Ontario boreal fire regimes in the context of lightning-caused ignition point spatial patterns

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Lightning-caused forest fires are one of the major natural disturbances in Ontario managed boreal forests. Survival of these forests with fires for centuries shows that such disturbances are integral to the boreal ecosystem and its ecological functioning. Characterizing the fire regimes defined by fire ignition frequency, fire sizes and their spatial distribution patterns etc. thus can help to improve our understanding of the boreal forest dynamics and provide guidance for management practices attempting to maintain biodiversity and achieve sustainability.

In this thesis the lightning-caused fire ignitions data for four ecoregions in Ontario managed boreal forests (3E, 3W, 3S and 4S) for 1960–2009 were analyzed using pattern analysis and density estimation to determine the spatial nature of fire ignitions. These fire ignition spatial patterns were further used (as weighted ignition scenario) to simulate forest fire regimes in the study area. Fire regimes were also simulated using spatially unweighted ignitions (unweighted ignition scenario). Non-spatial (total number of fires, total burn area, number of fires by size classes, annual burn fraction) and spatial (spatial burn probability) indicators of the simulated fire regimes under both ignition scenarios were compared to test the null hypothesis that modeled forest fire regime is not affected by the spatial patterns of input fire ignitions. All data analysis were performed for individual ecoregions. Spatial pattern of ignitions were analyzed using the nearest neighbour index and Ripley's *K*-function. Ignition densities were estimated using the adaptive kernel density estimation method and the fire regimes were simulated using BFOLDS (Boreal Forests Landscape Dynamics Simulator).

Results showed that lightning-caused fire ignitions are clustered in all ecoregions. Fire ignition density also varied spatially within ecoregions. Overall fire ignition density was highest in the northwestern ecoregion (4S) and lowest in the eastern ecoregion (3E), which corresponds to the combined gradient of effective humidity and temperature in Ontario. For each ecoregion, comparison of non-spatial simulated fire regime indicators showed statistically non-significant differences between unweighted and weighted ignitions. The spatial burn probability however captured clear spatial differences between unweighted and weighted ignitions. Spatial differences in spatial burn probability between both ignition scenarios were more prominent in ecoregions of high fire occurrence. Results of the weighted ignition scenario closely followed the spatial patterns of the estimated fire ignition density in the study area. Based on these results this thesis rejects the null hypothesis and emphasizes that ignition patterns must be considered in simulating fire regime in Ontario boreal forests.

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Dedication

I dedicate my thesis to my ever loving parents, respectful parents-in-law and dearest family members who always pray for my success in all fields of life.

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Chapter 1

Introduction

This introduction provides the necessary background information about the need to understand boreal forest fire regimes and how lightning-caused ignitions spatial point patterns could be used to improve how they are modeled. Section 1.1 reviews the natural disturbance emulation concept in forest management with particular emphasis on managed boreal forests in Ontario, Canada. In Section 1.2 the role of fires in Ontario boreal forests is discussed. Section 1.3 presents a brief discussion about fire regime characterization methods and their limitations. Further discussion explains the scope of simulation modeling in characterizing forest fire regimes. In Section 1.4 fire ignition and spread in fire models is discussed. In Section 1.5 the need to investigate the fire ignition spatial patterns and their subsequent use in fire regimes simulations is reviewed. In Section 1.6 the research aim, hypothesis and objectives are stated. Finally structure of the thesis is described in Section 1.7

1.1 The Need to Emulate Natural Disturbance in Forest Management

Boreal forests (Figure 1.1) have played a pivotal role in Canada's economic, social and environmental landscape for several centuries (Drushka, 2003; Johnston et al., 2006). Since the 1940s these forests have been increasingly managed for sustained yield and to meet the increasing demand for timber. This management strategy, which focused on harvesting commercially valuable species and effective wildfire suppression (Gauthier et al., 2009) has significantly changed these forests (Kimmins, 2004). Compared to naturally burnt forests, managed boreal forests now have less diversity in age-class distribution (Franklin, 1993; Long, 2003), and they are more prone to catastrophic fires due to accumulated forest fire fuel as a result of logging slash and fire protection (Covington, 2000; Díaz-Avalos et al., 2001; Flannigan et al., 2009). The more-or-less exclusive focus on pulp and lumber production also overlooked other ecological processes including biodiversity conservation that are necessary for ecosystem resilience and sustained forest productivity (Chapin et al., 1997; Schwartz et al., 2000; Seymour & Hunter, 1999). To address these concerns, the concepts of ecosystem sustainability based forest management (Leopold et al., 1963) gained in popularity during the 1980s (Hunter, 1990; Long, 2009). Among these strategies is the Emulating Natural Disturbances approach (hereafter called END), which focuses on natural disturbances as inherent ecological processes responsible for shaping and sustaining natural forest landscape (Attiwill, 1994; White & Pickett, 1985).

Figure 1.1 The geographic extend of boreal forests and other forest types in Canada (Source: The Atlas of Canada http://atlas.nrcan.gc.ca/).

According to Seymour & Hunter (1999) preserving natural forest landscapes and their attributes is the best way to maintain biodiversity and ecological processes. END has therefore gained considerable popularity and is a prominent goal for Canadian boreal forests to reproduce the main attributes of natural landscape (Bergeron et al., 2007; Krawchuk & Cumming, 2009).

According to Perera & Buse (2004, p.4) END *is an approach in which forest managers develop and apply specific management strategies and practices, at appropriate spatial and temporal scales, with the goal of producing forest ecosystems as structurally and functionally similar as possible to the ecosystems that would result from natural disturbances, and that incorporate the spatial, temporal, and random variability intrinsic to natural systems.*

The 17.1% of Canadian boreal forests that is in Ontario extends between the northern limits of the Great Lake St. Lawrence forests to the Hudson Bay lowlands. Out of the total 50 million ha of boreal forests in Ontario, 49% are actively managed (OMNR, 2010a). Figure 1.2 shows the distribution of these managed boreal forests in the province. In Ontario END became a legislated management strategy with enactment of the Ontario Crown Forest Sustainability Act 1994 (Statutes of Ontario, 1995, c.25, s.2(3)), which states:

Crown forests should be managed to provide for long term health and vigor by using forest practices that, within the limits of Silvicultural requirements, emulate natural disturbances and landscape patterns while minimizing adverse effects on plant life, water, soil, air and social and economic values, including recreational values and heritage values.

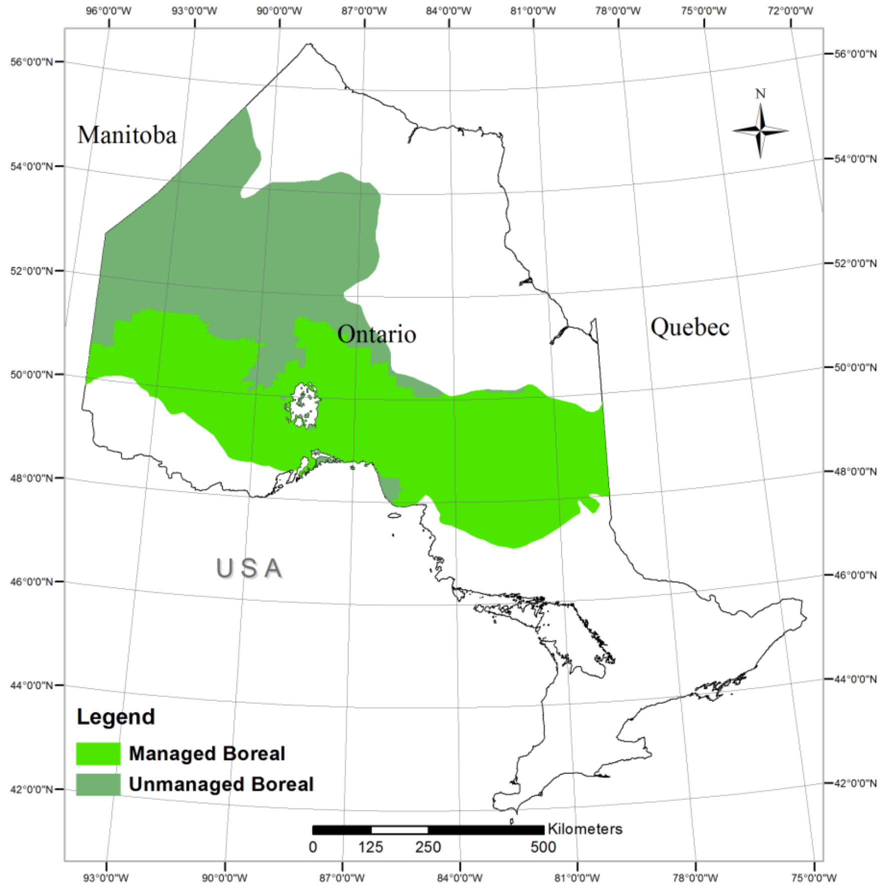

Figure 1.2 Geographic extent of managed and unmanaged boreal forests in Ontario as demarcated by Ontario Ministry of Natural Resources.

The rationale of this management concept is that biodiversity will be preserved and sustainability will be maintained if the human induced disturbances (mainly harvesting) are within the range of variability of natural disturbances (Andison et al., 2009; Bergeron et al., 2004a; Crow & Perera, 2004; Drever et al., 2006) as historically forest ecosystems have been resilient to these disturbances (Holling, 1981). In practice END does not aim to emulate all the effects and processes of natural disturbances, instead it satisfies the needs for harvesting while attempting to maintain ecosystem functions and structure (Kimmins, 2004). It uses knowledge of disturbance regimes to guide forest managers to adequately represent age class diversity across landscape (Gauthier et al., 2009; Valliancourt et al., 2009). Good understanding of the disturbance regimes and associated forest dynamics is therefore very important for the success of END (Bergeron et al., 2007; Jetté et al., 2009; Klenk et al., 2008; Perera & Buse, 2004).

1.2 Fire as Natural Disturbance in Ontario Boreal Forests

Fires are a dominant natural disturbance in Ontario boreal forests. According to OMNR (2010b), an area of 14823 ha burned due to 939 fires during 2010, and on average 76021 ha forests burned with average number of 1087 fires during the last ten years. These fires play an integral role in the ecological functions by removing the vegetation layer and shape the landscape by affecting post fire vegetation composition (Perera et al., 1998; Suffling, 1995; Suffling et al., 1988; Veraverbeke et al., 2010). Characterization of the fire regimes defined by frequency, size, probability/density, severity and spatial pattern distribution etc. (Amatulli et al., 2007; Pennington, 2007; Weber & Flannigan, 1997) is a common focus of research aimed to understand ecological effects of forest fire for implementing END in Ontario (Suffling & Perera, 2004). Figure 1.3 represents the conceptual model of Bergeron et al. (2007). There, a fire regime in a forest ecosystem is characterized by a wide range of variability in fire size, fire frequency and fire severity (Figure 1.3a) that maintains biodiversity. The management regime, on the other hand, has a considerably narrow range of variability in harvest size, harvest interval and harvest severity and can also be outside the natural range of variability of fire regime (Figure 1.3b). They conclude that in a fire prone ecosystem only a forest management (managed disturbance) that is fully within the reference frame of forest fire regime (Figure 1.3c) will sustain ecological processes and biodiversity. Similar concepts are supported by others in the literature (Duncan et al., 2009; Krawchuk & Cumming, 2009; Pennington, 2007; Perera & Buse, 2004).

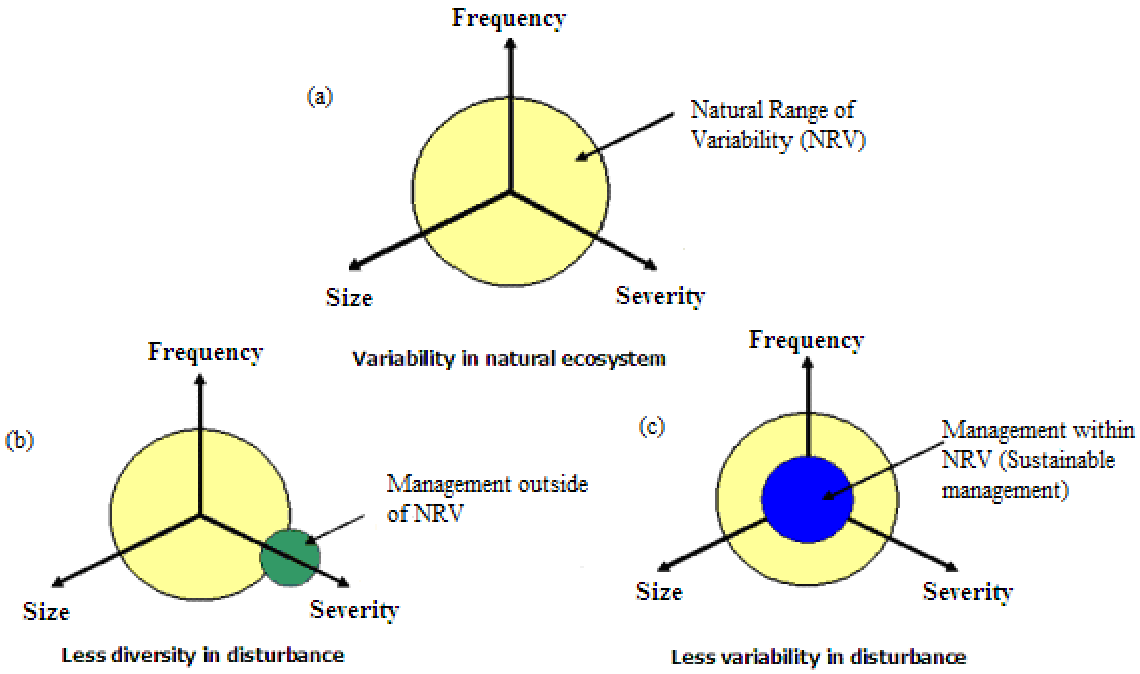

Figure 1.3 Conceptual model of natural and managed disturbances (a) variability in natural disturbance (b) forest management that incorporates little of the diversity of the natural disturbance, and (c) forest management reproducing natural disturbance (Source: Bergeron et al., 2007).

1.3 Fire Regime Characterization

A variety of methods, including tree rings analysis, sedimentary charcoal analysis, fire scars, historical narratives and photographs, land survey and management records, have been used to reconstruct the spatio-temporal reference conditions from naturally burnt forests (Carcaillet et al., 2007; Gauthier et al., 2009; Long, 2009; Perera et al., 2004b; Suffling & Perera, 2004). These methods however, provide insufficient information for reference conditions (Cui et al., 2009; Li, 2004; Perera & Buse, 2004) due to their incapacity to fully capture the range of fire disturbance variability (Bergeron et al., 2007; Scoular et al., 2010). Simulation modeling – the techniques to quantitatively express forest landscape dynamics by abstracting forest fire and forest cover changes related scientific knowledge (Perera et al., 2008) – is therefore, considered a feasible alternative (Cary et al., 2006; Crow & Perera, 2004; Gardner et al., 1999; Keane et al., 2004; Suffling & Perera, 2004).

Although modeling fire regimes is a complex problem due to the complex nature of fire phenomena (Couce & Knorr, 2010), various models can be used to simulate fire regimes. Mechanistic models like Prometheus (Tymstra et al., 2009) use mathematical equations to link the physical environment to the resulting phenomena. These normally deal with an individual fire event over the life of that fire and, in some scenarios, reasonably predict the local fire spread. The stochastic models like FIRE-BGC (Keane et al., 1996) are used to simulate multiple fire events over long time periods and are more suitable for landscape scale studies (He & Mladenoff, 1999).

Korzukhin et al. (1996) considered models as tools to facilitate the evolution of knowledge about a phenomenon, and classified models into two broad groups: empirical models and process (mechanistic) models. They stated that empirical models primarily describe the statistical relationship among observed variables. On the other hand, process models aim to understand relationships and describe data using key mechanisms or processes that determine an object's internal structure, rules and behaviour. They further argue that in process models more insight into ecological parameters can be gained whereas, in empirical models statistical relationships are the main determinants of the output. They concluded that process models impart knowledge about the forest system functioning and are suited for landscape level studies.

Regardless of the model classification, a variety of models are available to simulate forest fire regimes. Examples include BFOLDS (Perera et al., 2004a), Biome-BGC (Thornton et al., 2002), DRYADES (Mailly et al., 2000), FIRE-BGC (Keane et al., 1996), INTELAND (Gauthier et al., 1994), LANDIS (Mladenoff et al., 1996), MFFM (D'Andrea et al., 2009), SEM-LAND (Li, 2000) and Tardis (Cumming & Armstrong, 2001).

Keane et al. (2004) termed spatial models that simulate the dynamic interaction of fire, vegetation, and often climate, as landscape fire succession models (LFSMs). LFSMs have four essential components: vegetation succession, fire ignition, fire spread, and fire effects. Their output is commonly time-dependent, geo-referenced digital maps or GIS layers. They also compared 44 models on the basis of their approaches, design and scale of application. Among these, BFOLDS appears to be the only model being used for climate, vegetation and fire dynamics related research applications in Ontario.

1.4 Fire in Simulation Modeling

The occurrence of natural forest fires depends on a combination of an ignition source (lightning), climatic conditions (temperature, moisture and wind), fuel (distribution, condition and load) and topography (Ku-Muhammad & Yun, 2009; Price & Rind, 1994; Vázquez & Moreno, 1993). Likewise, the models simulate fires as a function of forest fire weather (temperature, relative humidity, precipitation and wind), forest fuel (derived from forest types) and topography, using the most sophisticated fire spread algorithms available (Millers et al., 2008). Most of the Canadian forest fire models use output from the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group, 1992; Wotton, 2009) which uses forest fire weather, forest fuel type and topography as inputs to calculate fire behaviour variables. An overview of the structure of the Canadian FBP system is presented in Figure 1.4. This system is based on physical models calibrated with empirical observations of fuel moisture, fuel consumption and fire behaviour. For fire weather, it relies on another system: the Canadian Forest Fire Weather Index (FWI) system. FWI (Figure 1.5) integrates weather information (air temperature, relative humidity, wind speed and precipitation) and provides numerical ratings of fuel moisture in important fuel layers and fire weather indices without regard to differences in forest type (Wotton, 2009).

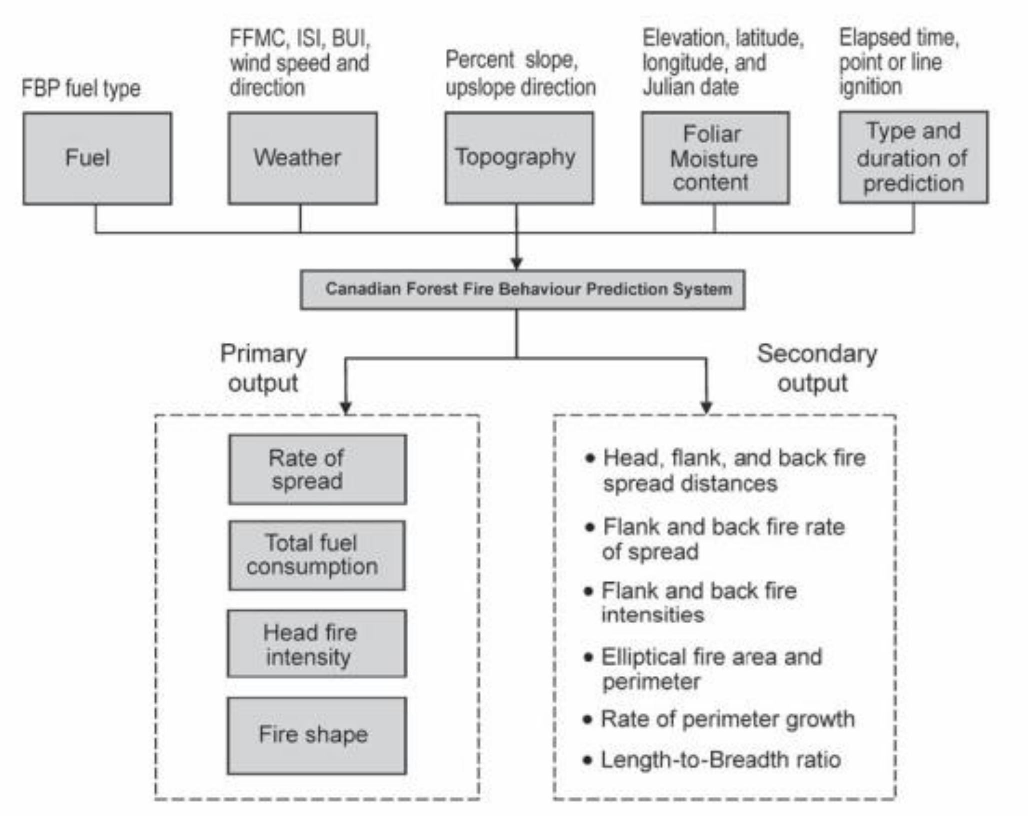

Figure 1.4 An overview of the Canadian Forest Fire Behaviour Prediction (FBP) System (Source: Perera et al., 2008).

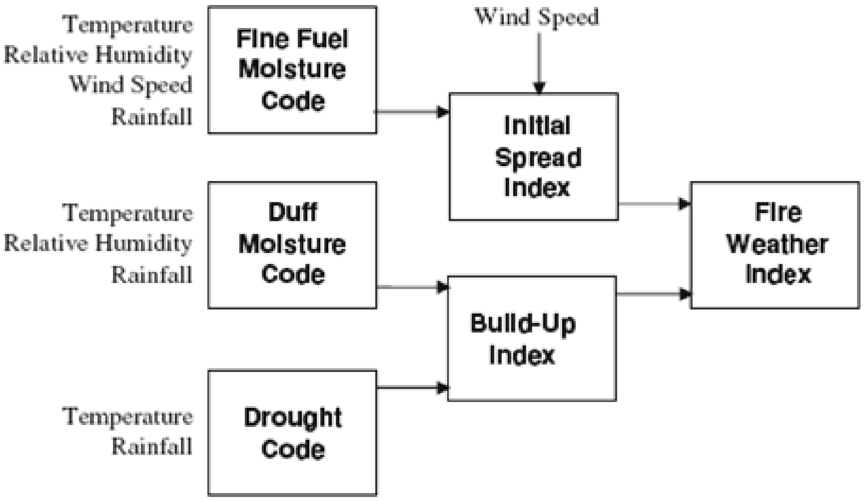

Figure 1.5 The structure of Canadian Forest Fire Weather Index (FWI) System (Source: Wotton, 2009).

Another important aspect to consider is the fire ignition process. Naturally occurring forest fires in Ontario are caused by lightning. However, not every lightning strike ignites a fire because of variability in moisture, bulk density, depth of the fuel (Kourtz & Todd, 1992), long continuing current (Latham & Williams, 2001), lightning polarity, multiplicity of lightning strikes (Fuquay et al., 1979) and many other factors interacting at multiple spatio-temporal scales (Keane et al., 2004). Due to limited lightning related data and knowledge (Perera et al., 2008) and poor understanding of the relationship/s between lightning strikes and realized ignitions (Genton et al., 2006; Larjavaara et al., 2005; Podur et al., 2003) lightning data are not commonly used in simulation modeling. Instead, many models follow a stochastic strategy that simulates ignition randomly or from probability distributions of fire starts using vegetation characteristics, climatic indicators, and/or topographical settings as independent variables (Keane et al., 2004).

1.5 Fire Ignition Patterns

Lightning-caused fire ignitions locations do not follow a uniform distribution (Dickson et al., 2006; Vázquez & Moreno, 2001). They typically occur in clusters (Amatulli et al., 2007; Genton et al., 2006; Telesca et al., 2005), which may result into large interconnected burned patches (Vázquez & Moreno, 2001). Therefore, the spatial distribution of fire ignitions across the landscape has a significant role in the subsequent fire regime, and if ignition distribution patterns are not modeled properly, results could be erroneous (Doran, 2004). Despite its importance, some modeling efforts e.g; using LANDIS (Chang et al., 2007; Chang et al., 2008) or BFOLDS (Munoz-Marquez, 2005; Rempel et al., 2007) do not appear to properly addressed the spatial patterns of ignition points in their research.

In many other studies either random distributions and/or density based methods are used to emulate the spatial pattern of natural fires and to seed fire ignitions in their study areas. D’Andreas et al. (2009) ignited forest fires randomly to assess the future land cover scenarios in his study areas (Region of Liguria, Italy and Alachua County, Florida, USA) by using MFFM (Modified Forest Fire Model). Doran (2004) assessed forest fire risk in Ontario’s Algonquin Provincial Park using the Prometheus model and applied two different approaches to capture natural range of fire ignition variability. In his first approach (lightning dependent ignition) he used annual maximum natural fire counts (i.e; 34 for the year 1997) to calculate the number of ignitions per month based on the percentage of lightning strikes during that month, which were then randomly distributed for simulation. In his second approach (random ignition) he randomly distributed 1000 ignition points, of which 775 were in fuels (forest) and were used in subsequent fire simulations. Similarly, Perera et al. (2009) and Perera & Cui (2010) applied two different scenarios i.e; (i) random and (ii) ignition density based on 42 years fire data, of fire ignition patterns in BFOLDS to account for the uncertainty in spatial patterns knowledge. Cui et al. (2009) also used a weighted fire ignition pattern based on the 42 years ignition density data to characterize fire regimes for ecoregion 3W in Ontario. Beverly et al. (2009) used ignition point densities of fires in Prometheus to assess the pattern for modeling fire susceptibility in West-central Alberta. These examples illustrate that most of the studies generate ignitions spatially random. Some also attempted to capture ignition spatial patterns in their modeling efforts by counting number of ignitions in a unit area.

On the other hand, studies investigating the spatial distribution (of fire occurrence) commonly use more advanced quantitative methods, such as those from point pattern analysis. Podur et al. (2003) used the *K*-function to identify the clustering nature of lightning fires in Ontario forests. They further estimated the spatial intensity of ignitions using kernel density estimation. Amatulli et al. (2007) applied an adaptive kernel density estimation approach to estimate the fire ignition density in their study area. They applied an analytical calibration procedure to estimate reliable fire density surfaces. Their results also demonstrated that fires are clustered. Genton et al. (2006) in their field-based analysis of wildfire ignitions in the St. Johns River Water Management District, Florida used distance-based point pattern tools (the *K*-Function & the *L*-Function) to describe departures from complete spatial randomness (CSR). Their results show that fire events tend to occur in clusters at all spatial scales examined (~ 2 km or more). Later, Hering et al. (2009) noted that, in field situations, fire intensities vary spatially and the constant intensity assumption can misinterpret trends as clusters. Their re-analysis of the same data using an inhomogeneous *K*-function resulted in less clustering as previously observed by Genton et al. Hering et al. (2009) therefore suggested that trends in fire events should be included in the model for fire ignition. In a recent study for the province of Alberta, Canada Wang & Anderson (2010) also used the *K*-function and the *L*-function to identify spatial clustering of fires. They also applied kernel density methods to estimate fire intensity surfaces. These aforementioned studies confirm that spatial randomness is not a valid option for simulating fire ignitions. The variation in observed ignition spatial distribution (mostly the clustering) is due to varying suitability of physical landscape, climatic conditions and fuel (O’Sullivan & Unwin, 2010). I therefore, propose in this study to conduct a detailed analysis of lightning-caused ignition in a northern Ontario study area and to further use these results in subsequent BFOLDS simulations to characterize fire regimes.

1.6 Research Aim

The purpose of this thesis is to quantify the spatial patterns of forest fire regimes in Ontario managed boreal forests, with emphasis on lightning-caused fire ignitions, using advanced spatial statistical tools. As BFOLDS is used to characterize fire regimes and to evaluate policy guidelines for END in Ontario, this thesis focuses on BFOLDS and addresses the following questions:

(1) What are the spatial patterns of lightning-caused fire ignitions in Ontario managed boreal forests?

(2) How can these patterns be used in BFOLDS and what are their effects (if any) on BFOLDS results/outcomes?

The thesis tests the null hypothesis that modeled forest fire regime is not affected by the spatial patterns of input fire ignitions.

The objectives of this thesis are:

(1) To understand the spatial patterns of lightning-caused fire ignitions in Ontario managed boreal forests at ecologically homogeneous scale.

(2) To estimate reliable lightning-caused fire ignition density surfaces that can further be used in research, planning and management activities, especially the BFOLDS landscape simulation model.

(3) To model forest fire regimes of the study area using these spatial patterns of fire ignitions.

(4) To assess the outcomes of BFOLDS in simulating forest fire regimes on the basis of fire ignition patterns.

1.7 Thesis Structure

The rest of the thesis is organized as follow

Chapter 2 introduces the study area and briefly describes the methods used in fire ignition pattern analysis and fire density estimation. This chapter also provides the details of fire regime simulations and the description of the employed model (BFOLDS).

Chapter 3 contains the first manuscript “Spatial patterns of lightning-caused forest fire ignitions in boreal Ontario, 1960–2009”. This manuscript will be submitted to International Journal of Wildland Fire for publication. Though I am the sole author of this thesis, my academic supervisor Professor Dr.

Roger Suffling and thesis committee members Dr. Ajith Perera and Dr. Douglas Woolford has valuable contribution in research problem identification, study design, data analysis and results interpretation. They will be the co-authors of this publication.

Chapter 4 contains the second manuscript “Sensitivity of simulated fire regime parameters to spatial patterns of fire ignition assumptions: a case study from Ontario managed boreal forests”. This is also a complete manuscript that will be submitted to Forest Ecology and Management journal for publication. The intended co-authors of this manuscript will be the same as that of first manuscript due to their valuable contribution in study design, interpretation of results and critical reviews of the manuscript.

Chapter 5 summarizes the findings of this thesis as detailed in the manuscripts, and suggests future work.

Chapter 2

Methodology

The methodology of the research is discussed in detail in the relevant sections of manuscript chapters (Chapter 3 and Chapter 4). Here I cover some information that is not included in these manuscripts chapters. In Section 2.1 a brief overview of the study area is provided. Section 2.2 discusses the pattern analysis of wildfire ignitions in the study area. Section 2.3 provides details about the fire density estimation method used in this research. Section 2.4 provides some details about BFOLDS, its main assumptions, and how fire ignition scenarios are incorporated into the fire regime simulations. In Section 2.5 list of data used in this research is provided with their sources.

2.1 Study Area

In Ontario, stand replacing fires are the most dominant natural disturbances in boreal forests (Perera at al., 1998) whose frequency changes across a longitudinal gradient (Beverly & Martell, 2005; Suffling, 1995). To capture this variation, the selected study area covers the full extent from East to West of the province between 47°15' - 53°2.5'N and 79°30' - 95°10'W, with an elevation range from 44 to 613 meters above sea level (Figure 2.1). Some study areas were excluded during fire regimes simulations due to non-availability of some relevant data as discussed in Section 4.2.

The area is underlain by Archean rocks (gnesis, granite, granodiorite, metasedimentary and metavolcanic) and Proterozoic rocks (southern province) of the Canadian Shield (Baldwin et al., 2000). The study area consists of four ecoregions: 3E, 3W, 3S and 4S (Hills, 1959). Forests in these ecoregions are predominantly Crown (i.e., government) owned and are managed extensively for timber harvest. Implementation of changing provincial forest harvest policies over time has resulted in various landscape patterns (Perera et al., 2009). The characteristic forest species under various climate and soil conditions for these ecoregions are shown in Table 2.1. The sequence of the species are adapted from Hills, 1969. The scientific and common names of these species are shown in Table 2.2

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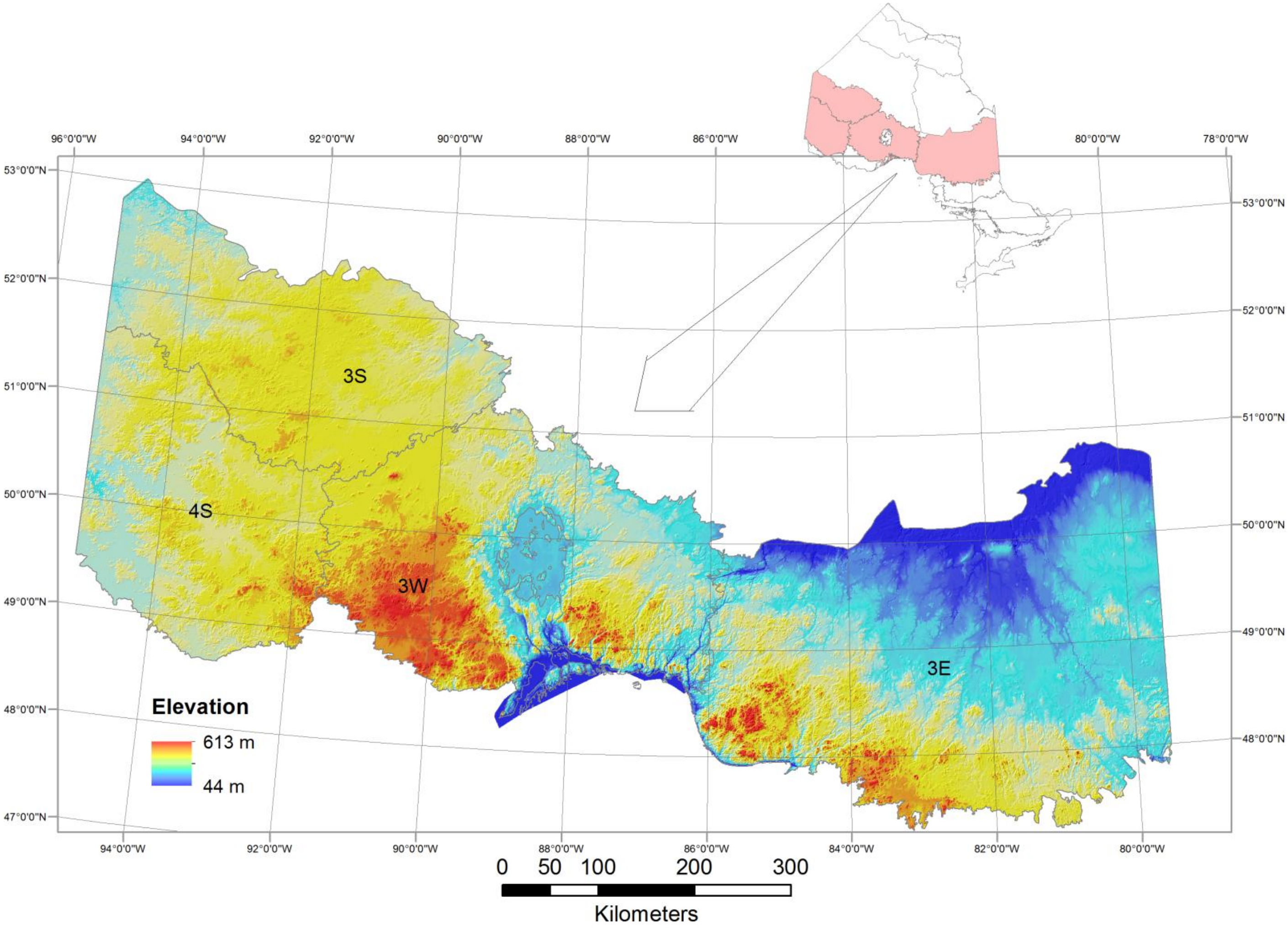

Figure 2.1 The Ontario study area. The letters (4S etc) represent the ecoregions.

Table 2.1 Characteristic forest species in the study area (Source: Hills, 1969).

Eco-Climate	**Soils**	**Ecoregions**			
		3E	**3W**	**3S**	**4S**
Hotter	Drier	JP-SB	JP-PW-PR-SB-SW-Poplar	JP-BW	JP-PW-BW-BO
	Fresh	JP-SW-PR-PW	Poplar-BW-PW-PR	SB-SW-Poplar	SW-Poplar-PW
	Wetter	Poplar-CE-AE	Poplar-BF	SB-BF	Poplar-BS-CE-AE
Normal	Drier	JP-BW-Poplar	BW-Poplar-JP-PW-PR	JP-SB	JP-PW-PR-SW-BW-Poplar
	Fresh	BF-SW-Poplar-BW	SW-BF-JP-PW-PR	Poplar-RS-SW	SW-BF-Poplar
	Wetter	SB-BF	SB-LA	Poplar-SB-SW	SB-BF
Colder	Drier	SB-JP-LA	SB-JP-LA	SB-JP	SB-JP
	Fresh	SB-LA	SB-SW-LA	SB-JP	SB-JP
	Wetter	Mosses-Lichens	Mosses-Lichens	SB-LA	SB-LA

Table 2.2 Nomenclature of the forest species shown (in abbreviation) in Table 2.1.

Abbreviation	**Common Name**	**Scientific name**
AE	American Elm	*Ulmus americana*
LA	American Larch	*Larix laricina*
BS	Black Ash	*Fraxinus nigra*
BF	Balsam Fir	*Abies balsamea*
BO	Bur Oak	*Quercus macrocarpa*
SB	Black Spruce	*Picea mariana*
PJ	Jack Pine	*Pinus banksiana*
PR	Red Pine	*Pinus resinosa*
BW	White Birch	*Betula papyrifera*
CE	White Cedar	*Thuja occidentalis*
PW	White Pine	*Pinus strobus*
SW	White Spruce	*Picea glauca*

2.2 Point Pattern Analysis

A stochastic process that generates random points in space (e.g; forest fire ignitions) is termed a spatial point process. The study of realizations of a spatial point process as a spatial point pattern (e.g., Genton et al., 2006) may help to characterize that phenomenon and provide some insight (Turner, 2009). Two statistics were used to study the patterns of lightning-caused forest fire in the study area: the nearest neighbor index (NNI) and Ripley's *K*-function (the *K*-function). These methods are discussed in detail in Section 3.4.2 but a brief outline is provided here.

The NNI provides insights about spatial point patterns by comparing the distance between the nearest point locations (of the phenomenon) and the mean distance between the point locations (Clark & Evans, 1954). In this research, NNI was calculated up to neighbours of order 50 using the following equation (Levine, 2010).

$$NNI = \frac{\left[\sum_{i=1}^{N}\left\{\frac{min\left(d_{ij}\right)}{N}\right\}\right]\left[\left(2^{k}k!\right)^{2}\sqrt{{}^{N}\!/_{A}}\right]}{k(2k)!} \tag{2.1}$$

where N is the total number of fires in the study area of size A, $min\left(d_{ij}\right)$ is the distance between a fire location i and its nearest fire location j, k is the order (number) of the nearest fire location and ! is the factorial function.

The *K*-function uses distance bins to test the nature of observed spatial point patterns (Ripley, 1977). In particular, it is used to look for departures from CSR. In its simple form the *K*-function for a distance bin t is defined as

$$K(t) = E(\text{number of events within a distance } t \text{ of an arbitrary event})/\lambda \tag{2.2}$$

where E is the mathematical expectation and λ is the intensity of the point process. The exact form of the equation for the *K*-function used in this research appears in Section 3.4.2. Results of the *K*-function were further transformed to its linear representation the *L*-function (Equation 2.3) for ease of interpretation (Besag, 1977; Cressie, 1993). The *L*-function is given by

$$L(t) = \sqrt{\frac{K(t)}{\pi}} - t \tag{2.3}$$

Following O'Sullivan & Unwin (2010) an acceptance envelope, calculated using a Monte Carlo procedure of 100 simulations under the assumption of CSR, was generated to assess whether there was a statistically significant deviation from CSR.

2.3 Fire Density Estimation

Density estimation commonly refers to non-parametric modeling of a probability density $f(x)$ given a finite number of data points. Here, x can be scalar or multivariate.

In this research the fire densities in the study area were estimated using a non-parametric density estimation method, kernel density estimation. In this non-parametric approach no prior assumptions are made about the density shape. Instead the data itself determine the estimate (Silverman, 1986). A simple kernel density estimate, donated here by $\hat{f}(x)$, can be calculated using

$$\hat{f}(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{|\mathrm{x} - \mathrm{x}_i|}{h}\right) \tag{2.4}$$

for data $x_1, \ldots \ldots, x_n$. $K(\,)$, the kernel function, is a symmetric zero-mean probability density function with scale parameter *h*, the "bandwidth". The choice of *h* is critical, as it controls the smoothness of the estimated density. To account for the clustering nature of ignitions the adaptive kernel density estimation approach was used. It allows h to vary with the concentration of observation points (Silverman, 1986; Worton, 1989). The estimated fire densities were evaluated using a calibration procedure based on the minimization of a goodness of fit criteria $(\hat{S})$ (Breiman et al., 1977).The adaptive kernel density estimation parameters and $\hat{S}$ calculations, used in this study, are further discussed in detail in Section 3.4.3.

2.4 Fire Regime Simulations

To test the null hypothesis that spatial heterogeneity in the patterns of fire ignitions do not affect the modeled forest fire regimes, simulations were run using Ontario Ministry of Natural Resources (OMNR) model BFOLDS. Further details of this model appear in Section 2.4.1. Simulations were run for each ecoregion under two ignition scenarios: "unweighted" (scenario A) and "weighted" (scenario B). Under the unweighted scenario the seeding of fire ignitions in the model was spatially random. Under the weighted scenario, the estimated fire densities (Section 3.5) were used to spatially weight the ignition seeding in the model. Each simulation was run for 200 years, and 30 simulations were run for each ecoregion under each ignition scenario. Prior to these simulations the model was initialized with a run of 100 years.

Table 2.3 shows different spatial and non-spatial fire regime indicators that were compared for both ignition scenarios.

Table 2.3 List of fire regime indicators studied under unweighted and weighted ignition scenarios.

Aspect	Indicator
Non-spatial	Total number of fires
	Number of fires in different size classes
	Total burnt area
	Annual burnt fraction
Spatial	Burn probability

2.4.1 BFOLDS

BFOLDS is a raster-based, spatially explicit hybrid model that quantitatively abstracts the boreal landscape dynamics (fires and forest cover changes) to understand their variability and probability of occurrence (Perera et al., 2008). A conceptual overview is shown in Figure 2.2. BFOLDS has two modules: (i) a process based fire event simulation module and (ii) an empirically based forest succession simulation module.

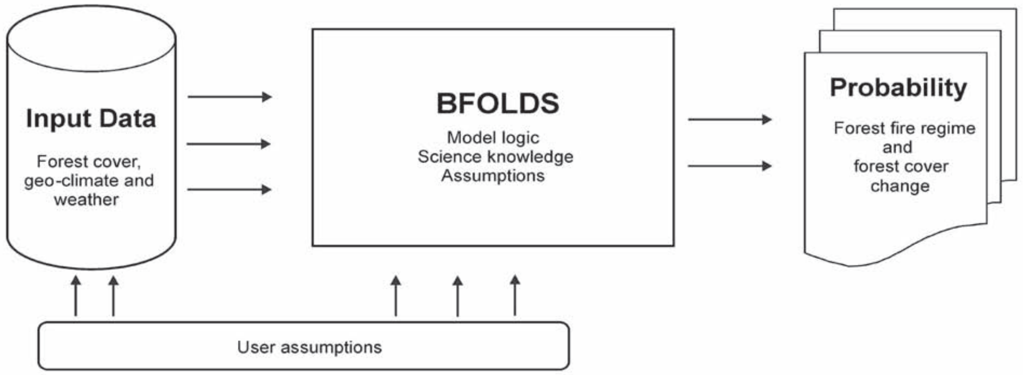

Figure 2.2 A conceptual overview of major components of BFOLDS (Source: Perera et al., 2008).

The BFOLDS fire event module uses the principles of the FBP System (Forestry Canada Fire Danger Group, 1992) and simulates multiple fire events on a given landscape at 1-ha resolution and daily intervals. It derives the mean number of potential fire ignitions from the daily ignition data of fire weather input. It also assumes that potential ignitions follow a Poisson distribution if the mean number of potential fire ignitions for a weather day is less than 30, otherwise it uses a normal distribution (Perera et al., 2008).

Fuel moisture is an important factor for a successful ignition. In BFOLDS the fuel moisture is indicated by the Duff Moisture Code (DMC), a Canadian forest fire weather index component that rates the moisture contents in the upper layers of the forest floor that gain moisture directly from the rainfall and where litter is beginning to decay (Wotton, 2009). In BFOLDS the seeded ignitions succeed only if the DMC at the ignition location is below a threshold value (Perera et al., 2008). Table 2.4 shows the DMC threshold values for the ecoregions used in this study. A systematic flow chart of fire events in fire module of BFOLDS is presented in Figure 2.3.

Table 2.4 Duff Moisture Code (DMC) threshold values (with 10% variation) used in the study.

Ecoregions	**DMC Value**	**DMC Range**
3E	20	20 ± 2 (18 – 22)
3W	20	20 ± 2 (18 – 22)
3S	40	40 ± 4 (36 – 44)
4S	40	40 ± 4 (36 – 44)

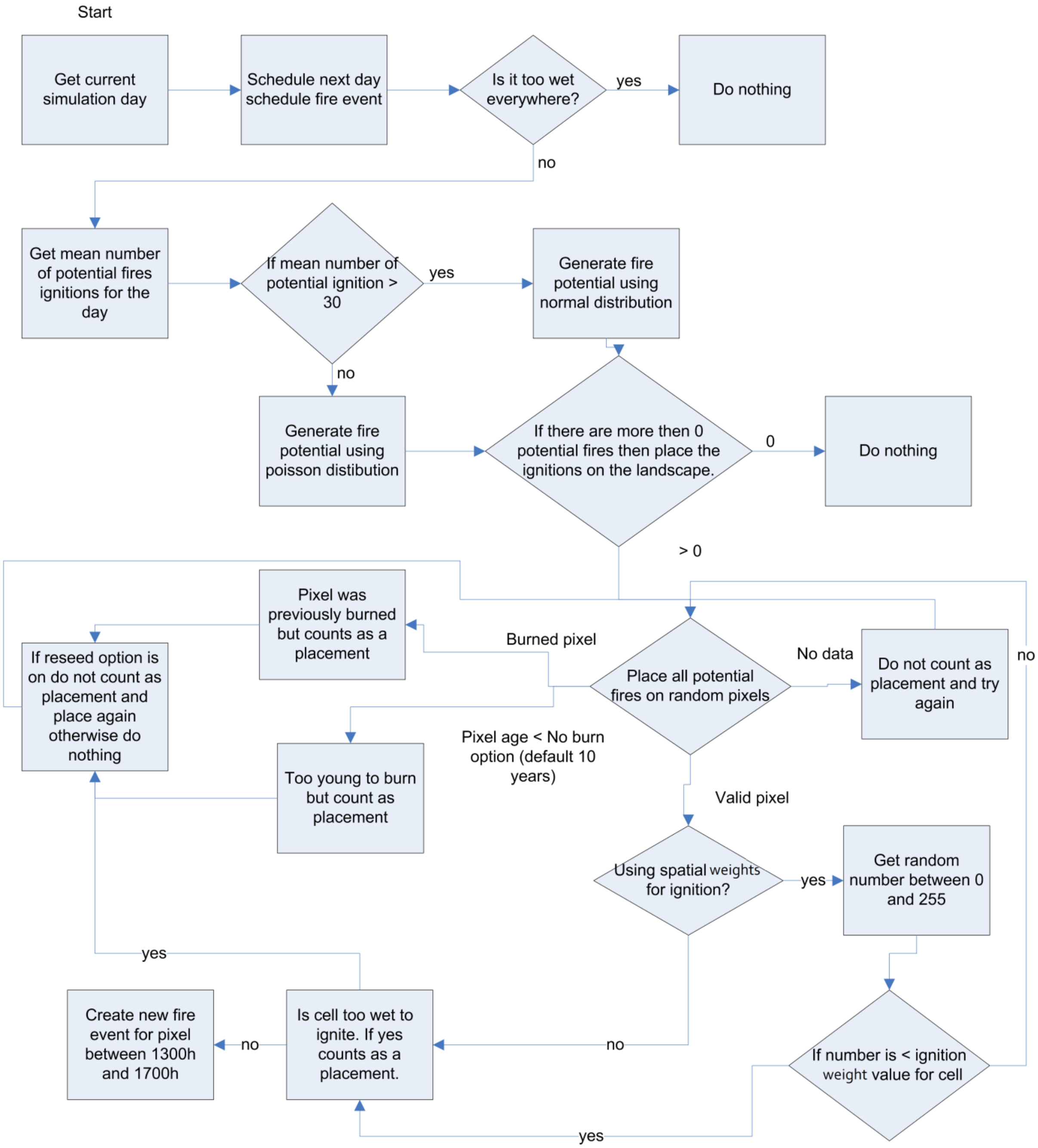

Figure 2.3 Flow chart of schedule fire event in BFOLDS.

The seeding of fire ignitions in BFOLDS can be spatially unweighted or weighted, though fires in nature by and large are spatially clustered. Difficulty in characterizing reliable fire ignition patterns has led many fire regime modeling studies to seed ignitions spatially random. There does not appear to be any study, particularly for BFOLDS, which demonstrates the effect of input ignition patterns on the model performance in simulating fire regime. Perera et al. (2008) reported that the simulated fire regime characteristics of BFOLDS constitute an entirely emergent property that is the combined effect of model logic, input data and various user assumptions. In this study all these were kept constant and the model performance in simulating fire regimes was evaluated under two ignition scenarios.

2.5 Data

A number of data were used in this research, the details of which are given below in Table 2.5.

Table 2.5 List of data used in this research and their sources.

Type	Data	Data Source	Remarks
Forest	Cover type Cover age Fuel Type	1:20,000 forest resources inventory (FRI) of Ontario	Derived from FRI using forest unit classification rules and fuel classification rules modified by Elkie et al., 2007
Soil	Soil moisture Soil nutrient	1:250000 Ontario Land Inventory	Site classification rules modified by Elkie et al., 2007
Weather	Fine fuel moisture code Duff moisture code Drought code Initial spread index Build-up index Fire ignitions	Daily weather data (temperature, relative humidity, wind and rainfall) of weather stations in the study area for 1963-2009 from OMNR fire weather archive	Point data interpolated following Flannigan & Wotton, 1989
Geo-Topographic	Elevation Slope Aspect	Canadian Digital Elevation Data from https://geobase.ca	
	Latitude Longitude		Gridded data at 1 ha resolution
	GIS layers of Ontario and its ecoregions	ESRI ®	Obtained from University of Waterloo Map Library
	GIS layers of water bodies in the study area	DMTI	Obtained from University of Waterloo Map Library
	GIS layers of Geological features	Ontario Geological Survey	Obtained from University of Waterloo Map Library
Fire	Lightning-caused fire ignitions	OMNR forest fire archive data for 1960-2009	

Chapter 3

Spatial patterns of lightning-caused forest fire ignitions in boreal Ontario, 1960–2009

Summary

Lightning-caused fires in Ontario managed boreal forests may exhibit various spatial patterns depending on the study locations and scale. In this study forest fire ignition data for four ecoregions (3E, 3W, 3S and 4S) for 1960-2009 were analyzed using point pattern and density estimation methods. Ecoregions were employed as study regions, because they are commonly used for forest land-use plans and policies in Ontario. Nearest neighbour index and Ripley's K-function analyses showed that fire ignitions are spatially clustered in all four ecoregions. Kernel density estimation with an adaptive bandwidth was used to estimate the corresponding spatially inhomogeneous lightning-caused ignition densities. Bandwidths were chosen quantitatively through a calibration process that minimizes a goodness of fit criterion. Results show that fire ignition density is the highest in the northwestern ecoregion (4S) and the lowest in the eastern ecoregion (3E). Within each ecoregion fire ignition density also varies spatially and exhibits distinctive areas of varying fire densities. Overall the estimated fire ignition density follows the temperature-humidity gradient of this province. The ecoregion with the highest estimated fire ignition density (4S) falls in areas of the lowest humidity and the highest temperature. The ecoregion with a lower overall fire ignition density (3E) experiences most humidity and coolest temperature. Fire ignition density estimated in this study can provide useful information for forest management activities particularly in characterizing forest fire regimes in its spatial context.

3.1 Introduction

Fire is one of the most important disturbances that shape vegetation dynamics in forested landscapes. Canadian boreal forests are characterized by frequent fires (Suffling, 1995; Suffling et al., 1988). The majority of the fires are human-caused and are concentrated mainly near human activity centers: residential, recreational, industrial; and also the transportation networks (Wang & Anderson, 2010; Woolford & Braun, 2007; Wotton et al., 2003). These are easily detectable, receive a quick fire-suppression to protect life and property, and hence, usually result in a smaller burnt area. On the other hand, lightning-caused forest fires have a wider geographic occurrence. These can result in larger burnt areas as detection is often slower, and fire fighting units may give them less priority or have limited resources to fight fire in remote areas. In Canada overall, though lightning-caused fires are less in number than human-caused fires they result in about 85% of the total annual burnt area (Wang & Anderson, 2010; Weber & Stocks, 1998).

Lightning-caused fire ignition and propagation processes involve complex interactions between different contributing biotic and abiotic factors (Telesca et al., 2005). Likewise, lightning-caused fire ignition patterns, the fundamental characteristic, are also difficult to describe precisely because of wide range of spatio-temporal variations in their occurrence. Understanding of these fire patterns is important to many activities such as predicting fire occurrence, planning fire management, understanding the role of fire in landscape processes, improving plant succession predictive modeling, and implementing management based on the natural disturbance emulation concept (Perera et al., 1998; Telesca et al., 2007; Tuia et al., 2007). Due to inherent spatio-temporal variations in the fire ignitions, analysis of ignition data over decades is required to understand fire patterns in a particular study area.

It is generally agreed that lightning-caused fire ignitions cluster spatially (Cochrane et al., 1999). This clustering is attributed to a complex array of factors that are in nature spatially non-random too. The source of ignition is cloud to ground lightning strikes with long continuing current that occur during the thunderstorms (Latham & Williams, 2001). Hence the spatial patterns of thunderstorms are the basic determinant of natural fire patterns (Wang & Anderson, 2010). However, the majority of lightning strikes fail to ignite fires in the absence of fuels on the forest floor (Podur et al., 2003).

Vegetation composition as it affects the availability of fuel also plays important role in fire ignitions. Krawchuk et al. (2006) found more ignitions in patches of coniferous species when compared with deciduous species. Wang & Anderson (2010) concluded that topography (higher elevations) and the forest composition (presence of coniferous species) were the main determinants of ignition patterns in their study area. Podur et al. (2003) also found topography as a likely factor affecting ignition patterns in Ontario boreal forests. There are also studies that do not find any relationship of fire ignitions with topography (e.g., McRae, 1992). Some studies, particularly in Canada, also used fuel moisture descriptions of the Canadian Forest Fire Weather Index (FWI) system (Van Wagner, 1987) to understand what may affect the risk of lightning-caused fire ignitions. In the FWI system daily weather observations are used to calculate numerical ratings representing the moisture contents of different fuel types (Wotton, 2009). Nash & Johnson (1996) correlated lightning-caused fires in Canadian boreal forests with the Fine Fuel Moisture Code[1] (FFMC) of the FWI system. Flannigan & Wotton (1991) concluded that the Duff Moisture Code[2] (DMC) of the FWI system is the main predictor of lightning-caused fire ignitions. Wotton & Martell (2005) identified the Sheltered Duff Moisture Code[3] (SDMC) as the most significant indicator of fire ignitions in Ontario forests. These are but a few of the many studies that have used different bio-physical factors to explain the underlying causes of lightning-caused fire ignitions patterns. Previous fires may also influence the ignition patterns by reducing the fuel loads in local areas (Krawchuk et al., 2006).

In recent years, many studies also applied state of the art spatial statistical tools to gain better insight into the spatial patterns of fire ignitions. Larjavaara et al. (2005) reported a gradient of decreasing density of fires from South to North in Finland based on fire data from 1985–1992 and 1996–2001. Turner (2009) explored the patterns of fires in New Brunswick, Canada from 1987 to 2003 using the *K*-function and kernel density estimation. He focused only on the usability of these statistical techniques and did not draw any final conclusion about fire patterns. Wang & Anderson (2010) studied spatio-temporal patterns of all fire ignitions in Alberta, Canada, excluding major national parks and southern prairie areas. They performed their analysis on a yearly basis (1980–2007) using the *K*-function and kernel density estimation. Their results illustrated the wide variability in the spatial distribution of fire ignitions from year to year, and also showed that in the North, lightning-caused fires are more likely to occur than human-caused fires. In an earlier study, Podur et al. (2003) used lightning-caused fire data for the period 1976–98 to conclude that fires in Ontario are spatially clustered. As in other studies, they also applied the *K*-function to test their null hypothesis of complete spatial randomness (CSR), and used kernel density estimation method to generated fire density surfaces. They also performed some detailed analyses of fire data for an area of high fire occurrence (and detection) in the North of the province. Their results showed strong evidence of clustering in the lightning-caused ignitions at a distance of approximately 200 km; and two distinct hotspots in the province, one in the northwest and the other in the southeast. Woolford & Braun (2007) utilized a mode-seeking algorithm, a technique to reduce bias in kernel density estimation, to demonstrate that lightning fires in Ontario occur in spatio-temporal clusters.

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[1] Index that represents the moisture in the small readily consumable fuels on the surface of the forest floor.

[2] Index that represents the moisture contents of the upper layers of forest floor where litter begins to decay.

[3] Index that represents the amount of moisture in the upper part of organic layer in very sheltered locations near the boles of over-storey trees.

Many of the above mentioned studies used the *K*-function as the main statistical method for exploring fire ignition patterns. Besides the *K*-function, there are other reliable methods for pattern analysis that are not common in fire studies. One such exploratory method, which is widely used for pattern analysis in ecological studies, is the nearest neighbour index (NNI). Some studies using this method are mentioned in Section 3.4.2. Use of multiple exploratory methods can help to get better insight of the complex nature of point patterns. The identified patterns also depend heavily on the scale of investigations, a facet of the problem to which many studies do not give proper consideration.

For density estimation, a priori selection of the kernel function K and its associated smoothing parameter (bandwidth or window size) *h* are required to obtain a reliable density surface (see Section 3.4.3). The kernel function ensures that the kernel density estimation results in a probability density function; and the average of the corresponding distribution is equal to that of the sample used. The bandwidth, *h* is a free parameter that is used to adjust the bias in density estimation. Small values of *h* result in a more variable (i.e., less smooth) density estimate, whereas, large values of *h* will reduce the random variation but may over-smooth the resulting fit (Silverman, 1986). Hence, it is critical that care be taken when determining the bandwidth. In the studies mentioned above and many others not cited here, the kernel function and smoothing parameter are selected subjectively. Such selection, in the absence of an expert knowledge, may lead to erroneous results. Amatulli et al. (2007) discussed these issues in detail, and proposed an analytical calibration procedure for kernel density to yield reliable density surfaces.

This study addresses the above issues. The study area was selected to ensure that results are meaningful for future applications. Two exploratory methods were used to assess the behaviour of lightning-caused fire ignitions at the ecoregion level and to test the hypothesis that the distribution of fire ignitions in Ontario managed boreal forests is spatially homogeneous. In addition, the spatial fire ignition density was estimated using a quantitative approach, namely adaptive kernel density estimation. This reduces the risk of under/over–density estimation by allowing the bandwidth to vary spatially. Further details are discussed in subsequent sections.

The broader objectives of the study are (i) to understand the spatial patterns of lightning-caused fire ignitions in Ontario managed boreal forests at ecologically homogeneous landscape scale, and (ii) to generate reliable fire ignition density surfaces that can further be used in research, planning and management activities.

3.2 Study Area

The study area in Ontario consists of ecoregions 3E, 3W, 3S and 4S (Figure 3.1). Stretching from East to West across the entire province, this area encompasses the majority of the Ontario (boreal) shield ecozone where fire detection efficiency is relatively high due to active forest fire management. The area is also representative of full range of humidity (Hills, 1959) and forest fire frequency (Beverly & Martell, 2005; Suffling, 1995) in the province.

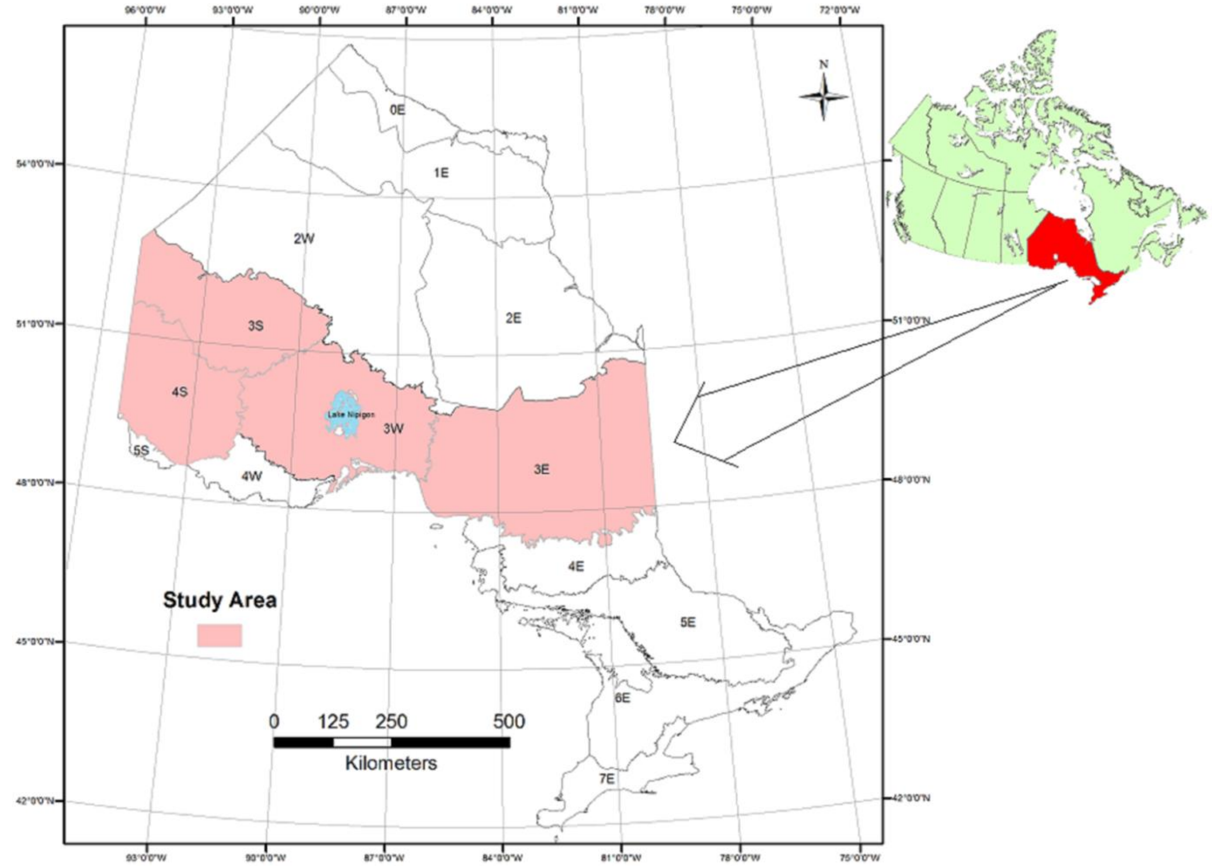

Figure 3.1 Location of the study area in relation to Ontario ecoregions.

The majority of this area is Crown (i.e., government) owned and its vegetation is mainly boreal forest. There is also some Great Lakes St. Lawrence forest in the southwest part (4S) of the area. The dominant species in the northeast (3E) are black spruce (*Picea mariana*), trembling aspen (*Populus tremuloides*), jack pine (*Pinus banksiana*), white birch (*Betula papyrifera*), balsam fir (*Abies balsamea*) and white spruce (*Picea glauca*) (Latremouille et al., 2008). In the central region (3W), black spruce is the dominant species in the older forests. Other species are jack pine, white birch, poplar and balsam fir. Similarly, in the upper northwest (3S) black spruce is the dominant species. Natural regeneration is mostly of black spruce and jack pine (Racey et al., 2000).The majority of the forests in the lower northwest (4S) are younger stands of jack pine, black spruce and poplar with a high recruitment of black spruce and jack pine (Racey et al., 2000). Details on the composition of the forested area in each ecoregion are provided in Table 3.1.

Table 3.1 Land-use distribution in the study area (in thousand hectares) Source: (Forest Management, 2006; Hills, 1959).

Ecoregions	Water	Wetland	Field/ Agri	Other	Treed Bog/Fen	Forest	Total
3E (Medium Humid)	922.4	251.2	40.9	84.9	899.9	11478.7	13678.0
3W (Driest Humid)	1515.9	70.1	0.0	62.7	301.1	6940.5	8890.4
3S (Sub Humid)	980.9	123.5	0.0	164.6	484.4	4870.5	6624.0
4S (Sub Humid)	1440.4	27.2	14.7	130.0	123.4	4220.8	5956.5

3.3 Data

The fire data for the period 1960–2009 were obtained from the Ontario Ministry of Natural Resources (OMNR) fire database. This database is an archive of all fires detected and reported to the provincial aviation and forest fire management center by fire managers through Fire Information Reports (Form 208). Each fire report includes fire location, forest type(s), weather, fire cause, detection date, attack date, suppression date, area burned, etc. The number of fires in each region is detailed in Table 3.2. Forest cover type data (FRI, 2007) of the study area were also obtained from the OMNR.

University of Waterloo Map Library services were used to obtain geographic data of ecoregions from ESRI (ESRI, 2001), water bodies (lakes, rivers etc.) from DMTI (DMTI, 2010) and geological data from Ontario Geologic Survey (OGS, 1988). Canadian Digital Elevation Data (CDED) was obtained from GeoBase ® (GeoBase, 2007).

Table 3.2 Fire ignition statistics in the study area during 1960-2009.

Ecoregions	Number of Fire ignitions	Fire ignitions reported as in water		
		% of total ignitions	Maximum distance from nearest land (m)	Ignitions > 1000m distance from nearest land
3E	2948	4.1	766.6	0
3W	5107	8.5	3462.2	8
3S	2329	10.9	720.3	0
4S	7213	15.4	1741.6	2

3.4 Methods

3.4.1 Data Preparation

Spatial pattern analysis and density estimation can be sensitive to the size and shape of the study area. Analysis output may change with changes in boundary (Clark & Evans, 1954). It is therefore important to carefully select a representative study area. In this study, all data analyses were based on individual ecoregions (3E, 3W, 3S and 4S) because these are the representative land units for forest land-use plans and policies in Ontario (Perera et al., 2009). The fire ignition density in the overall study area will provide a broader picture for the managed boreal forests of the province.

Fire ignition locations in the study area for the study period (1960-2009) were extracted from the OMNR fire database and exported as a point shapefile using ArcGIS 9.3 ®. Fire ignitions and all other data were projected to OMNR's standard map projection Lambert Conformal Conic projection. Fires ignitions were then separated in individual shapefiles for each ecoregion. Inspection of data revealed that some ignitions were erroneously shown to occur in water (Table 3.2). A similar data error was discussed in detail by Podur et al. (2003) and Turner (2009). The most likely sources of such errors are data entry error and the relatively coarse scale used to record fire locations. Turner (2009) reported that rounding to the nearest minute can result in up to 1 km datum displacement but this may not have much effect on pattern detection (Freeman & Ford, 2002). In our case, the majority of in-water fire ignitions were well within this 1 km range except a few in 3W and 4S (Table 3.2). In the absence of any other record to precisely correct such locational errors, these fires origins were arbitrarily relocated[4] 25 m inland from the nearest shoreline.

Data also showed that some fire ignitions occurred at the same location. Two such examples from ecoregion 3W are shown in Figure 3.2(a) alongwith their year of occurrence. In one case three fires during 1965, 1966 and 1970 occurred at the same place. The other highlighted sample location shows where two fires occurred during 1979 and 1980 at the same place. To account for each fire ignition separately in data analyses, all such fires were also relocated with a grid of 100 m x 100 m (~ 141 m). Results for sample locations are shown in Figure 3.2(b). As the purpose of this study was to investigate the long term overall average spatial distribution of fire ignitions, year to year temporal variation in the number of fires was not considered.

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[4] No data were available about the actual shape of burnt area and the relative location of the ignition point in the burnt area. It was thus assumed that such fires would have started close to the shoreline.

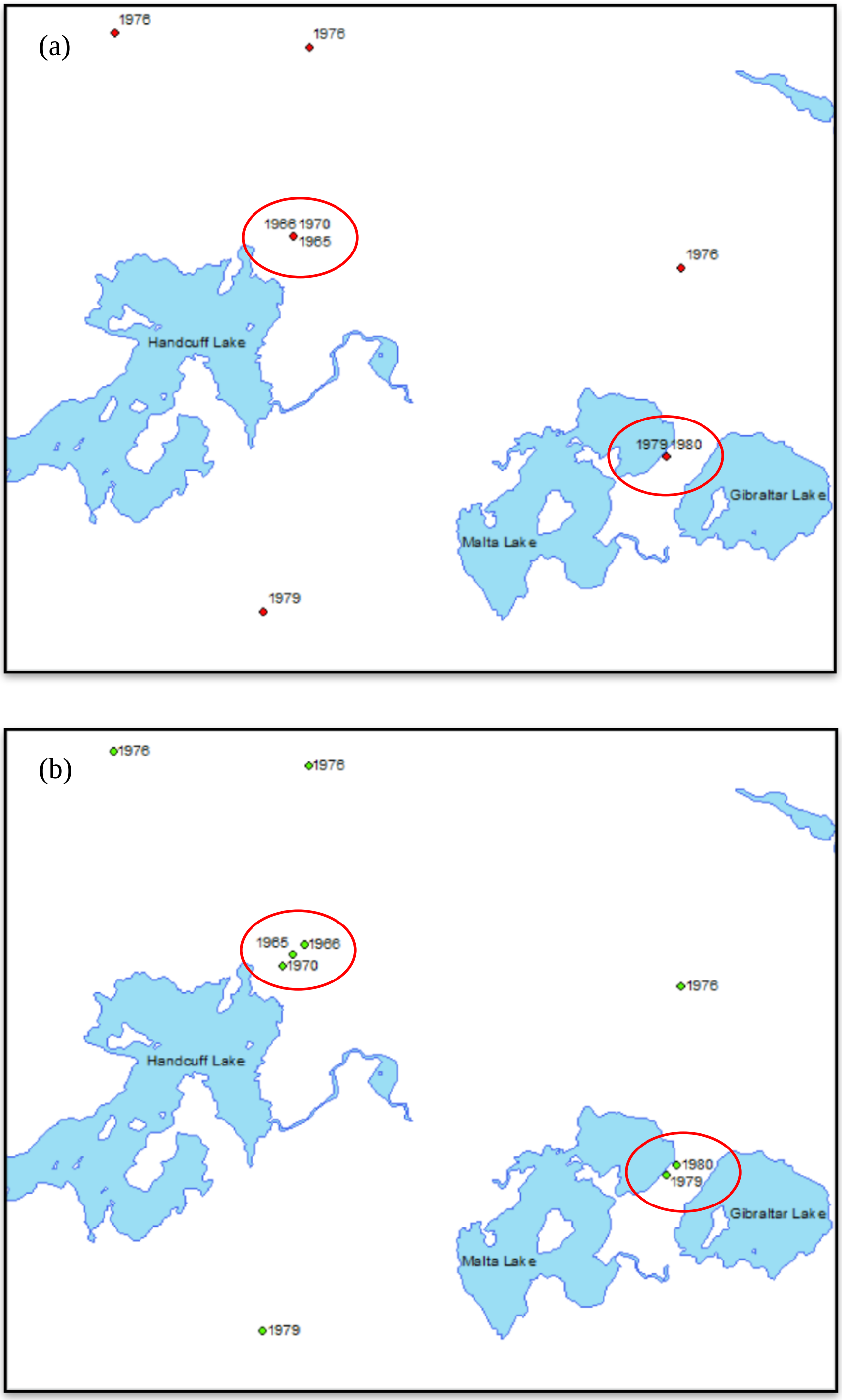

Figure 3.2 Sample locations (red ovals) from 3W where multiple fires occurred during different years (a) the original locations (b) location after adjustments.

3.4.2 Exploratory Data Analysis

Among a wide variety of exploratory data analyses methods, indices (the descriptive adjuncts to statistical tests) are commonly used for spatially non-random phenomena such as forest fires to test the degree of departure from CSR (Ghent & Zucker, 1990). In this study, two second-order distance statistics (NNI and the *K*-function) were used to study the fire ignition patterns within the overall distribution of fire ignitions in the study area.

NNI is extensively and effectively used to investigate spatial patterns (Bleacher et al., 2009; Getis, 1964; Herbers & Foitzik, 2002; Kenkel, 1988; Kolbei & Janzen, 2002; Lee et al., 1997; Rogerson & Sun, 2001; Young & Merriam, 1994; Zenner, 2000). It is a ratio (Equation 3.1) that compares the observed distance between the nearest points and the mean distance between points that follow CSR (Clark & Evans, 1954)

$$NNI = \frac{d(NN)}{d(RAN)} \tag{3.1}$$

where $d(NN)$ is the nearest neighbour distance and $d(RAN)$is the mean distance that are calculated using equations 3.2 and 3.3 respectively.

$$d(NN) = \sum_{i=1}^{N} \left[\frac{Min\left(d_{ij}\right)}{N} \right] \tag{3.2}$$

$$d(RAN) = 0.5\sqrt{{}^{A}/_{N}} \tag{3.3}$$

where $Min\left(d_{ij}\right)$ is the distance between a point i and its nearest neighbour, denoted point j, and N is the number of points in the study area A.

Under CSR, the expected value of the index is 1. A value less than 1 shows clustering, and greater than 1 shows inhibition (dispersion). Normally, this index is calculated using the distance to the very first neighbour. In this study, to capture spatial pattern at multiple scale, NNI was calculated using *Crimestat*® software (Levine, 2010) for the first 50 nearest neighbours using:

$$d(k_{RAN}) = \frac{k(2k)!}{(2^k k!)^2 \sqrt{\left[{}^{N}/_{A}\right]}} \tag{3.4}$$

where k is the order of nearest neighbour and ! is the factorial function.

The *K*-function is also widely used in pattern analysis studies, particularly for fire, (Freeman & Ford, 2002; Genton et al., 2006; Hering et al., 2009; Kenkel, 1988; Podur et al., 2003; Sterner et al., 1986; Turner, 2009; Wang & Anderson, 2010). Unlike the NNI it uses distance bins up to the limit of study area to test the nature (clustering, CSR, or inhibition) of spatial point patterns (Ripley, 1977). Mathematically, it is defined as

$$K(t) = \frac{A}{N^2}\sum_{i}^{N}\sum_{i\neq j}^{N} I(t_{ij}) \tag{3.5}$$

where *A* is the study area, *N* is the number of points and $I(t_{ij})$ is the number of other points j found within a circle of radius t from a point i. Generally, radii are increased in small increments. 50–100 intervals are commonly used to plot the *K*-function.

A revised equation with a weighting factor to adjust the boundary effects of the study area (Venables & Ripley, 1997) is given by:

$$K(t) = \frac{A}{N^2}\sum_{i}^{N}\sum_{i\neq j}^{N} {W_{ij}}^{-1} I(t_{ij}) \tag{3.6}$$

where ${W_{ij}}^{-1}$ is the inverse of the proportion of the circumference of a circle of radius t placed over each point that is within the study area. A value of 1 was used for ${W_{ij}}^{-1}$ where circle was within the study area.

Besag (1977) proposed the *L*-function, $L(t)$ as a linear representation of $K(t)$ that also stabilizes the variance and has zero value under CSR (Cressie, 1993; Freeman & Ford, 2002). It is shown in Equation 3.7.

$$L(t) = \sqrt{\frac{K(t)}{\pi}} - t \tag{3.7}$$

Spatstat package in R (Baddeley & Turner, 2005) was used to calculate the *K*-function and the *L*-function. For each ecoregion, 100 simulations under the assumption of CSR were run to obtain Monte Carlo based envelops to test the departure from random expectations. For 3E and 3S analysis were run using ignition data for 1960-2009. For 3W and 4S the analysis was based on the last 20 years of data, namely 1990-2009 inclusive. This was necessary due to computational constraints caused by the large number of fires in the historical records for these two ecoregions.

3.4.3 Fire Density Surfaces

A variety of interpolation techniques exists that generalize finite point data values to an entire area of interest. Among these, kernel density estimation is widely used due to well understood statistical properties. This non-parametric technique usually employs a symmetric probability density function (Katkovnik & Shmulevich, 2002; Silverman, 1986; Worton, 1989) to estimate the density as

$$\hat{f}(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{|\mathrm{x} - \mathrm{x}_i|}{h}\right) \tag{3.8}$$

where $\hat{f}(\ )$ is kernel estimator, $K(\ )$ is the kernel function, h is the smoothing parameter (bandwidth or window size), n is the number of observations and x is a coordinates vector representing the location of the function being estimated.

The choice of the kernel function and of the smoothing parameter is important. The performance of different kernel functions has been discussed in the literature. For example, Amatulli et al. (2007); Breiman et al. (1977) and Levine (2010) preferred the Gaussian (normal) kernel function. Others (Podur et al., 2003; Wang & Anderson., 2010) suggested using a quartic kernel function. Levine (2010) argues that subjectively kernel function can be selected based on the decision of relative weight of near points to the far points. Silverman (1986) compared the performance of five kernel functions and did not find any significant differences in their performance. He however favoured the normal function as it yields a smooth curve with derivatives of all orders. Following the suggestion of Amatulli (2011) to achieve an expected normal distribution of the data in the neighbourhood of each point, a normal kernel function was used in this study.

Selection of the bandwidth, h, is also an important consideration when employing kernel density estimation, and there are “rules of thumb” for choosing a fixed h (e.g; Sheather & Jones, 1991; Wand & Jones, 1995). However, to account for the irregular spatial distribution of fire ignitions, an adaptive approach (Silverman, 1986) was used to allow h to vary with the concentration of observation points. It is narrow in areas of high concentration and vice versa (Worton, 1989). To calculate an optimal value for h, the *k*th nearest neighbour estimate approach was followed. In this method h is based on the distance between a point and its *k*th nearest point that will minimize the mean square error between the true and estimated densities (Katkovnik & Shmulevich, 2002; Levine, 2010). Practically, this is not possible due to unknown true (real) density. To deal with this problem, a number of approaches have been suggested and discussed (Amatulli et al., 2007; Silverman, 1986). In this study, the calibration and validation procedure (minimization of goodness of fit criteria ($\hat{S}$)) proposed by Breiman et al. (1977) was followed. It is calculated by using following equation:

$$\hat{S} = \sum_{1}^{n} \left(\widehat{w}_{(i)} - \frac{k}{n} \right)^2 \tag{3.9}$$

where k is the number of neighbours and n is the number of data points, whereas, $\widehat{w}_{(i)}$ is calculated using Equation 3.10 (Amatulli et al., 2007)

$$\widehat{w}_{(i)} = e^{-n\hat{f}(x_{i,k})A_{(r)_{i.k}}} \tag{3.10}$$

where $\hat{f}(x_{i,k})$ is the estimated kernel density at sample point i using kth nearest neighbour and $A_{(r)_{i.k}}$ is the area of circle having radius (r) equal to the distance between kth nearest neighbour and each sample point i.

This procedure is computationally demanding. For efficiency it was performed in two stages. First, the density surfaces were generated with 3, 6, 9 and 12 nearest neighbours (referred as k-3, k-6, k-9 and k-12 respectively), and $\hat{S}$ was calculated for each of these density surfaces. This helped to identify the possible value of k with minimum $\hat{S}$. In the second stage, the density surfaces were generated using the number of nearest neighbours surrounding the k that yielded minimum $\hat{S}$ in first stage. The k values that yielded the minimum $\hat{S}$ in the second stage were finally selected to generate fire density surfaces for their respective ecoregions. All density surfaces were generated at a 250 m pixel resolution. The results are discussed in the following section.

3.5 Results and Discussions

As mentioned in Section 3.4.1, selection of the study area is very important and results can vary with changes in boundary. Figure 3.3(a) shows the NNI up to 50th neighbouring fire ignitions in ecoregion 3S, 4S and their combined area (3S4S). Lower values on the NNI scale represent more clustering and vice versa. The graph clearly shows that, at every scale of neighbour (up to 50th), fire ignitions in 4S are less clustered compared to fire ignitions in 3S. When both ecoregions were combined (3S4S) and fire ignitions were analyzed collectively for NNI, clustering was stronger at all scales. Boundary effects were also explored by adding a 50 km buffer[5] to 3S, 4S and 3S4S (namely 3S_b50, 4S_b50

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[5] Buffers on the western sides of 3S and 4S could not be included due to non-availability of fire data in the adjoining province of Manitoba

and 3S4S_b50 respectively) and then calculating NNI. These results are shown in Figure 3.3(b). In this case the clustering signals were different. Clustering was highest in 4S_b50, lowest in 3S_b50, and moderate in 4S3S_b50.

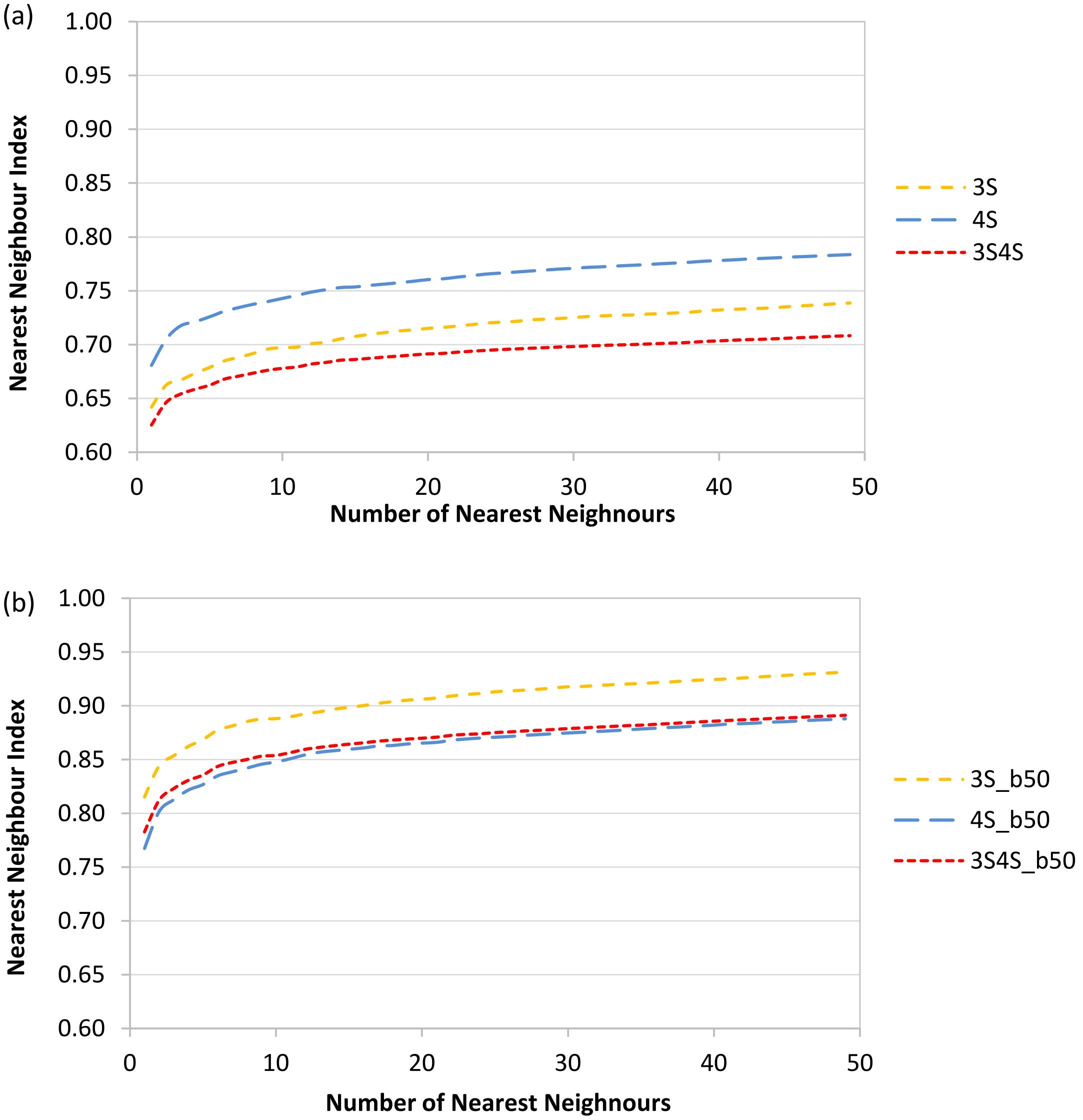

Figure 3.3 Effect of study area boundary on fire ignition clustering patterns reflected by NNI for 3S, 4S and combined 3S4S (a) without buffer (b) with a buffer of 50 km.

Figure 3.4 shows the NNI for all ecoregions. Results of this analysis clearly demonstrate that fire ignitions are clustered in all ecoregions with the highest degree of clustering in 3S and the least in 3E.

Results also illustrate that the concentration of points gradually decreases as the number of neighbours increase.

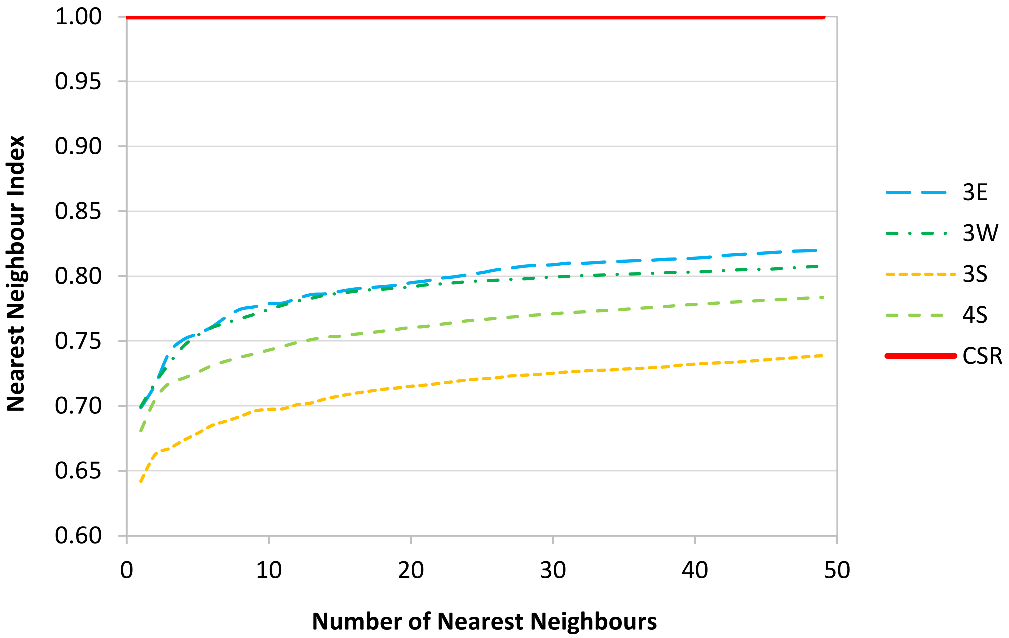

Figure 3.4 Nearest Neighbour Index (NNI) for 50th neighbouring fire ignitions in study area ecoregions.

Linear transformations ($L(t)$) of the *K*-function are plotted in Figure 3.5. In every ecoregion, $L(t)$ values are much higher than what should be expected from a simulation envelope. Hence, the hypothesis of CSR can be rejected in favour of clustered behaviour. Results not only confirm the findings of an earlier study that fires in boreal Ontario are clustered at larger distances (Podur et al., 2003), but also provide more insight to the spatial patterns at shorter distances. Higher values of $L(t)$ at all distances also show that fires are more clustered in ecoregions 3E and 3W than others. These results are different from NNI analysis, which shows fires in 3E are the least clustered. The simple explanation is that for non-random distribution different statistics will yield different results due to differences in methods. In this study, the analysis was based on neighbours for NNI whereas distances independent of number of neighbours form the basis of the *K*-function.

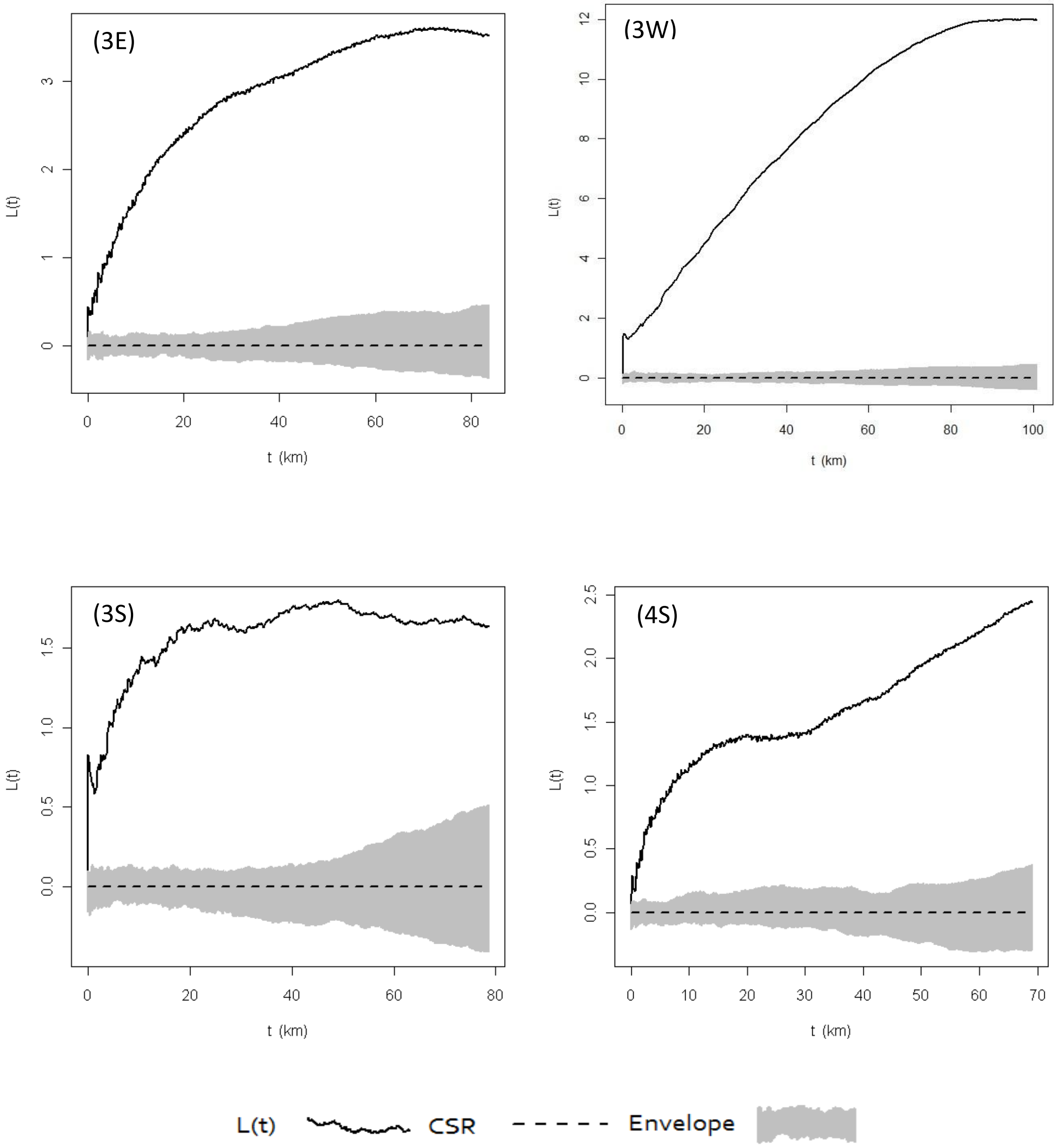

Figure 3.5 Results of the *K*-function represented by its linear transformation *L*(t) for study area ecoregions.

Fire ignition density surfaces using the adaptive kernel estimation method were estimated by employing different number of neighbours (*k*). Performance of each *k* was assessed by $\hat{S}$, which validates the procedure by calculating under/over-estimation at each point. Results of the first stage analysis are presented in Table 3.3, which shows $\hat{S}$ values for different *k* in each ecoregion. The $\hat{S}$ values for *k*-3 are quite high compared to others mainly due to some very close fire ignitions. For example, in 4S the average distance of the 3rd neighbouring ignition was 2426 m but many fire ignitions were as close as 141 m. Results show that the minimum value of $\hat{S}$ for ecoregions 3E, 3W and 4S was from *k*-9. For ecoregion 3S, the minimum value of $\hat{S}$ was from *k*-6.

Table 3.3 $\hat{S}$ values for fire ignition density surfaces generated by different number of neighbours (1st Stage).

Smoothing Parameter / Ecoregions	***k*-3**	***k*-6**	***k*-9**	***k*-12**
3E	27.994	0.101	0.027	0.049
3W	49.157	0.280	0.016	0.028
3S	13.119	0.021	0.035	0.062
4S	39.586	0.037	0.011	0.020

In order to find the least $\hat{S}$ values, further density surfaces were generated using different number of neighbours surrounding the ones that yielded minimum $\hat{S}$ in the first stage. Results presented in Figure 3.6 show that least $\hat{S}$ values for 3E, 3W, 3S and 4S were from *k*-8 (0.021), *k*-8 (0.015), *k*-6 (0.021) and *k*-7 (0.007) respectively. The $\hat{S}$ value for *k*-5 in 3S is 0.970 and is not shown in the figure.

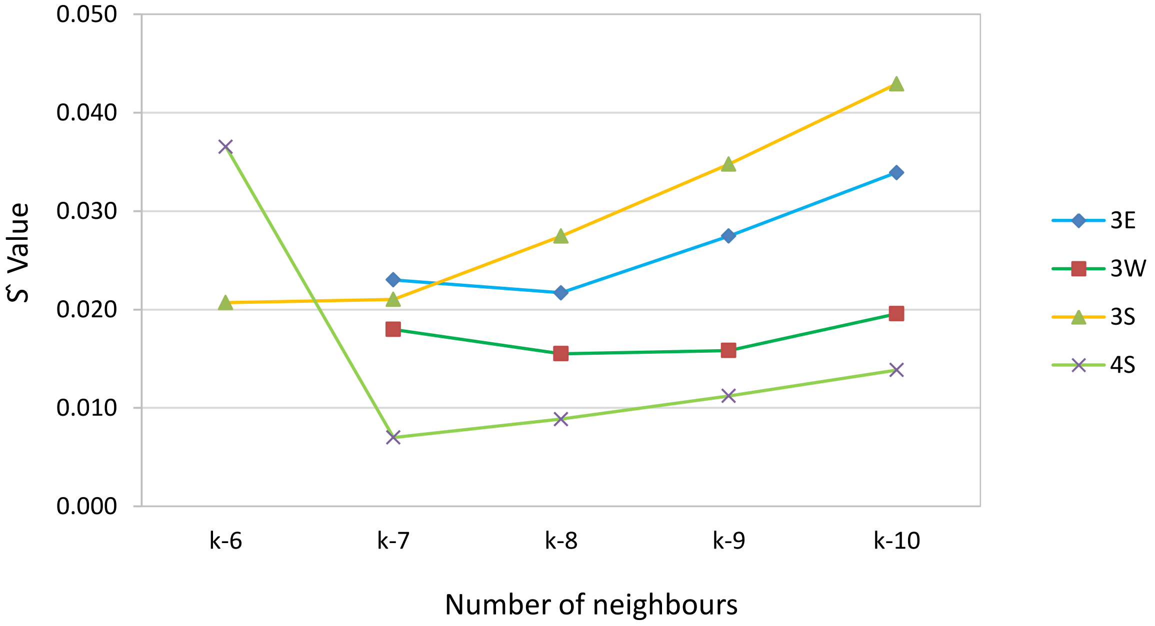

Figure 3.6 Comparison of $\widehat{S}$ values for fire ignition density surfaces (2^{nd} Stage).

Based on these least $\hat{S}$ values, the most representative fire ignition density surfaces generated for different ecoregions are shown in Figure 3.7–3.10. The white areas in these figures are the water bodies (i.e; rivers, lakes etc.). Overall, the highest fire density (1.092) is in 4S, followed by 3W (0.681), 3S (0.401) and 3E (0.328).

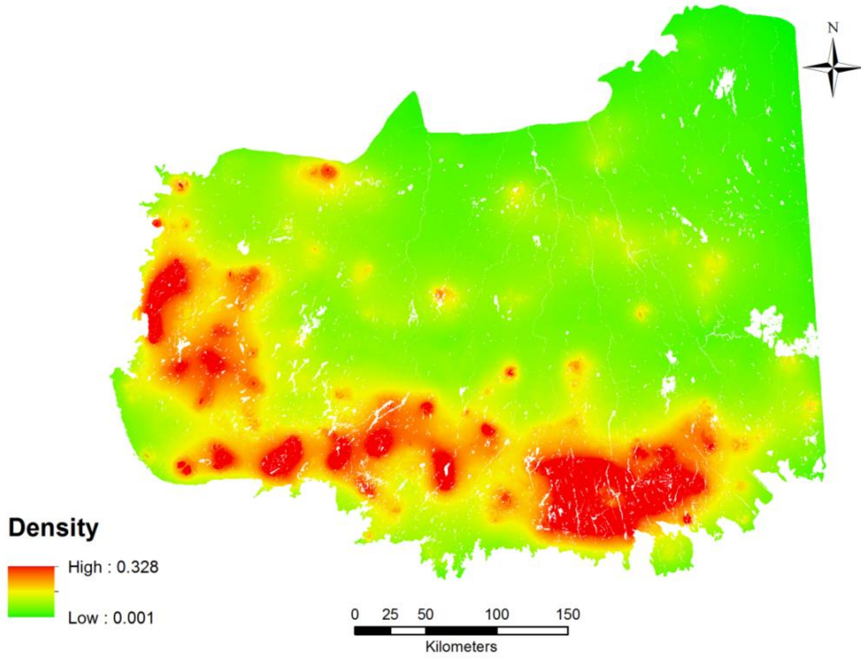

Figure 3.7 Relative fire ignition density in 3E for period (1960-2009) with adaptive kernel density estimation method using *k*-8.

In 3E (Figure 3.7) fire ignition density is higher in the South and West compared to rest of the region. There are also few isolated areas of medium to high fire ignition density in central and northwestern part of the region. The largest contiguous area with high fire ignition density is in the South.

In 3W areas of high fire ignition density are spread over the whole region except the northeastern part. Figure 3.8 also shows three big clusters of high fire ignition density in 3W. There are also isolated small patches of medium to high fire ignition density throughout the region.

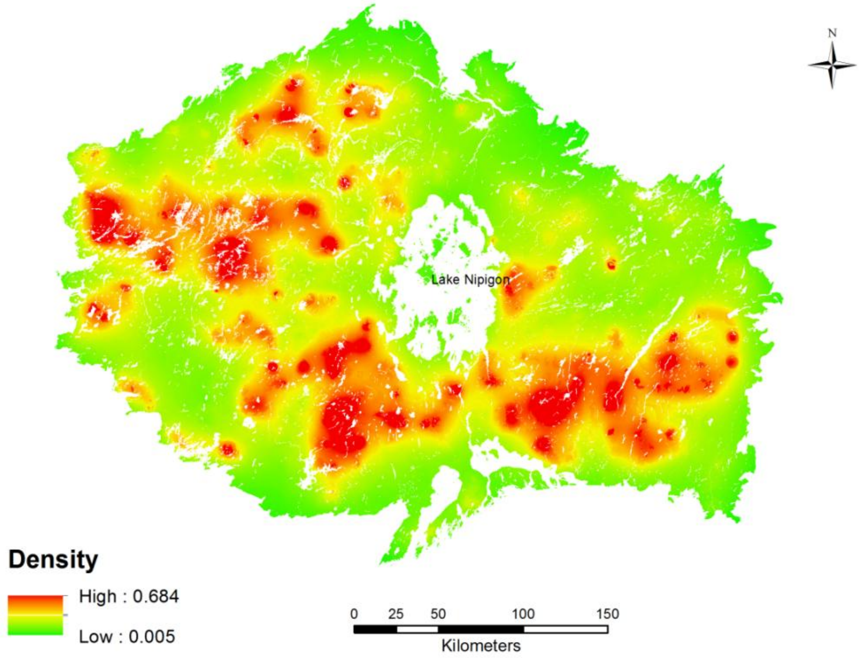

Figure 3.8 Relative fire ignition density in 3W for period (1960-2009) with adaptive kernel density estimation method using *k*-8.

In 3S (Figure 3.9) the largest contiguous area of higher fire ignition density is along the southern border. Areas in the eastern half of the region have more patches of higher fire ignition density compared to the western half. Contrarily, in 4S (Figure 3.10) clusters of high fire ignition density are more in western half of the region. In the East there are also small clusters of high fire ignition density.

The fire ignition density distribution in the whole study area is represented in Figure 3.11. It shows that northwestern part of the province (4S) has the highest fire ignition density and it decreases towards East. Fire ignition density is also low in far northern areas. There are also few isolated patches of medium fire ignition density in the southeast (3E). These results partially confirm the findings of an earlier study (Podur et al., 2003) that found a zone of high fire density in the northwest of the province. Their finding of another high fire density zone in the southeast of the province can not be confirmed as the location is mainly outside the area of this study. Overall, this study provides more details at finer spatial scale.

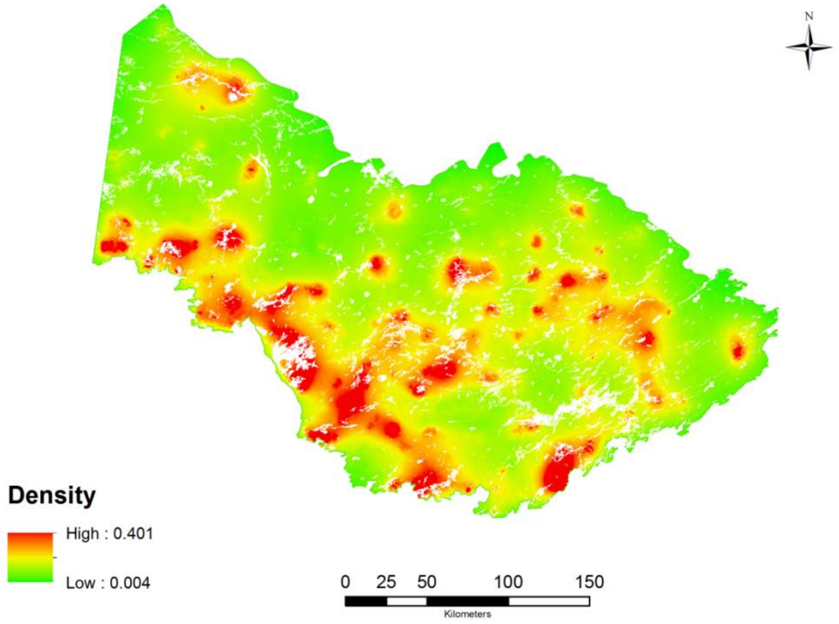

Figure 3.9 Relative fire ignition density in 3S for period (1960-2009) with adaptive kernel density estimation method using *k*-6.

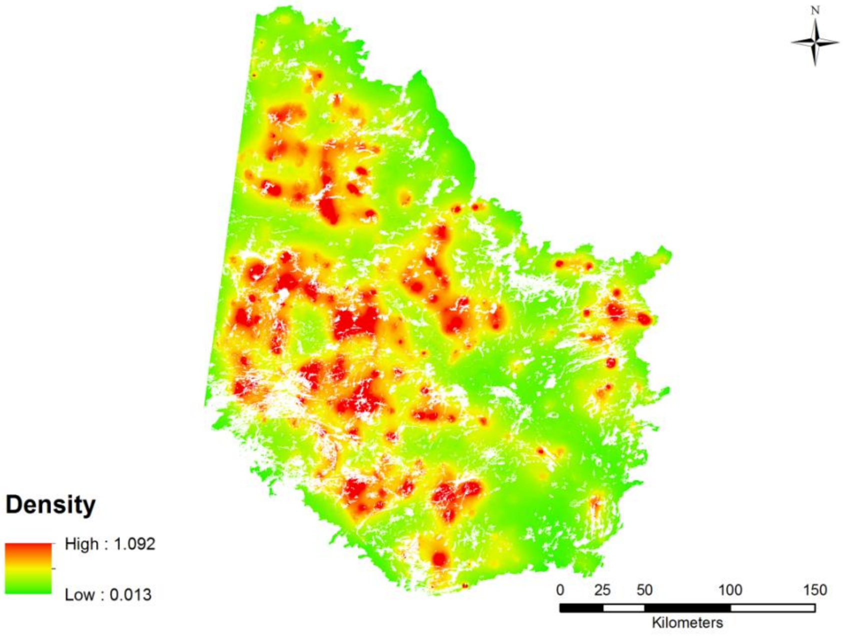

Figure 3.10 Relative fire ignition density in 4S for period (1960-2009) with adaptive kernel density estimation method using *k*-7.

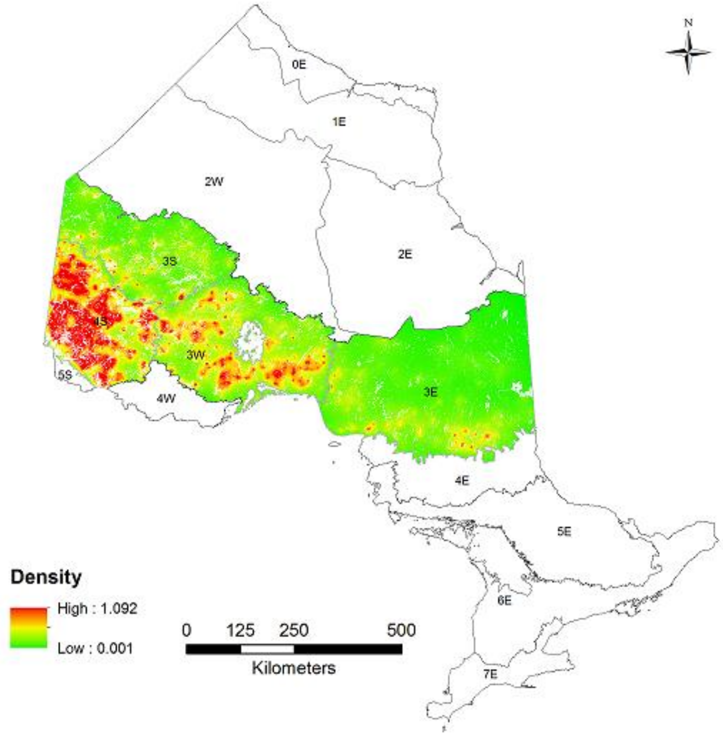

Figure 3.11 Estimated fire ignition density in the study area using adaptive kernel density estimation for the period 1960–2009.

A detailed investigation of underlying causes of these ignition patterns was not possible since the exploratory techniques used for this study do not incorporate covariates. Moreover, recall the purpose of this study was to produce ignition density maps that could be used as input for spatially explicit landscape planning models. However, results were visually compared with some physical factors to gain some insight. In their study, Podur et al. (2003) found more fires in elevated areas and suggested topography as the possible driving factor in the fire patterns. Results of this study support their opinion as majority of the fire ignitions are in higher elevation areas.

Fire ignition patterns were also compared with distribution of different forest cover types in the study area and no visual relationship was observed. It is also likely that certain geological features may influence the occurrence of lightning strikes and contribute in fire pattern formation. Maps of various geological features (geological formations, major iron formations and faults) were therefore overlaid on fire density maps to find any relationship visually. Fire ignition density did not follow the patterns of any of these. According to Hills (1959) Ontario has three regions of effective humidity:

medium humid (humid eastern), driest humid (humid western) and sub humid, with a decreasing gradient from the northeast to the southwest. According to this classification, 4S and 3S are in sub humid region, 3W is in driest humid region and 3E in medium humid region He also discussed that the temperature gradient decreases from the south to the north. Following this classification, 4S is in the higher effective temperature region whereas 3S, 3W and 3E are in lower temperature region. This also provides a likely explanation for the fire ignition patterns found in this study. 4S, where the ignition density is the highest, experiences the most dry and hot climate. 3S though falls in sub humid region and shares the same temperature zone with 3W. However, some areas of 3S being in more north than 3W have less temperature than 3W and resultantly less fire ignitions. Southern parts of 3S though have high fire ignition density but overall 3W experiences more fires than 3S. 3E being in the most humid region experiences the least fire ignitions which are mostly in the southern areas where temperatures are relatively high. Thus results of this study confirm Podur et al. (2003) association of high fire areas with higher elevations but these areas also coincide broadly with regions of Northern Ontario that are relatively warm and dry. The relative influence of the causal factors of this geographic fire pattern remains to be elucidated in details.

This study shows that fire ignitions in the study area are clustered. It is likely that the degree of clustering is affected by other prominent landscape features. The landscape is characterized by hundreds to thousands of lakes of different sizes that were not considered in this study for fire ignition pattern analysis. The research question about the scale of lightning-caused ignition clustering in Ontario boreal forests can be revisited by including the patterns of lakes in the analysis.

Also, the lakes act as fire barrier that, due to the limitation of the statistical method, was not possible to consider in the density estimation. It is therefore likely that in some areas of high concentration of lakes, the ignition density is over-estimated due to smoothing across the areas.

3.6 Conclusions

This study is a part of a project investigating the boreal fire regimes due to natural fires; therefore only lightning-caused fire ignitions were analyzed. Our study employed spatial statistical tools to analyze fire ignition patterns in Ontario managed boreal forests, and a calibration process for adaptive kernel density estimation to reliably estimate fire ignition density by reducing over/under-estimation error. Results were also compared visually with some bio-physical factors to identify the potential causes of the observed fire ignition patterns in the study area. The main findings of the study are; (i) selection of a representative study area is important because spatial patterns change with changes in the boundary, (ii) NNI and the *K*-function analyses both showed that lightning-caused fire ignitions in the study area are spatially clustered, (iii) the estimated degree of the clustering can depend on the method used, (iv) reliable density estimates can be obtained by using a smoothing parameter that minimizes over/under-estimation error, (v) the fire ignition density in the northwest ecoregion (4S) is the highest and (vi) the fire ignition density in the eastern ecoregion (3E) is the lowest. It was also noticed that Ontario forest fire data are not free from locational errors although, such errors appear to be minor in magnitude and frequency, nor should such small errors have a large impact on the estimated densities.

It was observed that at a broader scale fire ignitions in the study area follow the well-known combined humidity-temperature gradient. Also the visual comparisons of ignition patterns with forest types, topography and different geological formations did not show any relationship. Further research is suggested to investigate the combined effect of these factors on ignition patterns in the study area.

Chapter 4

Sensitivity of simulated fire regime parameters to spatial patterns of fire ignition assumptions: a case study from Ontario managed boreal forests

Summary

The characterization of forest fire regimes is pivotal to improve our understanding of boreal forest dynamics and for the success of management practices attempting to emulate fire disturbances. In this study the BFOLDS model was used to simulate boreal forest fire regimes for four ecoregions (3E, 3W, 3S and 4S) in Ontario, under two fire ignition scenarios: unweighted and weighted. Four non-spatial (total number of fires, total burn area, number of fires by size classes, annual burn fraction) and one spatial (spatial burn probability - SBP) fire regime indicators were compared to test the hypothesis of statistically no difference under unweighted and weighted ignition scenarios. Overall, the results for non-spatial indicators at 95% confidence interval (CI) showed no significant differences in the simulated fire regimes under unweighted and weighted ignition scenarios. However, the spatial indicator – SBP – captured clear spatial differences between unweighted and weighted ignitions. Results of the weighted scenario closely followed the spatial patterns of fire ignition density in the study area. Under the unweighted scenario, SBP in some areas was under-estimated and in some other areas it was over-estimated. Based on the results of SBP, this study rejects the null hypothesis and emphasizes that ignition patterns must be considered in simulating forest fire regimes.

4.1 Introduction

Fires occur frequently in the boreal forests (Rowe & Scotter, 1973; Telesca et al., 2005) and are believed to shape boreal vegetation dynamics (Payette, 1992; Suffling et al., 1988; Turner & Dale, 1991) by influencing many aspects including species distribution (Flannigan & Bergeron, 1998; Suffling, 1995), species composition (Bergeron et al., 2004b: Veraverbeke et al., 2010), species age class distribution (Bergeron et al., 2001), etc. The survival of boreal forests despite the presence of these disturbances, for centuries, provides sufficient evidence that fires are an integral part of that ecosystem (Millers et al., 2008; Rowe & Scotter, 1973) and the natural variability in the system caused by them is a vital attribute that can provide guidance for forest management to maintain biodiversity and achieve forest sustainability (Attiwill, 1994; Landres et al., 1999; Leopold et al., 1963; Perera & Cui, 2010).

In Ontario, two thirds (about 50 million ha) of the forests are boreal. These extend between the northern limits of the Great Lakes St. Lawrence forests to the Hudson Bay lowlands. Like most boreal forests, these forests are also characterized by fires (Perera et al., 1998). To maintain biodiversity and achieve forest sustainability, the provincial forest management guidelines emphasize preserving the fire-driven natural dynamics in these forests (OMNR, 2001). The fire driven vegetation dynamics are however, poorly understood due to the complexity in fire phenomena (Telesca et al., 2005). Fire ignition and its spread are highly variable processes controlled by a complex interaction between different environmental factors (Millers et al., 2008), including the sources of ignition, weather conditions, vegetation and topography (Mermoz et al., 2005). Characterization of the fire regimes is therefore needed for understanding fire phenomena and the subsequent vegetation dynamics (Perera et al., 2009; Suffling & Perera, 2004; Telesca et al., 2007; Vázquez & Moreno, 2001). One approach to characterize such a regime is the empirical studies of fire histories. Due to spatio-temporal variability in fire occurrence there are many possible forest fire regime characterizations (Perera & Buse, 2006) that empirical studies can not capture (Perera et al., 2009). Results of such studies therefore can not be generalized for forest management purposes. An alternative approach is to use models that incorporate knowledge about large scale fire processes to simulate fire regimes (Cary et al., 2006; Li, 2000a; Suffling & Perera, 2004). Generally, these models simulate fires as a function of different environmental factors (fuel, weather, topography) using sophisticated fire spread algorithms (Couce & Knorr, 2010; Cui et al., 2009; Millers et al., 2008; Weaver & Perera, 2004).To capture long term fire dynamics, simulations are normally run over hundreds of years (Li, 2000b, Wimberely et al., 2000).

Each fire event in simulation modeling is characterized by its location, occurrence time and area burned (Tuia et al., 2007). Due to spatial variability of relevant environmental factors (weather, vegetation, topography) the ignition locations can substantially influence fire occurrences and the subsequent fire regime (de Vasconcelos et al., 2001; Parisien & Moritz, 2009). This accentuates the need to properly consider the fire ignition patterns of the study area while seeding ignitions in the model (Catry et al., 2008; Krenn & Hergarten, 2009; Weaver & Perera, 2004). Though fire ignition locations are spatially non-random (Genton et al., 2006), many simulation studies randomly distribute fire ignition across the landscape (D’Andrea et al., 2009; Doran, 2004; Munoz-Marquez, 2005; Perera

& Cui, 2010). Some of these studies (Doran, 2004; Perera & Cui, 2010) also ran simulations based on a weighted ignition scenario to account for the uncertainty about real ignition spatial patterns. For the studies that seeded fire ignitions spatially random in the simulations, it was assumed that either these were lacking the data for spatial patterns or that they relied on the assumption that including or ignoring the ignition spatial patterns would not affect the model output. In the context of the latter assumption, no study was found in the literature, particularly for Ontario boreal forests that analyzed the modeled forest fire regimes under unweighted and weighted ignition scenarios. The objective of this study is to demonstrate the implications of accounting for ignition spatial patterns in simulated forest fire regimes. The weighted ignition scenarios for this study are generated from analyzing 47 years lightning-caused fires, as discussed in detail in Chapter 3. Here we test the null hypothesis that statistically there is no significant difference in simulated forest fire regimes, in Ontario managed boreal forests, with and without accounting for forest fire ignition patterns.

4.2 Study Area

The study area (Figure 4.1) includes Ontario managed boreal forests in ecoregions 3E, 3W, 3S and 4S. Some areas of 3S in the North and northwest; and of 3E in the northeast (shown white in Figure 4.1) were excluded in the analysis due to non-availability of soil and forest cover data.

Throughout the study area, black spruce (*Picea mariana*) is the main species in old forests. Although, black spruce and jack pine (*Pinus banksiana*) are the main species in young stands (Racey et al., 2000), the species composition varies throughout the study area due to differences in geo-climatic patterns (Hills, 1959) and is also mediated by fire regimes (Suffling, 1995). In 3E besides black spruce, trembling aspen (*Populus tremuloides*), white birch (*Betula papyrifera*), balsam fir (*Abies balsamea*) and white spruce (*Picea glauca*) are also abundant (Latremouille et al., 2008). In 3W, white birch, and poplar are common species; and conifer-conifer mixedwood is more dominant than conifer-hardwood mixedwood. In 3S poplar forms both pure and mixedwood stands. About a quarter of this ecoregion is mixedwood with major proportion of conifer-hardwood. In 4S, other pine species are red pine (*Pinus resinosa*) and white pine (*Pinus strobus*); and conifer-conifer mixedwood is dominant (Racey et al., 2000). Details on species composition are also provided in Section 2.1.

Stand replacing fires are the most dominant natural disturbances that shape the landscape of the forests in the study area (Latremouille et al., 2008; Perera at al., 1998; Racey et al., 2000).

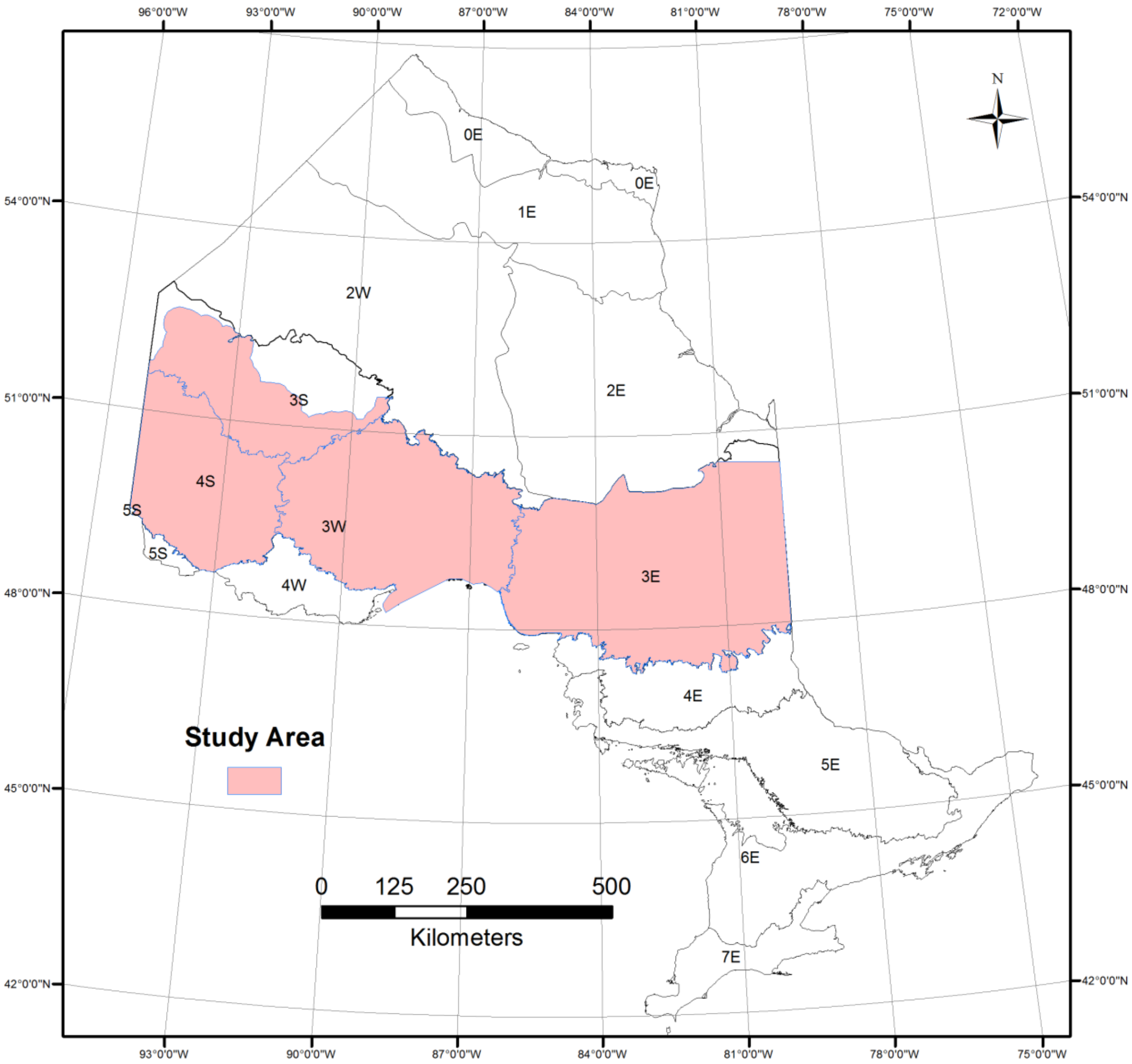

Figure 4.1 Location of the study area in Ontario, Canada. Labels are the name of ecoregions (Hills, 1959).

4.3 Methods

4.3.1 Simulation Model

In this study BFOLDS was used to simulate forest fire regimes. This model developed by the Ontario Forest Research Institute (OFRI) is used by OMNR and academic researchers for studies involving boreal forest fire regimes (Cui et al., 2009). BFOLDS is a raster-based spatially explicit model that uses a process-based fire simulation module to simulate forest fire events at a 1 ha spatial resolution. BFOLDS follows the principles of Canadian Fire Behaviour Prediction (FBP) system (Forestry Canada Fire Danger Group, 1992) and is capable of simulating multiple fires simultaneously over a large area. It simulates different fire processes (ignition, spread, and extinguishment) as a function of fire weather, topography and fuel type. A fire in BFOLDS burns any 1-ha cell only when it has burnable fuel types and when the duff moisture code[6] (DMC) is above a standard threshold value. The model also assumes that (i) once burnt a cell consumes all its fuel it cannot burn again for next ten years; and (ii) regardless of the above mentioned favourable conditions, all fires extinguish at the end of fire season (Julian day 304). Description and functioning of the model is discussed in details by Ouellette (2008) and Perera et al. (2008).

4.3.2 Simulation Scenarios

As mentioned in Section 4.3.1 BFOLDS requires a threshold value of DMC to ignite fires. In this study the threshold values were set following Perera et al. (2009). For ecoregions 3E and 3W a threshold of 20±2 was employed; and for 3S and 4S a threshold of 40±4 was used. The model was initialized for 100 years for each ecoregion using present day land cover composition (forest type and age). Forest composition at the end of initialization period was then used as base forest composition in simulations. Two fire ignition scenarios, namely unweighted (scenario A) and weighted (scenario B), were used in this study. Under the unweighted scenario, fire ignitions were seeded randomly across the study area. Under the weighted scenario, fire ignition patterns were used to spatially weight the seeding of fire ignitions. These ignition patterns were estimated using forest fire data in the study area for the period 1960–2009. The details of the methodology used to calculate these weighted grids are discussed in Chapter 3 of this thesis. For each of the 4 ecoregions, 30 simulations were run under each of the 2 scenarios resulting in total 240 simulations. To capture robust estimates of fire regime characteristics each simulation ran for 200 years (Perera et al., 2009). During a simulation run, each year was randomly assigned a weather year from 1963-2009. For consistency, corresponding simulation years under both scenarios were assigned the same weather year. Once a simulation started, the land cover changed as a function of age and/or due to fire disturbance and subsequent succession.

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[6] Index that represents the moisture contents of the upper layers of forest floor where litter begins to decay.

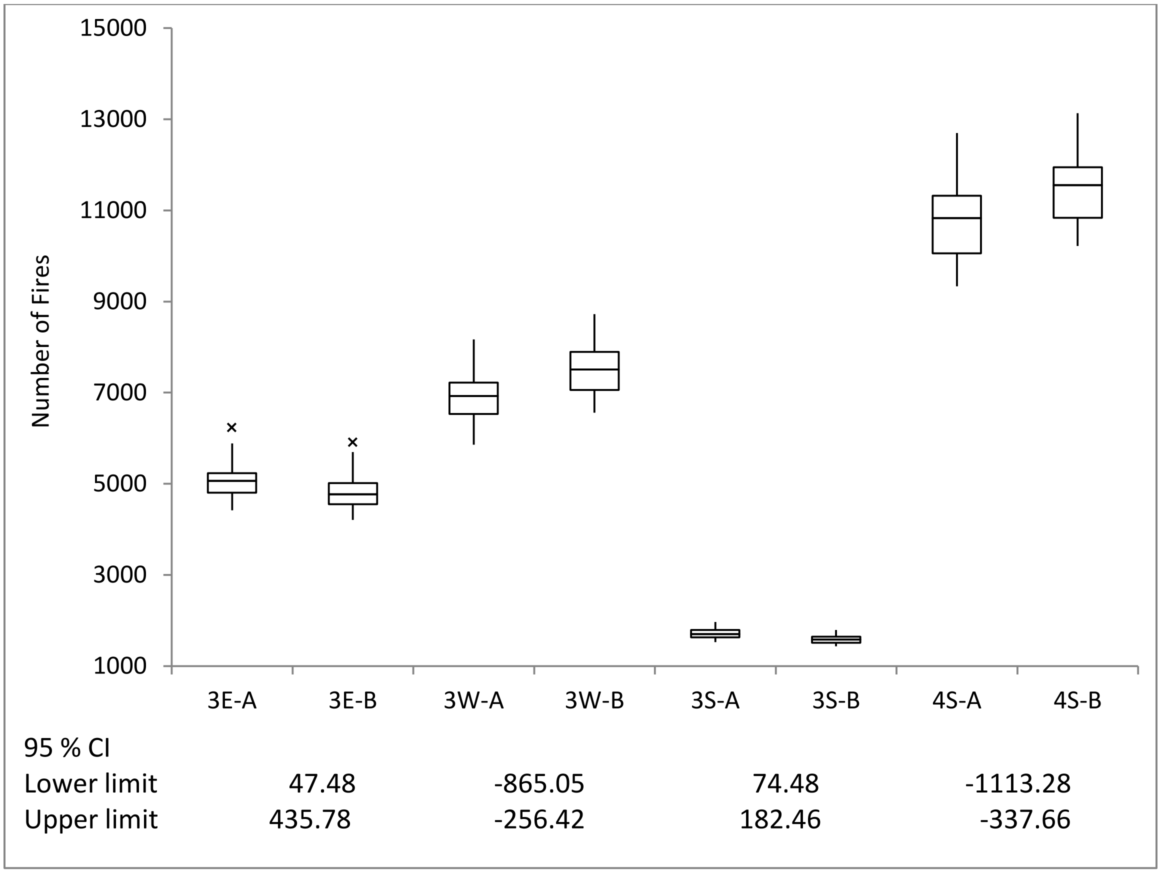
4.4 Results and Discussions

To reduce boundary effects, a buffer of 25 km was clipped from each ecoregion used in the simulations, and data analysis was performed on the remaining study area. Data were analyzed for four non-spatial (total number of fires, number of fires in different size classes, total burnt area, annual burn fraction - ABF) and one spatial (spatial burn probability – SBP) fire regime indicators. Each indicator was calculated for each simulation under each scenario.

4.4.1 Fire Regimes – Non-spatial Aspect

Results for non-spatial fire regime indicators for unweighted and weighted ignition scenarios were statistically compared by calculating 95% confidence intervals (CI). If limits of CI contain the value 0, the P-value is at least 0.05. In this case differences in values are considered statistically non-significant at the 5% level.

Results for each indicator for 30 simulations under each scenario are shown with boxplots and discussed in detail in this section. In each boxplot, the boxed area represents the interquartile range and the horizontal line in each box shows the median. The ends of the vertical bars extend above and below 1.5 times the interquartile range and potential outliers outside of this range are identified by an x. Naming scheme on the X-axis represents the ecoregion and the scenario. For example 3E-A means unweighted scenario for ecoregion 3E and 3E-B means weighted scenario for ecoregion 3E.



95 % CI				
Lower limit	47.48	-865.05	74.48	-1113.28
Upper limit	435.78	-256.42	182.46	-337.66

Figure 4.2 Boxplots and 95% CI limits for the number of fires in each ecoregion over the simulation period.

Figure 4.2 shows the boxplots (for 30 simulations) for the number of fires over the simulation period and 95% CI limits for the corresponding difference in the means for each ecoregion. Results show that overall 4S has the maximum number of fires with a mean of 10743 and 11468 fires for scenario A and scenario B respectively. 3W (6931, 7492) has the second most number of fires followed by 3E (5046, 4805) whereas; 3S received the least number of fires (1712, 1584). Results at 95% CI show that for each ecoregion the mean number of fires under both scenarios are significantly different.

To see the differences in the distribution of the number of fires in different fire sizes, and to investigate the source of the results presented in Figure 4.2, the total number of fires were divided in five size classes: namely C1 (1-10 ha), C10 (11-100 ha), C100 (101-1000 ha), C1000 (1001-10000 ha) and C10000 (over 10000 ha). Figure 4.3 shows the boxplots of simulated number of fires in these size classes for individual ecoregions under the two scenarios. CI values are presented in Table 4.1.

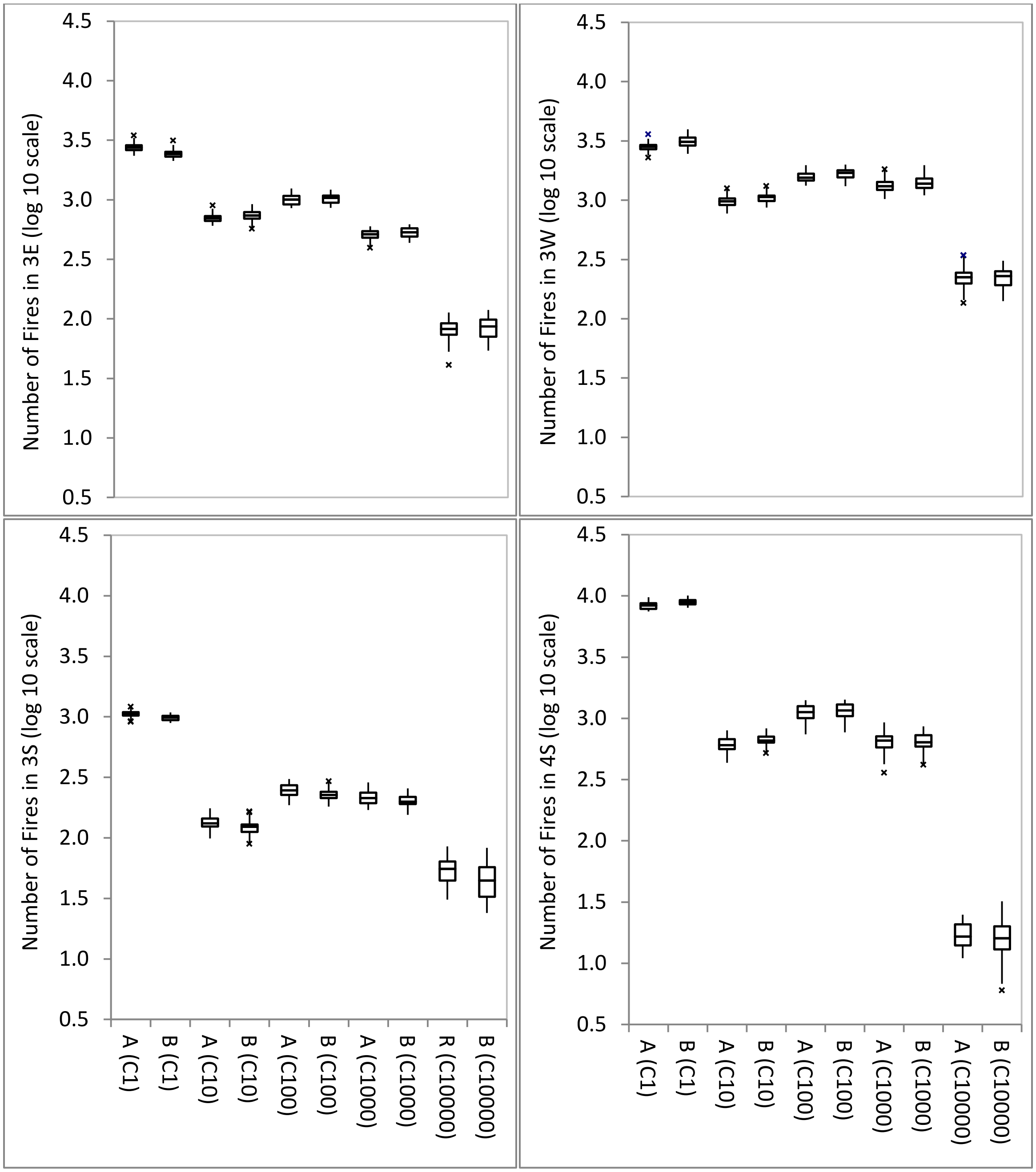


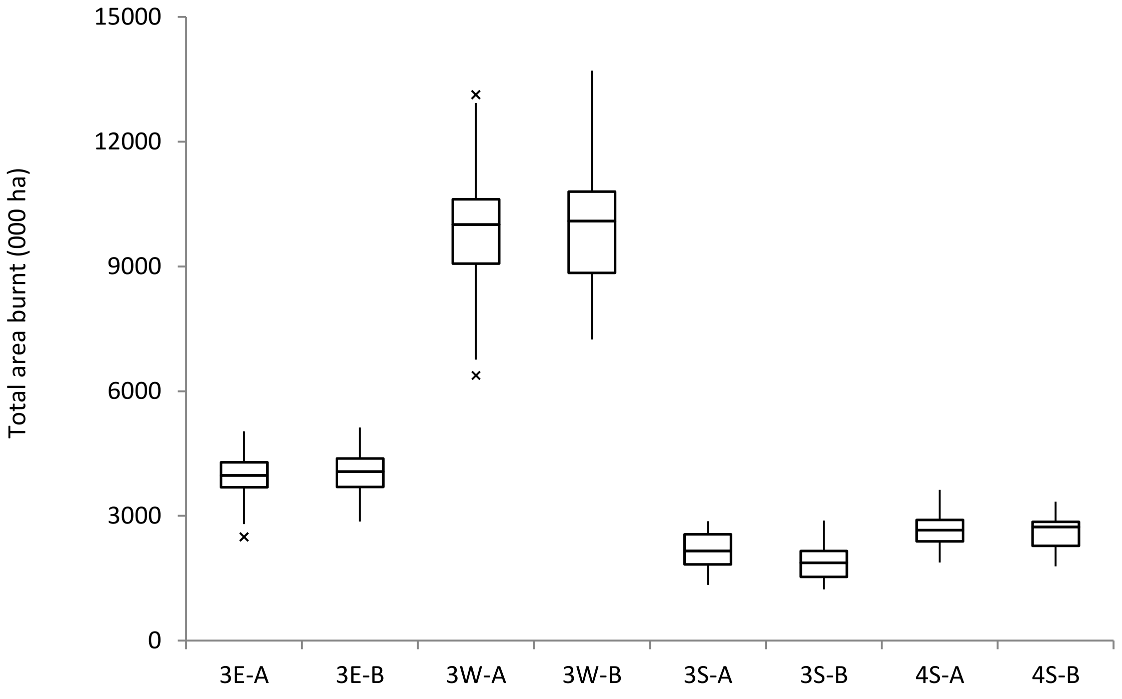
Figure 4.3 Boxplots for number of fires in size classes (C1, C10, C100, C1000 and C10000) in each ecoregion over simulation period under unweighted (A) and weighted (B) ignition scenarios.

Table 4.1 95% Confidence intervals for the difference in the mean number of fires for each of the five fire size classes.

	3E		3W		3S		4S	
Fire Size Classes	Lower limit	Upper limit	Lower limit	Upper limit	Lower limit	Upper limit	Lower limit	Upper limit
C1	200	432	-480	-171	40	104	-924	-354
C10	-71	-2	-124	-118	0.43	18.64	-92	-10
C100	-64	36	-190	-17	7	37	-127	39
C1000	-46	5	-154	29	0.89	32	-53	69
C10000	-13	6	-22	25	1.21	16.32	-2	3

Results show that under both scenarios the number of fires in 3E, 3W and 4S in larger size classes (C1000 and C10000) are similar. The numbers of fires in smaller size classes (C1 and C10) are significantly different in all ecoregions. Since in size class C1 fires (the smallest fires) are the most frequent, this has influenced the results of total number of fires (Figure 4.2). Results for 3S show that numbers of fires in all classes under both scenarios are significantly different.

Results shown in Figure 4.4 represent the boxplots of simulated burnt areas over the simulation period and 95% CI limits for each ecoregion. Overall the maximum area was burnt in 3W with mean burnt area of 9880912 ha (scenario A) and 10007115 ha (scenario B); followed by 3E (3931369 ha, 4006461 ha), 4S (2660488 ha, 2593918 ha) and 3S (2161422 ha, 1893180 ha). Results at 95% CI show that in 3E, 3W and 4S total burnt areas have no differences at 95% CI under both scenarios whereas, total burnt areas in 3S under unweighted and weighted ignition scenarios are significantly different. As fewer large fires are responsible for most of the area burnt, the results of number of fires in larger size classes (Figure 4.3, Table 4.1) corroborate the results of total burnt area.



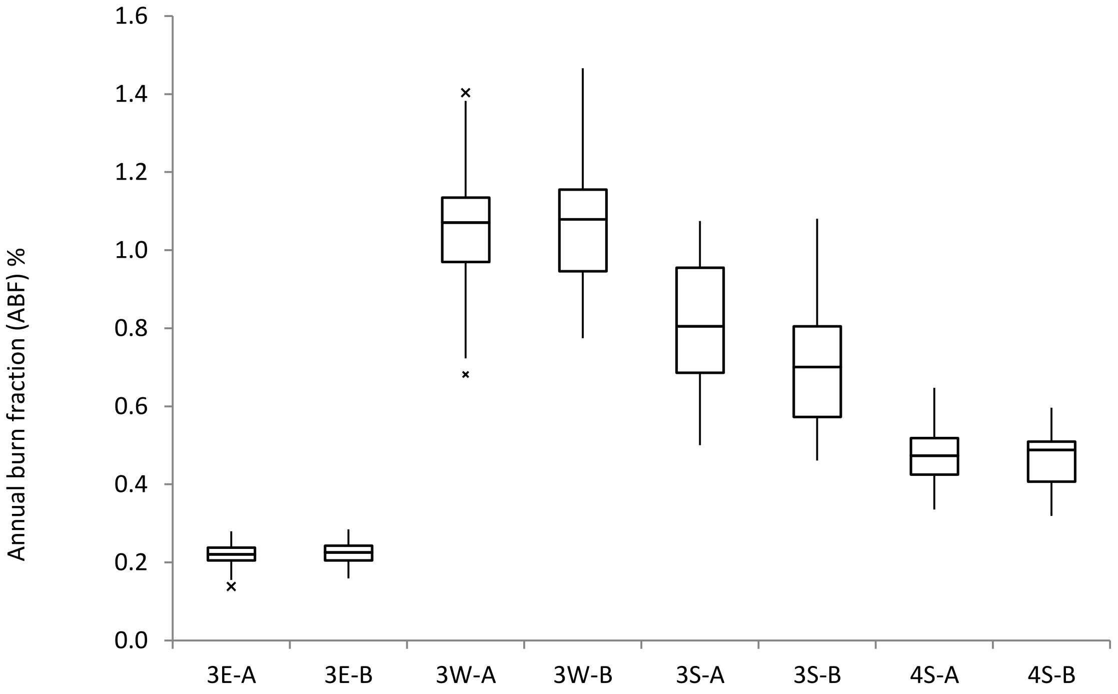
95% CI				
Lower limit	-347600	-874207	46855	-141394
Upper limit	197416	621801	489631	274533

Figure 4.4 Boxplots and 95% CI limits for total area burnt in each ecoregion over the simulation period.

Comparing the total area burnt is not a useful measure if study areas have different sizes. In such situations annual burn fraction (ABF) is a better indicator. ABF is the average annual percentage area burnt out of the total forested area during the simulation period (Perera et al., 2009). Equation 4.1 shows the mathematical expression to calculate ABF

$$ABF = \frac{Total\ area\ burnt\ during\ the\ simulation\ period}{Simulation\ period\ in\ years \times Total\ area\ under\ forest} \times 100 \qquad (4.1)$$

The boxplots of simulated ABF over the simulation period and 95% CI limits for each ecoregion are shown in Figure 4.5.The mean ABF (for 30 simulations) is highest for 3W: scenario A (1.06%), scenario B (1.07%); followed by 3S (0.81%, 0.71%) and 4S (0.47%, 0.46%). 3E has the least ABF (0.22%, 0.22%). For 3E, 3W and 4S corresponding values of CI (-0.02, 0.01), (-0.09, 0.07) and (-0.03, 0.05) respectively show no significant difference in ABF under both scenarios. Contrarily, CI for 3S (0.02, 0.18) shows that ABFs are significantly different under both scenarios. In this respect results for 3S are justified as burnt areas for it are also significantly different under both scenarios.



95% CI				
Lower limit	-0.02	-0.09	0.02	-0.03
Upper limit	0.01	0.07	0.18	0.05

Figure 4.5 Boxplots and 95% CI limits for annual burn fraction (ABF) in each ecoregion over the simulation period.

The results for 3S were further investigated to find plausible cause for different behaviour. Figure 4.6 shows the ignition density of 3S used for simulations under the weighted scenario. It shows that the ignition density is the highest along the southern border of the ecoregion. However, when buffer was clipped from the area majority of the high ignition density area was left out. The actual data used in final analysis was for the area inside the polygon (black outlined area in Figure 4.6). This means that due to the buffer a reasonable number of fires and the burnt areas under the weighted scenario were excluded from the analysis. The spatial burn probability map for the weighted scenario (Figure 4.9(b)) also illustrates more fire occurrence along the southern border. Comparison of numbers of fires and areas burnt (Table 4.2) also confirms that number of fires and the burnt area were less under weighted scenario. Due to non-availability of data for the adjoining areas it was not possible to create an outside buffer and run an analysis for the entire ecoregions. This suggests, however, that results could be improved if the data for these adjoining areas were available.

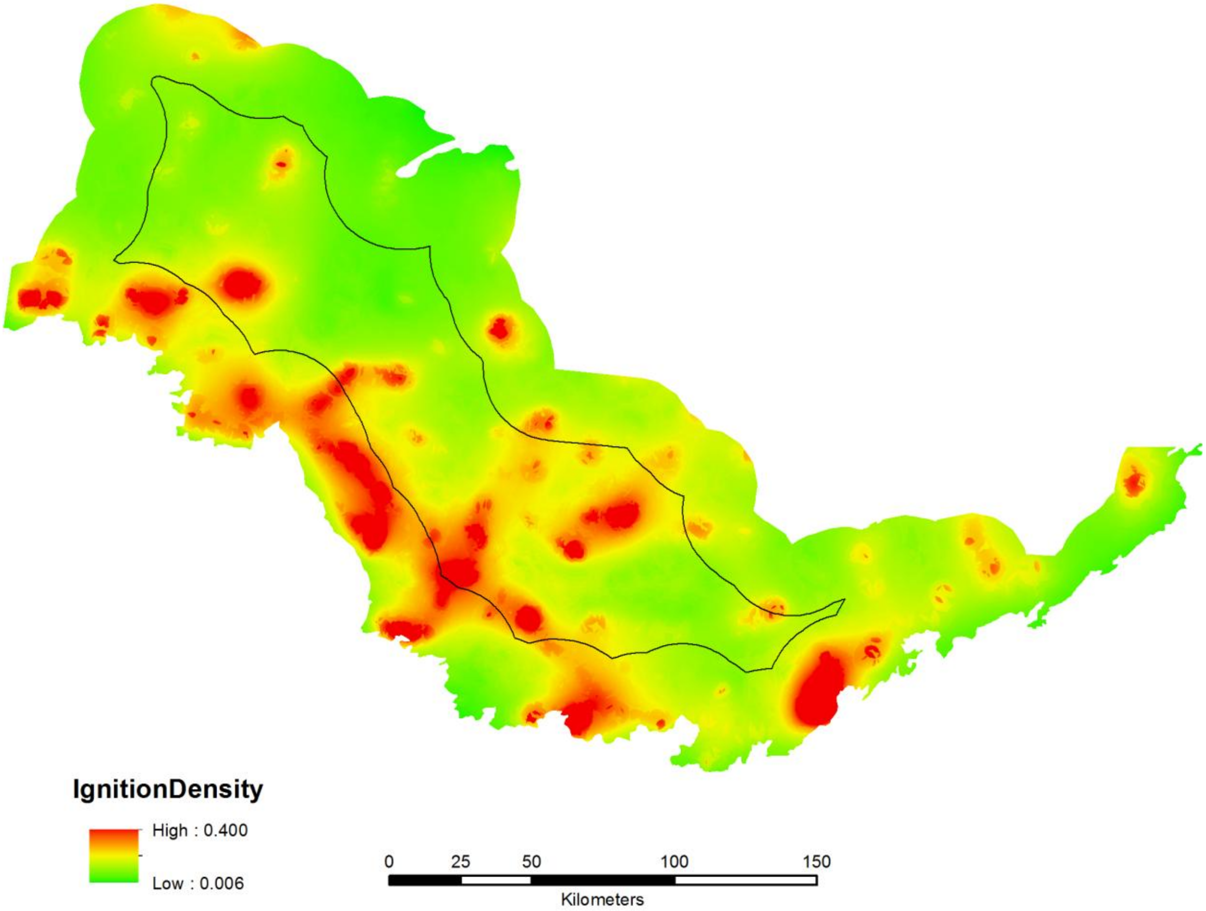


Figure 4.6 Ignition density in 3S used for weighted scenario in BFOLDS simulations. Black line shows the boundary of the clipped area.

Table 4.2 Comparison of average number of fires and burnt area for 30 simulations in 3S

	Unweighted Scenario	**Weighted Scenario**
Fire Size Classes	**Number of fires**	
C1 (1-10 ha)	1058	986
C10 (11-100 ha)	133	123
C100 (101-1000 ha)	248	226
C1000 (1001-10000 ha)	219	203
C10000 (>10000 ha)	55	46
Total Burnt Area	**000 ha**	
	2161.4	1893.2

4.4.2 Fire Regimes – Spatial Aspect

Forest fires are a spatial phenomenon whose distribution and behaviour can vary across a landscape. The quantification of these spatial characteristics is very important for forest management. To explore for any spatial patterns in the fire regimes, spatial burn probability (SBP) was calculated for each pixel. Equation 4.2 shows the mathematical expression for SBP for a given pixel.

$$SBP = \frac{Total\ burn\ count}{Number\ of\ simulations \times Simulation\ period} \tag{4.2}$$

SBP maps (Figure 4.7–4.10)[7] show the spatial variability in burn probability in the study area and illustrate the general findings that fire regimes in boreal forests have considerable spatial variation (Keane et al., 2004). In 3E under unweighted scenario (Figure 4.7(a)), areas of medium to high[8] SBP are throughout the ecoregion except the northeastern part whereas, under weighted scenario (Figure 4.7(b)) areas of medium to high SBP are mainly concentrated in the South and the West. In 3W under unweighted scenario (Figure 4.8(a)) some areas in the North have very high SBP; and medium SBP areas are spread throughout the region whereas, under weighted scenario (Figure 4.8(b)) most of the medium to high SBP areas are in the South and the West with a few areas of medium SBP in the North and northeast. SBP of 3S also show clear differences under both scenarios. Under unweighted scenario (Figure 4.9(a)) areas with medium SBP are spread throughout the region whereas, under

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[7] White areas in the maps are areas under water bodies (lakes, rivers etc)

[8] The terms “medium”, “high” used in this section are for individual ecoregions.

weighted scenario (Figure 4.9(b)) medium SBP areas are mainly concentrated in the South and southeast with two prominent patches of high SBP. In the western part, there is another area of high to medium SBP that stretches from the South to the North. Spatial differences of SBP are also obvious in 4S. Under unweighted scenario (Figure 4.10(a)) medium to high SBP areas are manly stretched from southeast to northwest whereas, under weighted scenario (Figure 4.10(b)) areas with medium to high SBP are throughout the region with higher concentration in central and western parts.

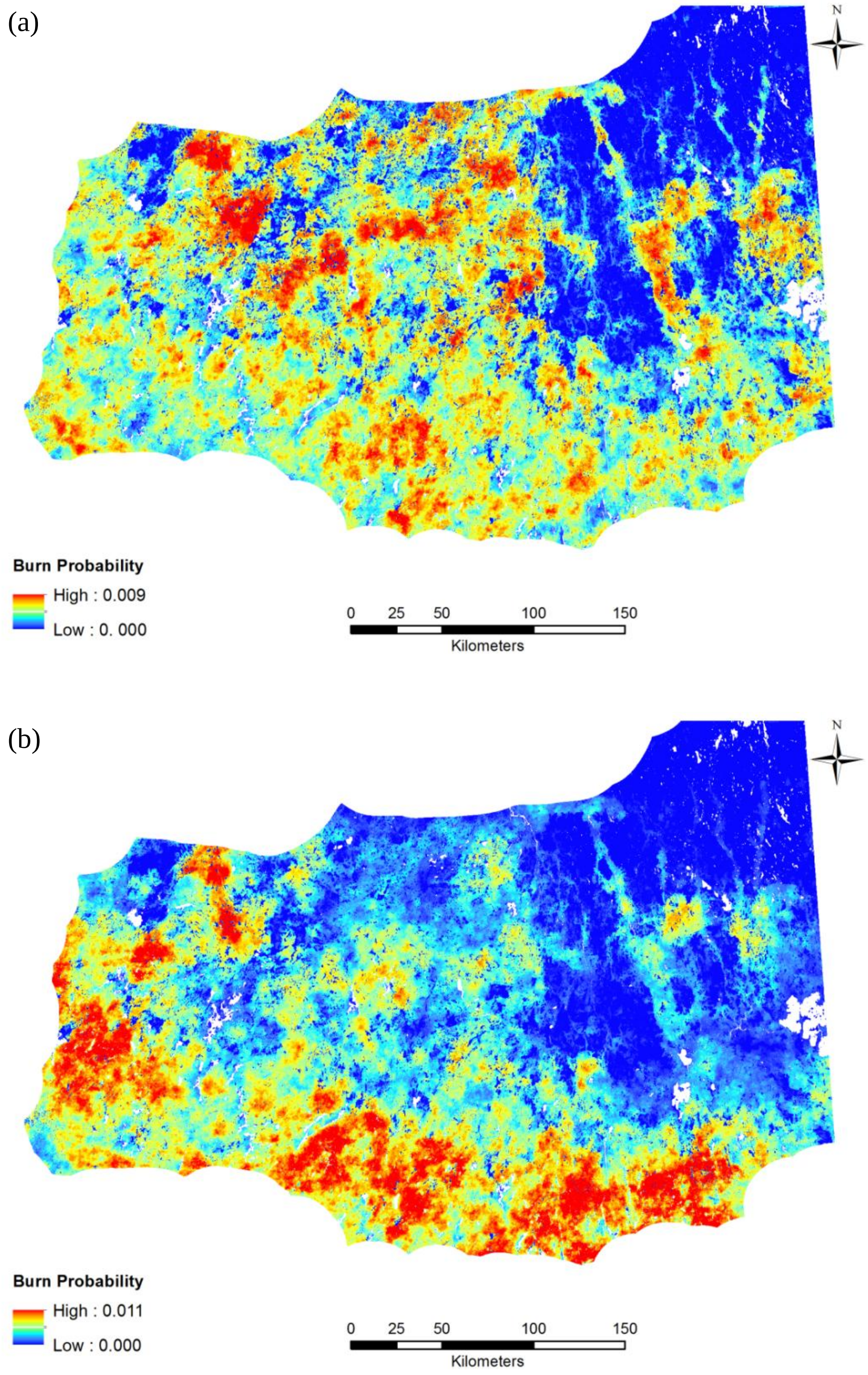

Figure 4.7 Spatial burn probability maps of 3E under ignition scenarios (a) unweighted (b) weighted.

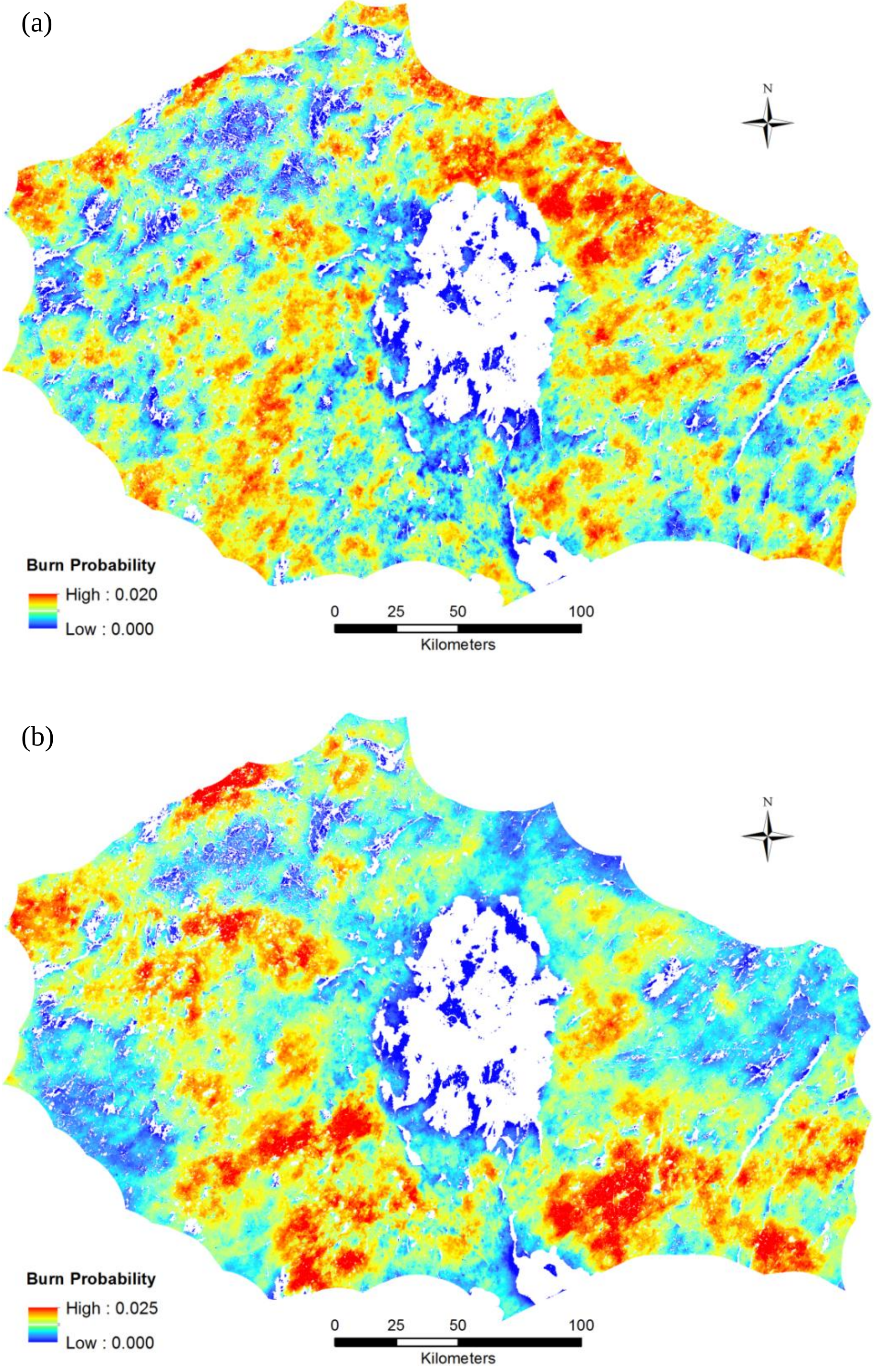

Figure 4.8 Spatial burn probability maps of 3W under ignition scenarios (a) unweighted (b) weighted.

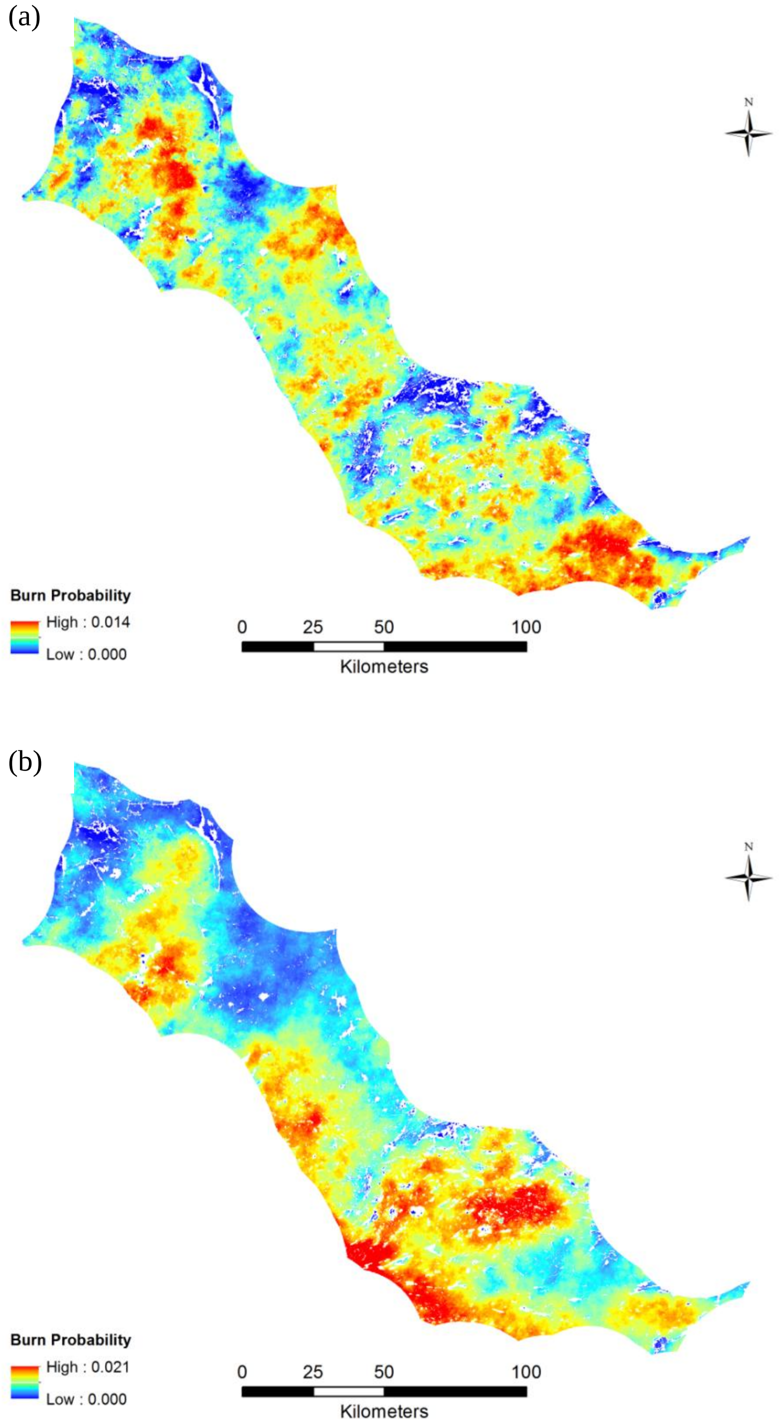

Figure 4.9 Spatial burn probability maps of 3S under ignition scenarios (a) unweighted (b) weighted.

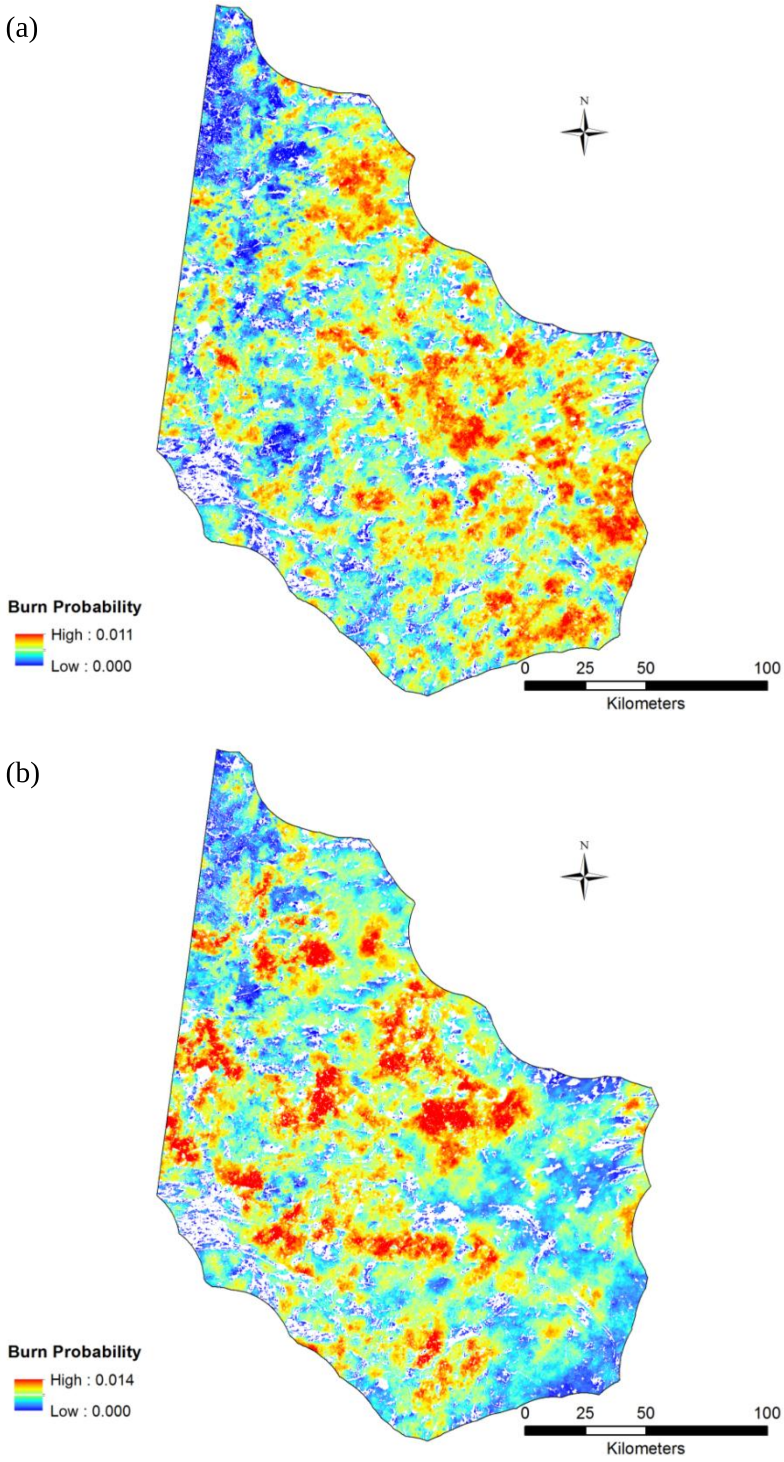

Figure 4.10 Spatial burn probability maps of 4S under ignition scenarios (a) unweighted (b) weighted.

Visually the maps (Figure 4.7–4.10) show spatial differences of SBP for each ecoregion under both ignition scenarios. To statistically test these results a Kappa statistic was calculated. It quantitatively measures the degree of agreement based on the difference between observed (actual) and expected (by chance) agreement (Cohen, 1960). A Kappa value of 1 represents perfect agreement and a value of 0 equates to by chance agreement (Viera & Garrett, 2005). A scale (Table 4.3) proposed by Landis & Koch (1977) was used in this study to interpret the results of Kappa analysis.

Table 4.3: Interpretation of Kappa statistic for categorical data (Source: Landis & Koch, 1977).

Kappa Statistic	Strength of Agreement
< 0.00	Poor
0.00 – 0.20	Slight
0.21 – 0.40	Fair
0.41 – 0.60	Moderate
0.61 – 0.80	Substantial
0.81 – 1.00	Almost perfect

To conduct a Kappa analysis, the SBP for individual ecoregion under each ignition scenario was categorized into six ordinal classes: 0, (0, 0.005], (0.005, 0.01], (0.01, 0.015], (0.015, 0.020] and >0.020 (Figure 4.11). All the analysis for Kappa and its P value (Viera & Garrett, 2005) were done in R (R Development Core Team, 2009) using the vcd package (Meyer et al., 2009).

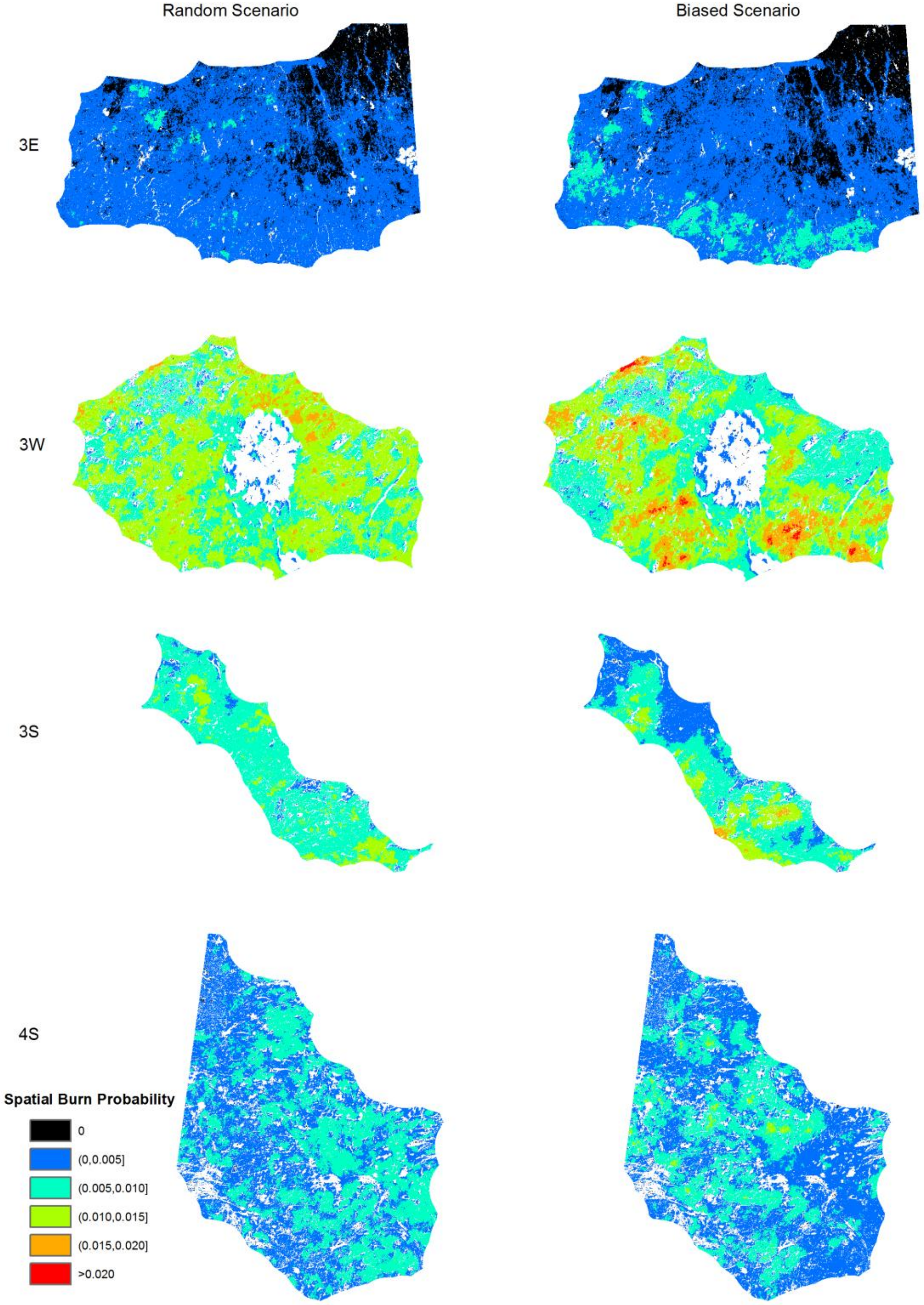

Figure 4.11: Comparison of spatial burn probability between scenarios and ecoregions.

Table 4.4: Results of Kappa statistic for spatial burn probability under unweighted and weighted ignitions.

Ecoregion	Kappa Value	Approximate St. Error	P value	Remarks
3E	0.675	0.0003	0	Substantial agreement
3W	0.194	0.0004	0	Slight agreement
3S	0.086	0.0008	0	Slight agreement
4S	0.240	0.0006	0	Fair agreement

Results of Kappa shown in Table 4.4 demonstrate that SBP under both ignition scenarios are statistically different in all ecoregions. The high agreement in 3E is due to low fire activity in this ecoregion. These results also imply that the higher the fire activity in a region the more the spatial differences in burn probability when comparing unweighted and weighted ignition scenarios.

Further, to highlight the areas of high differences in SBP of both ignition scenarios, the SBP difference maps were created. Figure 4.12–4.15 show the colour-coded difference maps for all ecoregions that were generated by subtracting the SBP of unweighted scenario from the SBP of the weighted scenario. Red colour represents the 20% of the forested area where the SBP under weighted scenario was higher than unweighted scenario. Blue colour represents the 20% of the total forested area where SBP under unweighted scenario was higher than weighted scenario. Grey areas represent 60% of the forested areas that is marked as transition zone (where SBP differences are less) of SBP under both scenarios.

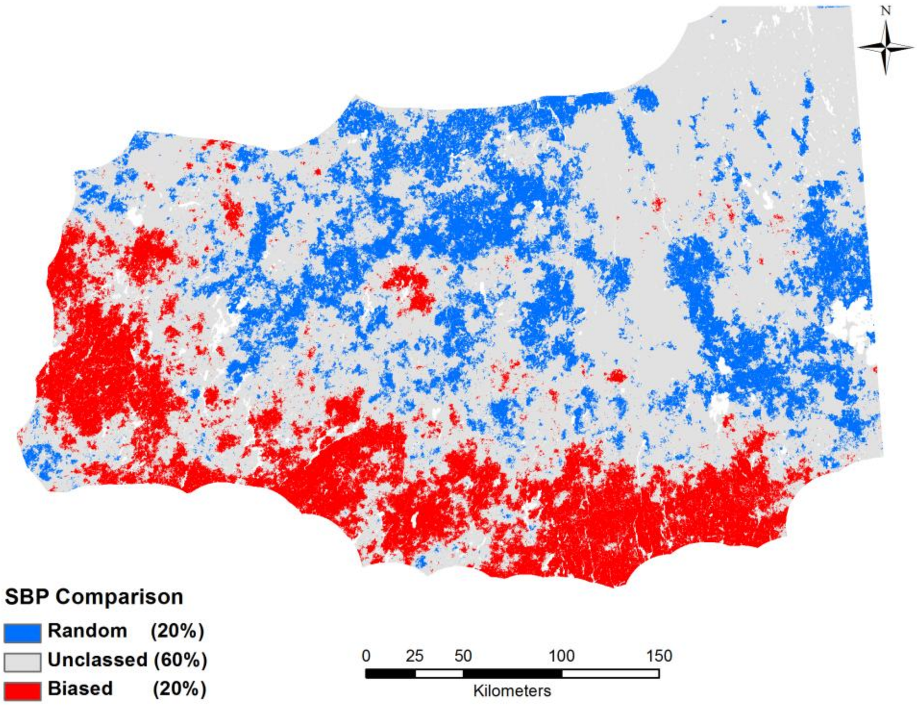

Figure 4.12 Spatial burn probability (SBP) difference map for 3E.

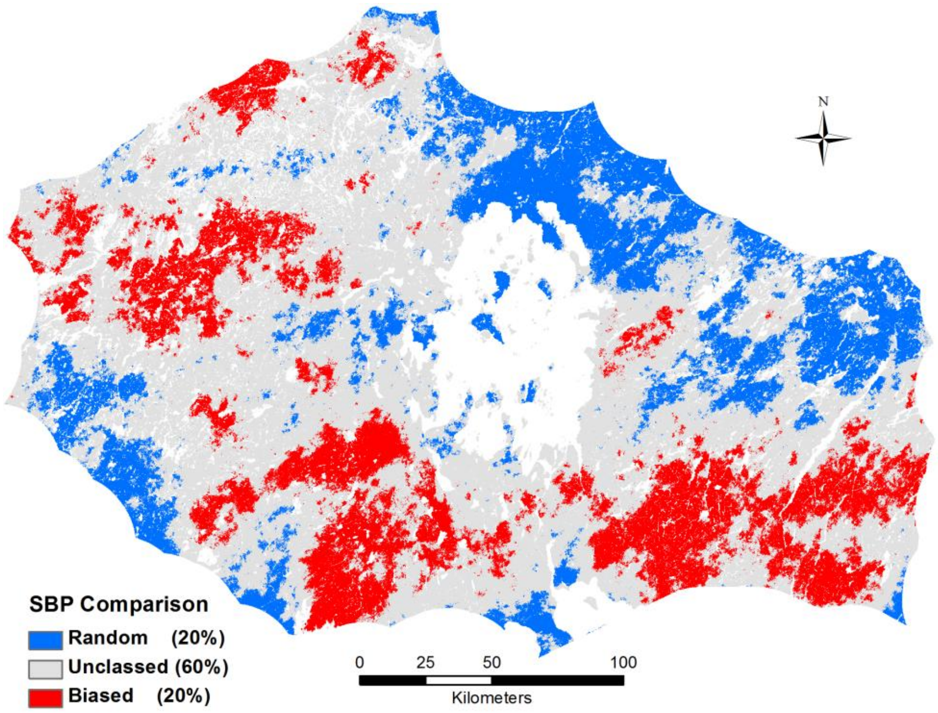

Figure 4.13 Spatial burn probability (SBP) difference map for 3W.

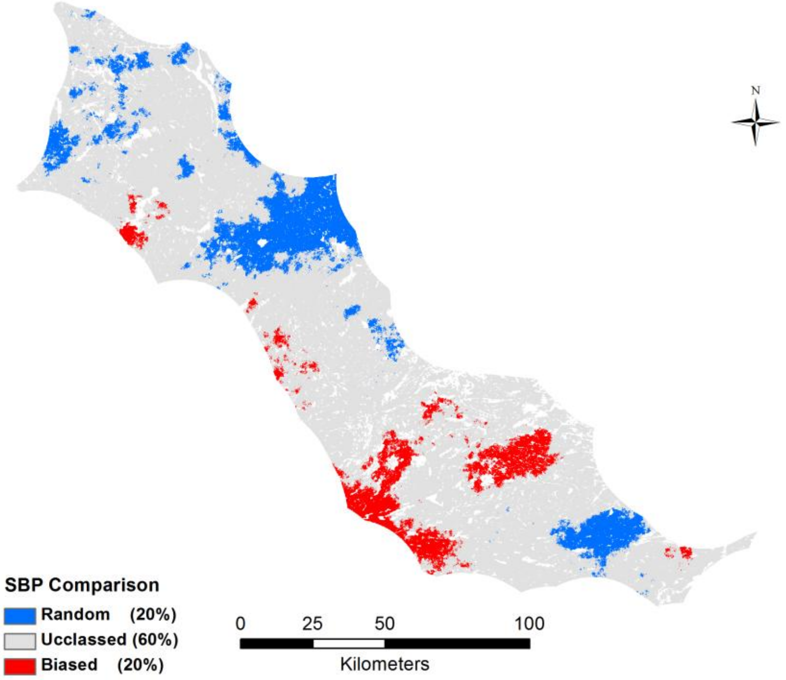

Figure 4.14 Spatial burn probability (SBP) difference map for 3S.

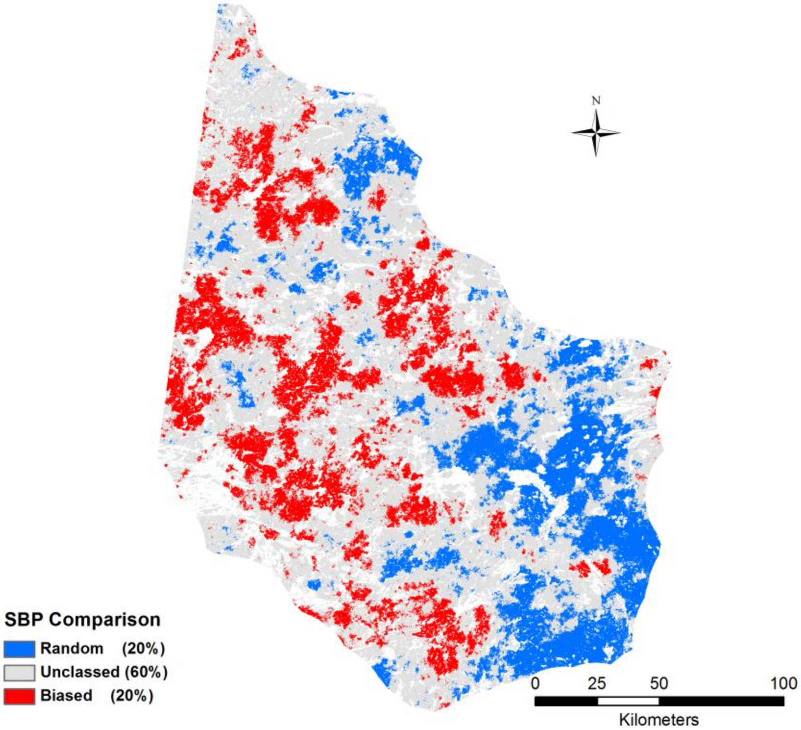

Figure 4.15 Spatial burn probability (SBP) difference map for 4S.

These results clearly show the remarkable differences in spatial aspect of simulated fire regimes under unweighted and weighted ignition scenario. As discussed in Section 4.3.2 both scenarios received the same forest compositions and weather conditions. The only difference was the spatial distribution of ignition seeding. Also, the forest compositions and weather conditions used in this study were the major determinants of the current fire ignition spatial distribution. Thus, comparing the modeled SBP of each scenario with the current spatial distribution of fire ignitions can give insight to evaluate the results of both scenarios for reliability. Lightning-caused forest fire data from OMNR forest fire database, for the period 1960–2009, was used for this purpose. The fire locations were plotted on SBP difference maps (Figure 4.12–4.15) and results are shown in Figure 4.16–4.19. Visual comparison shows that for all ecoregions fire density (number of fires) is high in areas where modeled SBP under weighted ignition scenario is high. The areas with high SBP under unweighted scenario actually received fewer fires during 1960-2009. In other words the unweighted scenario overestimates SBP at places shown blue in figures and underestimate at locations shown red in figures. These results illustrate that weighted scenario closely follows the actual spatial fire ignition density and provide more realistic picture about the SBP.

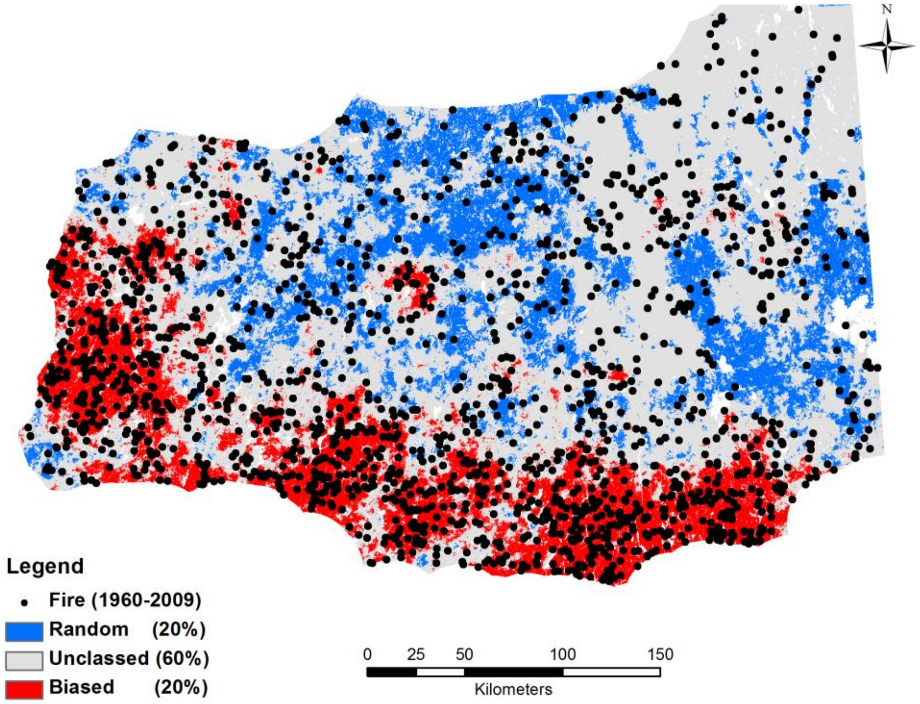

Figure 4.16 Modeled SBP difference map with locations of fires during 1960-2009 in 3E.

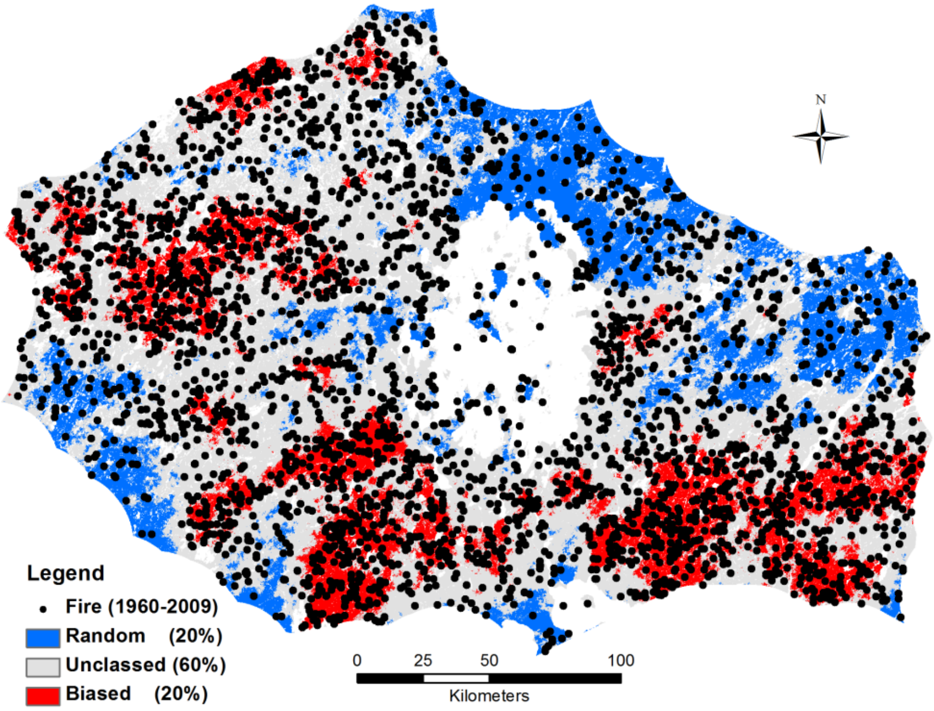

Figure 4.17 Modeled SBP difference map with locations of fires during 1960-2009 in 3W.

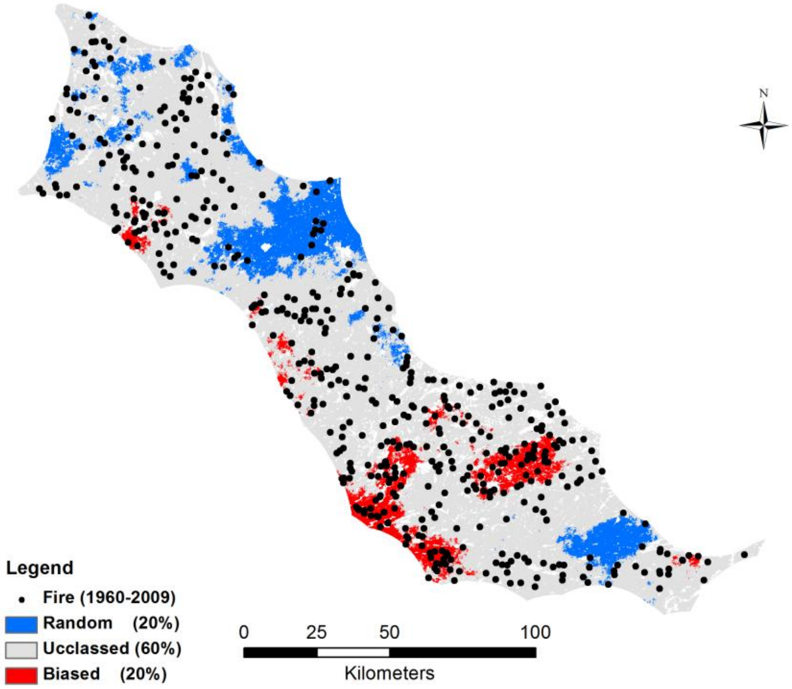

Figure 4.18 Modeled SBP difference map with locations of fires during 1960-2009 in 3S.

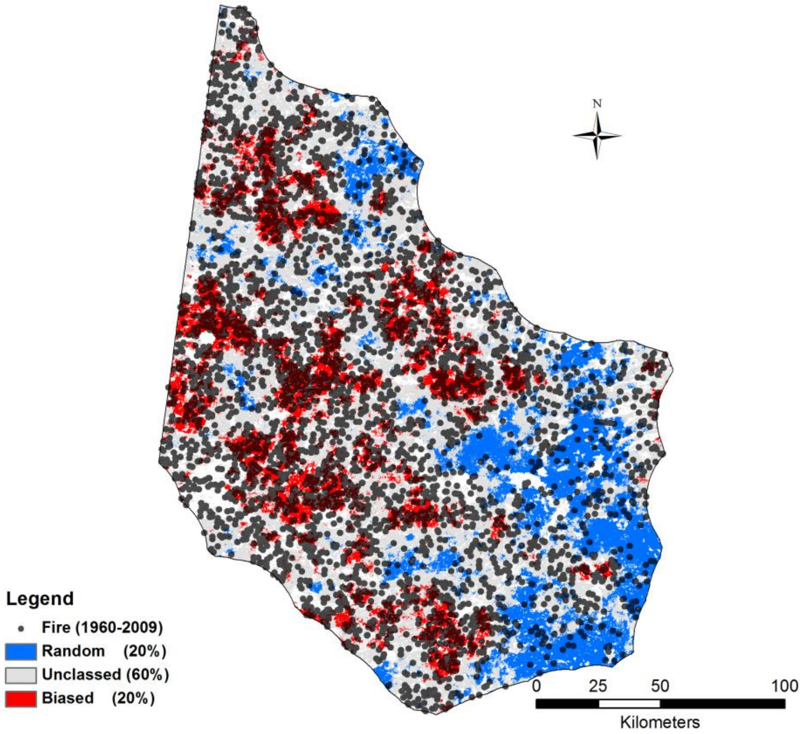

Figure 4.19 Modeled SBP difference map with locations of fires during 1960-2009 in 4S.

4.5 Conclusions

The characterization of fire regimes is important to improve our understanding of boreal forests dynamics and to improve methods that attempt to emulate fire driven disturbances in management practices aimed at maintaining biodiversity and achieving forest sustainability. This study was conducted to demonstrate the effects of changes in ignition patterns on the simulated fire regime. The BFOLDS model was used to run simulations under unweighted and weighted ignition scenarios for four ecoregions of Ontario boreal forests: namely 3E, 3W, 3S and 4S. Simulation data were analyzed for different fire regime indicators and results were compared at 95% CI. Comparison of non-spatial indicators between unweighted and weighted ignition scenarios showed no significant differences in fire regime for 3E, 3W and 4S. Results for 3S showed significant differences at 95% CI in fire regime characteristics under both ignition scenarios. Further analysis of the data showed that in 3S differences occurred due to removing some areas as buffer. Overall these results using non-spatial indicators suggest that changes in ignition patterns do not significantly alter such aggregate measures.

Contrary to the non-spatial indicators, the SBP captured clear spatial differences under both ignition scenarios. Kappa statistics showed that differences are more in ecoregions of high fire activity. Fire occurrence is a spatial phenomenon and, for an accurate understanding of forest dynamics, this spatial aspect must be accounted for. In the light of these results therefore, this study rejects the null hypothesis and concludes that spatial patterns of fire ignitions should be considered when modeling the boreal forest fire regimes.

Despite the clear differences in modeled SBP under both scenarios, the different behaviour (non-significant differences) of non-spatial indicators needs further investigation. Under both scenarios, majority of the fires in all ecoregions were from small size classes and were significantly different at 95% CI. The burnt areas and the number of fires in larger size classes were similar under both ignition scenarios. Under weighted ignition scenario, the patches of high SBP indicate high fire occurrence in those areas, which should reduce the possibility of large fire by reducing fuel (already burnt areas). As the number and sizes of large fires do not differ significantly between unweighted and weighted scenarios, this lends indirect evidence that earlier fires do not inhibit later ones. This is possible as most of the modeled fires were of smaller size (1-10 ha) whereas BFOLDS uses a 9 x 9 (ha^2) search window to determine potential spread the fire (Perera et al., 2008). In BFOLDS a fire extinguishes if any of the following conditions is met in all pixels adjacent to the fire front: (i) no fuel, (ii) DMC is higher than the threshold value, or (iii) the fire season ends. Hundreds to thousands of lakes in the study area also act as no-fuel pixels in BFOLDS. Presence of these lakes or the DMC above threshold values may also influence the non-spatial indicators of modeled fire regime. These opinions however, can not be confirmed as BFOLDS does not record the final cause of extinguishment of a fire.

The objective of the study was to demonstrate the effects of incorporating spatial non-randomness of fire ignitions. Consequently, only a few fire regime indicators were investigated. Further studies could be conducted using the weighted ignition patterns (i) by extending the buffers outside the ecoregions if relevant data are available; and (ii) for a wider range of fire regime indicators to capture more features of fire dynamics in the study area. Depending on the resources available studies could also be conducted over longer simulation periods using more simulations. This may help to capture more variability or at least identify threshold values for number of simulations and/or number of years in a simulation for an individual ecoregion.

Chapter 5

Conclusions and Recommendations

The research undertaken in this thesis was motivated by the essential need to improve our understanding about the spatial patterns of fires in Ontario managed boreal forests, and their role when simulating a forest fire regime. In this chapter the main findings of the research are discussed in Section 5.1. In Section 5.2 recommendations are made for future research.

5.1 Conclusions

Lightning-caused forest fires play an important role in Ontario boreal forest dynamics. For sustainable management of these forests and biodiversity conservation it is necessary to consider forests fires as an integral part of the boreal ecosystem and the management activities should mimic these fires. This accentuates the need first to understand the fire behaviour as reflected in forest fire regimes. Simulating forest fire regimes is a preferred choice to capture inherent spatio-temporal variability in fire regimes (Perera & Cui, 2010). Though, fire ignition in the model is an important consideration to achieve reliable simulated forest fire regimes (Krenn & Hergarten, 2009), none of the fire regime studies in the literature thoroughly investigated spatial fire ignition patterns.

To fill this gap in the literature, this thesis presents a two-phase approach. Each phase is fully discussed in an individual chapter of this thesis. In the first phase (Chapter 3) point pattern analyses of lightning-caused fire ignitions in the study area were performed to demonstrate the inhomogeneous nature of ignition patterns. Further, fire ignition densities were estimated. In the second phase (Chapter 4) estimated fire density surfaces were used to seed fire ignitions in BFOLDS. An unweighted ignition seeding grid was also used in BFOLDS. Finally, BFOLDS's performance was assessed by comparing the results of both ignition scenarios for some major fire regime indicators. All the analyses, in both phases, were based on individual ecoregions (3E, 3W, 3S and 4S) of the study area.

5.1.1 Spatial Ignition Patterns

Two spatial statistical methods: NNI and the *K*-function were used for point pattern analysis of the lightning-caused fire ignitions. To see the effects of study area size, analyses were performed also by combining areas of two ecoregions (3S and 4S) and adding a buffer around ecoregions. Regardless as to whether or not ecoregions were combined/buffers were employed, results demonstrate that the distribution of lightning-caused forest fires does not follow CSR. The results also demonstrated the need to carefully define the study area, so that the identified patterns can further be used for policy and management applications.

To generate ignition density surfaces, an adaptive kernel density estimation approach was used. This method is particularly applicable to a phenomenon whose distribution is not spatially homogeneous. By adjusting the bandwidth depending on the density of incident points of the phenomenon, this method yields reliable density estimates. Bias (over/under estimation) in the density estimation was further reduced by adopting a quantitative validation procedure: goodness of fit criteria. This procedure helped to identify the bandwidth settings to generate reliable fire density surface for each ecoregion.

Results of density estimation showed that fire density varies among the ecoregions. Overall the highest fire density was in ecoregion 4S followed by 3W and 3S. Fire density in ecoregion 3E was the least among all the ecoregions. These results also showed that at ecoregion-scale fire ignition density follows the combined gradient of effective humidity and temperature (Hills, 1959). Ecoregion 4S is the one that experiences the highest temperature and the least humidity among all the four ecoregions. On the other hand, ecoregion 3E where the estimated fire density was the least is the one with minimum temperature and the highest humidity. This has implications for the allocation of resources for fire management activities in the study area.

Within each ecoregion fire density also varied. Overall the southern and the western parts of all ecoregions showed clusters of higher to medium fire density. At this local scale the GIS layers of different biophysical factors were overlaid to estimated fire density maps to find any visual correlation. These included elevation, forest cover types and various geological features (geological formations, iron formations and faults). Visually spatial relations of fire ignition density were noticed only with elevation. Fire ignition density was high in elevated areas.

5.1.2 Simulated Fire Regimes

In Ontario, BFOLDS is widely used by the OMNR and researchers for boreal forest fire regime related studies. In this research BFOLDS was used to simulate forest fire regimes under two ignition scenarios: unweighted and weighted. For each ecoregion 30 simulations were run under each ignition scenario and each simulation span for 200 years. After the simulations a buffer of 25 km was clipped to reduce any boundary effects on further data analyses. Data were analyzed for four non-spatial fire regime indicators: total number of fires, fires distribution in different size classes, total burnt area and annual burn fraction (ABF); and results under both ignition scenarios were compared at 95% CI level. To capture the spatial aspect of simulated fire regime, the spatial burn probability (SBP) of individual pixel over the simulation period (200 years) for 30 simulations was calculated. Results of SBP under both ignition scenarios were compared using Kappa statistic and the SBP difference maps.

Comparison of results revealed that, for each ecoregion, the total number of fires was significantly different between ignition scenarios but there were no differences in the total burnt area except in ecoregion 3S. Results of 3S differed from other ecoregions for all non-spatial fire regime indicators, and are thus discussed in separate paragraph in this section. For remaining ecoregions (3E, 3W and 4S) total number of fires were further divided in five size classes of sizes 1-10 ha (C1), 11-100 ha (C10), 101-1000 ha (C100), 1001-10000 ha (C1000) and > 10000 ha (C10000). Number of fires in each ecoregion in smaller size classes were significantly different under both ignition scenarios Differences in number of fires in larger size classes (C1000 and C10000) were not significant. This explained the results for total burnt area as larger fires contribute more in total burnt area compared to small fires. Comparison of ABF also showed non-significant differences under both ignition scenarios for each ecoregion.

In the case of ecoregion 3S, the comparison under both ignition scenarios showed significant differences for all non-spatial fire regime indicators. Clipping of the buffer was the most likely cause for this different behaviour. In 3S the actual number of fires and the estimated fire ignition density was high in the southern areas. Under weighted ignition scenario this area received more fires and more area was burnt that were left out after clipping the buffer.

Simulation results also showed that overall number of fires is greatest in 4S followed by 3W and 3E (Figure 4.2). The least number of fires is in 3S. These results partially confirm the spatial ignition density results discussed in Section 5.1.1. According to that the highest ignition density is in 4S followed by 3W, 3S and 3E. Two possible reasons justify the lesser number of simulated fires in 3S compared to 3E. First, in density estimation all fires and total area of 3S were considered whereas, in fire regime simulations a reasonable part of the ecoregion in the North and northwest was left out due to non-availability of other relevant datasets. Second, the analyses for fire regimes indicators were performed after clipping a buffer from the simulated area. This again left out a reasonable number of simulated fires from 3S as discussed in preceding paragraph.

The sequence of simulated number of fires (among ecoregions) was however not the same when the total number of fires were distributed in different size classes. Though 4S had the highest number of fires, majority of these were in size class 1 (1-10 ha). In all other size classes 3W had maximum number of fires followed by 3E for C10 and C10000; and 4S for C100 and C1000. In the largest size class (C10000) 4S had the least number of fires (Figure 4.3). These results were reflected in total burnt area. Total burnt area was the maximum in 3W followed by 3E and 4S. ABF values of 3W were also highest followed by 3S, 4S and 3E (Figure 4.5). These results imply the highest fire activity is in ecoregion 3W and the least in 3E.

Overall the comparisons of non-spatial fire regime indicators among ecoregions imply that fires of larger size classes contributed more towards fire activity. Though 3E had more simulated larger fires than 3S and 4S, it had the minimum ABF due to its larger area.

Contrary to non-spatial indicators, SBP showed remarkable differences in burn probability of pixels under both ignition scenarios. Results presented in Figure 4.12 – 4.15 clearly show that in each ecoregion some areas had high burn probability under unweighted ignition scenario and some other areas under weighted ignition scenarios. When compared with spatial distribution of actual fires, for all ecoregions weighted ignition scenario provided more realistic picture and reliable results. Spatial differences also existed in burn probability among ecoregions. The areas of highest burn probability were in 3W followed by 3S, 4S and 3E.

Overall, the comparisons under both ignition scenarios showed that fire regimes were similar when only non-spatial aspects were considered, and were different remarkably when compared spatially. Fire is a spatial phenomenon and ignoring spatial aspects in simulated fire regimes will therefore provide unrealistic results. I therefore reject the null hypothesis of the thesis and conclude that spatial ignition patterns should be an important consideration in simulating fire regimes in boreal forests.

In Ontario the recent forest management guide suggests that to emulate fire disturbances a range of clearcut sizes should be created and 80% of the clearcuts in boreal forests or 90 % of the clearcuts in Great Lakes St. Lawrence should be less than 260 ha size (OMNR, 2001). However, there is dire need to estimate fire disturbances frequency by size classes and their spatial distribution to properly plan for range of the clearcut sizes. Results of this study can provide some bench mark conditions to define clearcut sizes for each ecoregion and their spatial arrangements. The modeled spatial burn probability can also serve as a guiding tool to identify hot spot areas for lightning-caused fire ignitions and for appropriate allocation of forest fire management resources.

5.2 Recommendations

Some locational errors were noted in Ontario forest fire data. Some fires locations were in water bodies. It is suggested that OMNR should take some quality control measures to avoid such errors in future data.

In this research only lightning-caused data were analyzed to determine the ignition patterns. Results showed that fire ignitions in the study area are clustered. The landscape in the study area is characterized by hundreds of thousands of lakes that may have strong influence on these identified patterns. Further research is recommended to investigate lakes' spatial patterns and revisit the research question of fire ignition spatial patterns by including the spatial patterns of lakes in the analysis.

In this research only a few fire regime indicators were investigated to demonstrate the effects of fire ignition patterns on simulated fire regimes. Further studies can be conducted for a wider range of fire regime indicators, particularly the spatio-temporal ones, to capture more features of fire dynamics in the study area.

Due to data availability limitations, (i) fire regime simulations could not be conducted for whole ecoregion 3S; and (ii) data analyses were performed by clipping buffers (to reduce edge effects) inside the ecoregions. If relevant data are available, similar studies can be conducted to the full extent of ecoregions with outside buffers.

It is also recommended that if resources permit, studies could also be conducted over longer simulation periods using more simulations. This may help to capture more variability or at least identify threshold values for number of simulations and/or number of years in a simulation for an individual ecoregion.

Results of non-spatial fire regime indicators overall showed that simulated fire regimes under both ignition scenarios are similar whereas there were clear spatial differences. The causes of similar results of non-spatial fire regime indicators under both ignition scenarios could not be properly addressed due to model limitations. Results suggest that fuel reduction due to earlier fires may not be the factor to extinguish large simulated fires. This could not be confirmed as BFOLDS provides no information that how a fire finally extinguishes in the model. Including this component in BFOLDS output can improve our understanding about the role of earlier fires, lakes and weather in fire extinguishment in the study area.

Bibliography

Amatulli, G. (2011). Discussion on kernel density through e-mail on February 02, 2011.

Amatulli, G., Peréz-Cabello, F., & de la Riva, J. (2007). Mapping lightning/human-caused wildfire occurrence under ignition point location uncertainty. *Ecological Modelling*, 200, 321-333.

Andison, D., Damme, L.V., Hebert, D., Moore, T., Bonar, R., Boutin, S., & Donnellt, M. (2009). The healthy landscape approach to land management – A Foothills Research Institute, Natural Disturbance Program Project. [Online]. Available: http://foothillsresearchinstitute.ca/Content_Files/Files/ND/Healthy_ Landscapes_Report.pdf

Attiwill, P.M. (1994). The disturbance of forest ecosystems: the ecological basis for conservative management. *Forest Ecology & Management*, 63, 247-300.

Baddeley, A. & Turner, R. (2005). Spatstat: an *R* package for analyzing spatial point patterns. *Journal of Statistical Software*, 12, 1-42.

Baldwin, D.J.B., Desloges, J.R., & Band, L.E. (2000).Physical geography of Ontario. In A.H. Perera, D.L. Euler, & I.D. Thompson (Eds.), *Ecology of a managed terrestrial landscape: patterns and processes of forest landscapes in Ontario* (pp.12-29). Vancouver: UBC Press.

Bergeron, Y., Drapeau, P., Gauthier, S., & Lecomte, N. (2007). Using knowledge of natural disturbance to support sustainable forest management in the northern Clay Bely. *Forestry Chronicle*, 83, 326-337.

Bergeron, Y., Flannigan, M., Gauthier, S., Leduc, A. & Lefort, P. (2004a). Past, current and future fire frequency in the Canadian boreal forest: implications for sustainable forest management. *Ambio*, 33(6), 356-360.

Bergeron, Y., Gauthier, S., Flannigan, M.D., & Kafka, V. (2004b). Fire regimes at the transition between mixedwood and coniferous boreal forest in northwestern Quebec. *Ecology*, 85, 1916-1932.

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P., & Lesieur, D., (2001). Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. *Canadian Journal of Forest Research*, 31, 384-391.

Besag, J. (1977). Contribution to the discussion of Dr. Ripley's paper. *Journal of the Royal Statistical Society*, B 39, 193-195.

Beverly, J. L., & Martell, D. L. (2005). Characterizing extreme fire and weather events in the boreal shield ecozone of Ontario. *Agricultural & Forest Meteorology*, 133, 5-16.

Beverly, J.L., Herd, E.P.K., & Conner, J.C.R. (2009). Modeling fire susceptibility in west central Alberta, Canada. *Forest Ecology & Management*, 258, 1465-1478.

Bleacher, J. E., Glaze, L. S., Greeley, R., Hauber, E., Baloga, S. M., Sakimoto, S. E. H., Williams, D.A. & Glotch, T.D. (2009). Spatial and alignment analyses for a field of small volcanic vents south of pavonis mons and implications for the Tharsis province, Mars. *Journal of Volcanology & Geothermal Research*, 185, 96-102.

Breiman, L., Meisel, W., & Purcell, W. (1977). Variable kernel estimates of multivariate densities. *Technometrics*, 19(2), 135-144.

Carcaillet, C., Bergman, I., Delorme, S., Hornberg, G., & Zackrisson, O. (2007). Long-term fire frequency not linked to prehistoric occupations in northern Swedish boreal forest. *Ecology*, 88(2), 465-477.

Cary, G.J., Keane, R.E., Gardner, R.H., Lavorel, S., Flannigan, M.D., Davies, I.D., Li, C., Lenihan, J.M., Rupp, T.S., & Mouillot, F. (2006). Comparison of sensitivity of landscape-fire-succession models to variation in terrain, fuel pattern, climate and weather. *Landscape Ecology*, 21, 121-137.

Catry, F.X., Rego, F.C., Moreira, F., & Bacao, F. (2008). Characterizing and modelling the spatial patterns of wildfire ignitions in Portugal: fire initiation and resulting burned area. In: J. de la Heras, C.A. Brebbia, D Viegas, & V. Leone (Eds.).*Modelling, monitoring and management of forest fires* (pp 213-221). Southampton, UK: WIT Press.

Chang, Y., He, H.S., Bishop, I., Hu, Y., Bu, R, Xu, C., & Li, X. (2007). Long-term forest landscape responses to fire exclusion in the Great Xing'an Mountains, China. *International Journal of Wildland Fire*, 16, 34-44.

Chang, Y., He, H.S., Hu, Y., Bu, R., & Li, X. (2008). Historic and current fire regimes in the Great Xing'an Mountains, northeastern China: implications for long-term forest management. *Forest Ecology & Management*, 254, 445-453.

Chapin, F.S., Walker, B.H., Hobbs, R.J., Hooper, D.U., Lawton, J.H., Sala, O.E., & Tilman, D. (1997). Biotic control over the functioning of ecosystems. *Science*, 277, 500-503.

Clark, P. J., & Evans, F. C. (1954). Distance to nearest neighbor as a measure of spatial relationships in populations. *Ecology*, 35(4), 445-453.

Cochrane, M. A., Alencar, A., Schulze, M. D., Souza Jr., C. M., Nepstad, D. C., Lefebvre, P., & Davidson, E.A. (1999). Dynamic of closed canopy tropical forests. *Science*, 284, 1832-1835.

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational & Psychological Measurement*, 20, 37-46.

Couce, E., & Knorr, W. (2010). Statistical parameter estimation for a cellular automata wildfire model based on satellite observations. In: G. Perona, & C.A. Brebbia (Eds.).*Modelling, monitoring and management of forest fires II* (pp 47-55). Southampton, UK: WIT Press.

Covington, W.W. (2000). Helping western forests heal: the prognosis is poor for US forest ecosystems. *Nature*, 408, 135-136.

Cressie, N.A.C (1993). Statistics for spatial data (revised Ed). Toronto, Canada: John Wiley & Sons, Inc.

Crow, T.R., & Perera, A.H. (2004). Emulating natural landscape disturbance in forest management – an introduction. *Landscape Ecology*, 19, 231-233.

Cui, W., Ouellette, M.R., Perera, A.H., & Gluck, M. (2009). Using BFOLDS to characterize fire regimes: a case study from a boreal forest landscape. Forest Research Report No. 173. Sault Ste Marie, ON: Ontario Forest Research Institute, Ontario Ministry of Natural Resources.

Cumming, S.G., & Armstrong, G.W. (2001). Divided land base and overlapping forest tenure in Alberta, Canada: a simulation study exploring costs of forest policy. *Forestry Chronicle*, 77, 501-508.

D'Andrea, M.D., Fioruccii, P., & Holmes, T. (2009). A modified forest fire model to assess future land cover scenario. XIII World Forestry Conference, 18-23 October 2009. Buneos Aires, Argentina. [Online]. Available: http://www.cfm2009.org/es/programapost/resumenes/uploads/A_modified_forest_fire_model_FD.pdf de Vasconcelos, M.J.P., Silva, S., Tomé, M., Alvim, M., & Pererira, J.M.C. (2001). Spatial prediction of fire ignition probabilities: comparing logistic regression and neural networks. *Photogrammetric Engineering & Remote Sensing*, 67, 73-81.

Dickson, B.G., Prather, J.W., Xu, Y., Hampton, H.M., Aumack, E.N., & Sisk, T.D. (2006). Mapping the probability of large fire occurrence in northern Arizona, USA. *Landscape Ecology*, 21, 747-761.

DMTI. (2010). CanMap water [computer file]. Markham, Ontario: DMTI Spatial Inc.

Doran, H. (2004). Using probability surfaces to assess forest fire risk in Algonquin Provincial Park. MES thesis, University of Waterloo.

Drever, C.R., Peterson, G., Messier, C., Bergeron, Y. & Flannigan, M. (2006). Can forest management based on natural disturbances maintain ecological resilience? *Canadian Journal of Forest Research*, 36, 2285-2299.

Drushka, K. (2003). Canada's forests: a history. Montréal, Québec: McGill Queen's University Press.

Duncan, B.W., Shao, G., & Adrian, F.W. (2009). Delineating a managed fire regime and exploring its relationship to the natural fire regime in East Central Florida, USA: a remote sensing and GIS approach. *Forest Ecology & Management*, 258, 132-145.

Díaz-Avalos, C., Peterson, D.L., Alvarado,E., Ferguson, S.A., & Besag, J.E. (2001). Space-time modeling of lightning-caused ignition in the Blue Mountains, Oregon. *Canadian Journal of Forest Research*, 31, 1579-1593.

Elkie, P., Gluck, M., Boos, J., Bowman, J., Daniel, C., Elliott, J., Etheridge, D., Heaman, D., Hooper, G., Kushneriuk, R., Lucking, G., Mills, S., Naylor, B., Pinto, F., Pond, B., Rempel, R., Ride, K., Smiegielski, A., Watt, G., & Woods, M. (2007). Science and Information in support of the Forest Management Guide for Landscapes: Package A. Simulations, rationale and inputs. Sault Ste. Marie, ON: Forest Policy Section, Ontario Ministry of Natural Resources.

ESRI. (2001). Arc Canada version 3.1 [computer file]. Redlands, California: Environmental Systems Research Institute.

Flannigan, M.D., & Wotton, B.M. (1989). A study of interpolation methods for forest fire danger rating in Canada. *Canadian Journal of Forest Research*, 19, 1059-1066.

Flannigan, M.D., & Wotton, B.M. (1991). Lightning-ignited fires in northwestern Ontario. *Canadian Journal of Forest Research*, 21, 277-287.

Flannigan, M.D., Bergeron, Y. (1998). Possible role of disturbance in shaping the northern distribution of *Pinus resinosa*. *Journal of Vegetation Science*, 9, 477-482.

Flannigan, M.D., Krawchuk, M.A., de Groot, W.J., Wotton, B.M., & Gowman, L.M. (2009). Implications for changing climate for global wildland fire. *International Journal of Wildland Fire*, 18, 483-507.

Forest Management (2006). Forest resources of Ontario 2006. Ontario: Ontario Ministry of Natural Resources.

Forestry Canada Fire Danger Group (1992). Development and structure of the Canadian Forest Fire Behaviour Prediction System. Information Report ST-X-3. Ottawa, ON: Science & Sustainable Development Directorate, Forestry Canada.

Franklin, J.F. (1993). Fueling controversy and providing direction: lessons from old growth. *Journal of Forestry,* 91, 11-13.

Freeman, E. A., & Ford, D. (2002). Effects of data quality on analysis of ecological pattern using the K(d) statistical function. *Ecology*, 83(1), 35-46.

FRI (2007). [computer file]. Sault Ste Marie: Ontario Ministry of Natural Resources.

Fuquay, D.M., Baughman, R.G., & Latham, D.J. (1979). A model for predicting lightning fire ignitions in wildland’s fuels. Research Paper INT-217. Ogden, Utah, USA: Intermountain Forest and Range Experiment Station, USDA Forest Service.

Gardner, R.H., Romme, W.H., & Turner, M.G. (1999). Predicting forest fire effects at landscape scales. In D.J. Mladenoff & W.L. Baker (Eds.), *Spatial modeling of forest landscape change: approaches and applications* (pp.163-185). Cambridge, UK: Cambridge University Press.

Gauthier, S., Flannigan, M.D., McAlpine, R.S., Wotton, B.M., Duchesne, L.C., & Thompson, I.D. (1994). Boreal forest, fire and climate: development of an integrated terrestrial landscape model. In: *Fire management under fire (adapting to change)*. Proceedings of the 1994 interior west fire council meeting and program (pp. 217-226). Coeur d’Alene, ID, USA: International Association of Wildland Fire.

Gauthier, S., Valliancourt, M.A., Kneeshaw, D., Drapeau, P., Grandpré, L.D., Claveau, Y., & Paré, D. (2009). Forest ecosystem management: origins and foundations. In S. Gauthier, M.A. Valliancourt, A. Leduc, L.D. Grandpré, D. Kneeshaw, H. Morin, P. Drapeau & Y. Bergeron (Eds.), *Ecosystem management in the boreal forests* (pp.13-37). Québec, Canada: Presses de ĺUniversité du Québec.

Genton, M. G., Butry, D. T., Gumpertz, M. L., & Prestemon, J. P. (2006). Spatio-temporal analysis of wildfire ignitions in the St. Johns River water management district, Florida. *International Journal of Wildland Fire*, 15, 87-97.

GeoBase. (2007). CDED version 3.0 [computer file]. Sherbrooke, Quebec: Natural Resources Canada. [Online]. Available: http://geobase.ca/geobase/en/data/cded/index.html

Getis, A. (1964). Temporal land-use pattern analysis with the use of nearest neighbor and quadrat methods. *Annals of the Association of American Geographers*, 54(3), 391-399.

Ghent, A. W., & Zucker, N. (1990). A readily interpreted index of dispersion, based on nearest-neighbor analysis. *American Midland Naturalist*, 124(1), 184-187.

He, H.S., & Mladenoff, D.J. (1999). Spatially explicit and stochastic simulation of forest landscape fire disturbance and succession. *Ecology*, 80(1), 81-99.

Herbers, J. M., & Foitzik, S. (2002). The ecology of slavemaking ants and their hosts in North temperate forests. *Ecology*, 83(1), 148-163.

Hering, A. S., Bell, C. L., & Genton, M. G. (2009). Modeling spatio-temporal wildfire ignition point patterns. *Environmental & Ecological Statistics*, 16, 225-250.

Hills, G. A. (1959). A ready reference to the description of the land of Ontario and its productivity. Toronto, ON: Ontario Department of Land and Forests.

Hills, G.A. (1969). A physiographic approach to the classification of terrestrial ecosystems with respect to representative biological communities. Toronto, ON: Ontario Department of Land and Forests.

Holling, C.S. (1981). Forest insects, forest fires and resilience. In H.A. Mooney, T.M. Bonnicksen, N.L. Christensen, J.E. Jotan, & W.A. Reiners (Eds), *Proceedings of the conference on fire regimes and ecosystem properties* (pp 445-463). General Technical Report WO-26. Washington DC: USDA Forest Service.

Hunter, M.L. (1990). Wildlife, forests and forestry: principles of managing forests for biological diversity. New Jersey, USA: Prentice Hall Inc.

Jetté, J.P., Valliancourt, M.A., Leduc, A., & Gauthier, S. (2009). Ecological issues related to forest management. In S. Gauthier, M.A. Valliancourt, A. Leduc, L.D. Grandpré, D. Kneeshaw, H. Morin, P. Drapeau & Y. Bergeron (Eds.), *Ecosystem management in the boreal forests* (pp.1-10). Québec, Canada: Presses de ĺUniversité du Québec.

Johnston, M., Williamson, T., Price, D., Spittlehouse, D., Wellstead, A., Gray, P., Scott, D., Askew, S., & Webber, S. (2006). Adapting forest management to the impacts of climate change in Canada. Final Report, BIOCAP Research Integration Program Synthesis Paper. Kingston, ON: Queen's University. [Online]. Available: rom http://biocap.ca/rif/report/Johnston_M.pdf

Katkovnik, V., & Shmulevich, I. (2002). Kernel density estimation with adaptive varying window size. *Pattern Recognition Letters,* 23, 1641-1648.

Keane, R.E., Carey, G.J., Davies, I.D., Flannigan, M.D., Gardner, R.H., Lavorel, S., Lenihan, J.M., Li, C., & Rupp, T.S. (2004). A classification of landscape fire succession models: spatial simulations of fire and vegetation dynamics. *Ecological Modelling*, 179(1), 3-27.

Keane, R.E., Morgan, P., & Running, S.W. (1996). FIRE-BGC—a mechanistic ecological process model for simulating fire succession on coniferous forest landscapes of the northern Rocky Mountains. Research Paper INT-RP-484. Ogden, UT, USA: Forest Service Intermountain Forest and Range Experiment Station, United States Department of Agriculture.

Kenkel, N. C. (1988). Pattern of self-thinning in jack pine: Testing the random mortality hypothesis. *Ecology*, 69(4), 1017-1024.

Kimmins, J.P. (2004). Emulating natural forest disturbances: what does it mean? In A.H. Perera, L.J. Buse, & M.G. Weber (Eds.), *Emulating natural forest landscape disturbances: concepts and applications* (pp.8-28). New York, USA: Columbia University Press.

Klenk, N., Bull, G., & Cohen, D. (2008). What is the ''END'' (emulation of natural disturbance) in forest ecosystem management? an open question. *Canadian Journal of Forest Research*, 38, 2159-2168.

Kolbei, J. J., & Janzen, F. J. (2002). Impact of nest-site selection on nest success and nest temperature in natural and disturbed habitats. *Ecology*, 83(1), 269-281.

Korzukhin, M.D., Ter-Mikaelian, M.T., & Wagner, R.G. (1996). Process versus empirical models: which approach for forest ecosystem management? *Canadian Journal of Forest Research*, 26(5), 879-887.

Kourtz, P., & Todd, B. (1992). Predicting the daily occurrence of lightning-caused forest fires. Inf. Rep. PI-X-112. Chalk River, Ontario: Petawawa National Forestry Institute, Forestry Canada.

Krawchuk, M.A., & Cumming, S.G. (2009). Disturbance history affects lightning fire initiation in the mixedwood boreal forest: observations and simulations. *Forest Ecology & Management*, 257, 1613-1622.

Krawchuk, M.A., Cumming, S.G., Flannigan, M.D., & Wein, R.W. (2006). Biotic and abiotic regulation of lightning fire ignition in the mixedwood boreal forest. *Ecology*, 87, 458-468.

Krenn, R., & Hergarten, S. (2009). Cellular automation modeling of lightning induced and man made forest fire. *Natural Hazards & Earth System Science*, 9, 1743-1748.

Ku-Muhammad, K.R., & Yun, K.J. (2009). Pattern extraction and rule generation of forest fire using sliding window techniques. *Computer & Information Science*, 2(3), 113-121.

Landis J.R., & Koch, G.G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, 33, 159-74.

Landres, P.B., Morgan, P., & Swanson, F.J. (1999). Overview of the use of natural variability concepts in managing ecological systems. *Ecological Applications*, 9, 1179-1188.

Larjavaara, M., Kuuluvainen, T., & Rita, H. (2005). Spatial distribution of lightning ignited forest fires in Finland. *Forest Ecology & Management*, 2008, 177-188.

Latham, D., & Williams, E. (2001). Lightning and forest fires. In E.D. Johnson & K. Miyanishi (Eds.). *Forest Fires* (pp 375-418). San Diego, CA, USA: Academic Press.

Latremouille, C., Parker, W. C., McPherson, S., Pinto, F., Fox, B., & McKinnon, L. (2008). Ecology and management of eastern white pine in the lake abitibi (3E) and lake temagami (4E) ecoregions of Ontario. Science Development & Transfer Series No. 004. Sault Ste Marie , ON: Ontario Forest Research Institute, Ontario Ministry of Natural Resources.

Lee, P. C., Crites, S., Nietfeld, M., Nguyen, H. V., & Stelfox, J. B. (1997). Characteristics and origions of deadwood material in aspen - dominated boreal forests. *Ecological Applications*, 7(2), 691-701.

Leopold, A.S., Cain, A., Cottom, C.M., Gabrielson, I.N., & Kimball, T.L. (1963). The wildlife management in the national parks: The Leopold report. 28. [Online]. Available: http://www.cr.nps.gov/history/online_books/leopold/leopold.htm

Levine, N. (2010). CrimeStat 3.3: A spatial statistics program for the analysis of crime incident locations. Ned Levine & Associates, Houston, TX; The National Institute of Justice, Washington, DC.

Li, C. (2000a). Fire regimes and their simulations with reference to Ontario. In: A.H. Perera, D.L. Euler, & I.D. Thompson, (Eds.).*Ecology of managed terrestrial landscape: Patterns and processes in forest landscapes of Ontario* (pp 115-140). Vancouver, BC: UBC Press.

Li, C. (2000b). Reconstruction of natural fire regime through ecological modelling. *Ecological Modelling*, 134(2-3), 129-144.

Li, C. (2004). Simulating forest fire regimes in the foothills of Canadian Rockey Mountains. In A.H. Perera, L.J. Buse, & M.G. Weber (Eds.), *Emulating natural forest landscape disturbances: concepts and applications* (pp.98-111). New York, USA: Columbia University Press.

Long, J.N. (2003). Diversity, complexity and interactions: an overview of Rocky Mountain forest ecosystems. *Tree Physiology*, 23, 1091-1099.

Long, J.N. (2009). Emulating natural disturbance regimes as a basis for forest management: A North American view. *Forest Ecology & Management*, 257, 1868-1873.

Mailly, D., Kimmins, J.P., & Busing, R.T. (2000). Disturbance and succession in a coniferous forest of northwestern North America: simulation with DRYADES, a spatial gap model. *Ecological Modelling*, 127, 183-205.

McRae, R.H.D. (1992). Prediction of areas prone to lightning ignition. *International Journal of Wildland Fire*, 2, 123-130.

Mermoz, M., Kitzberger, T., & Veblen, T.T. (2005). Landscape influences on occurrence and spread of wildfires in Patagonian forests and shrublands. *Ecology*, 86, 2705-2715.

Meyer, D., Zeileis, A. & Hornik, K. (2009). vcd: Visualizing Categorical Data. R package version 1.2-7.

Miller, C., Parisien, M.A., Ager, A.A., & Finney, M.A. (2008). Evaluating spatially-explicit burn probabilities for strategic fire management planning. In: J. de la Heras, C.A. Brebbia, D.Viegas,&

V Leone (Eds.).*Modelling, monitoring and management of forest fires* (pp 245-252). Southampton, UK: WIT Press.

Mladenoff, D.J., Host, G.E., Boeder, J., & Crow, T.R. (1996). LANDIS: a spatial model of forest landscape disturbance, succession and management. In M.F. Goodchild, L.T. Steyaert, & B.O. Parks (Eds.). *GIS and environmental modelling: progress and research issues* (pp.175-180). New York, USA: GIS World & Oxford University Press.

Munoz-Marquez, R.A. (2005). Future climate change impacts on the boreal forest in northwestern Ontario: implication for the forestry sector and the local community. PhD Thesis, University of Waterloo.

Nash, C.H., & Johnson, E.A. (1996). Synoptic climatology of lightning-caused forest fires in subalpine and boreal forests. *Canadian Journal of Forest Research*, 26, 1859-1874.

O'Sullivan, D., & Unwin, D.J. (2010). Geographic Information Analysis (2nd Ed). Hoboken, New Jersey, USA: John Wiley & Sons, Inc.

OGS. (1988). [computer file]. Toronto, Ontario: Ontario Geological Survey.

OMNR (2010a). Ontario's forests fact sheet – The boreal forests. [Online]. Available: http://www.mnr.gov.on.ca/stdprodconsume/groups/lr/@mnr/@forests/documents/document/241209.pdf

OMNR (2010b). Forest Fire Summary 2010. [Online]. Available: http://www.mnr.gov.on.ca/en/Business/AFFM/2ColumnSubPage/STDPROD_071284.html

OMNR, (2001). Forest management guide for natural disturbance pattern emulation. Technical Series Version 3.1. Peterborough, ON: Natural Resource Information Centre, Ontario Ministry of Natural Resources.

Ouellette, M. (2008). BFOLDS 1.0: A user's guide to the software package. Forest Research Report No. 171. Sault Ste Marie, ON: Ontario Forest Research Institute, Ontario Ministry of Natural Resources.

Parisien, M.A., & Moritz, M.A. (2009). Environmental controls on the distribution of wildfire at multiple spatial scales. *Ecological Monographs*, 79, 127-154.

Payette, S. (1992). Fire as a controlling process in the North American boreal forest. In: H.H. Shugart, R. Leemans, & G.B. Bonan (Eds.). *A system analysis of the global boreal forest* (pp 144-169). New York, USA: Cambridge University Press.

Pennington, D.D. (2007). Exploratory modeling of forest disturbance scenarios in central Oregon using computational experiments in GIS. *Ecological Informatics*, 2, 387-403.

Perera, A. H., Baldwin, D. J. B., Schnekenburger, F., Osborne, J. E., & Bae, R. E. (1998). Forest fires in Ontario: a spatio-temporal perspective. Forest Research Report No. 147. Sault Ste Marie, ON. Ontario Forest Research Institute, Ontario Ministry of Natural Resources.

Perera, A. H., Cui, W., & Ouellette, M. R. (2009). Size class distribution and spatial proximity of fires in a simulated boreal forest fire regime in relation to Ontario's policy directions for emulating natural disturbance. Forest Research Report No. 170. Sault Ste Marie, ON: Ontario Forest Research Institute, Ontario Ministry of Natural Resources.

Perera, A.H. & Buse, L.J. (2004). Emulating natural disturbance in forest management: an overview. In A.H. Perera, L.J. Buse, & M.G. Weber (Eds.), *Emulating Natural Forest Landscape Disturbances: Concepts and Applications* (pp. 3-7). New York, USA: Columbia University Press.

Perera, A.H. Yemshanov, D., Schnekenburger, F., Baldwin, D.J.B., Boychuk, D., & Weaver, K. (2004a). Spatial simulation of broad scale fire regimes as a tool for emulating natural forest landscape disturbance. In A.H. Perera, L.J. Buse, & M.G. Weber (Eds.), *Emulating natural forest landscape disturbances: concepts and applications* (pp.112-122). New York, USA: Columbia University Press.

Perera, A.H., & Buse, L.J. (2006). Multiple-scale research studies on boreal forest fire regimes to inform Ontario's policies for emulating natural forest disturbances: a prospectus. Forest Research Report No. 164. Sault Ste Marie, ON: Ontario Forest Research Institute, Ontario Ministry of Natural Resources.

Perera, A.H., & Cui, W. (2010). Emulating natural disturbances as a forest management goal: lessons from fire regime simulations. *Forest Ecology & Management*, 259, 1328-1337.

Perera, A.H., Baldwin, D.J.B., Schnekenburger, F., Osborne, J.E., & Bae, R.E. (1998). Forest fires in Ontario: a spatio-temporal perspective. Forest Research Report No. 147. Sault Ste Marie, ON: Ontario Forest Research Institute, Ontario Ministry of Natural Resources.

Perera, A.H., Buse, L.J., & Weber, M.G. (Eds.). (2004b). Emulating Natural Forest Landscape Disturbances: Concepts and Applications. New York, USA: Columbia University Press.

Perera, A.H., Cui, W., & Ouellette, M.R. (2009). Size class distribution and spatial proximity of fires in a simulated boreal forest fire regime in relation to Ontario's policy directions for emulating natural disturbance. Forest Research Report No. 170. Sault Ste Marie, ON: Ontario Forest Research Institute, Ontario Ministry of Natural Resources.

Perera, A.H., Ouellette, M., Cui, W., Drescher, M., & Boychuk, D. (2008). BFOLDS 1.0: A spatial simulation model for exploring large scale fire regimes and succession in boreal forest landscapes. Forest Research Report No. 152. Sault Ste Marie, ON: Ontario Forest Research Institute, Ontario Ministry of Natural Resources.

Podur, J., Martell, D. L., & Csillag, F. (2003). Spatial patterns of lightning-caused forest fires in ontario, 1976-1998. *Ecological Modelling*, 164, 1-20.

Price, C., & Rind, D. (1994). The impact of 2 x CO2 climate on lightening caused fires. *Journal of Climatology*, 7, 1484-1494.

R Development Core Team (2009). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org .

Racey, G. D., Wiltshire, R. O., & Archibald, D. J. (2000). Ecoregional forest composition analysis for northwestern Ontario: Present forest condition. NWST Technical Report TR – 123. Thunder Bay, ON: Northwest Science & Technology Ontario Ministry of Natural Resources.

Rempel, R.S., Baker, J., Elkie, P.C., Gluck, M.J., Jackson, J., Kushneriuk, R.S., Moore, T., & Perera, A.H. (2007). Forest policy scenario analysis: sensitivity of songbird community to changes in forest cover amount and configuration. *Avian Conservation and Ecology - Écologie et conservation des oiseaux*, 2(1): 5. [Online]. Available: http://www.ace-eco.org/vol2/iss1/art5/

Ripley, B. D. (1977). Modelling spatial patterns. *Journal of the Royal Statistical Society*, B39(2), 172-212.

Rogerson, P., & Sun, Y. (2001). Spatial monitoring of geographic patterns: an application to crime analysis. *Computers, Environment & Urban Systems*, 25, 539-556.

Rowe, J.S., & Scotter, G.W. (1973). Fires in the boreal forests. *Quaternary Research*, 3, 444-464.

Schwartz, M.W., Brigham, C.A., Hoeksema, J.D., Lyons, K.G., Mills, M.H., & van Mantgem, P.J. (2000). Linking biodiversity to ecosystem function: implications for conservation biology. *Oecologia*, 122, 297-305.

Scoular, M., Suffling, R., Matthews, D., Gluck, M., & Elkai, P. (2010). Comparing various approaches for estimating fire frequency: the case of Quetico provincial park. Climate Change Research Report CCRR-18. Sault Ste Marie, ON: Ontario Forest Research Institute, Ministry of Natural Resources.

Seymour, R.S., & Hunter, M.L. Jr. (1999). Principles of ecological forestry. In M.L. Hunter Jr., (Ed.), *Maintaining biodiversity in forest ecosystems* (pp.22-61). Cambridge, UK: Cambridge University Press.

Sheather, S.J., & Jones, M.C. (1991). A reliable data-based bandwidth selection method for kernel density estimation. *Journal of the Royal Statistical Society,* Series B, 53, 683-690.

Silverman, B. W. (1986). Density estimation for statistics and data analysis (monographs on statistics and applied probability). London, UK: Chapman & Hill.

Statutes of Ontario (1995). Crown Forest Sustainability Act, R.S.O. 1998. Chapter 25 and Ontario Regulation 167/95.

Sterner, R. W., Ribic, C. A., & Schatz, G. E. (1986). Testing for life historical changes in spatial patterns of four tropical tree. *Journal of Ecology*, 74(3), 621-633.

Suffling, R. (1995). Can disturbance determine vegetation distribution during climate warming? A boreal test. *Journal of Biogeography*, 22, 501-508.

Suffling, R., & Perera, A.H. (2004). Characterizing natural forest disturbance regimes: concepts and approaches. In A.H. Perera, L.J. Buse, & M.G. Weber (Eds.), *Emulating natural forest landscape disturbances: concepts and applications* (pp.43-54). New York, USA: Columbia University Press.

Suffling, R., Lihou, C., & Morand, Y. (1988). Control of landscape diversity by catastrophic disturbance: a theory and a case study of fire in Canadian boreal forest. *Environmental Management*, 12(1), 73-78.

Telesca, L., Amatulli, G., Lasaponara, R., Lovallo, M., & Santulli, A. (2005). Time-scaling properties in forest fire sequences observed in Gargano area (southern Italy). *Ecological Modelling*, 185, 531-544.

Telesca, L., Amatulli, G., Lasaponara, R., Lovallo, M., & Santulli, A. (2007). Identifying spatial clustering properties of the 1997-2003 liguria (northern italy) forest-fire sequence. *Chaos Solutions & Fractals*, 32, 1364-1370.

Thornton, P.E., Law, B.E., Gholz, H.L., Clark, K.L., Falge, E., Ellsworth, D.S., Goldstein, A.H., Monson, R.K., Hollinger, D.Y., Falk, M., Chen, J., & Sparks, J.P. (2002). Modelling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests. *Agriculture & Forest Meteorology*, 113, 185–222.

Tuia, D., Lasaponara, R., Telesca, L., & Kanevski, M. (2007). Identifying spatial clustering phenomena in forest-fire sequences. *Physica A*, 376, 596-600.

Turner, M.G., Dale, V.H. (1991). Modelling landscape disturbance. In: M.G. Turner, & R.H. Gardner (Eds.).*Quantitative methods in landscape ecology* (pp 323-351). New York, USA: Springer.

Turner, R. (2009). Point pattern of forest fire locations. *Environmental & Ecological Statistics*, 16, 197-223.

Tymstra, C., Bryce, R.W. Wotton, B.M. & Armitage, O.B. (2009). Development and structure of Prometheus: the Canadian wildland fire growth simulation model. Information Report NOR-X-417. Edmonton, AB: Northern Forestry Centre, Canadian Forest Service, Natural Resources Canada.

Valliancourt, M.A., Grandpré, L.D., Gauthier, S., Leduc, A., Kneeshaw, D., Claveau, Y., & Bergeron, Y. (2009). Forest ecosystem management: Origins and foundations. In S. Gauthier, M.A. Valliancourt, A. Leduc, L.D. Grandpré, D. Kneeshaw, H. Morin, P. Drapeau & Y. Bergeron (Eds.), *Ecosystem management in the boreal forests* (pp.39-55). Québec, Canada: Presses de ÍUniversité du Québec.

Van Wagner, C.E. (1987). Development and structure of the Canadian Forest Fire Weather Index System. Forest Technical Report-35. Ottawa, ON: Canadian Forest Service.

Vázquez, A., & Moreno, J.M. (1993). Sensitivity of fire occurrence to meteorological variables in Mediterranean and Atlantic areas of Spain. *Landscape Urban Planning*, 24, 129-142.

Vázquez, A., & Moreno, J.M., (2001). Spatial distribution of forest fires in Sierra de Gredos (Central Spain). *Forest Ecology & Management*, 147, 55-65.

Venables, W. N., & Ripley, B. D. (1997). Modern applied statistics with S-plus (2nd Ed). New York, USA: Springer-Verlag.

Veraverbeke, S., Lhermitte, S., Verstraeten, W., & Goossens, R. (2010). Assessing burn severity using satellite time series. In: G. Perona, & C.A. Brebbia (Eds.).*Modelling, monitoring and management Forest Fires II* (pp 107-118). Southampton, UK: WIT Press.

Viera, A.J., & Garrett, J.M. (2005). Understanding interobserver agreement: the Kappa statistic. *Family Medicine*, 37(5), 360-63.

Wand, M.P. & Jones, M.C. (1995). Kernel smoothing. London, UK: Chapman and Hall.

Wang, Y., & Anderson, K. R. (2010). An evaluation of spatial and temporal patterns of lightning- and human-caused forest fires in Alberta, Canada, 1980-2007. *International Journal of Wildland Fire*, 19, 1059-1072.

Weaver, K., & Perera, A.H. (2004). Modelling land cover transitions: a solution to the problem of spatial dependence in data. *Landscape Ecology*, 19, 273-289.

Weber, M.G., & Stocks, B.J. (1998). Forest fires and sustainability in the boreal forests of Canada. *Ambio*, 27, 545-550.

Weber, M.G., & Flannigan, M.D. (1997). Canadian boreal forest ecosystem structure and function in changing climate: impact on fire regimes. *Environmental Reviews*, 5, 145-166.

White, P.S., & Pickett, S.T.A. (1985). Natural disturbance and patch dynamics: an introduction. In S.T.A. Pickett & P.S. white (Eds.). *The ecology of natural disturbance and patch dynamics* (pp.3-13). New York, USA: Academic Press.

Wimberly, M.C., Spies, T.A., Long, C.J., & Whitlock, C. (2000). Simulating historical variability in the amount of old forests in the Oregon coast range. *Conservation Biology*, 14, 167-180.

Woolford, D.G. & Braun, W.J. (2007). Convergent data-sharpening for the identification and tracking of spatial temporal centres of lightning activity. *Environmetrics*, 18(5), 461-479.

Worton, B. J. (1989). Kernel methods for estimating the utilization distribution in home-range studies. *Ecology*, 70(1), 164-168.

Wotton, B.M. (2009). Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research applications. *Environmental & Ecological Statistics*, 16(2), 107-131.

Wotton, B.M., & Martell, D. (2005). A lightning fire occurrence model for Ontario. *Canadian Journal of Forest Research*, 35, 1389-1401.

Wotton, B.M., Martell, D.L., & Logan, K.A. (2003). Climate change and human-caused forest fire occurrence in Ontario. *Climatic Change*, 60, 275-295.

Young, A. G., & Merriam, H. G. (1994). Effects of forest fragmentation on the spatial genetic structure of *Acer caccharum* Marsh. (sugar maple) populations. *Heredity*, 72, 201-208.

Zenner, E. K. (2000). Do residual trees increase structural complexity in Pacific Northwest coniferous forests? *Ecological Applications*, 10(3), 800-810.