The goal of this research was to examine and quantify the spatial and temporal patterns of wildfire across Canada. This was completed by characterizing the spatial and temporal pattern of fire occurrence across Canada and developing an understanding of drivers influencing wildfire susceptibility. Together these studies provide a national framework for assessing where wildfire will ignite, where it will burn, and the factors influencing each.

The development of wildfire ignition density estimates and temporal trajectories in Chapter 2 are novel methods for representing ignition occurrence and variation through space and time. The creation of unique ignition-based regimes allows for spatial delineation of similar ignition behavior regions. Ignition density and both increasing and decreasing ignition trends were positively influenced by proximity to populated places and roads. Similarly, homogenous fire regimes are delineated based on anthropogenic covariates and most influenced by roads. Finally, a method for identifying anomalous ignition densities was utilized, demonstrating the effectiveness of our national ignition expectation method for providing spatially explicit delineation of non-normal fire pattern.

Drivers of wildfire susceptibility and pre- and post-fire landscape conditions were examined in Chapter 3. Large wildfire typically occurs in coniferous forest landscapes with high percentage forest cover, low number of forest patches, larger patch areas, and less fragmentation than the surrounding landscape. Landscapes are more likely to burn if they are moderately close to populated places (100 to 300 km away) and roads (12 to 72 km away), and at elevations below 1000 m. National scale drivers of wildfire susceptibility were determined to be non-sparse forest, anthropogenic proximity, and elevation. Lastly, wildfire immediately alters landscape pattern, increasing overall fragmentation. Landscapes were observed to regenerate to pre-fire forest pattern conditions in twenty years.

The influence of anthropogenic activity on wildfire occurrence and susceptibility is evident from both thesis chapters. Results also indicate that wildfire processes are spatially heterogeneous, however, and the influence of fire behavior, human activity, and suppression will vary across space and time. National scale studies are important for strategic planning of wildfire, but regional analysis is necessary for management and tactical planning.

4.2 Research Contributions

The major contribution of this research is the identification of the dominance of anthropogenic influences on wildfire occurrence and susceptibility at a national scale. Few studies exist that examine the national scale impacts of wildfire in Canada (e.g., Parisien et al. 2006; Flannigan et al. 2005; Stocks et al. 2002), and none exist that examine the relationship between large fires and land cover or anthropogenic variables. Identifying drivers of wildfire in Canada will improve understanding of fire behavior ecology, forest management, and wildfire monitoring.

The Fire Occurrence Prediction System in the Canadian Forest Fire Danger Rating System does not have a standardized mechanism for assessing fire ignition probability across Canada (Wotton 2009). By utilizing historic ignition information and quantifying change at a broad scale, I have contributed a method for determining ignition expectation in Canada. Additionally, the creation of ignition regimes and quantification of anomalous ignition densities allows for spatially explicit delineation of important wildfire behavior that can be integrated with future studies. Understanding where ignitions are occurring, where they are changing, and identifying abnormal occurrence is crucial for wildfire management in a changing climate. The importance of anthropogenic activity on ignitions means that human activities must be accompanied by increased public awareness and management.

The identification of wildfire susceptibility drivers provides insight into factors controlling wildfire pattern in Canada. I have identified which landscape compositions and configurations burn most often, which anthropogenic covariates influence susceptibility, and which elevations are most likely to experience wildfire. Understanding how often fire occurs in these landscapes will allow fire management agencies to estimate broad scale probabilities of large fire in Canada's forests. Spatial pattern is also important for wildfire prevention (Konoshima et al. 2010), and my results can be used to develop effective fuel management strategies to best mitigate the possibility of large fire occurring or spreading. I identified landscape pattern changes following fire and a twenty year regeneration time to pre-fire landscape pattern. Knowing that landscape pattern influences many processes such as animal habitat and behavior (Helzer and Jelinski, 1999), net primary productivity (Turner 1987), and future fire occurrence (Ryu et al. 2007), this research will contribute insight about post-wildfire effects on ecological processes.

The development of national datasets quantifying wildfire activity (Stocks et al. 2002) and land cover (Wulder et al. 2008a) provided the opportunity for integration and analysis. The Earth Observation for Sustainable Development of Forest (EOSD) product (Wulder et al. 2008a) and derived landscape pattern coverages (Wulder et al. 2008b) are invaluable datasets for spatial research in Canada. Quantifying land cover and landscape pattern at a national scale is an arduous task. This well established, highly accurate data aids researchers due to its large coverage and multi-use nature. Availability of such datasets ensures higher quality data with better inter-study comparability.

This thesis demonstrates how large datasets may be combined to answer questions on pattern and process both spatially and temporally. It is necessary to develop techniques for the fusion and manipulation of large scale datasets as highly accurate, large extent data are increasingly collected and distributed. Additionally, few methods exist that explicitly consider both space and time. The methods in this thesis provide examples of how large data may be analyzed, reduced, and visualized in space and time to effectively convey relationships between wildfire and possible covariates. I have combined techniques from spatial statistics, geographic information systems (GIS), landscape ecology, time series analysis, cluster analysis, classification and regression analysis, and remote sensing to fully explore landscape-wildfire relationships. I utilized the strength of each technique to address my research questions in an explicit spatial-temporal manner when traditional analysis has been aspatial. National scale datasets capable of integration must continue to be created, distributed and explored with spatial-temporal methods when addressing issues such as climate change and anthropogenic expansion.

4.3 Research Opportunities

This research addresses broad scale spatial and temporal pattern of wildfire occurrence and susceptibility in Canada. Influential factors of wildfire will vary depending on the scale of analysis (Turner et al. 2001). It is important to examine a process through multiple scales to determine scale-dependent controls and apply scale-appropriate management. Regional scale studies with smaller spatial and temporal resolutions will allow the inclusion of weather in the analysis and would integrate well with the Canadian Forest Fire Danger Rating System (Wotton 2009). Conversely, broad scale studies within non-boreal ecosystems (e.g., Mediterranean or Tropical) will allow comparison of biome-specific expectations of wildfire occurrence or susceptibility. Considering the spatially varying impacts of climate change and anthropogenic influence, such studies will contribute to a better understanding of future wildfire expectations globally.

The wildfire occurrence baseline provides a preliminary approach for evaluating ignition expectation and change. Though quantitative and based on frequency distribution outliers, detection of anomalous ignition densities is exploratory and future research should examine applying statistical significance to unexpected areas. Additionally, as climate change and anthropogenic influence alter fire behavior, it will be of interest to evaluate how, where and why fire ignition regimes are changing.

Fire severity, controlled by weather (Agee 1997), is considered to influence post-fire landscape composition, configuration, and regeneration (Key and Benson, 2005; Diaz-Delgado et al. 2003) yet was not available for inclusion in this thesis. Methods for estimating fire severity are currently being developed (Soverel et al. 2010). As fire severity is accurately included into fire datasets, multi-scale integration and analysis of its influence on landscape compositions and configuration would be beneficial. Additional, the analysis of the spatial and temporal distribution of varying severity fire would greatly compliment the work in this thesis: fire managers could identify where fires are igniting, which landscapes are susceptible and burning, and how severe a fire may be. Such an understanding of wildfire processes and pattern will help wildfire management agencies prepare and alleviate the impacts of extreme fire seasons.

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