

# **Spatial and Temporal Patterns of Forest Fire Activity in Canada**

by

**Justin J. Podur**

A thesis submitted in conformity with the requirements for the Degree of Master of  
Science in Forestry  
Graduate Department of Forestry  
University of Toronto

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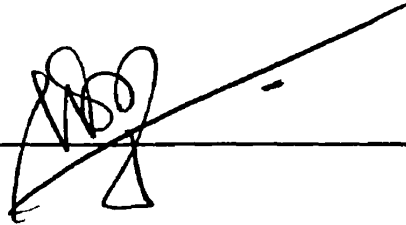
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University of Toronto

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# **Spatial and Temporal Patterns of Forest Fire Activity in Canada**

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**Master of Science in Forestry 2001**

**Graduate Department of Forestry, University of Toronto**

## **Abstract**

Fire and weather archive data for the province of Ontario and Canada were investigated using spatial statistical and time series analysis methodologies. Spatial point pattern analysis was used to investigate spatial patterns of lightning-caused fire occurrence in Ontario. Lightning-caused forest fires were found to be spatially clustered. Evidence was found that this clustering follows the spatial pattern of lightning strikes on dry weather days. Time series analysis was used to investigate cycles and trends in annual number of fires and area burned in Ontario and Canada from 1917 to the present. A 2-year autocorrelation was found in fire occurrence and a 14-year autocorrelation in annual area burned. Statistical quality control methods were used to investigate long term shifts in the mean and variance of annual number of fires and annual area burned in Ontario and Canada. Small significant increases in number of fires and area burned were found.

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# Chapter 1 Introduction: Spatial and Temporal Patterns of Forest Fire Activity in Ontario and in Canada

## 1.1 Spatial Analysis of Lightning Fire Occurrence

### *1.1.1 Literature Review*

Lightning ignited forest fires contribute 87 % of the area burned and 34 % of the fires reported in Canada (Kourtz and Todd 1991). Lightning fires burn a disproportionate share of area because they are more likely to occur in remote areas, where they are harder to detect and reach, and because they often arrive in temporal clusters, which can strain the fire organization. Both of these factors can lead to lightning-caused fires burning for a longer period of time before they are extinguished. Because of their important contribution to the total number of fires and area burned, research into them has been a priority since organized fire protection arose. Latham and Williams (2001) review many studies of lightning-caused fires. They cite Plummer (1912) who summarized research from Europe and US Forest Service lands. Plummer (1912) reported that any species of tree is equally likely to be struck by lightning. Gisborne (1926) studied 2 186 fire reports from the US covering a 3 year period and classified lightning storms as 'safe' and 'dangerous'. In a subsequent study, Gisborne (1931) found that 'safe' storms had both fewer cloud-to-ground lightning flashes and a longer duration of rainfall, but did not

resolve whether it was characteristics of the rainfall or the lightning which made safe storms safe.

Latham and Williams (2001) describe the characteristics of the lightning ground flash:

(Cloud-Ground) lightning is most commonly initiated within the cloud, in the vicinity of the lower charge reservoir (usually negative). An ionized path, the stepped leader, is forged through the air toward ground in a region of high electric field. This stepped leader carries the large negative potential of the lower charge region toward Earth. As the stepped leader nears the earth, an intense electric field develops between [the] leader and [the] ground. The field promotes electrical streamer propagation upward from elevated points on the ground that can connect to the approaching leader. When a connection is made, the bright, high-current (10-100 kA) return stroke is initiated and propagates upward toward the cloud at a speed approaching that of light ( $1-2 \times 10^8$  m/s)...

... In the majority of ground flashes, the return stroke current peaks, in less than 1 microsecond, to values in the range of 5-30 kA and then promptly decays in a few hundred microseconds. Despite the extraordinary peak power of such events, both observations and simulations have shown that the short duration of the return stroke is inadequate to raise trees and other flora in the path to kindling temperature and initiate fire. (Taylor, 1969; Darveniza and Zhou, 1994).

Latham and Williams (2001) describe how 30% of return strokes lead to a continuing current which is long enough in duration to raise vegetation to kindling temperature.

Many lightning strikes cause only mechanical damage and do not start fires, although no statistics are available on the proportion of strikes that do so (ibid.). There is anecdotal evidence that the ignition of forest fuels takes place in the fine fuels on the forest floor (ibid.).

Morris (1934) studied lightning and fire reports in Oregon and Washington and reported (1) that fires were no more likely at higher altitudes than at lower ones, (2) no reliable 'danger zones' for lightning fires based on historical distributions of fires (3) no definite lightning storm lanes or frequent 'breeding spots', (4) thunderstorm days can be classified to indicate fire-starting potential (using a classification like Gisborne (1931)), (5) storms with high rainfall lead to fewer fires. Fuquay et al. (1967, 1972) found evidence that the cause of lightning ignitions was the continuing current in the lightning flash. The duration of the continuing current in lightning flashes varies significantly (Uman 1987), and long continuing current (LCC) flashes are the only flashes which ignite forest fires. (Latham and Williams 2001)

More recent Canadian studies utilize the fuel moisture descriptions of the Canadian Forest Fire Danger Rating System (CFFDRS) (Van Wagner 1987) and lightning-locator technology. In the Fire Weather Index (FWI) system of the CFFDRS, daily weather observations are used to calculate numerical ratings of the moisture contents of different fuel layers. The calculated ratings are combined to generate general indices of potential fire spread and consumption. Lightning locators detect the location, time, and intensity of lightning strikes. They have an accuracy of location of 3-4 km and efficiency of 70% (Flannigan and Wotton 1991). Using these technologies, McRae (1992) found no connection between elevation, slope, aspect, or topography and lightning fires in the Australian Capital Territory, but Van Wagendonk (1991) found altitude dependence for lightning-caused fires in Yosemite National Park. Renkin and Despain (1992) found no

altitude dependence in Yellowstone Park but did find a dependence on fuel type and fuel moisture content.

An approach frequently employed is to study the lightning efficiency, that is, the number of fires per lightning strike, in different fuel types or areas of the landscape. Meisner (1993) took this approach for a small study area in Southern Idaho for lightning fires between 1985 and 1991. He found lightning efficiency to vary by fuel type. He also found that when there were more than 100 lightning strikes in the study area in a single day, correlations between fire weather indices and number of lightning fires were doubled. Nash and Johnson (1996) used the lightning efficiency approach to find that the Fine Fuel Moisture Code in the FWI system was the best fuel state predictor for lightning fires in the Canadian boreal forest, and also classified storm days, finding that lightning efficiency was higher under synoptic high pressure (associated with low precipitation). Wierzchowski et al. (in press) studied lightning fire occurrence in western Canada for 14000 fires from 1961-1994 and found lightning efficiency to be 1/50 in British Columbia and 1/1400 in Alberta. They found lightning fire occurrence to be correlated with the Daily Severity Rating of the CFFDRS.

Flannigan and Wotton (1991) used a study area in northwestern Ontario, the area of Ontario falling into UTM zone 15, to examine lightning-ignited fires. They found insignificant statistical correlations between the number of lightning strikes and the number of lightning-caused fires. They also found that the Duff Moisture Code component of the FWI system, a numerical rating of the moisture content of the loosely

compacted moderate depth duff layer, was an important predictor of lightning fires and that positively charged lightning strikes are not especially important in fire occurrence.

Kourtz and Todd (1991) combined real time lightning information with fuel, weather, and fire behaviour information to predict daily lightning ignitions. Their prediction system has 4 components. The landscape is partitioned into grid cells 50 km<sup>2</sup> in size.

Information on the cloud to ground (CG) lightning flashes, times, and types for each cell is found. In this component of the prediction the number of long continuing current (LCC) flashes is estimated. This information is combined with fuel and weather information concerning ignition probabilities in different fuel types to predict the number of firebrands produced. Next, the probability of a fire smouldering until detection is assessed based on fuel density and moisture content. The fourth step is the assessment of the probability of detection based on the length of time a fire has been burning, the fuel conditions, and the weather conditions. Anderson (1994) developed a similar model. In the US, Fuquay et al. (1979) developed a model for predicting lightning fire ignition based on stochastic and physical processes. Ignitions are based on (1) the density of CG lightning, (2) storm movement, (3) precipitation, (4) the moisture code of fine fuels (corresponding to the FFMC in the Canadian FWI system), (5) the lightning flash characteristics, and (6) the bulk density of fine fuels.

### *1.1.2 Current Study*

Chapters 1 and 2 of this thesis address the conclusions of Morris (1934). In particular, they are relevant to his conclusions that there are no danger zones for lightning fires nor are there lightning storm lanes or breeding zones. Spatial statistical analyses of lightning and lightning fire occurrence data in Ontario indicate that there are indeed areas of high lightning fire occurrence and high lightning occurrence.

## **1.2 Time Series and Quality Control Analysis of Forest Fire Statistics**

### *1.2.1 Literature Review*

Saunders (2001) conducted a time series analysis of temperature and precipitation data for the period 1916-1998 in northwestern Ontario and found both significant warming trends and cycles. Strong cycles were found with periods of 2.1 years, 3-5 years, and 16.5 years. There were overall warming trends in the mean temperature from 1916-1944, and again from 1970-present, with the period 1944-1970 classified as 'relatively benign'. Saunders (2001) lists some natural cycles which could influence northwestern Ontario's climate, including the ENSO (El Nino/Southern Oscillation), the QBO (Quasi-Biennial Oscillation), and the PNA (Pacific North American). Schindler et al. (1990) found lakes in northwestern Ontario had warmed by 2° C between 1969 and 1987. Corti et al. (1999), modeling the climate system as a nonlinear dynamical system with a chaotic attractor, generated results suggesting that climate change may project itself on natural patterns in complex ways. This means that finding the ultimate source of climate changes in anthropogenic activities or in natural variation could be impossible.

Lambert and Pross (1967) outline the history of forest fire protection in Ontario to the mid-1960s. The history is one of expanding fire protection and reporting, since 1878. The first systematic recording of fire outbreaks occurred in 1914. Significant technological changes have occurred over time, with aircraft introduced for detection in 1924 and a more significant expansion of aircraft use in the 1950s. Murphy (1985) notes a large change in Alberta's fire protection budget in the 1950s, from approximately 1 million to 20 million in inflation-adjusted dollars. Fire protection is not the only human impact that has increased over time. Logging, transportation, resource extraction, and road-building have all increased over the 20<sup>th</sup> century, the impacts of which could well affect fire activity.

In sum, then, there are a number of factors which have the potential to influence fire activity:

- A wetter climate could reduce fire activity;
- A warmer, drier climate could increase fire activity;
- Expanding fire protection could reduce fire activity;
- Expanding fire protection and detection capabilities could increase reported fire activity, making it seem like fire activity, in particular number of reported fires, is increasing whether it is or not;

- Other human impacts (logging, roads) could reduce fire activity (by fragmenting the landscape) or increase it (better road access and industrial activity can lead to fire ignitions, logging slash burns readily).

Since fire activity is driven by fuel and weather at many different temporal and spatial scales, it is difficult to assess what the effect changes in weather or climate, or fire suppression activities, or even record-keeping changes, have had.

### *1.2.2 Current Study*

Chapters 3 and 4 describe attempts to use time series and quality control methodologies to look for statistically significant trends or correlations in fire activity. The results provide some insight into which processes are dominating changes in fire activity. The study finds a significant two-year autocorrelation in number of fires, a 14-year autocorrelation in area burned, and an overall increasing trend in both series. This suggests that the factors which increase fire activity (climate change to warmer and drier climate, expanding detection capabilities, fuel changes that produce a more flammable landscape) dominate over those which may reduce it (climate change to a wetter climate, expanding fire protection, forest fragmentation). The 2- and 14- year autocorrelations suggest weather cycles are influencing fire activity. It will be noted below that the 'fire activity-reducing' factors could well be masking the true impacts of climate and fuel changes on the landscape.



## Chapter 2: Spatial Point Pattern Analysis of Lightning-caused Forest Fires in Ontario, 1976-1998

### 2.1 Abstract:

The spatial pattern of forest fires is of interest for understanding the role of fire in landscape processes and for fire occurrence prediction. A spatial statistical analysis of lightning-caused fires in the province of Ontario, between 1976-1998, was carried out to investigate the spatial pattern of fires, the way they depart from randomness, and the scales at which spatial correlation occurs. Fire occurrence was found not to be a spatially random process-- fire is more likely to occur at some locations than others.

### 2.2 Introduction

The province of Ontario in Canada experiences an average of 1 713 forest fires per year, with an average of 242 000 ha burned (Ontario Ministry of Natural Resources 2000).

Fire is a part of the ecology of the boreal forest. It is one of the primary agents of renewal and succession in the boreal forest. Many species are adapted specifically to fire-affected habitats. In many ways the boreal forest is a forest shaped by fire.

Although fire is natural, it can pose a threat to public safety. It can also destroy economically and socially valued forests. In Ontario, approximately \$85 million per year is spent on fire suppression programs. Fire managers seek to balance the ecological role

of fire, the threat it poses to public security and property, and the costs of fire suppression.

Fire management planning, particularly for the long term, requires an understanding of the relationships between fire, weather, vegetation, and fire management activities. These relationships can be investigated from many perspectives. The Canadian Forest Fire Danger Rating System (CFFDRS) (Van Wagner 1987), uses daily weather observations of temperature, precipitation, humidity, and wind speed, to generate numerical indices of fire danger. Landscape fire models such as the FIRE! model (Green et al. 1995) spatially simulate the impacts of fire in the landscape. The present study attempts to understand the spatial dynamics of lightning-caused fire occurrence. The study area is the province of Ontario, and the temporal scale is annual.

### **2.3 Previous Work**

Previous studies have related weather, vegetation and fire suppression activity to fire occurrence and burned area. Armstrong and Vines (1973) correlated drought periods in Canada to particularly severe fire years. Harrington et. al. (1983) found the Fire Weather Index variables which explained a maximum of variation in monthly area burned. Martell and Sun Hua (1997) used logistic regression analysis to relate annual area burned across the province of Ontario to median initial attack response time as a measure of level of protection, forest type, and fire danger rating information. The current study uses spatial point pattern analysis from the family of spatial statistical tools to examine the spatial pattern of lightning-caused fire occurrence in Ontario.

## **2.4 Lightning Fires**

Most fires are either human or lightning-caused. This study focuses on lightning-caused fire occurrence for a number of reasons. First, although lightning fires constitute only 36% of the fires that occur Ontario (Ontario Ministry of Natural Resources 2000), they occur in less populated areas where they are less likely to be quickly detected when they are still small and easy to extinguish. Secondly, lightning storms typically ignite multiple fires. This temporal clustering can strain resources of the fire suppression organization and increases the likelihood that a fire will grow to a large size. As a result, lightning fires caused 82.2% of the area burned in Ontario for the study period (ibid.). Finally, human-caused fires occur near populated areas. As a result, a study of the spatial pattern of human-caused fire occurrence would almost certainly have a trivial result: the fires will almost certainly be clustered around areas of intensive human land use—towns, roads, railways, and campgrounds.

## **2.5 Data**

The data used in this study was provided by the Ontario Ministry of Natural Resources (OMNR). The OMNR fire database is an archive of data on all reported fires from 1976-2001. The archive contains fire reports, one of which is prepared for each forest fire in the province. Each fire report contains many variables including the location, final size, forest type, weather, and fire suppression information. This study covers the period from 1976-1998. The records come from reports prepared by the fire boss after each fire is

extinguished. The fire boss is principally concerned with fighting the fire—preparing the final fire report is a secondary concern. It is therefore important to keep in mind that some data (e.g. final fire size) are to some extent the subjective estimates provided by the fire boss. This study is concerned principally with the locations of the fires. Fire locations are reported in the data in Universal Transverse Mercator coordinates to a precision of one metre but error estimates are not provided with the data. While error in locations could be quite high, it is unlikely to confound the results of this study. This is because the size of the study area and the length of the time scale (annual) can safely be assumed to be much larger than the size of the error in fire locations.

## **2.6 Study Area**

Two study areas were used. The first was the entire province of Ontario shown in Figure 2.1 below. The geographic limits were as follows: 57° N, 41.5°N, 95.5°W, 74.5°W. The second area studied was a rectangular region in northwestern Ontario: the region north of 49° N, 52°N, west of 89°W, and east of 95°W. This subset of Ontario was chosen in order to study spatial patterns of fire occurrence at a finer spatial scale than the all-Ontario scale. Northwestern Ontario was studied because

- It is widely recognized as a persistent ‘hotspot’ of forest fire activity, as the results below reveal,
- Fire protection, and hence detection, is quite uniform over this area, making detection bias unlikely to contribute to the observed spatial pattern.



Figure 2.1. The study region, Ontario, is shaded in gray, and the subregion in northwestern ontario is shaded in black.

## 2.7 Methods

Martell and Sun Hua (1997) investigated the relationship between lightning fire and weather, fire suppression activity, and forest type. They partitioned the province of Ontario into polygons based on forest type and level of fire management zone. The forest type was the type of vegetation, including the mix of aspen, spruce, and jack pine. The management zone is an administrative unit corresponding to the way that the fire management organization responds to detected fires. There are three zones: intensive, measured, and extensive. In the intensive zone, all fires are suppressed. In the extensive zone, fires are suppressed if they are a threat to human safety or forest values. In the measured zones, fires are initially attacked, but if initial attack fails, an escaped fire

situation analysis is carried out to determine the extent to which the fire will continue to be aggressively attacked. They developed a logistic regression model to predict the fraction of annual burned area using the mean initial attack time and a 'fire control difficulty index', a function of the forward rate of spread, a component of the CFFDRS system. Their approach advanced understanding of the relationships between fire suppression, forest type, and area burned, but it was essentially an aspatial study.

The current study relies on spatial statistical methods. Using spatial statistics it is possible to determine whether or not fires are more likely in some places than in others, and whether fires are more likely to be found in clusters or at some distance from one another. The techniques we used and the results of our analysis are described below.

Spatial Point Pattern (SPP) analysis is the spatial statistical method best suited to studying fire occurrence at a provincial scale. In general, SPP techniques are used to detect patterns in phenomena occurring at point locations. Important measures in SPP are spatial intensity, defined as the number of events per unit area, and the nearest neighbour statistic, a measure of how close events are to one another.

A collection of events is considered to be Completely Spatially Random (CSR) if the expected intensity is constant over space and events are neither clustered nor regularly spaced.

There are two ways a point pattern can depart from randomness. Clustering implies that events are found nearer to one another than a random distribution would suggest.

Regularity implies points are farther apart from one another than a random distribution would suggest.

### 2.7.1 Nearest Neighbour Statistics

A nearest neighbour statistic called the K-function can be used to test the extent to which a phenomenon is random, clustered, or regular. Let  $h$  be the distance from an event. Let  $\lambda$  be the intensity or mean number of events per unit area. Define  $K(h)$  as

$$\lambda K(h) = E(\text{number of events within distance } h \text{ of an arbitrary event}) \quad [2.1]$$

where  $E()$  is the expectation operator. If  $R$  is the size of the study area, then the expected number of events in the area is  $\lambda R$  (the number of events per unit area multiplied by the area). The expected number of ordered pairs of events less than  $h$  apart in the study area, is  $\lambda R * \lambda K(h) = \lambda^2 RK(h)$ . If  $d_{ij}$  is the distance between the  $i$ th and  $j$ th observed events in the area of size  $R$  and  $I_h(d_{ij})$  is an indicator function, 1 if  $d_{ij} \leq h$  and 0 otherwise, the observed number of ordered pairs of events a distance less than  $h$  apart in the study area is  $\sum_{i \neq j} I_h(d_{ij})$ . An estimate of  $K(h)$  is therefore

$$\hat{K}(h) = 1/(\lambda^2 R) * \sum_{i \neq j} I_h(d_{ij}) \quad [2.2]$$

$\lambda$  is estimated by  $n/R$ , where  $n$  is the number of events (Bailey and Gatrell 1995).

An intuitive understanding of  $K(h)$  can be achieved by imagining an algorithm that ‘visits’ each point in the study region and ‘counts’ the number of points within different radii  $h$ , and then takes the average number of neighbours at each radius  $h$ . This function, divided by the intensity (mean number of events per unit area), is  $K(h)$  (ibid.).

### 2.7.2 Kernel Estimation of Spatial Intensity

The spatial intensity of a point process, or  $\lambda$  as defined above, can be calculated by using Kernel estimation. If  $s_1, \dots, s_n$  are the locations of the  $n$  observed events then the intensity  $\hat{\lambda}_\tau(s)$  at location  $s$  is estimated by

$$\hat{\lambda}_\tau(s) = \frac{1}{\sigma_\tau(s)} \sum_{i=1}^n \frac{1}{\tau^2} k\left(\frac{(s-s_i)}{\tau}\right) \quad [2.3]$$

Where  $k()$  is a bivariate probability density function symmetric about the origin, known as the kernel (ibid.).  $\tau$  is the bandwidth and determines the radius of a disc centred on  $s$  within which points  $s_i$  will contribute significantly to the intensity  $\hat{\lambda}_\tau(s)$  (ibid.). The factor

$$\sigma_\tau(s) = \int \frac{1}{\tau^2} k\left(\frac{(s-u)}{\tau}\right) du \quad [2.4]$$



is an edge correction. It is the volume under the scaled kernel centred on  $s$  which lies inside the study area  $R$  (ibid.). The estimate of  $\lambda$  can be examined over a grid over the study area to provide a visual indication of the variation in the intensity over the area (ibid.). Such an examination can help to identify persistent ‘hotspots’ of high fire or weather activity, for example, and will be used for this purpose below.

An intuitive or visual understanding of kernel estimation can be achieved by imagining a moving window with a circular base, of radius  $\tau$ , and a shape like the kernel function  $k()$ , moving over the study area. When the window is centred at point  $s$ , events within the window contribute to the intensity at point  $s$ , weighted by the value of  $k()$ .

## 2.8 Hypotheses

The null hypothesis is that forest fires are Completely Spatially Random (CSR). There are reasons to suspect both regularity and clustering.

One reason lightning fires might be clustered is because lightning storms are localized phenomena. As was mentioned above, a lightning storm can ignite multiple fires in a single day. These fires would be closer to one another than a CSR distribution, and would therefore be clustered. This is true for a daily temporal scale, but it is possible this effect could be reduced over the annual temporal scale of this study.

A second reason for clustering is because vegetation, climate, and daily weather conditions (temperature, humidity, and wind) that are conducive to burning are also localized. Climate and vegetation vary over the province, and some forest types determined by climate and vegetation are more susceptible to fire than others<sup>1</sup>. Daily weather also varies over the province, so certain areas are dryer, hotter, or windier than others at various times. This effect could potentially result in the clustering of fires in such areas.

Third, a detection bias effect might cause clustering in the data set where clustering does not actually exist. Fires that start in remote areas and do not ever grow to large sizes will not be detected with the same frequency as similarly sized fires in populated areas. This could mean that detected and reported lightning-caused fires are clustered around these populated areas.

Conversely, it is conceivable that fires repel one another resulting in a regular pattern, because a forest where the vegetation has burned is unlikely to burn again for some time.

## **2.9 Results and Discussion**

### **2.9.1 Clustering**

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<sup>1</sup> The type of vegetation in an area can depend on the fire regime. This means that just as vegetation can determine, to some extent, the amount of fire activity, fire activity shapes vegetation over long time scales.

The K-function was calculated in S-Plus using the spatial module. The K-function itself, however, is difficult to visualize. It is difficult to look at a plot of the K-function and determine visually whether an SPP is clustered or regular. For this reason, a square root transformation was applied.

For a spatially random SPP, the probability of occurrence of an event is independent of the number of events that have already occurred and equally likely over the whole area. The expected number of events within a distance  $h$  of a randomly chosen event is therefore  $\lambda \pi h^2$ . So for a random process,  $K(h) = \pi h^2$ , from the definition of  $K(h)$  in section 2.7.1. A clustered process would have  $K(h) > \pi h^2$ , and a regular process would have  $K(h) < \pi h^2$ . To visualize this,  $\hat{L}(h)$  is plotted against  $h$ , where

$$\hat{L}(h) = \sqrt{\hat{K}(h) / \pi} \quad [2.5]$$

$\hat{L}(h)$  for a random process is  $\sqrt{\pi h^2 / \pi} = h$ , the 1:1 line. If  $\hat{L}(h)$  is above this line, the SPP is clustered, and if  $\hat{L}(h)$  is below this line, the SPP is regular. Graphs of  $\hat{L}(h)$  versus  $h$  for the years 1992-1998 are plotted in Figures 2.2 through 2.8. They show peak clustering at a scale of approximately 2.5 degrees, which corresponds to approximately 200 kilometres in the area under study.

As a test of significance, random SPP's were simulated using a uniform distribution and their K function calculated. The maximum and minimum K-function are shown as a

'simulation envelope' in Figures 2.2 through 2.8. The results show that  $\hat{L}(h)$  is much more clustered than random chance would allow. The graphs also show regularity at longer spatial scales. An examination of Figures 2.9 through 2.15 suggests why this occurs. The areas of high fire activity, where clustering occurs, are in two spots, with areas of low fire activity in between. This pattern could give rise to the pattern of clustering at shorter scales followed by regularity at longer scales in the  $\hat{L}(h)$  graphs.

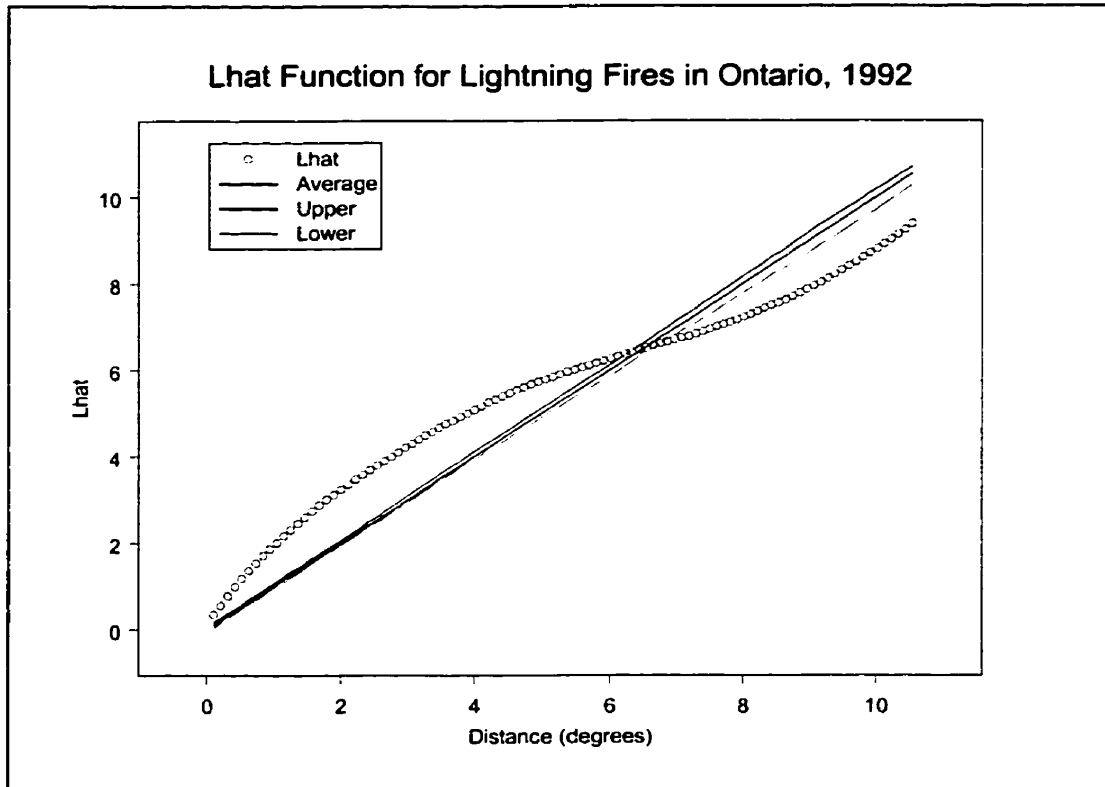


Figure 2.2. Lhat function for Lightning Fires in Ontario, 1992. Note the peak clustering around 3 degrees and the regularity beginning at 6 degrees.

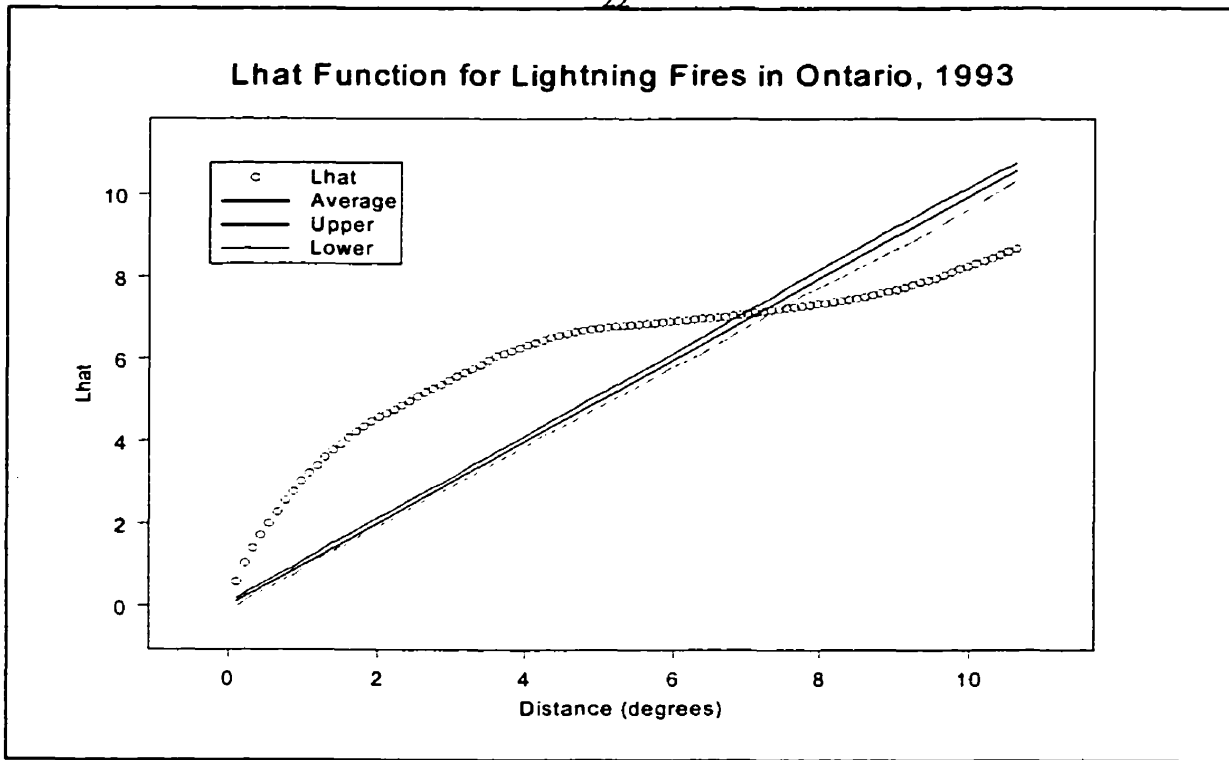


Figure 2.3. Lhat for Lightning Fires in Ontario, 1993.

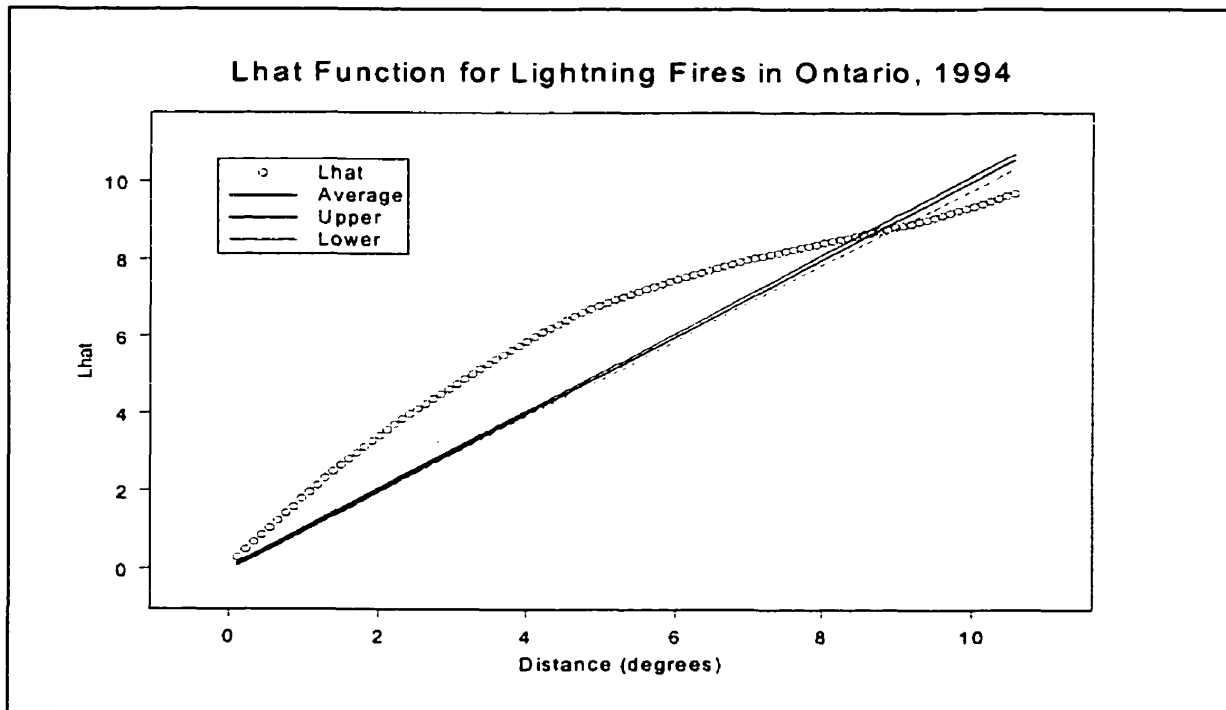


Figure 2.4. Lhat for Lightning Fires in Ontario, 1994

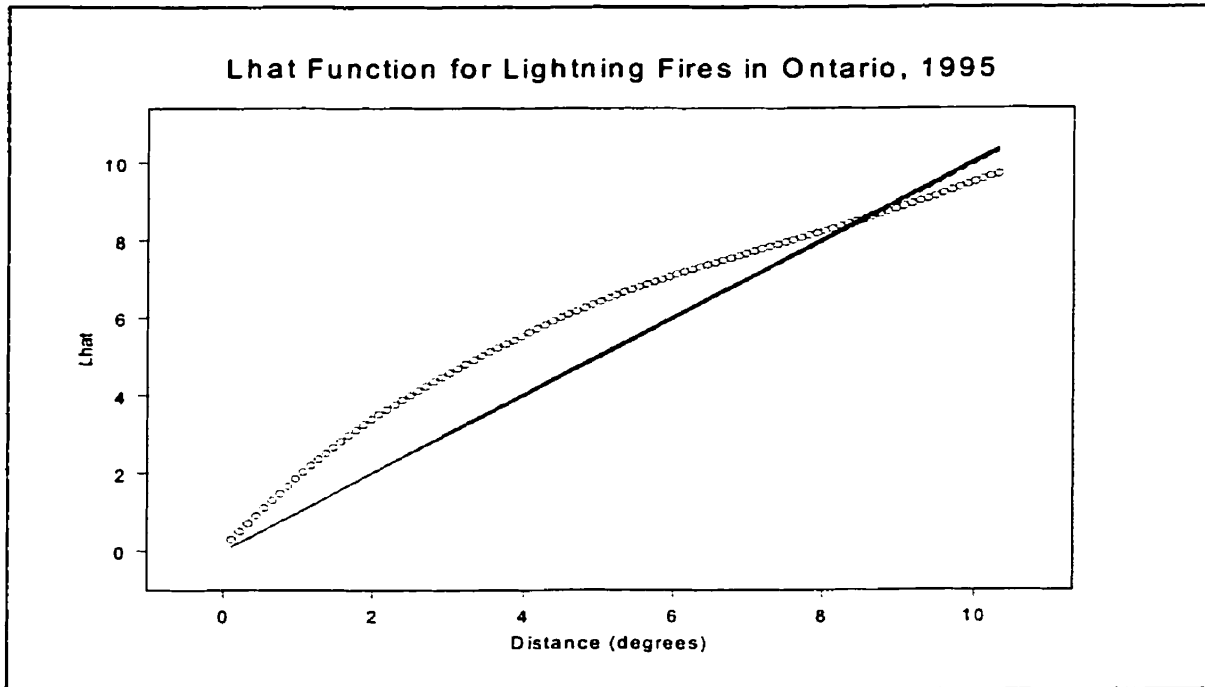


Figure 2.5. Lhat function for lightning fires in Ontario, 1995

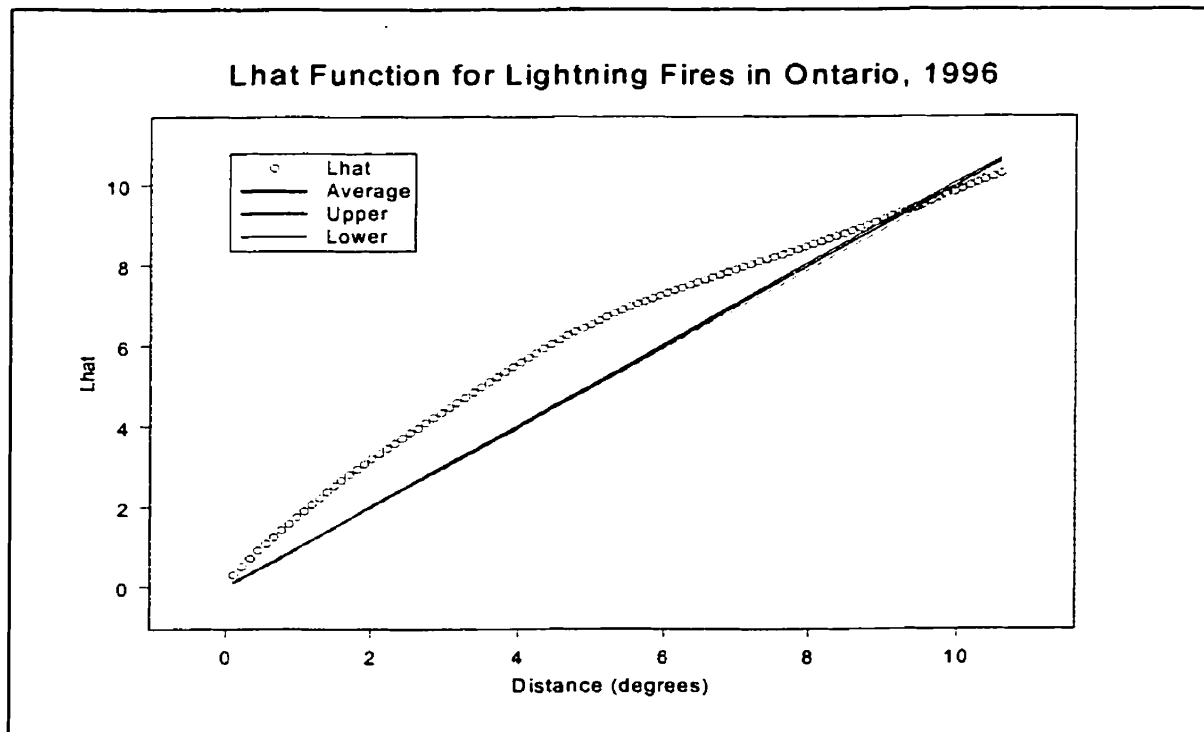


Figure 2.6. Lhat function for lightning fires in Ontario, 1996

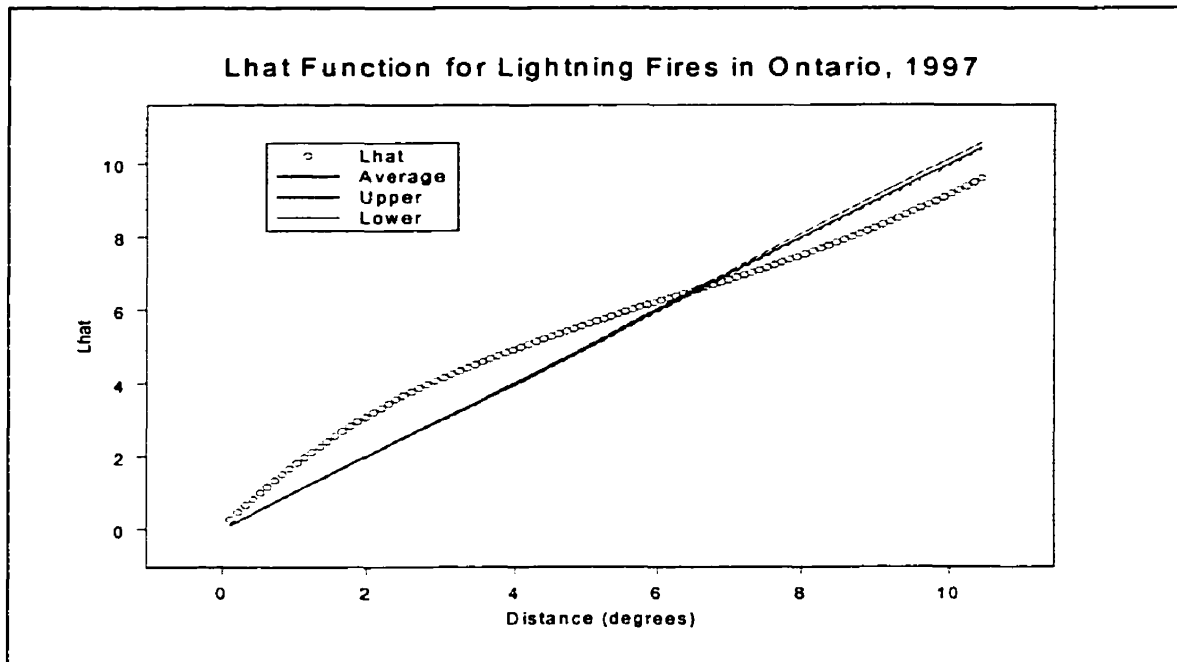


Figure 2.7. Lhat function for lightning fires in Ontario, 1997

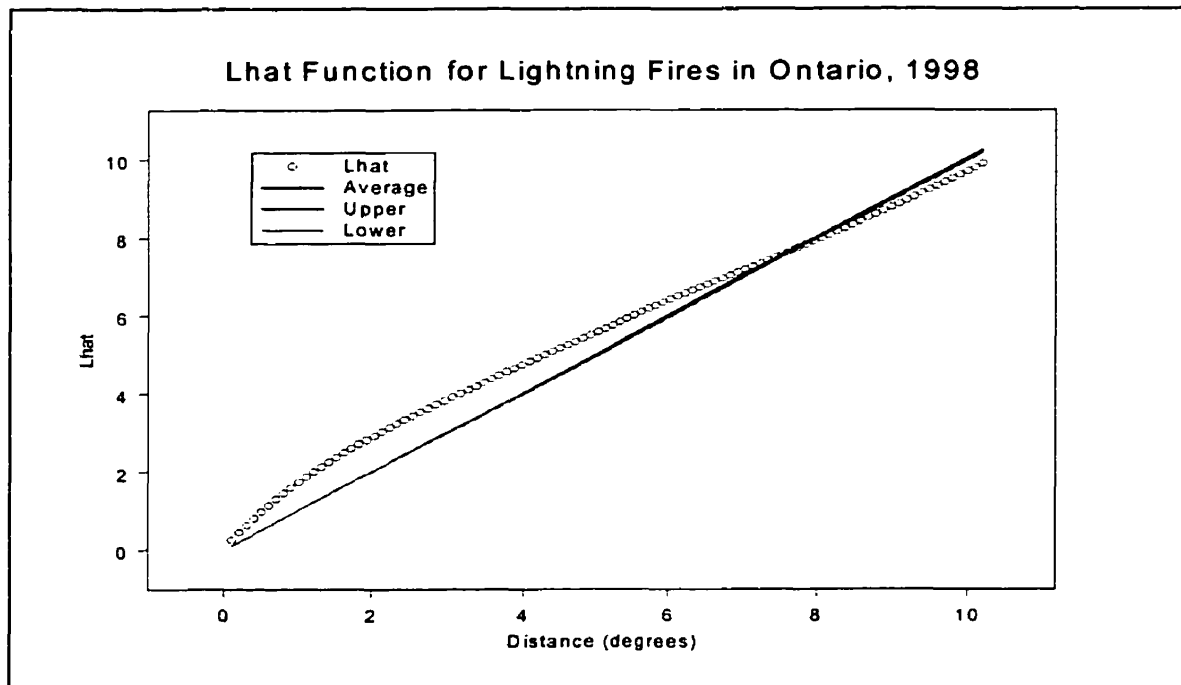


Figure 2.8. Lhat function for lightning fires in Ontario, 1998



These results suggest that the ‘clustering’ factors are dominant at scales of 150-200km. Chapter 3 examines each of these causal factors (weather, fuel, human activity and detection bias) in detail. GIS and spatial statistical methods will be used to investigate lightning strikes, detection bias, fire weather variables, and fire suppression.

### 2.9.2 Spatial Intensity Results

Kernel estimation of the spatial intensity of lightning fires was conducted using the Splus spatial module. Maps of the intensity for the years 1992-1998 are shown in Figures 2.9 through 2.15. These show two persistent ‘hotspots’ of fire: one in the northwest and one in the southeast. These plots show that the fires are clustered in these hotspots.

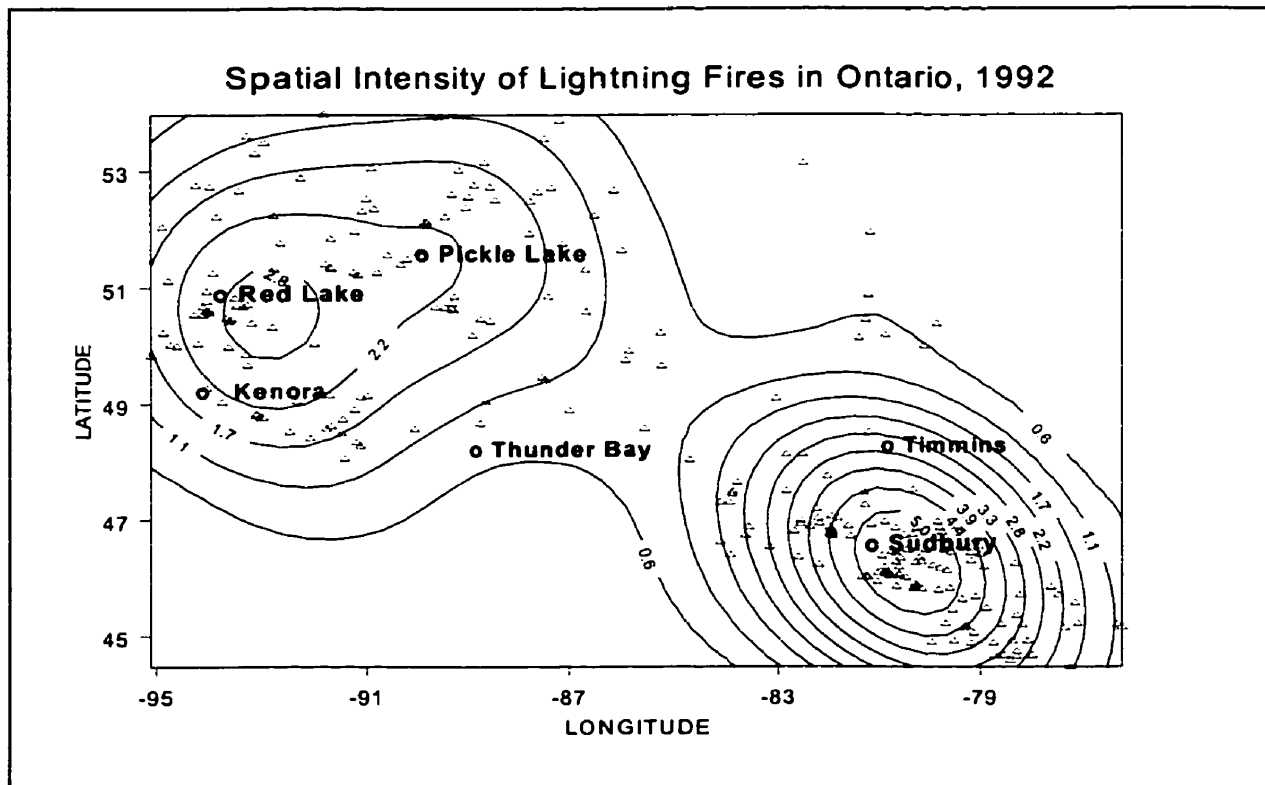


Figure 2.9. Spatial Intensity of Lightning Fires in Ontario, 1992

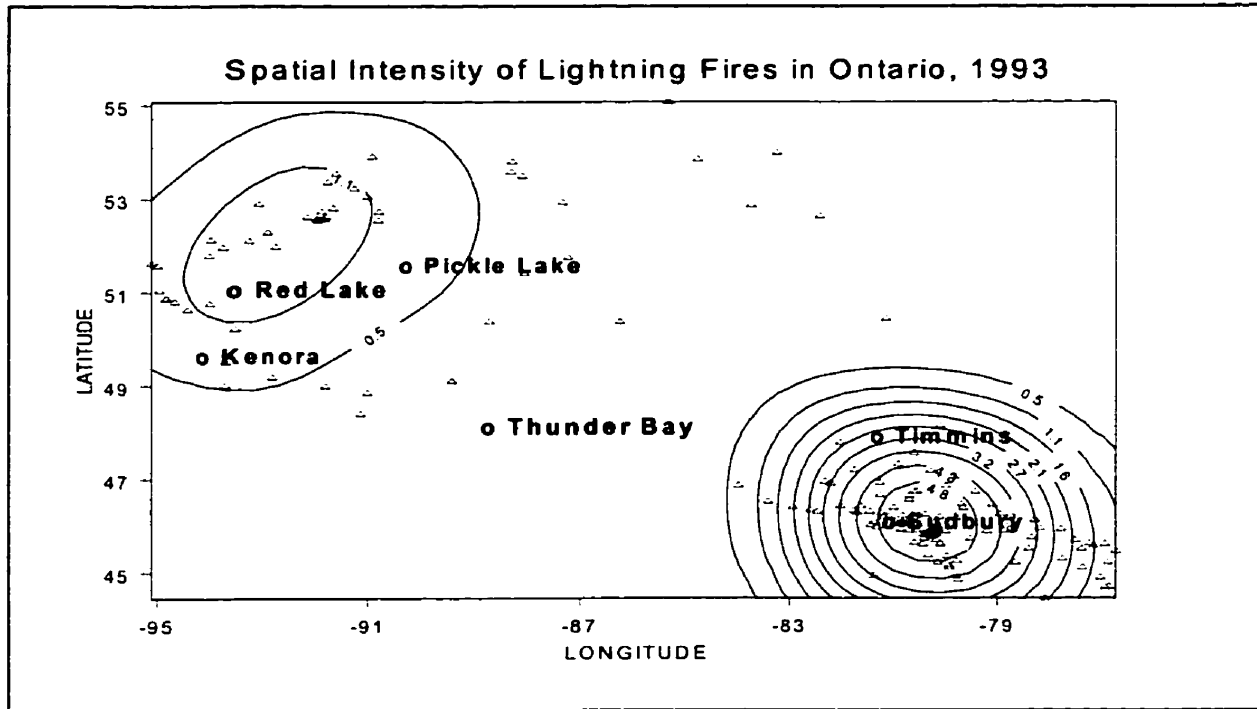


Figure 2.10. Spatial Intensity of Lightning Fires in Ontario, 1993

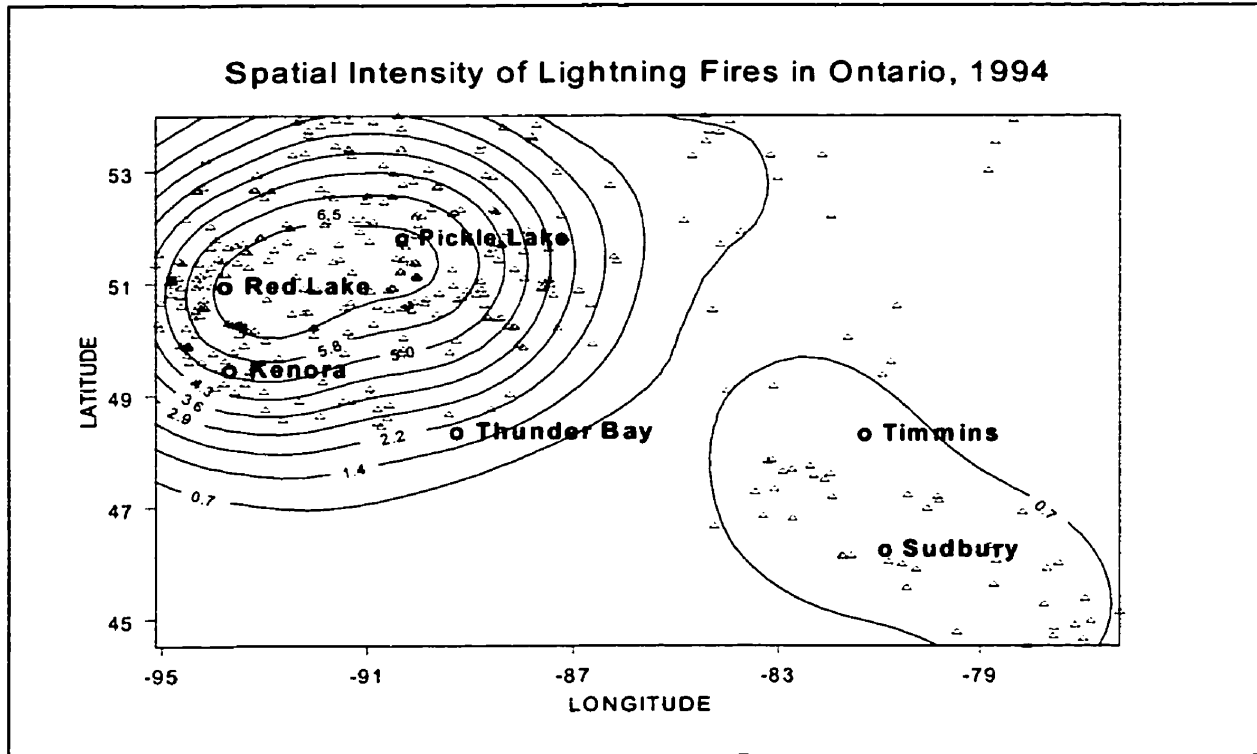


Figure 2.11. Spatial Intensity of Lightning Fires in Ontario, 1994

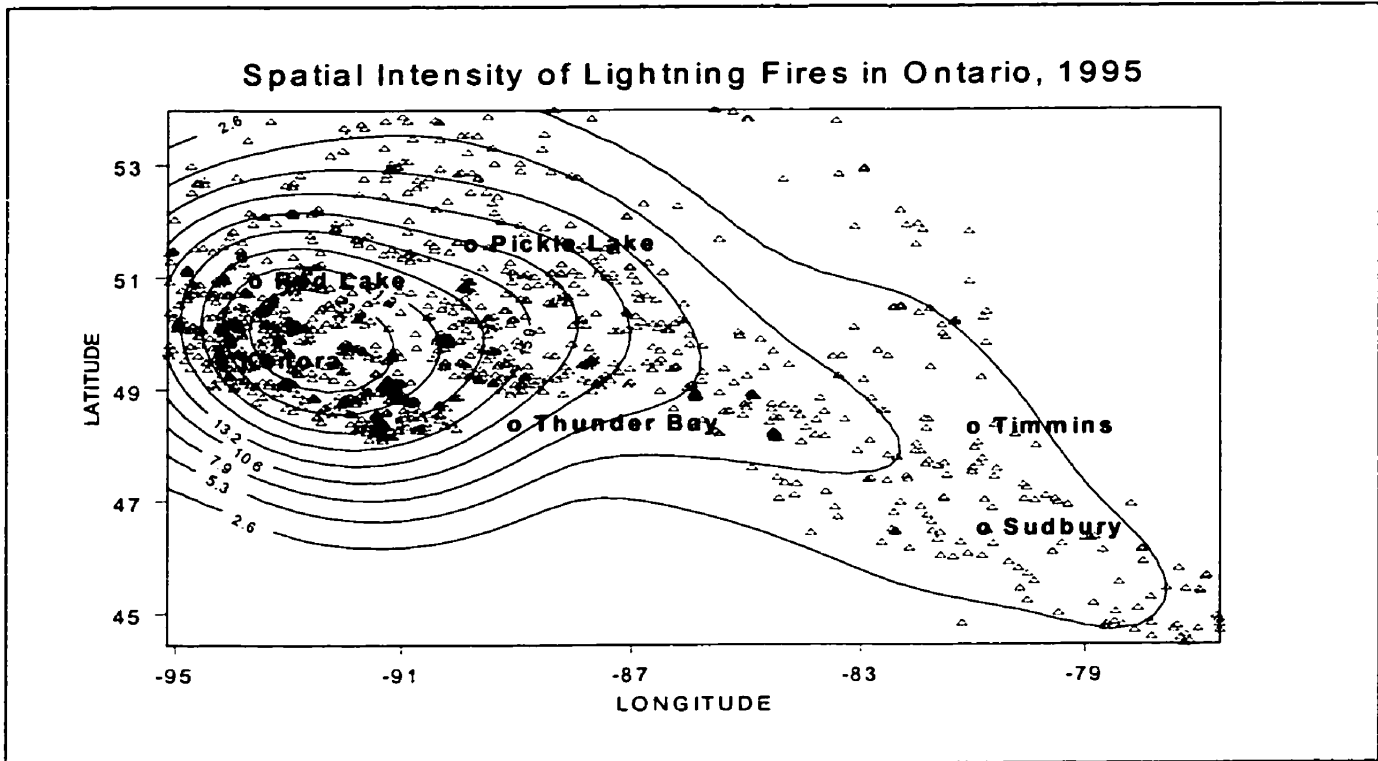


Figure 2.12. Spatial Intensity of Lightning Fires in Ontario, 1995

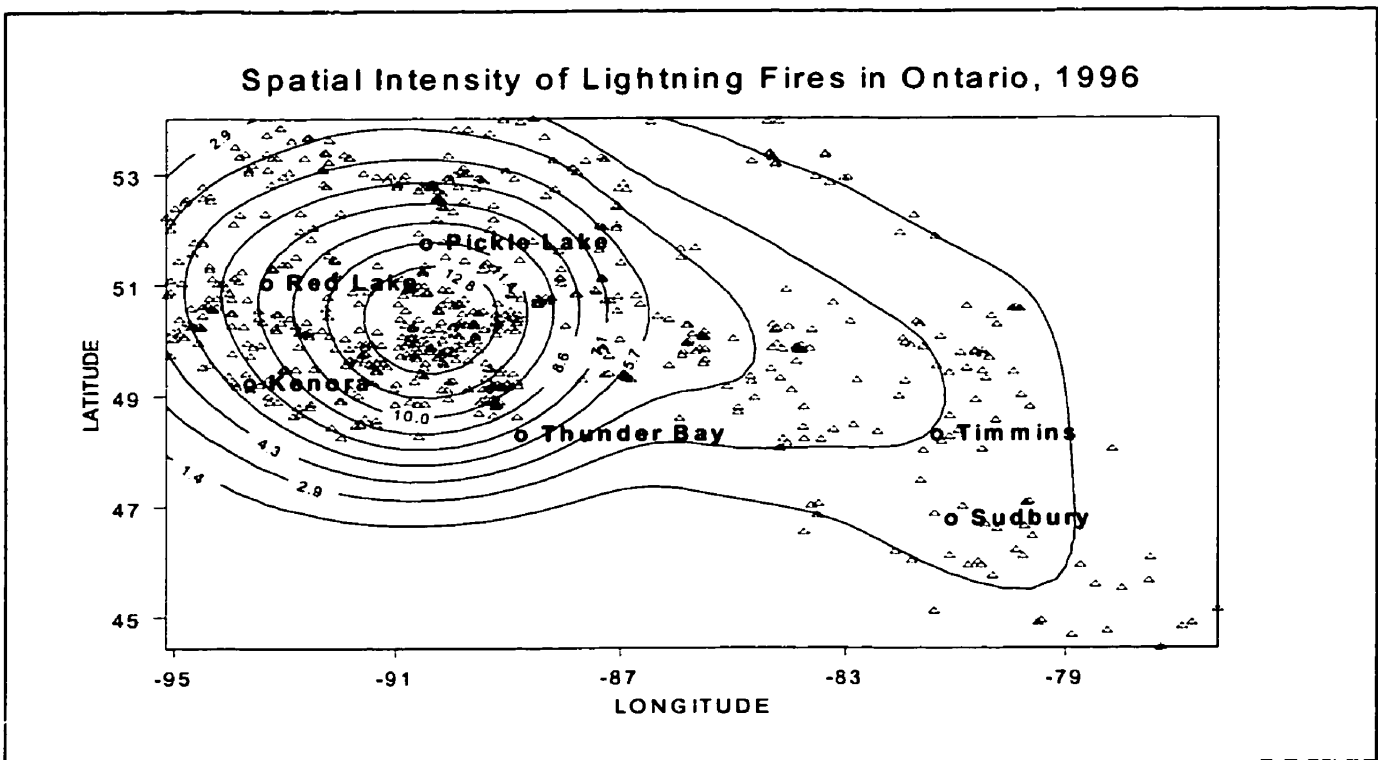


Figure 2.13. Spatial Intensity of Lightning Fires in Ontario, 1996

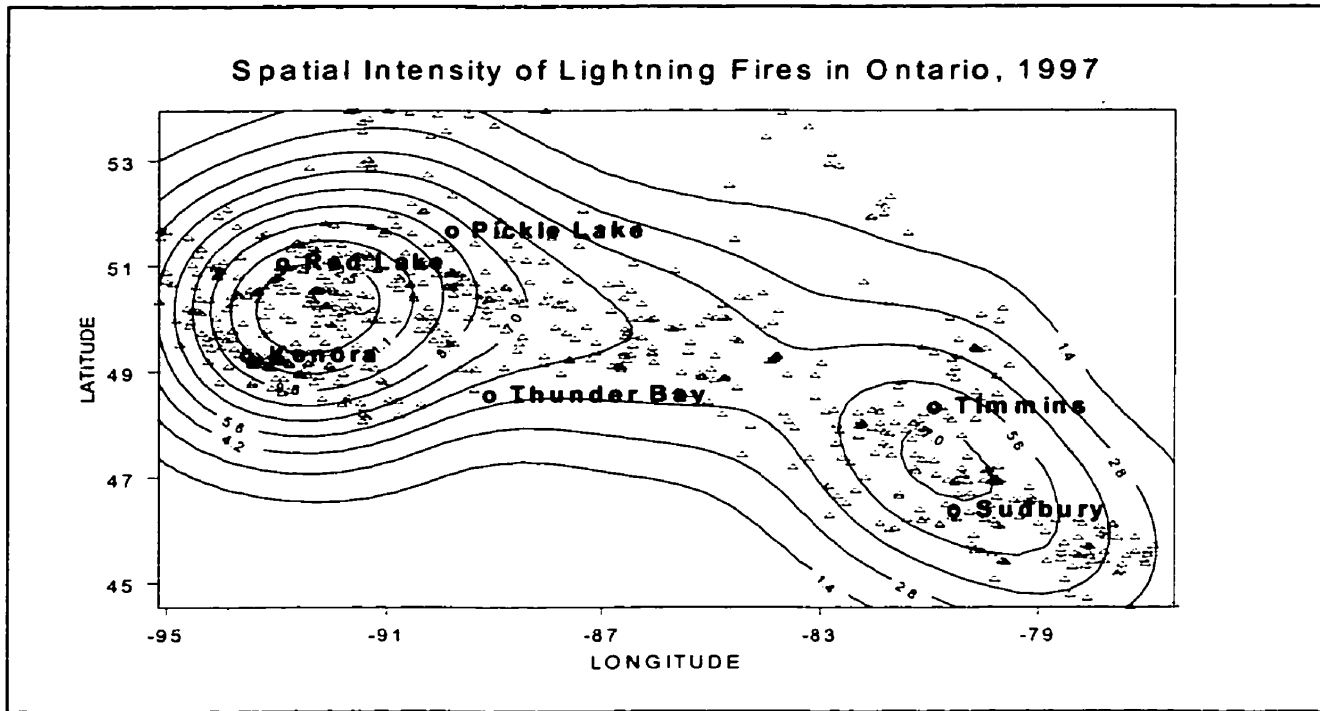


Figure 2.14. Spatial Intensity of Lightning Fires in Ontario, 1997

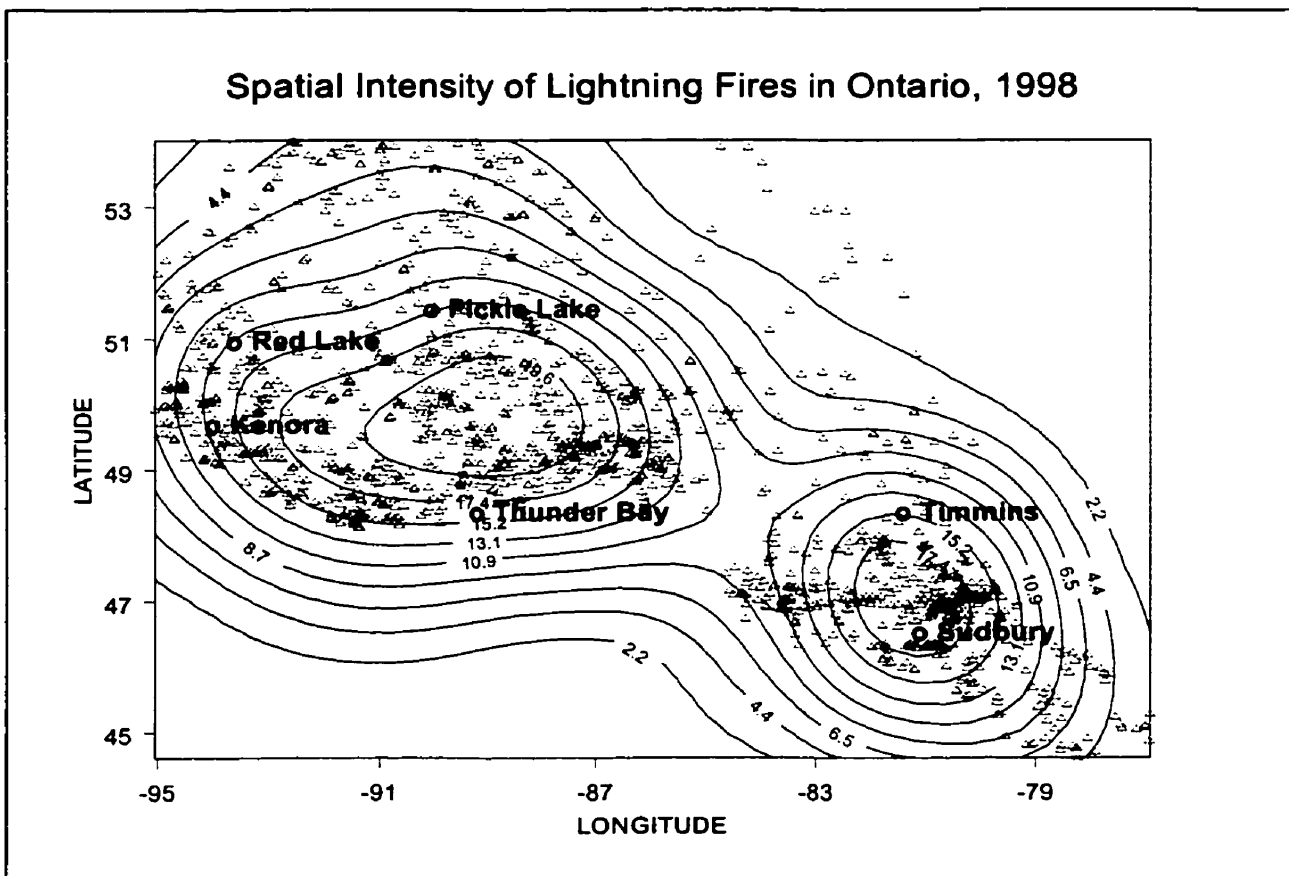


Figure 2.15. Spatial Intensity of Lightning Fires in Ontario, 1998

Because the spatial intensity was calculated on a regular grid of size 0.15 degrees in size, there was a resolution-dependence to the finding. The same patterns were found, however, using different grid cell sizes in exploratory analysis.

## **2.10 Conclusions**

A spatial statistical analysis of lightning-caused fires in Ontario from 1976-1998 was conducted. Spatial Point Pattern (SPP) analysis was employed. The results of the analysis are:

- A nearest-neighbour statistic, the K-function, showed fires to be found in clusters at a scale of approximately 150-200km (peak clustering at 3 degrees).
- At scales longer than 6 degrees, fires are regularly spaced.
- Kernel estimates of spatial intensity show that these clusters are located in the northwest and in the south eastern regions of Ontario.

These results conflict with the findings of Morris (1934), who found no ‘high’ and ‘low’ fire areas. There are, indeed, ‘high’ and ‘low’ fire areas in Ontario, as the spatial intensity maps of Figures 2.9 through 2.15 show.

Chapter 3 will examine some of the factors which might be contributing to this clustering.

## Chapter 3: Causes of Spatial Patterns of Lightning-caused Fire Occurrence in Ontario, 1992-1998

### 3.1 Abstract

A spatial point pattern analysis of lightning-caused fires in Ontario for 1976-1998 revealed that fires were clustered in the northwestern and southeastern regions of Ontario at a scale of 200-300km (Chapter 2). The current chapter attempts to explain this variation in terms of the spatial variation in the following potential causal factors: lakes, roads, weather, fuel, and lightning strikes. Linear Regression and Regression Tree analyses based on a partition of the province into 48 compartments did not unearth significant correlations between the spatial pattern of fires and the spatial patterns of potential causal factors. Kernel estimation (described in Chapter 2) of the spatial pattern of lightning strikes on days when the DMC exceeded 20 in the northwestern region yielded a good match with the spatial pattern of lightning fires. This confirms the empirical rule used by the OMNR in its operational fire prediction procedures<sup>2</sup> (Kourtz 1974).

### 3.2 Introduction

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<sup>2</sup> Kourtz (1974) calls this a 'Hatching Rule': 'An area is most likely to have lightning fires if the lightning sensor reports 50 or more counts and yesterday's DMC is 20 or greater.'

In Chapter 2 a spatial point pattern analysis was conducted to describe spatial variation of annual number of lightning-caused forest fires in Ontario. In this analysis forest fires were found to be clustered on a scale of 200-300 km in the northwestern and south-eastern areas of Ontario.

Forest fires are known to be ignited by lightning, and whether any given lightning strike in a forest results in a fire is a function of vegetation (fuel) at many scales, and weather. The presence of spatial clustering of lightning fire occurrence suggests that this clustering could be caused by clustering of lightning strikes or by spatial variation in weather or fuel conditions. Another possible factor is detection bias—more fires may be detected where there is increased human presence or detection effort.

In order to try to explain the variation in terms of these causal factors, the province was partitioned into 48 polygons used by Martell and Sun Hua (1996). These were defined by forest type and fire management zone. They were sufficiently large that the spatial correlation of fires would not have a significant effect between polygons. Martell and Sun Hua (1996) found evidence that the polygons were spatially independent with respect to forest fire activity.

### **3.3 Data**

In each polygon, the number of lightning strikes was counted for the years 1992-1998 using the OMNR lightning strike record. The Ministry uses a lightning location system that detects cloud to ground lightning discharges. This is done with an electric field

antenna to detect polarity and a magnetic field antenna to detect azimuthal angle. The incoming electromagnetic signal is compared with lightning signature profiles, and if it matches a cloud to ground lightning signature, it is recorded. When two or more sites detect a lightning discharge, the discharge location is triangulated by a central computer. (Flannigan and Wotton 1991). The FWI and DMC, two components of the Canadian Forest Fire Danger Rating System (Van Wagner 1987), were calculated at the centroid of each polygon using an interpolation program developed by Flannigan and Wotton (1989) from the OMNR weather station records. The forest type was taken from Rowe's (1972) forest region ecological classification system. This fuel data was used by Martell and Sun Hua (1996) to calculate a fire control difficulty index. This index was adopted as a measure of spatial variability of fuel for this study. The fire management zones were taken from the OMNR. Data on lakes and rivers was obtained from Geogratis and these data were used to calculate the total area of lake and river in each polygon. A digital map of roads in Ontario from the OMNR was also used, and the amount of road in each polygon was considered as a proxy for human presence and therefore detection bias.

Since the polygons differed in size, fire and lightning occurrence densities (fires or lightning strikes per square kilometre) were used instead of raw numbers, as was % of lake and river area, and kilometres of road per square km to correct for the differing sizes of the polygons.

### **3.4 Methods**



### 3.4.1 Linear Regression Analyses and Results

Standard linear regression approaches did not find significant correlations between fire occurrence density and any of the explanatory variables. R-values and p-values for these correlation analyses found all of the explanatory variables to be insignificant.  $R^2$ - values are given here for 1992, but the regression results were insignificant in all years.

- The number of days FWI was above threshold, with thresholds set to 4 [ $R^2 = 0.0492$ ], 11 [ $R^2 = 0.0028$ ], and 23 [ $R^2 = 0.0505$ ], were insignificant.
- Lake and river density [ $R^2 = 0.0064$ ] was insignificant.
- lightning strike density [ $R^2 = 0.0056$ ] and lightning strike density on days when DMC exceeded 20 [ $R^2 = 0.012$ ] was insignificant.
- Martell and Sun Hua's (1996) fire control difficulty index [ $R^2 = 0.0058$ ] was insignificant.
- Road density [ $R^2 = 0.0004$ ] was insignificant.

The complexity of the relationships between the variables, the significant margin of error in the interpolation and collection of the data, and possibility of threshold and interaction effects could possibly explain the failure of linear regression approaches to produce

significant results. These explanations suggest a less restrictive approach to seeking relationships between the spatial pattern of fire occurrence and factors which may be causing it.

### 3.4.2 Classification and Regression Tree Analyses and Results

Regression analyses assume a form of relationship between variables—typically linear, but other models are possible including polynomial, exponential, or logistic. With fire occurrence, however, it is likely that none of these relationships are appropriate. The process is too complex, involves many variables at many scales, and very likely has a number of threshold-type of responses. At the temporal and spatial scales for which data are available, simple relationships are unlikely to be found. For this reason Regression Trees, which assume only a monotonic relationship between the predictand and the predictors, were used<sup>3</sup>.

Regression trees work by successive binary partitioning of the dataset. A tree is grown by splitting the dataset successively at nodes. A node is a point at which the dataset is divided. The algorithm recursively splits the data in each node until either the node is homogeneous, meaning that there is no variance between the data under the node, or the node contains too few observations ( $\leq 5$ ). Any number of predictands can be used. The tree generated is essentially a set of rules which can then be used to make predictions.

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<sup>3</sup> It was noted by Keith Knight (personal communication, August 2001) that regression trees could have been done by assuming a conditional Poisson distribution for the response. Instead of using least squares likelihood estimation the algorithm would 'grow' the tree using Poisson likelihood. This would have been a better approach conceptually.

A simple example can illustrate this technique. Consider attempting to predict forest fire size based on the age of the stand. Assume a data set consisting of 1000 fire records, each of which contain a fire size (between 1 and 1000 ha) and a stand age (between 0 and 1000 yr). Assume further, for this example, that older stands experience larger fires (not necessarily a valid assumption). The regression tree algorithm would search the data set for a stand age to split on. The stand age split on would be the one that maximized the difference between the averages of the two resulting subsets. Say this first age was 500 yr, and that below this age the average fire size was found to be 100 ha, and above this age the average fire size was found to be 600 ha. There would now be a node at 500 yr. Next, the algorithm would search one of the new subsets of the data, either the fires in stands younger than 500 yr or older. Further partitions (nodes) would be found. The end result would be a set of rules, such that given a stand age, a fire size could be predicted. This technique is well explained in Breiman et al. (1984). Splitting continues until the nodes are homogeneous or until there are under 5 data points below the node.

Because of their flexibility regression trees are well-suited to the problem of explaining spatial variation in fire occurrence. The flexibility of regression trees, however, makes it difficult to test the validity of tree-based model. Since the relationships are so complex and the regression tree will only reach a part of the underlying complexity, there is no obvious test for whether the model is in fact explaining variation and not simply a result of pure chance.

One method of testing this is to see if the same relationships hold from one year to the next. If spatial relationships hold from year to year, for example if lightning is found to be a significant predictand in each year's tree, this would support the hypothesis that lightning fire occurrence depends on lightning occurrence. On the other hand, if lightning is found to be significant in 1992 but not in 1993 and 1994, this would suggest that random chance is responsible for the tree-model results. Seven years of lightning data are available, from 1992-1998, so seven trees were built modeling the relationships between lightning, weather, vegetation, lakes, roads, and fire occurrence.

This tree-based analysis showed that the same relationships did not hold year after year. The difference between two trees, 1992 and 1993, shown in figures 3.1 and 3.2, is sufficient to show this, but all seven trees were quite different from one another—different variables mattered to differing degrees in different years. This could suggest a number of problems:

- The explanatory variables chosen to represent weather and lightning do not do so adequately. For example, the number of days FWI exceeded a threshold value of 4, 11, or 23 at the centre of the fire management zone/fuel type polygon partition may not adequately express the fire weather for a season, whether because the polygon partition was inadequate, because the FWI is inadequate, or because counting the days it exceeded the threshold value is an inadequate.

- **The spatial or temporal scale is too coarse. A smaller study area may provide more stable results. Similarly, a study of the spatial pattern of fires over the duration of a lightning storm may yield better explanations in terms of weather and lightning than such a study over an entire fire season.**
- **The quality of the data is too poor, due to errors in collection and interpolation, to facilitate extraction of consistent relationships.**
- **Small Poisson counts contain very little information, and so a relationship between the response and the covariates has to be very strong to find statistically significant relationships (Knight, personal communication, August 2001).**

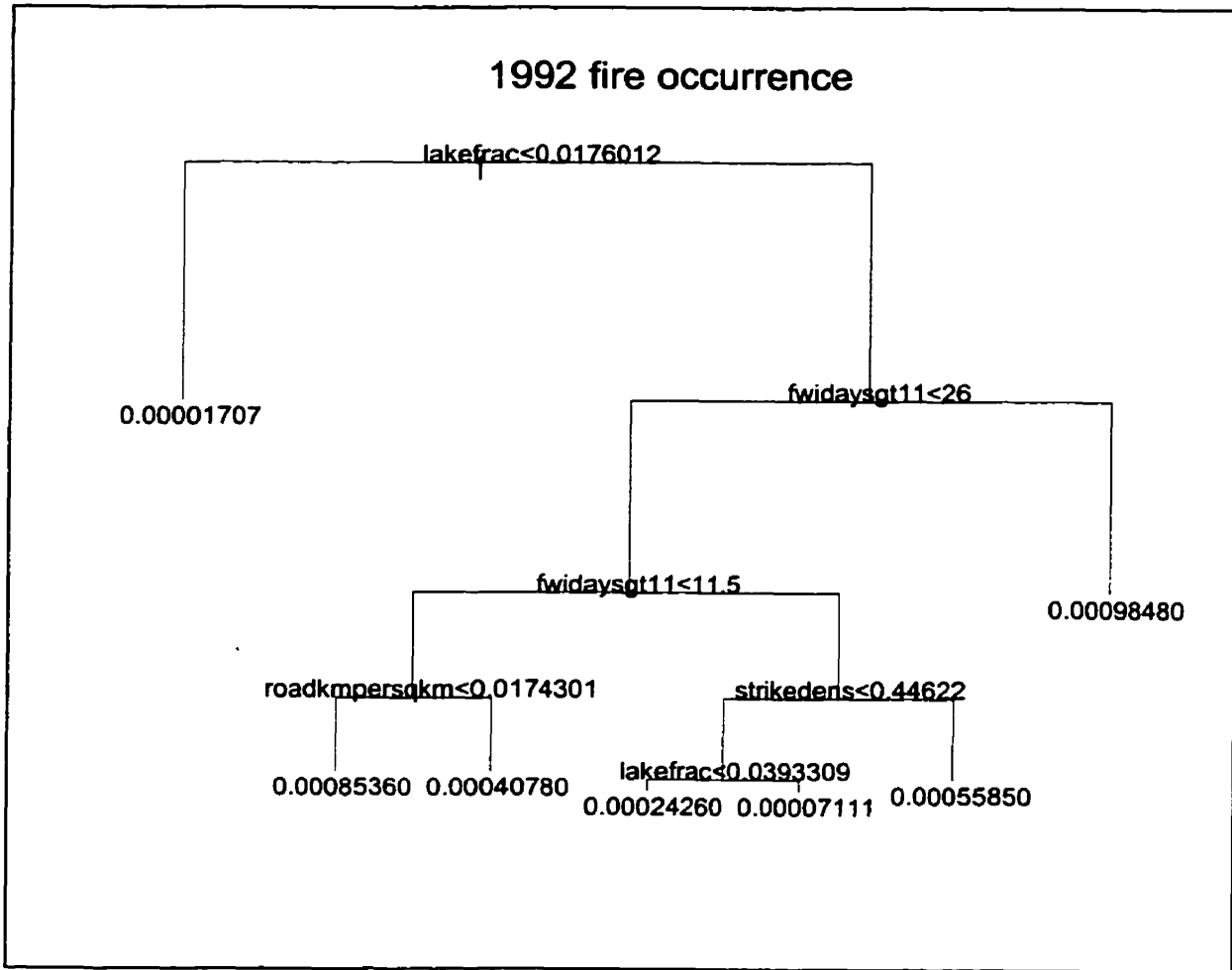


Figure 3.1. Regression tree explaining fire occurrence in 1992 in the fire management zone/forest cover type polygons in terms of lightning strike density, days FWI exceeded 11, fire control difficulty index, fire management zone, fraction of area under lakes, and number of kilometres of road per square kilometre.

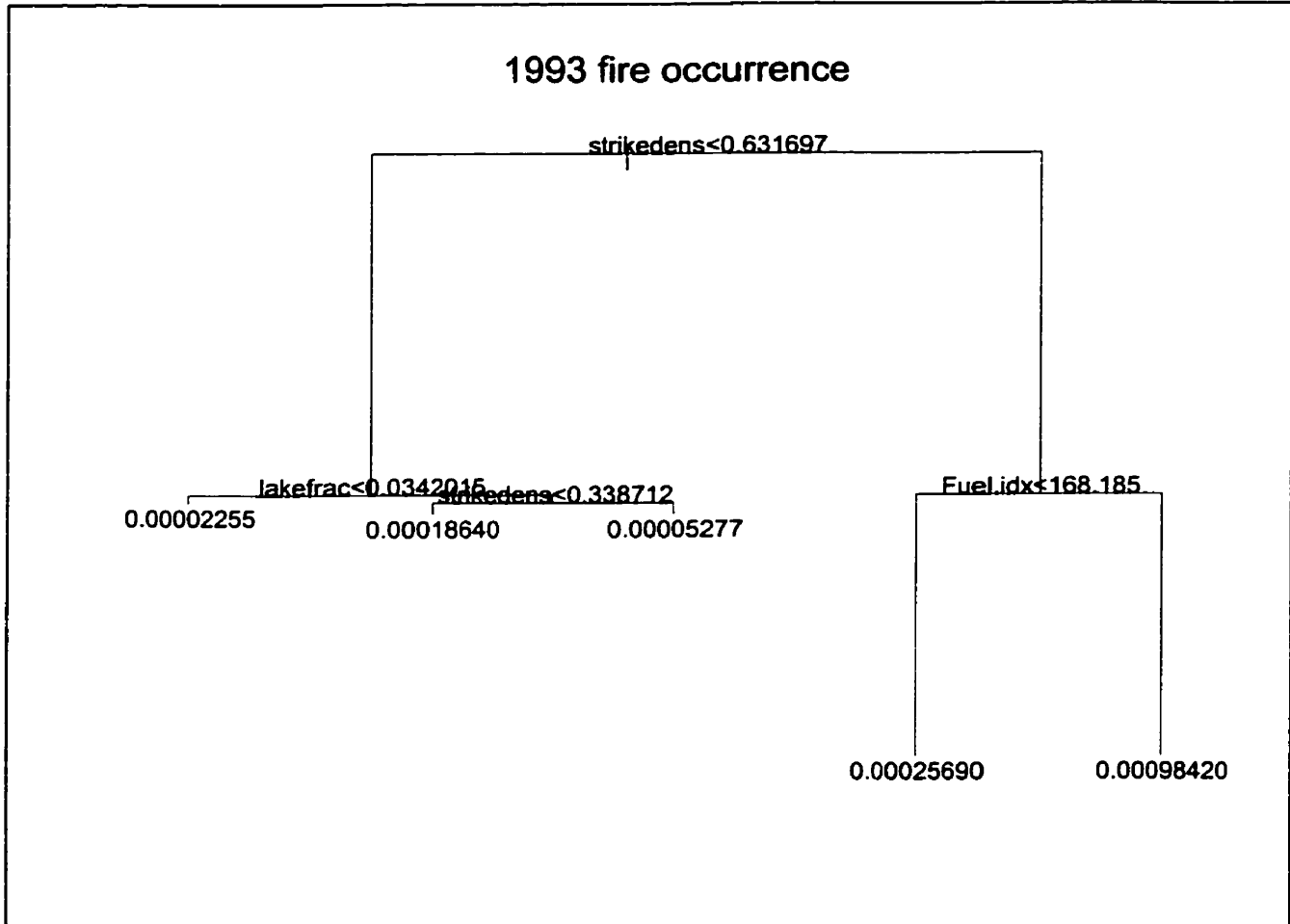


Figure 3.2. Regression tree explaining fire occurrence in 1992 in the fire management zone/forest cover type polygons in terms of lightning strike density, days FWI exceeded 11, fire control difficulty index, fire management zone, fraction of area under lakes, and number of kilometres of road per square kilometre.

Figures 3.1 and 3.2 are the regression trees for fire occurrence densities in 1992 and 1993. For Figure 3.1, fire occurrence in 1992, the largest partition was by fraction of area under lakes, followed by 'fwidaysgt11' twice, and then roads, strike density, and lake fraction again. The 1993 tree, shown in Figure 3.2, by contrast, partitions by lightning strike density, then by fuel index and lake fraction, has a different number of terminal

roads, and a different structure overall. All the regression trees for the years 1992 to 1998 are different from one another. As noted briefly above, there are a number of possible explanations for this:

- 1) Fire occurrence is a truly random process and the perceived spatial variation was just chance.
- 2) The time scale of the data (annual) and spatial scale (provincial) are insufficient to address the underlying processes.
- 3) There are more important explanatory variables than the ones suggested—for example better weather variates and more detailed information of on the ground fuel conditions—which dominate the process.

### 3.4.3 Spatial Intensity maps of lightning strike and fire densities, and DSR interpolations

The spatial intensity maps, and the interpolated sums of the DSR for the fire seasons for 1992-1998 for the region of Ontario north of 49 latitude, south of 52 latitude, and west of 89 latitude, are shown below in Figures 3.3-3.30. These maps show no obvious relationship between lightning strike density and lightning fire occurrence density over a fire season, nor do they show any obvious relationship between the sum of DSR over the



season and the fire occurrence density. The latter lack of a relationship could be a result of a poor quality interpolation due to insufficient weather stations.

The spatial pattern of annual fire occurrence described by the SPP analysis, which features points spatially clustered on a scale of about 200-300km in 'hotspots', was found to be inexplicable in terms of:

- lakes, which may have contributed to clustering by making parts of the landscape ineligible for ignition and clustering ignitions in eligible areas. That lake density cannot explain fire density suggests that lakes are ubiquitous and uniform enough to not cause fires to cluster in any particular part of the landscape
- roads, which may have contributed to clustering by bringing more people to certain places to detect more fires, causing clustering of fires where people are to detect them. That road density cannot explain fire density suggests that detection bias around roads is not causing clustering.
- fuel index, which could have contributed to clustering by causing ignition in favourable fuels. The tree analysis suggests that this variable is of some significance, but its lack of significance in the regression analyses suggests that it may not be an adequate measure of a fuel's tendency to ignite.
- number of days FWI exceeded 4, 11, 23 in an area. This suggests a different measure of a fire season is needed.

- sum of DSR over a fire season. This too suggests that either a different measure of a fire season is needed, or that the weather data are simply inadequate in terms of richness (not enough weather stations) to provide an accurate interpolation—this also applies to the FWI.
- lightning strike density. In the northwestern ontario study area where this was considered in some detail, the number of fires was of the order of 1-200, while the number of lightning strikes was 50-100 000. This suggests that there is more than enough lightning everywhere to ignite far more fires than those which did occur, and that the occurrence of fires depends on the weather and fuel conditions when and where the lightning strikes.

It is likely that the spatial pattern of lightning fires that arises over a fire season arises over a small number of intense days when dry weather and lightning strikes converge optimally on areas with favourable fuels. These few days give rise to the spatial pattern of ignitions that is left at the end of a fire season. In order to explain that pattern, then, it is necessary to look at lightning, weather, and fuel during those particular days.

Examining lightning, weather, and fuel over an entire fire season will overwhelm any signal which does exist with irrelevant data. If the lightning, weather, and fuel combinations during and just before fire events do show a specific pattern, then that pattern can be searched for on days and places when no fires occurred, to see how often it arose. A preliminary test of the hypothesis was conducted using the data on lightning strikes on days when DMC exceeded 20. The spatial pattern of these lightning strikes annually was much more similar to the pattern of fires, and different from the pattern of

total lightning strikes. These are included below. Thus a kernel estimate of the spatial intensity of lightning strikes on days when DMC exceeded 20 provided a reasonable visual match with the spatial intensity of lightning-caused fires.

### **3.5 Conclusions**

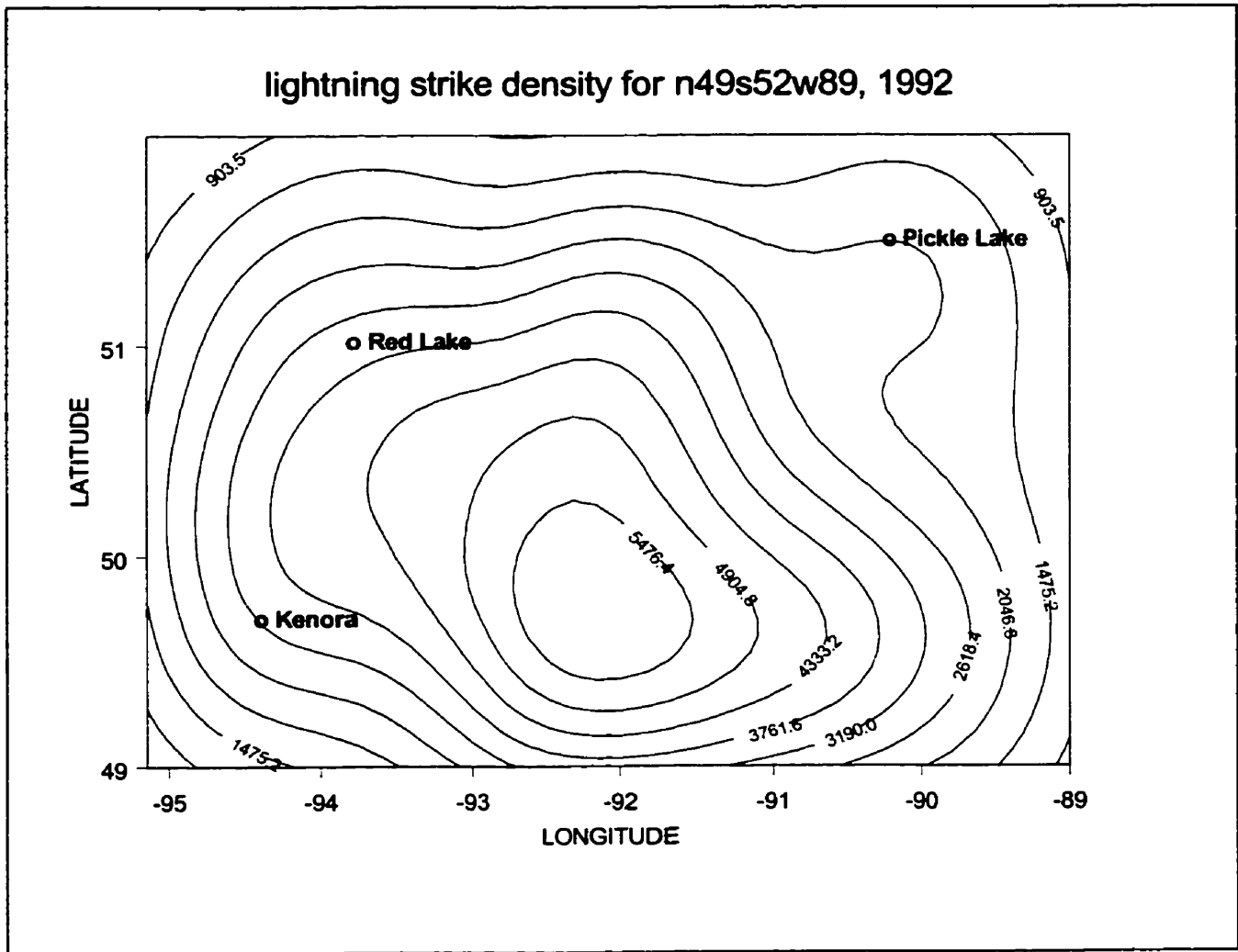
#### *3.5.1 Summary*

Linear regression and regression tree analyses to explain the spatial clustering of lightning-caused fire occurrence in terms of fraction of lakes, rivers, roads, a number of weather variables, the density of lightning strikes, did not yield stable correlations. Kernel estimation of the spatial intensity of lightning strikes on days when DMC exceeded 20 provided a spatial pattern quite similar to that of lightning-caused fires. This result confirms the rule of thumb used by the OMNR, which is to predict fire based on lightning strikes in areas where DMC exceeds 20. These findings support the following conclusion:

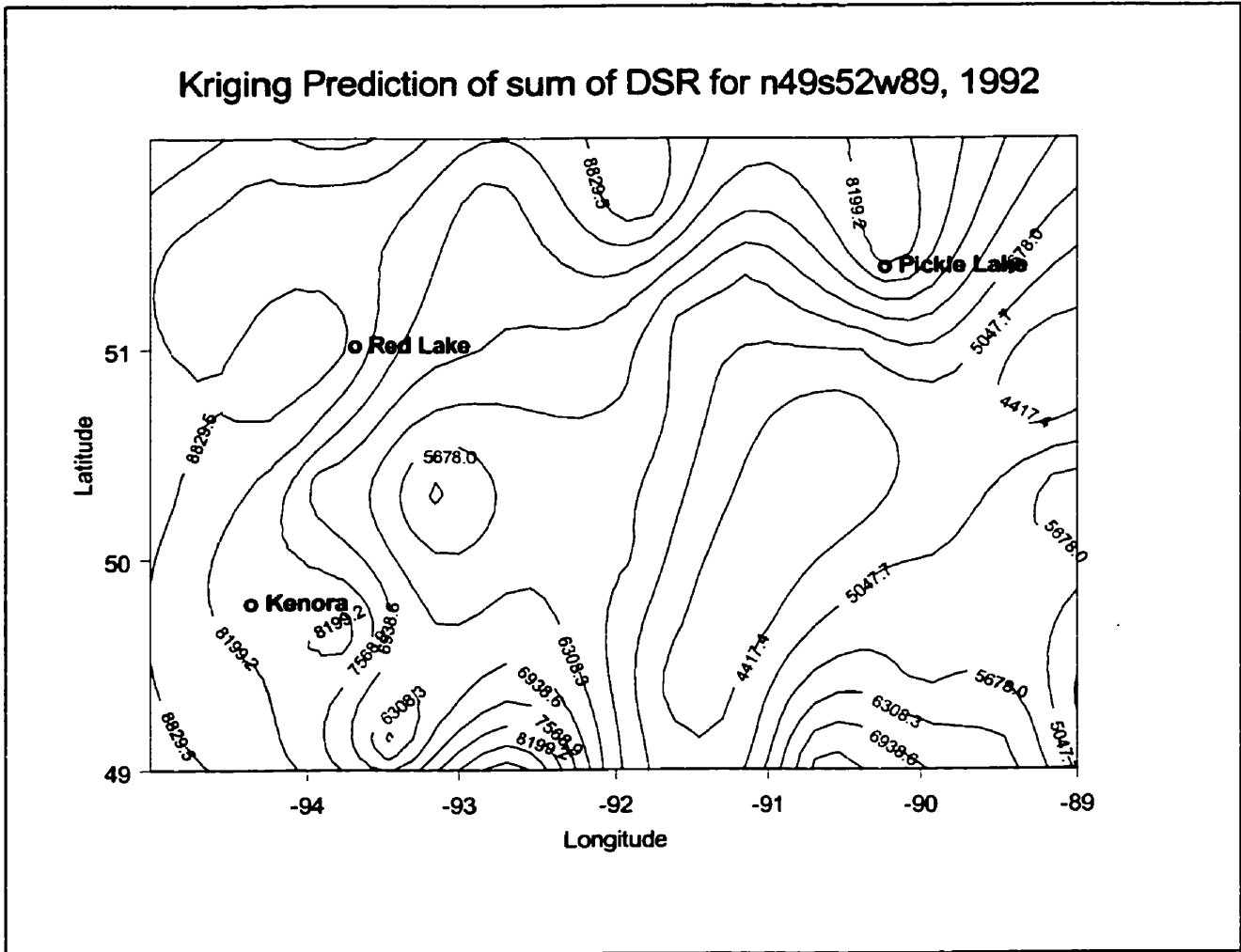
- Localized dry weather and lightning storm occurrence are the principal determinants of the spatial clustering of lightning caused fire occurrence.

#### **3.5.2 Future Work**

The use of  $DMC > 20$  as a threshold was adapted from a 'rule of thumb'. Future work on this problem could attempt to find a more precise value of an index at which lightning strikes become far more likely to cause ignitions. It is known that only long continuing current (LCC) flashes cause ignitions (Latham and Williams 2001). If detector technology were improved to detect LCC flashes, it is highly likely that the spatial pattern of lightning-ignited fires would be found to be even closer to the spatial pattern of LCC lightning strikes on dry days. Although elevation was not found to be important to ignition probability in some studies (McRae 1992), it was found important in others (Van Wagtenonk 1991) and it was not considered in this study and could be in future work. In Chapter 2, fires were found to be clustered in the north-western and south-eastern regions of the province. In this chapter, the northwestern area was examined in more detail. Spatial intensity of lightning-ignited fires was found to vary within this area, likely due to variation in lightning storms and dry weather systems. The presence of spatial variation at different extents suggests that different patterns could be revealed at even finer spatial scales. Finally, the problem was only examined on the annual temporal scale. The problem could be revisited to search for spatial patterns for finer and coarser temporal scales.



**Figure 3.3** Spatial intensity of lightning strikes in Ontario in the northwest region (north of 49 N, south of 52 N, west of 89 W) in 1992. There were 64312 lightning strikes and 54 lightning-caused fires in the region in that year.



**Figure 3.4** Interpolation of the sum of the Daily Severity Rating over the 1992 fire season for the same study region. A kriging interpolation was used, but there were insufficient stations to provide an adequate map.

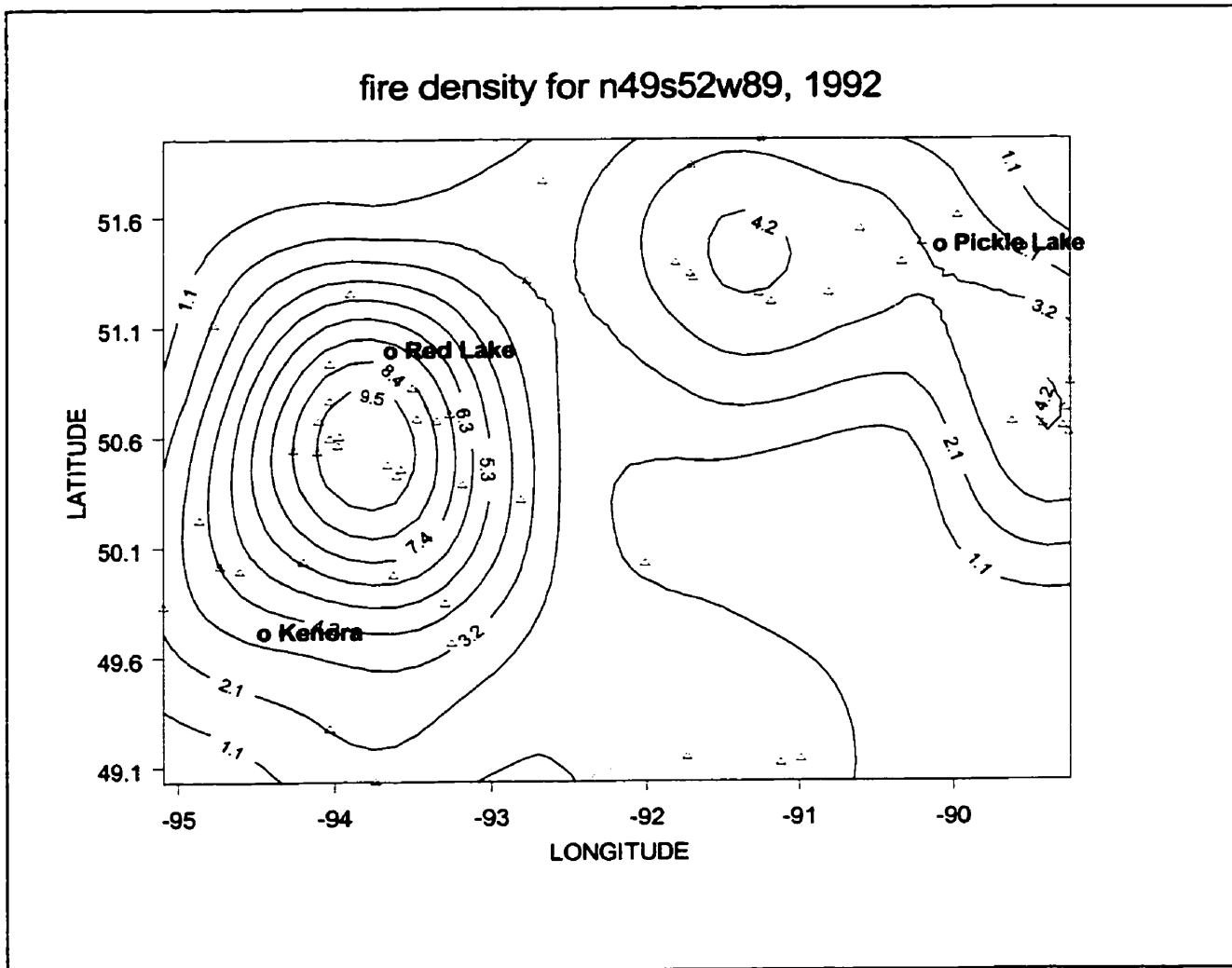
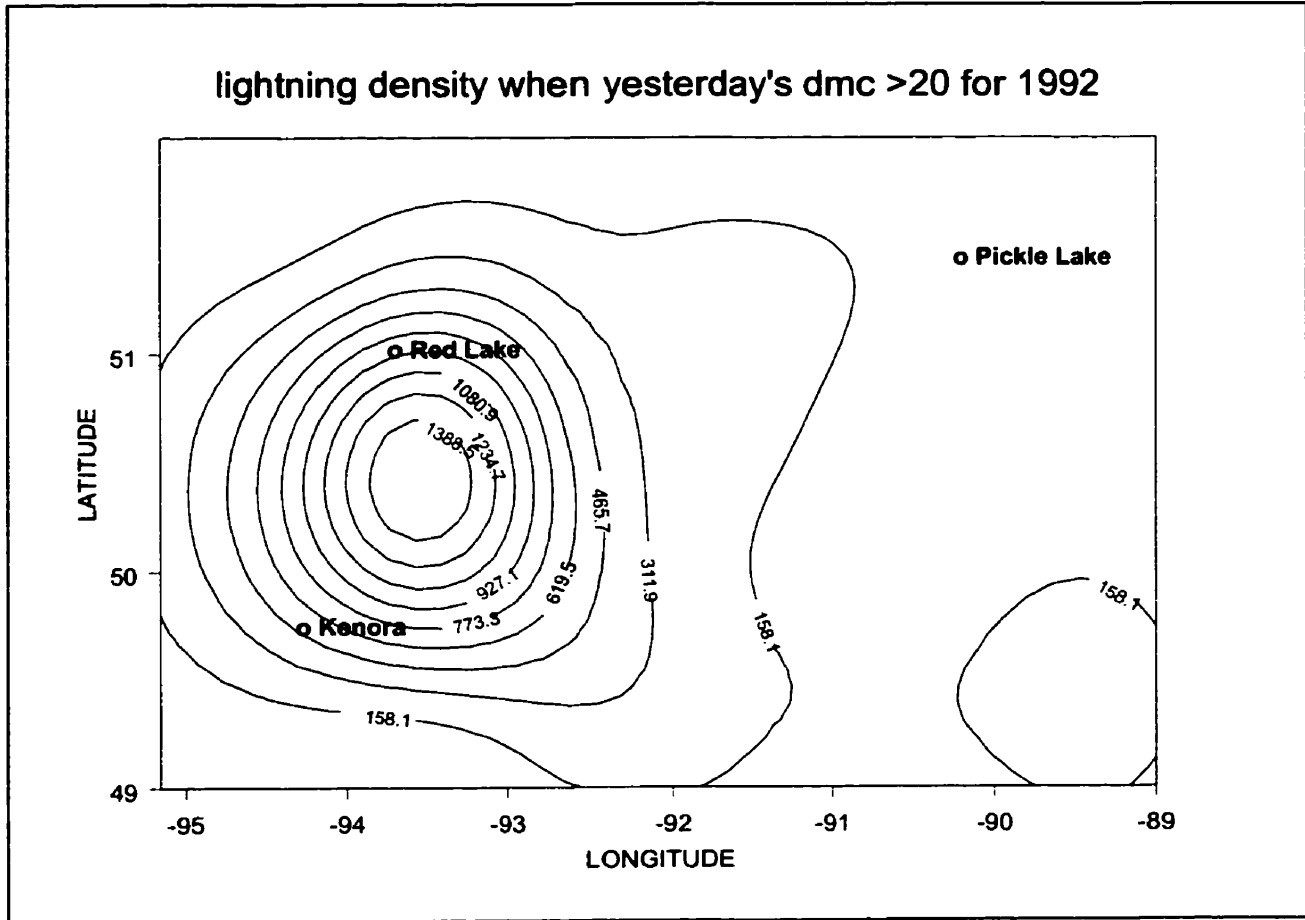


Figure 3.5 Spatial intensity of lightning-ignited fires in the northwest region for 1992. Note the dissimilarity with Figures 3.3 and 3.4.



**Figure 3.6** Spatial intensity of lightning strikes in the northwest region for 1992 on days when the Duff Moisture Code exceeded a value of 20. Note how much more similar this is to the spatial intensity of lightning ignited fires in the region compared to the spatial intensity of all lightning strikes.



## lightning strike density for n49s52w89, 1993

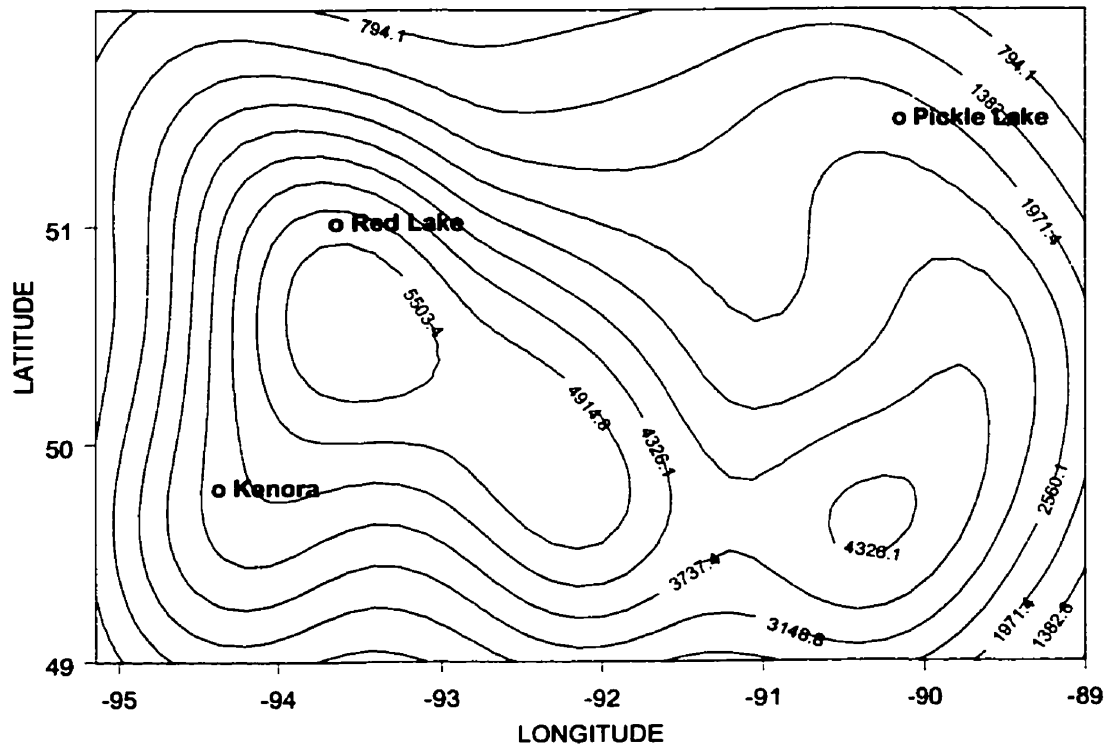
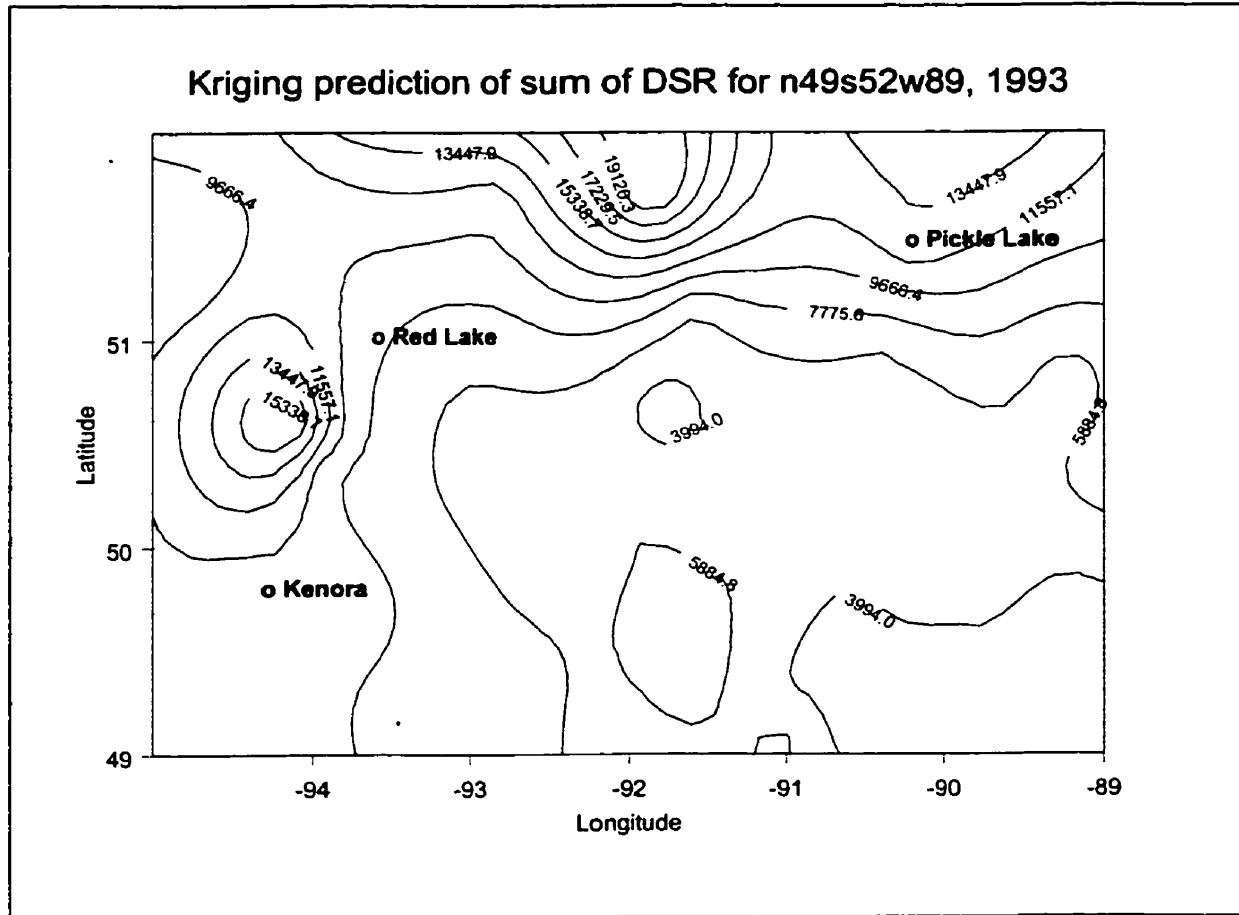


Figure 3.7 Spatial intensity of lightning strikes in Ontario in the northwest region in 1993. There were 65725 lightning strikes and 17 lightning-caused fires in the region in that year.



**Figure 3.8 Interpolation of the sum of the Daily Severity Rating over the 1993 fire season for the same study region.**

## fire density for n49s52w89, 1993

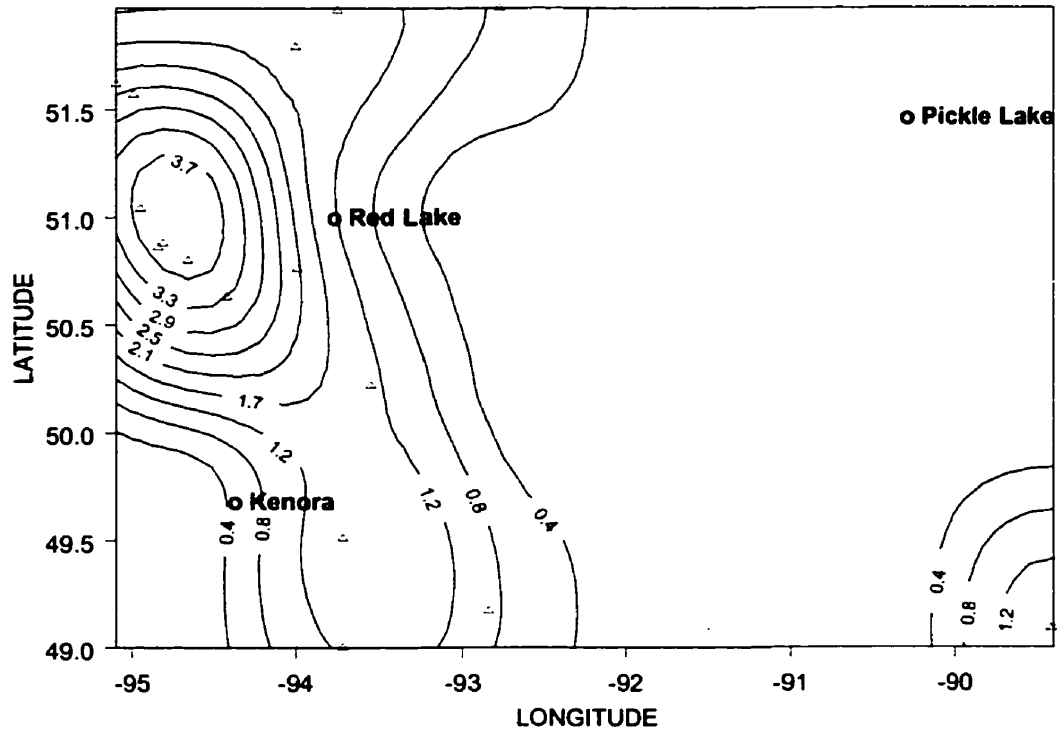


Figure 3.9 Spatial intensity of lightning-ignited fires in the northwest region for 1993.

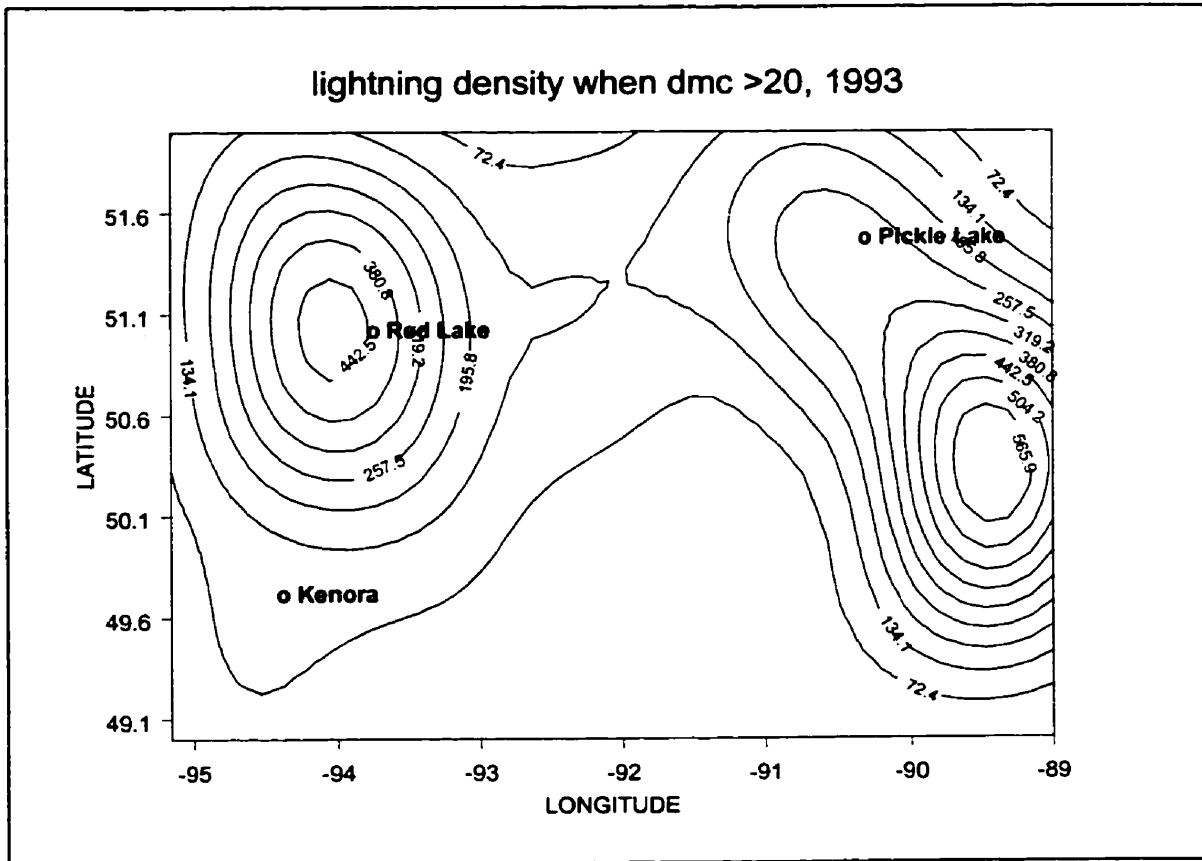


Figure 3.10 Spatial intensity of lightning strikes in the northwest region for 1993 on days when the Duff Moisture Code exceeded a value of 20.

## lightning strike density for n49s52w89, 1994

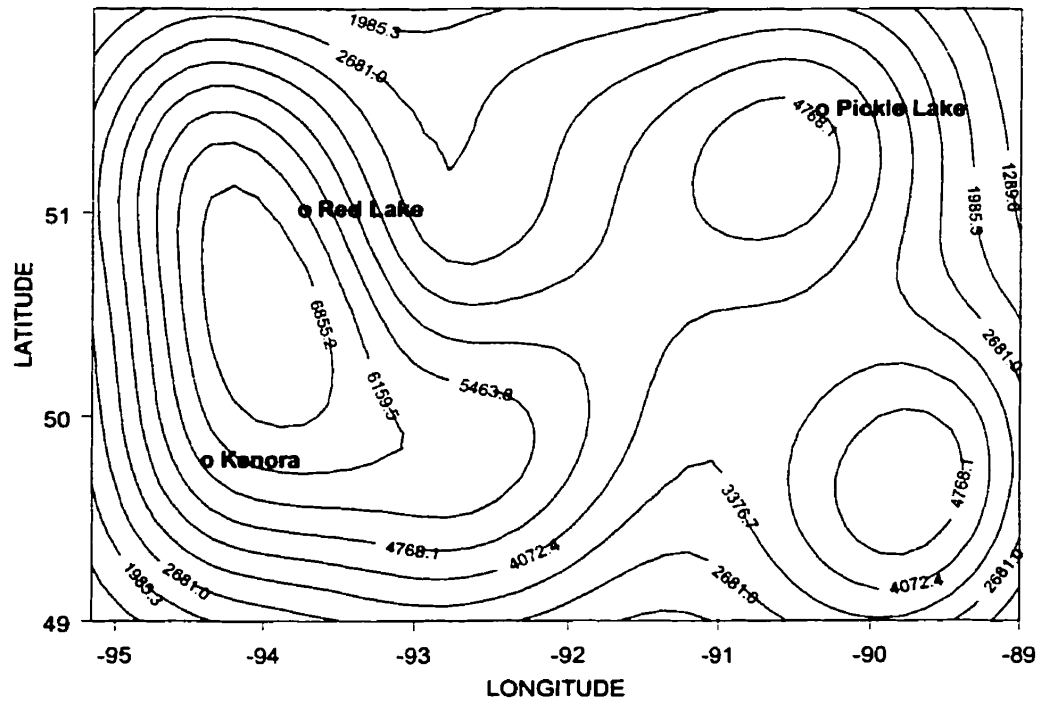


Figure 3.11 Spatial intensity of lightning strikes in Ontario in the northwest region in 1994. There were 90304 lightning strikes and 55 lightning-caused fires in the region in that year.

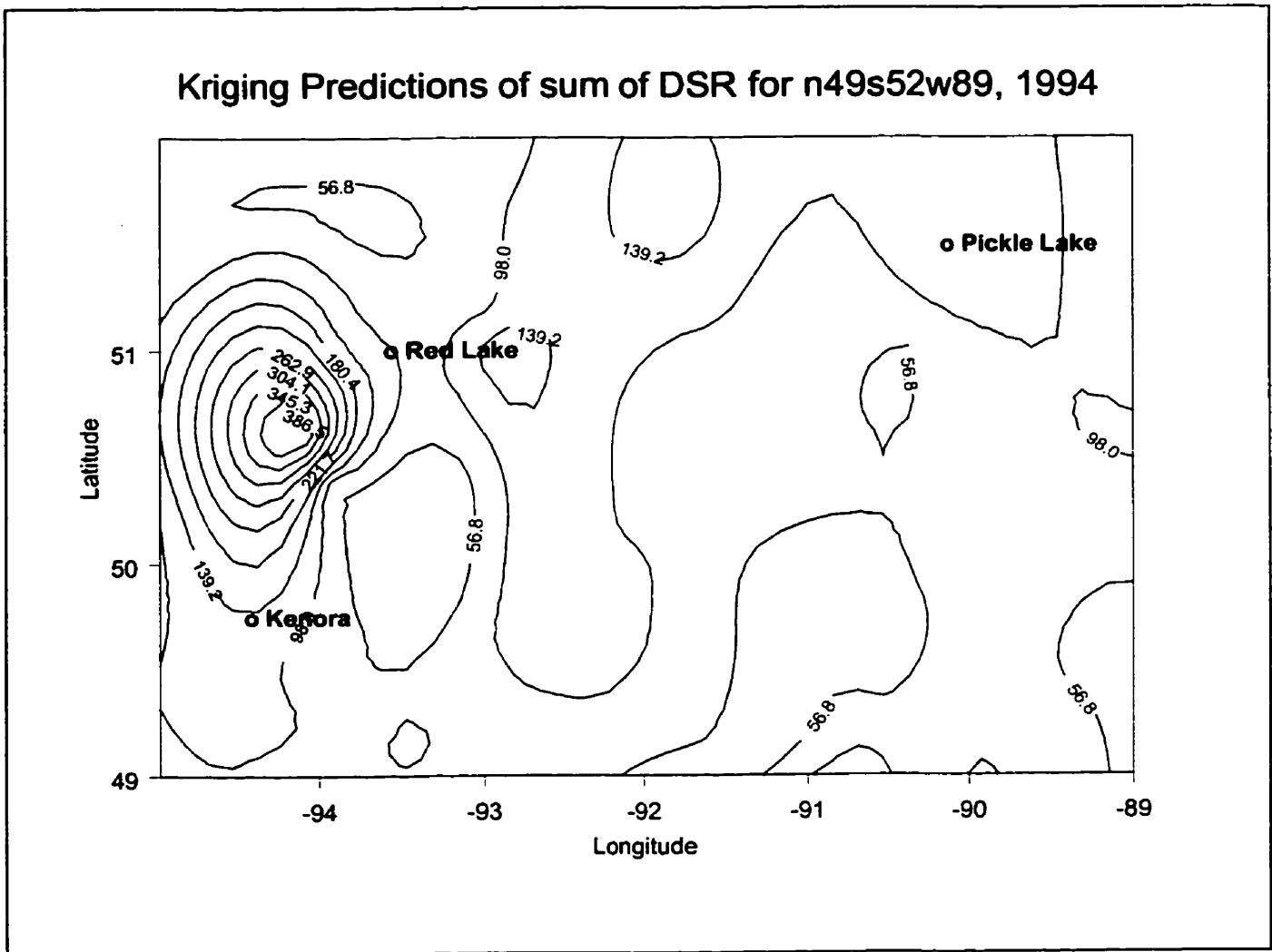


Figure 3.12 Interpolation of the sum of the Daily Severity Rating over the 1994 fire season for the same study region.

## fire density for n49s52w89, 1994

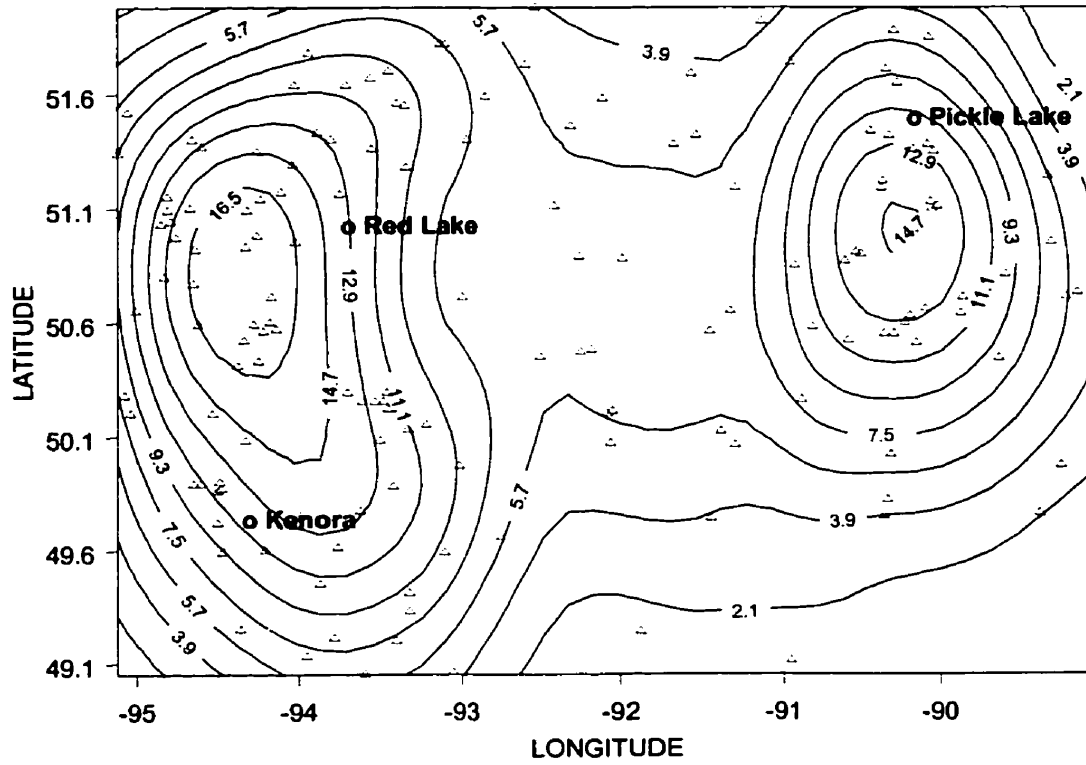


Figure 3.13 Spatial intensity of lightning-ignited fires in the northwest region for 1994.

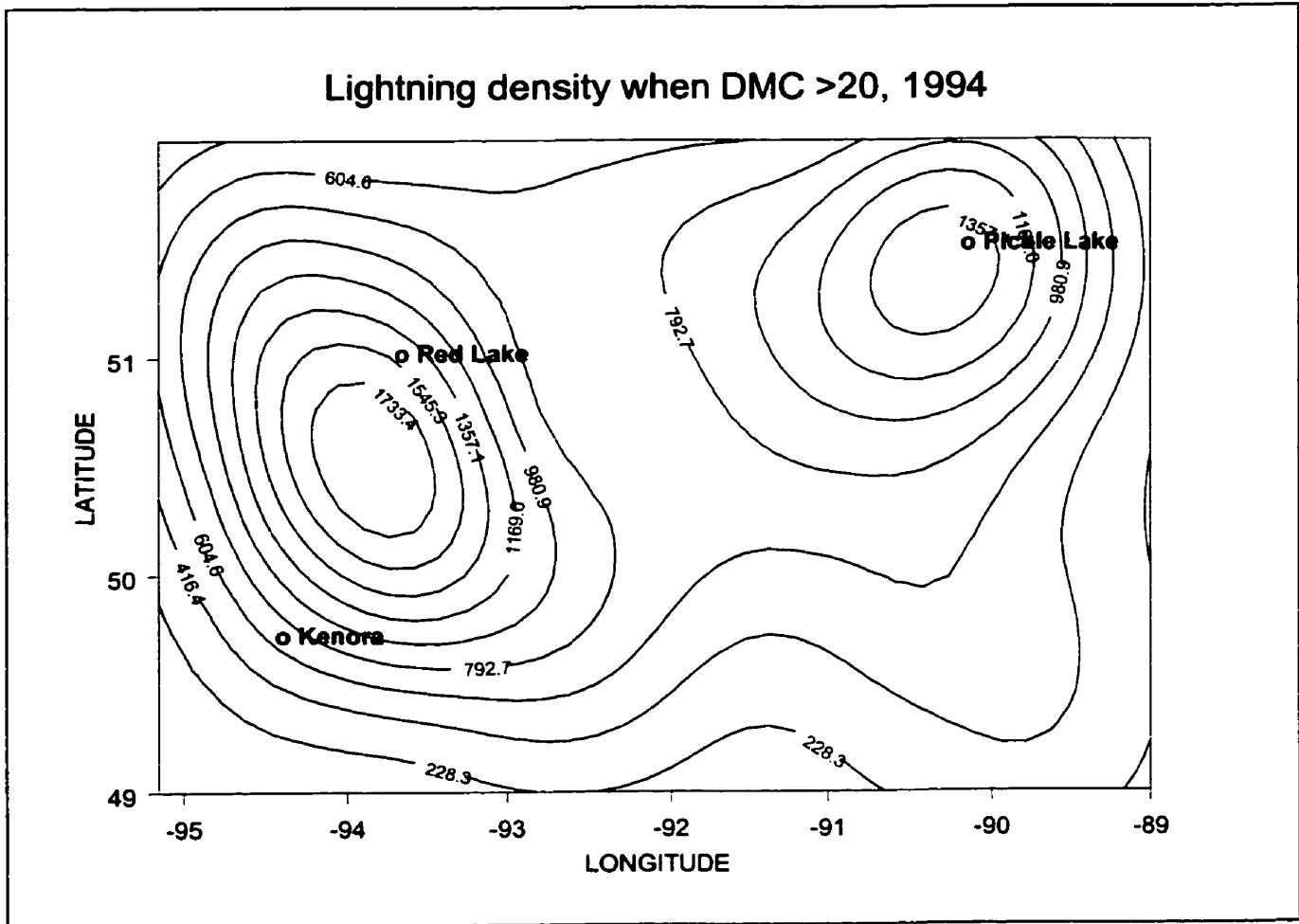


Figure 3.14 Spatial intensity of lightning strikes in the northwest region for 1994 on days when the Duff Moisture Code exceeded a value of 20.



### Lightning strike density for n49s52w89, 1995

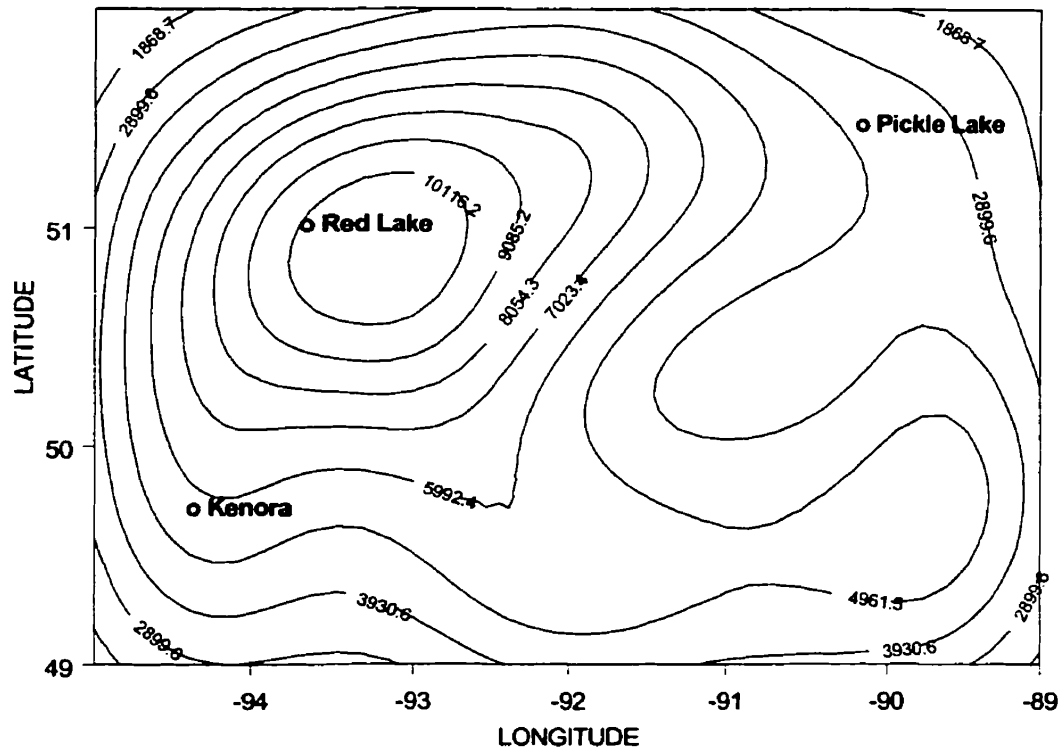
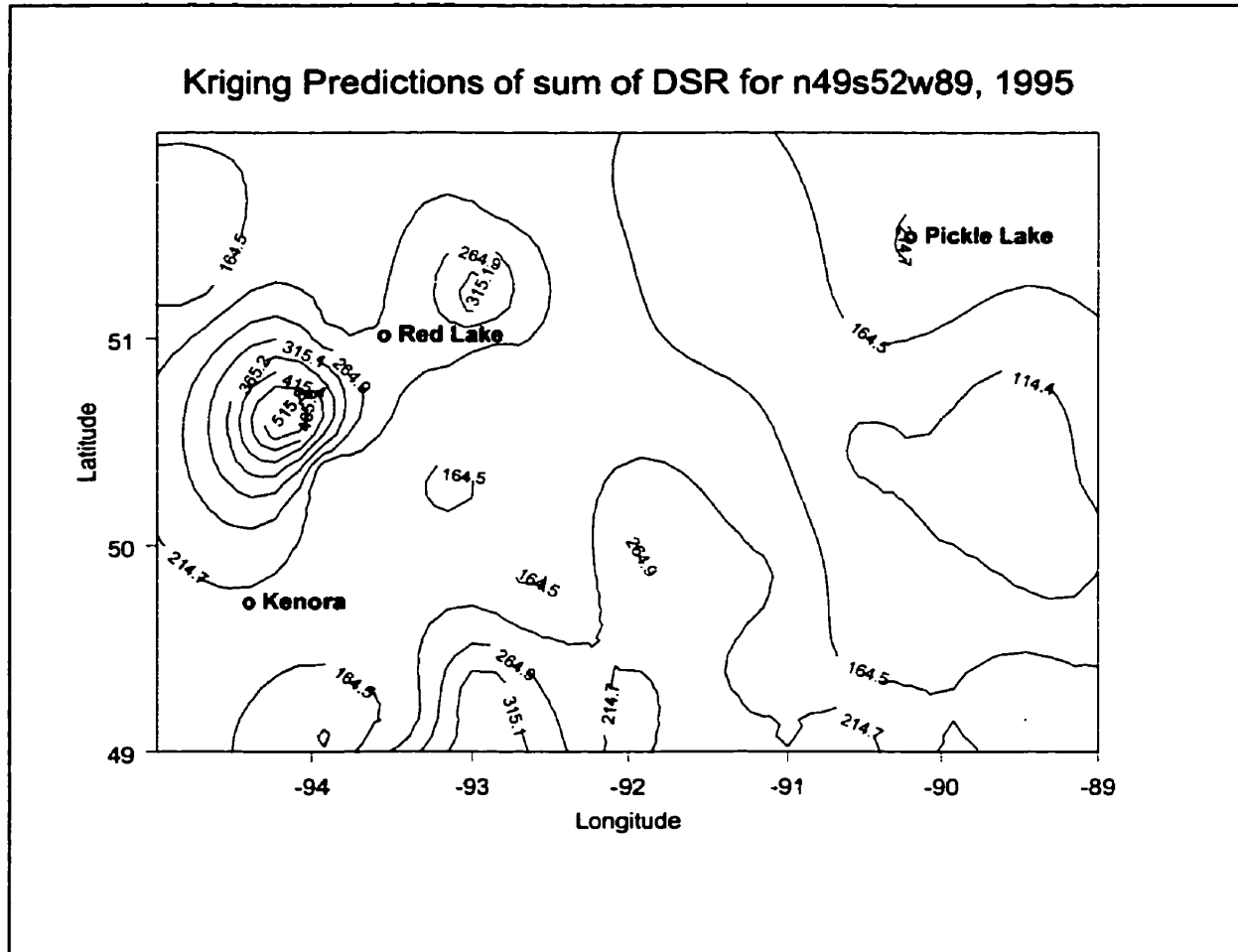


Figure 3.15 Spatial intensity of lightning strikes in Ontario in the northwest region in 1995. There were 80865 lightning strikes and 522 lightning-caused fires in the region in that year.



**Figure 3.16** Interpolation of the sum of the Daily Severity Rating over the 1995 fire season for the same study region.

## fire density for n49s52w89, 1995

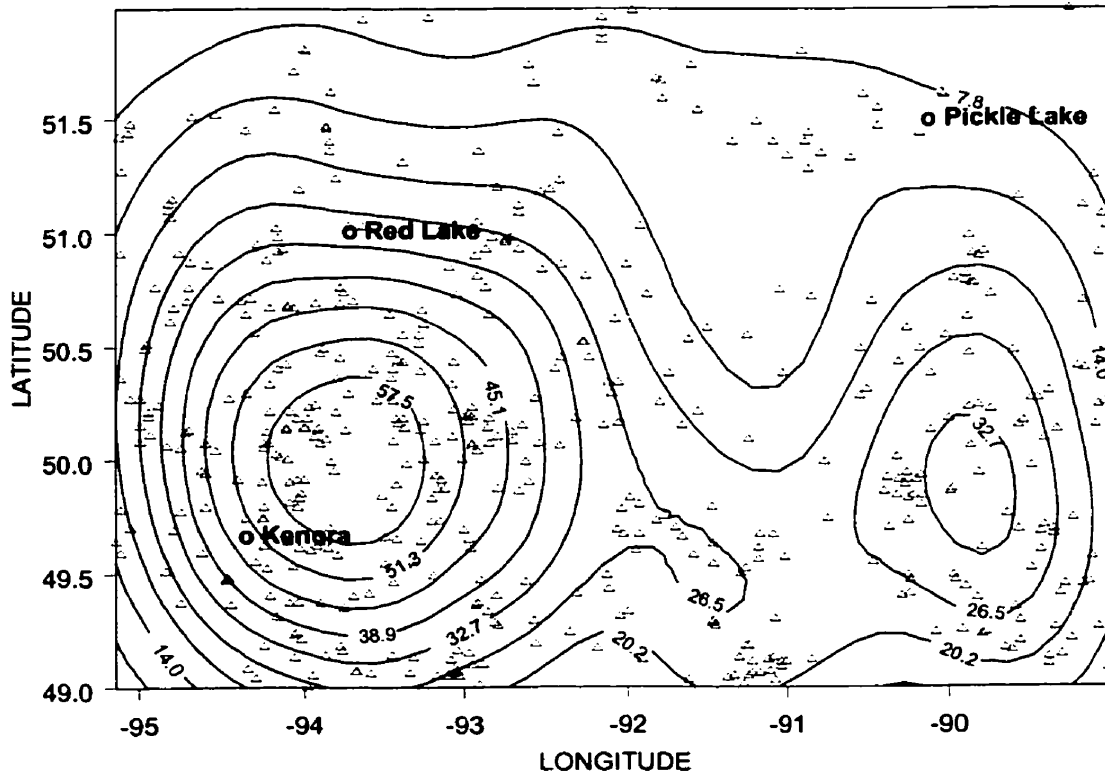
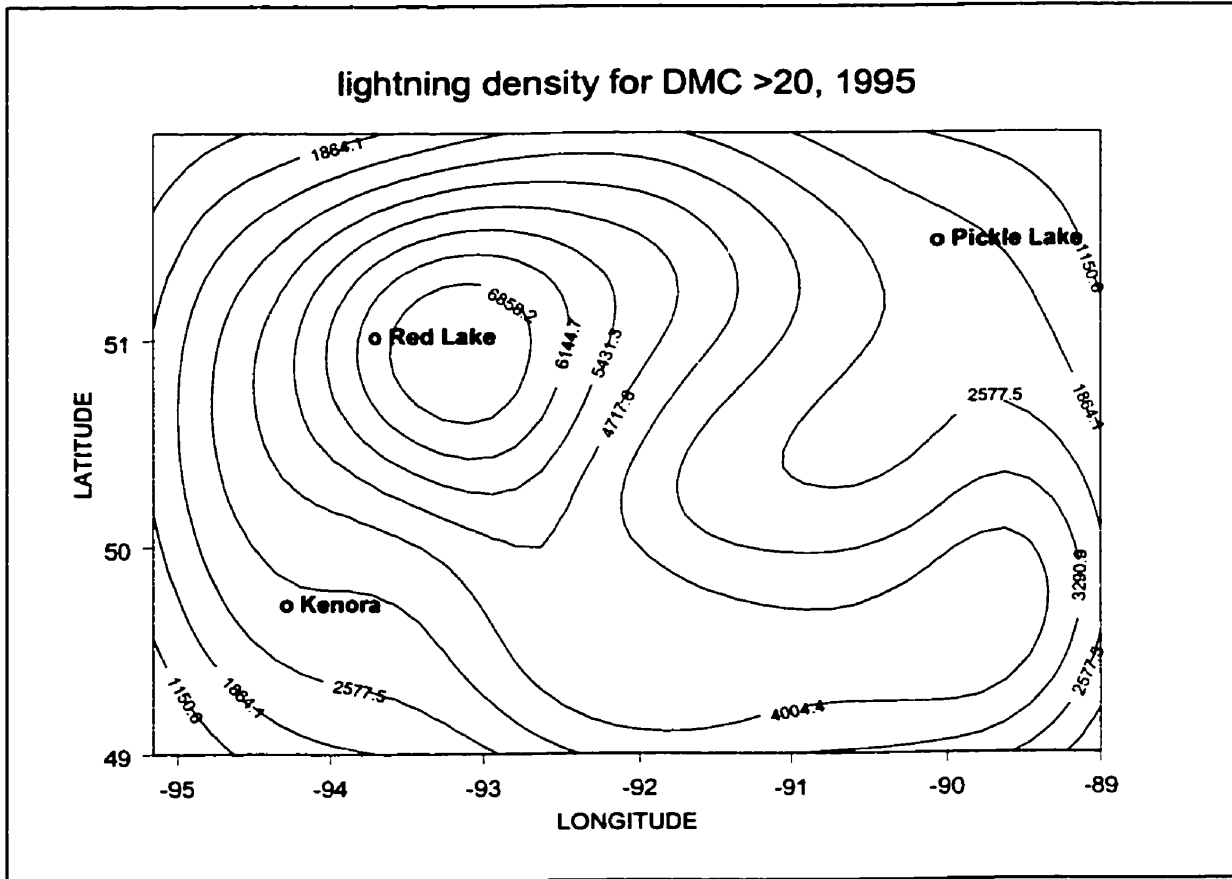


Figure 3.17 Spatial intensity of lightning-ignited fires in the northwest region for 1995.



**Figure 3.18** Spatial intensity of lightning strikes in the northwest region for 1995 on days when the Duff Moisture Code exceeded a value of 20.

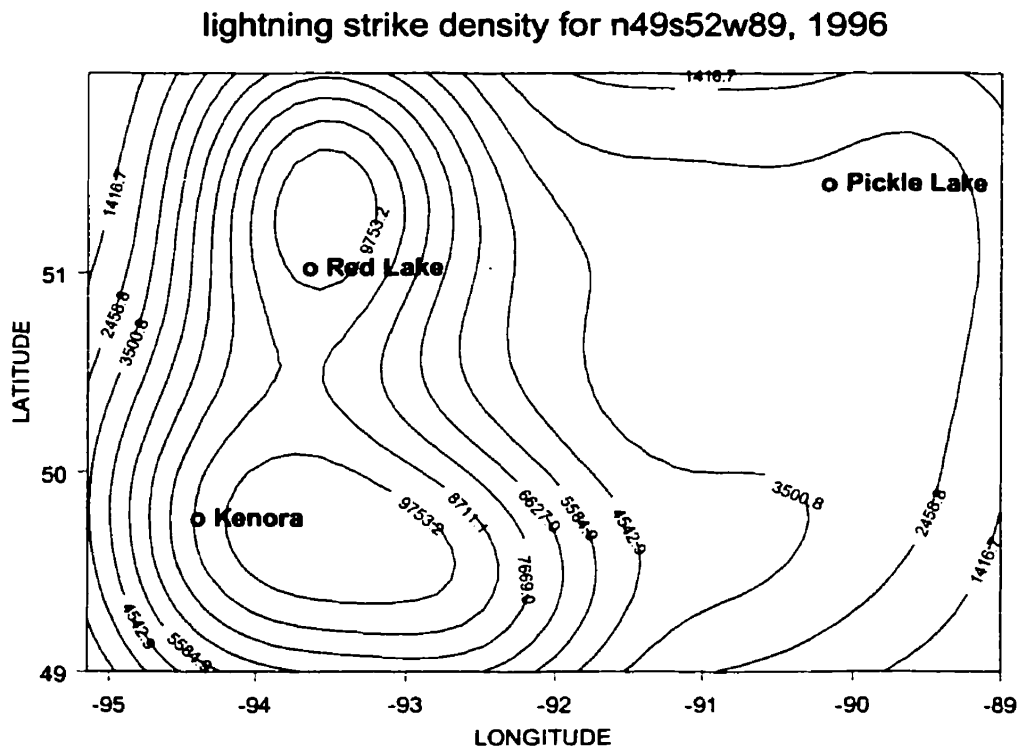


Figure 3.19 Spatial intensity of lightning strikes in Ontario in the northwest region in 1996. There were 109919 lightning strikes and 274 lightning-caused fires in the region in that year.

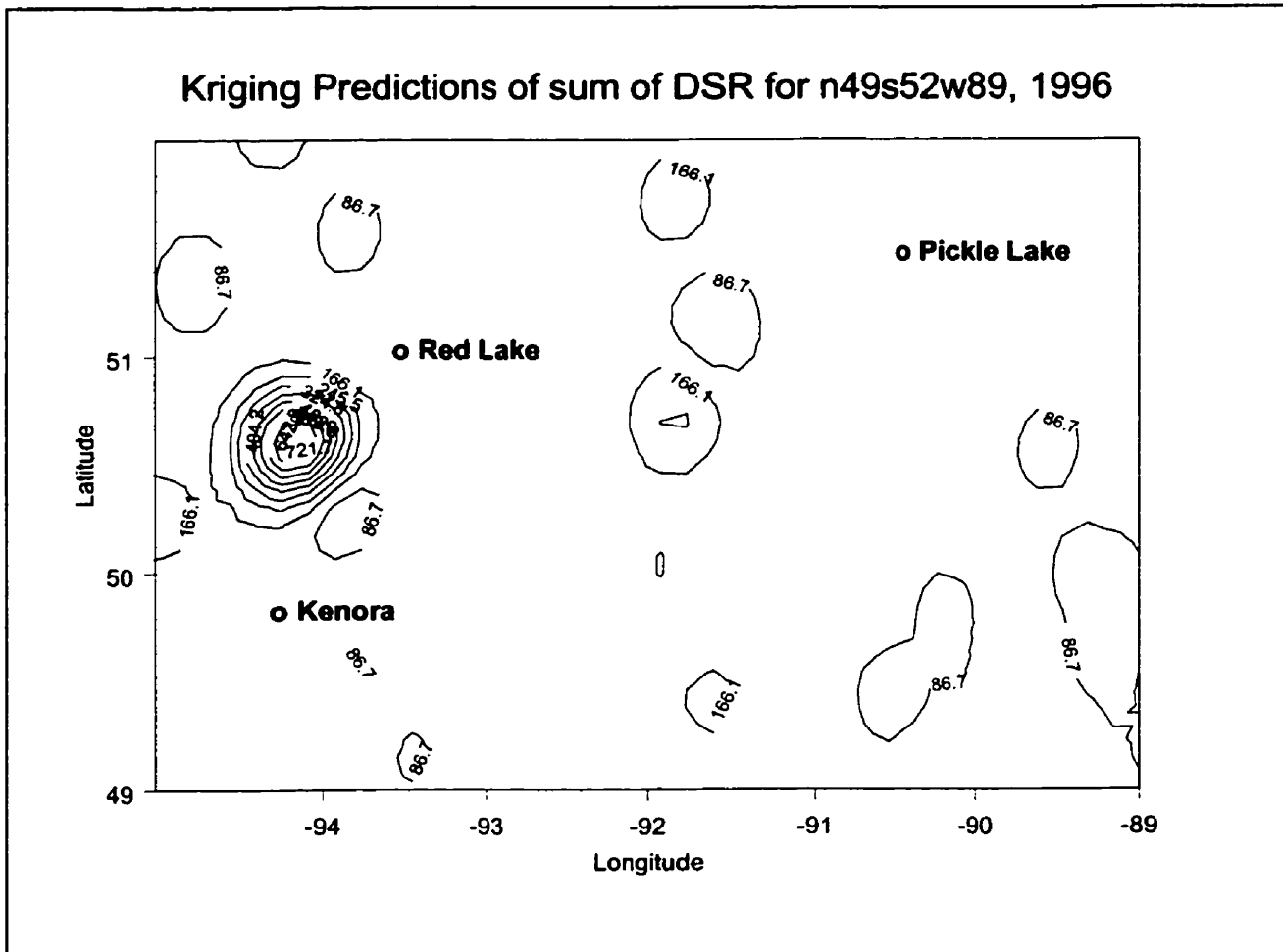


Figure 3.20 Interpolation of the sum of the Daily Severity Rating over the 1996 fire season for the same study region.

## fire density for n49s52w89, 1996

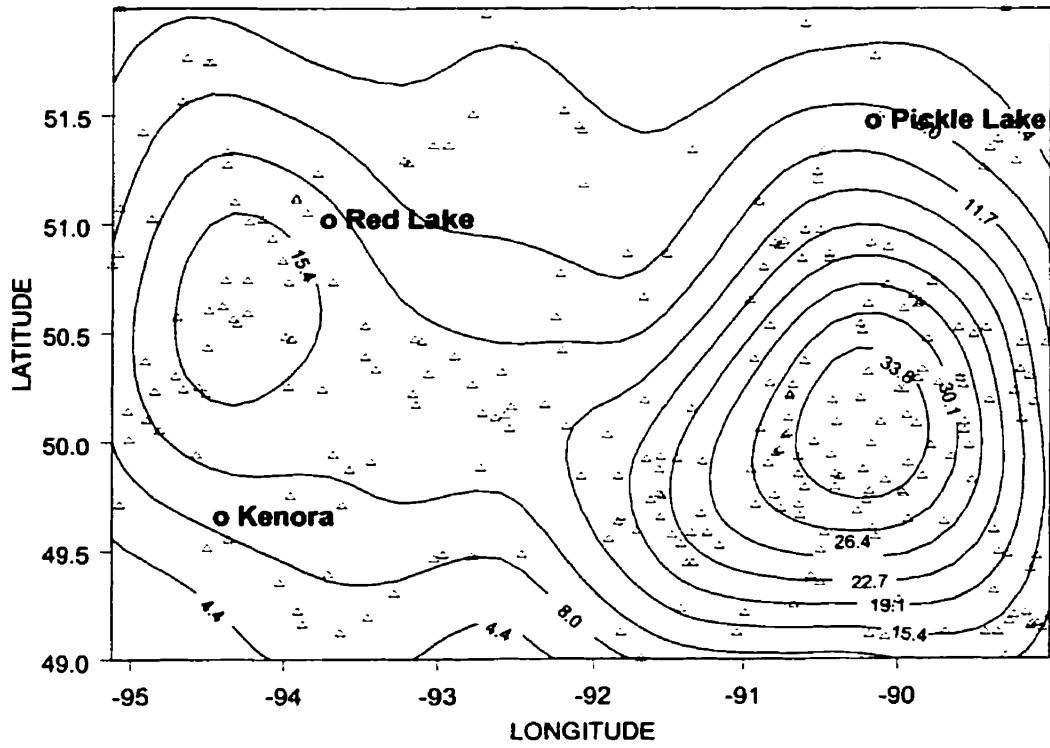


Figure 3.21 Spatial intensity of lightning-ignited fires in the northwest region for 1996.

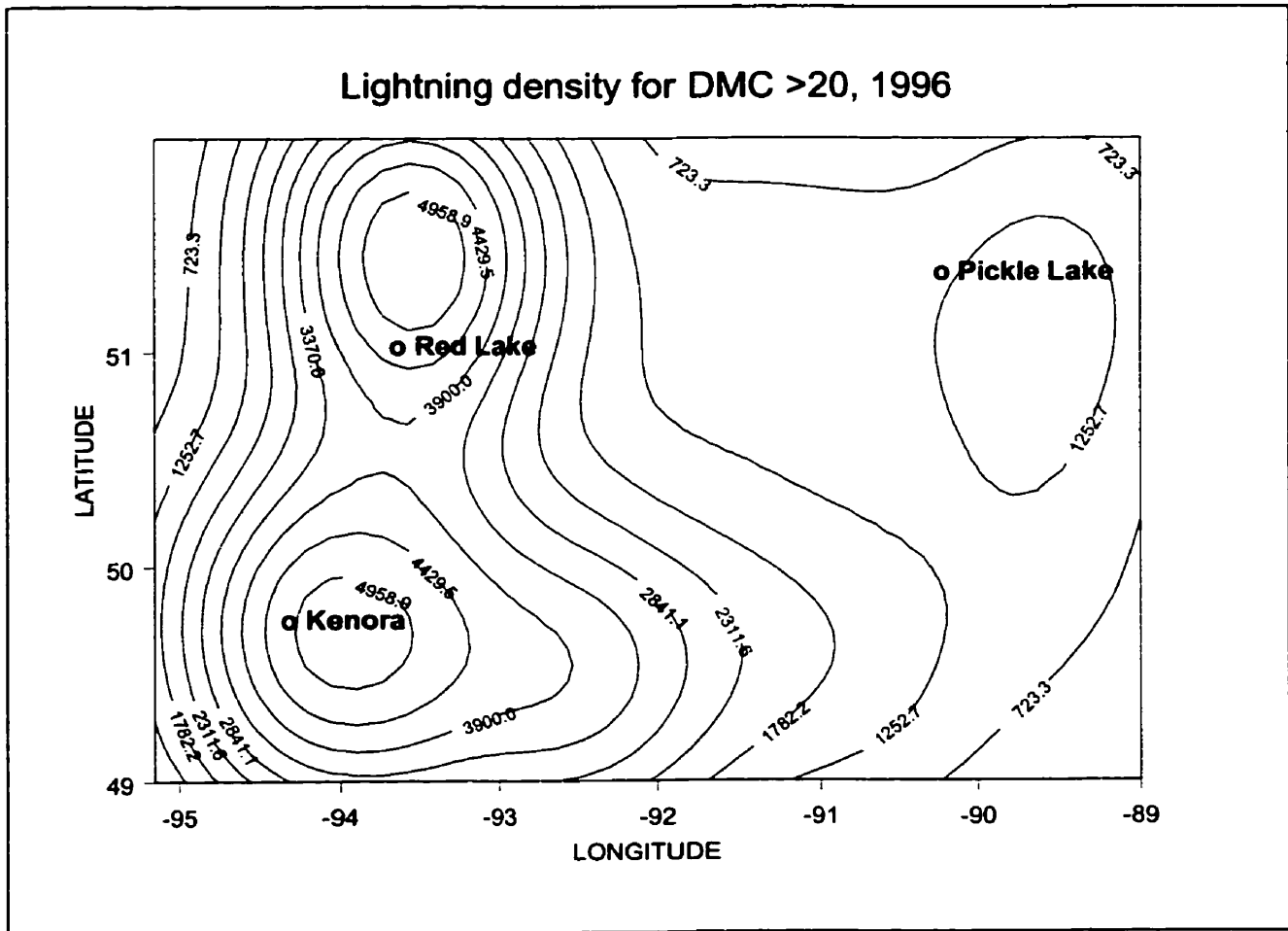


Figure 3.22 Spatial intensity of lightning strikes in the northwest region for 1996 on days when the Duff Moisture Code exceeded a value of 20.



## lightning strike density for n49s52w89, 1997

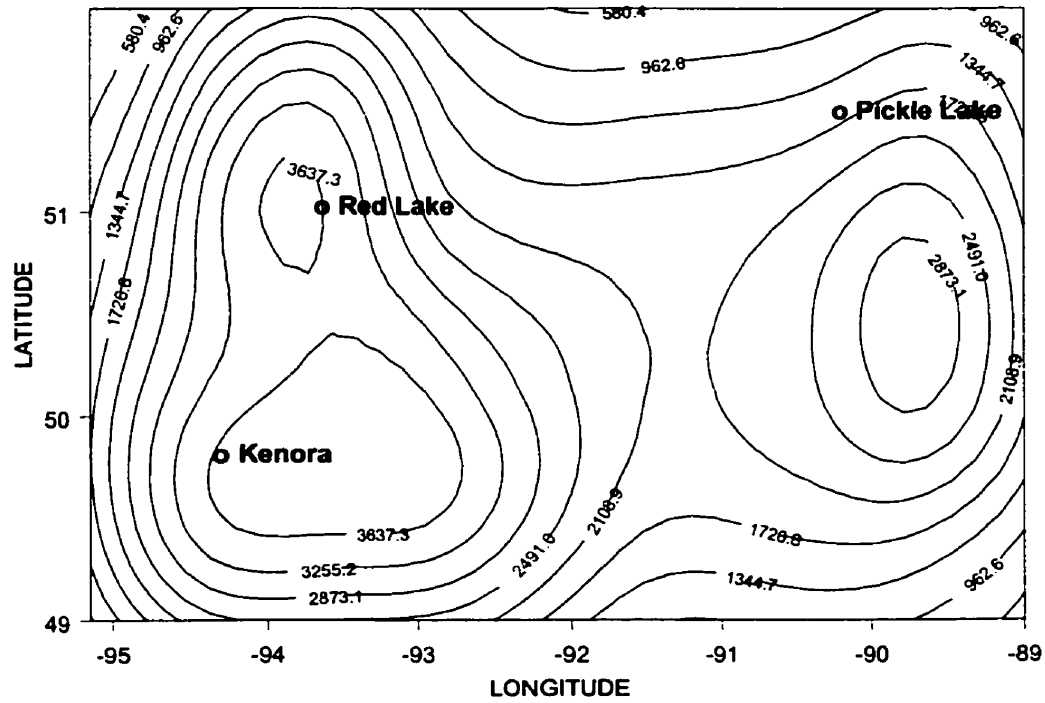
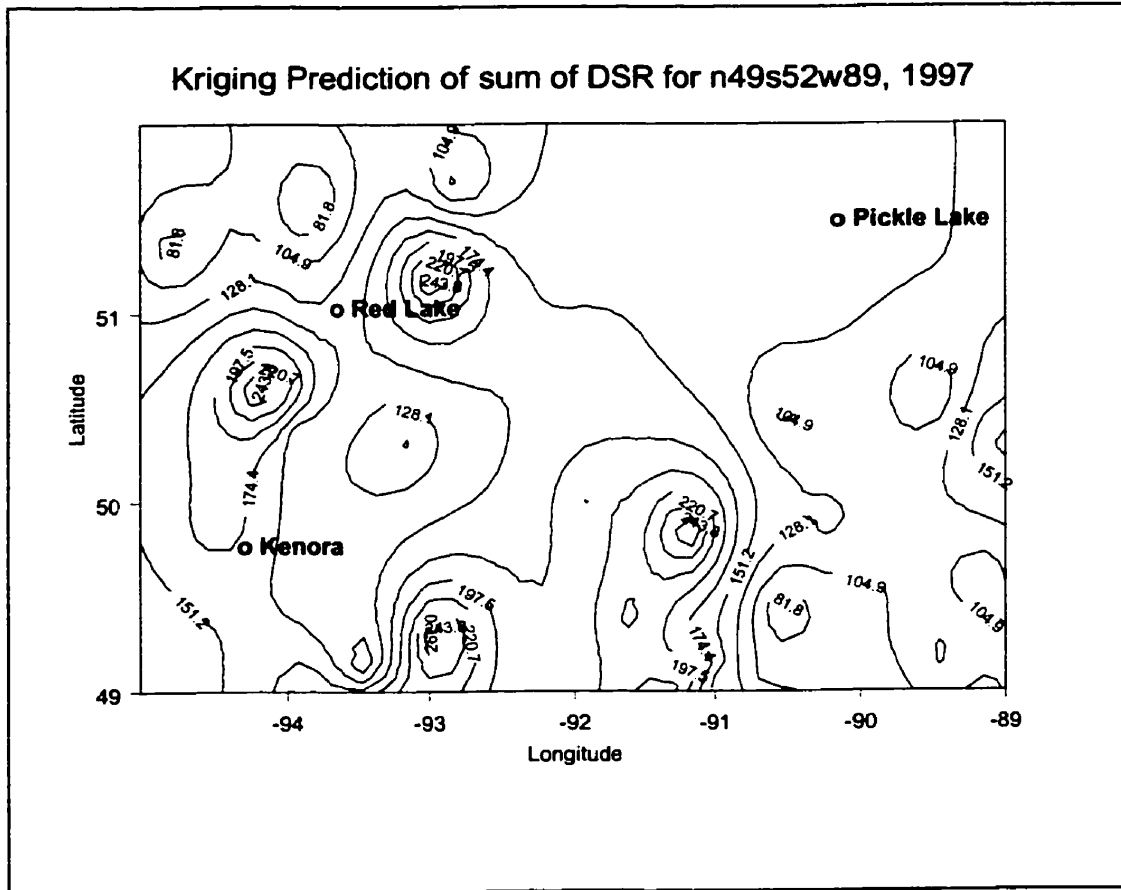


Figure 3.23 Spatial intensity of lightning strikes in Ontario in the northwest region in 1997. There were 50891 lightning strikes and 283 lightning-caused fires in the region in that year.



**Figure 3.24** Interpolation of the sum of the Daily Severity Rating over the 1997 fire season for the same study region.

## fire density for n49s52w89, 1997

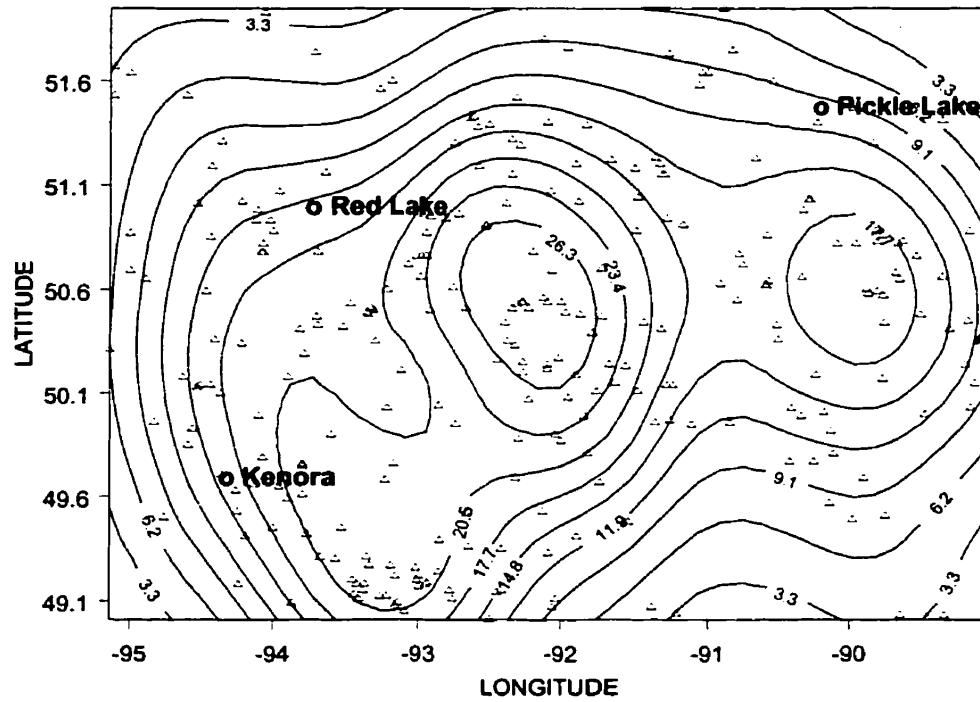


Figure 3.25 Spatial intensity of lightning-ignited fires in the northwest region for 1997.

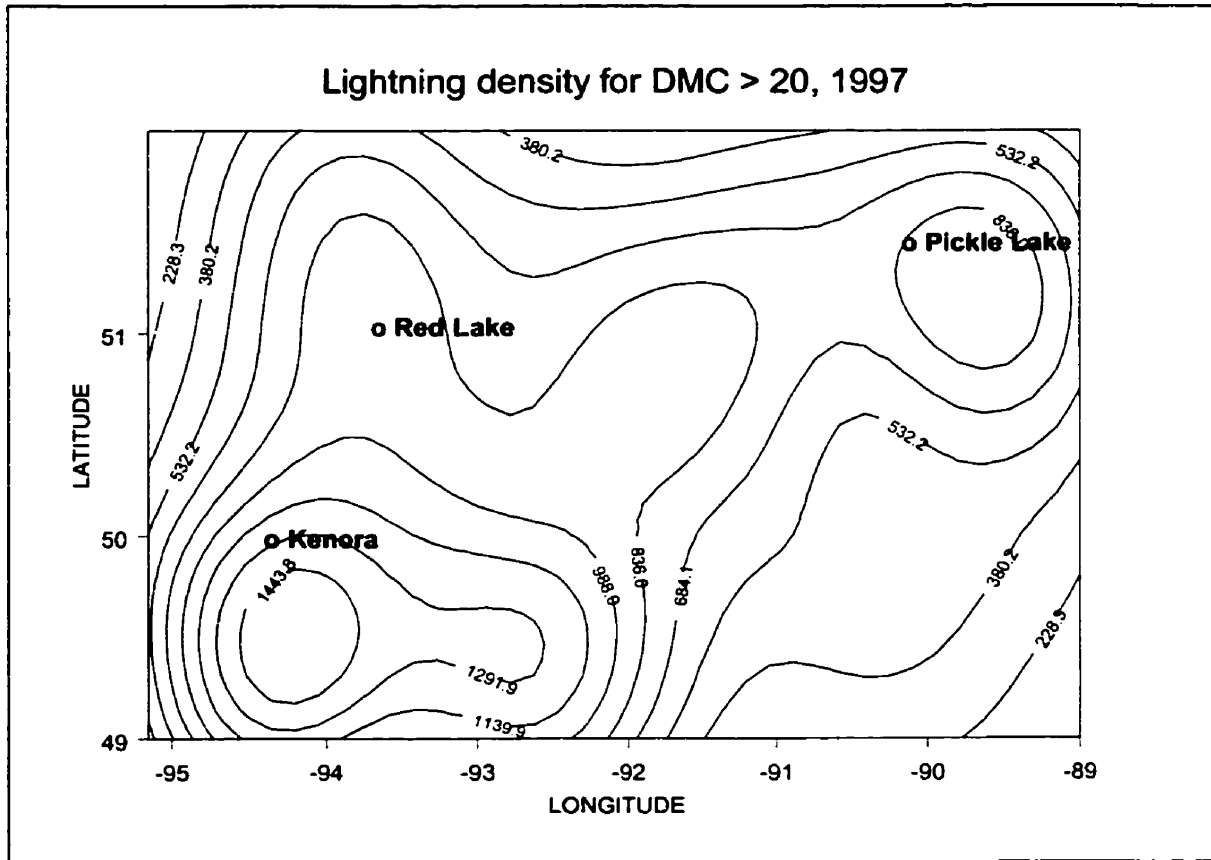


Figure 3.26 Spatial intensity of lightning strikes in the northwest region for 1997 on days when the Duff Moisture Code exceeded a value of 20.

## lightning strike density for n49s52w89, 1998

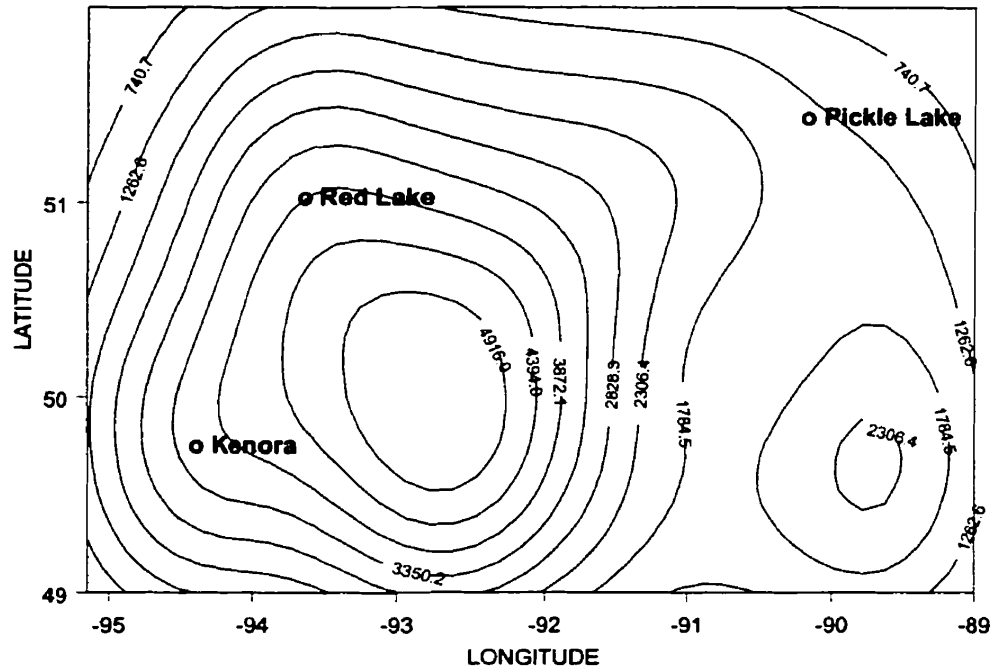


Figure 3.27 Spatial intensity of lightning strikes in Ontario in the northwest region in 1998. There were 54879 lightning strikes and 359 lightning-caused fires in the region in that year.

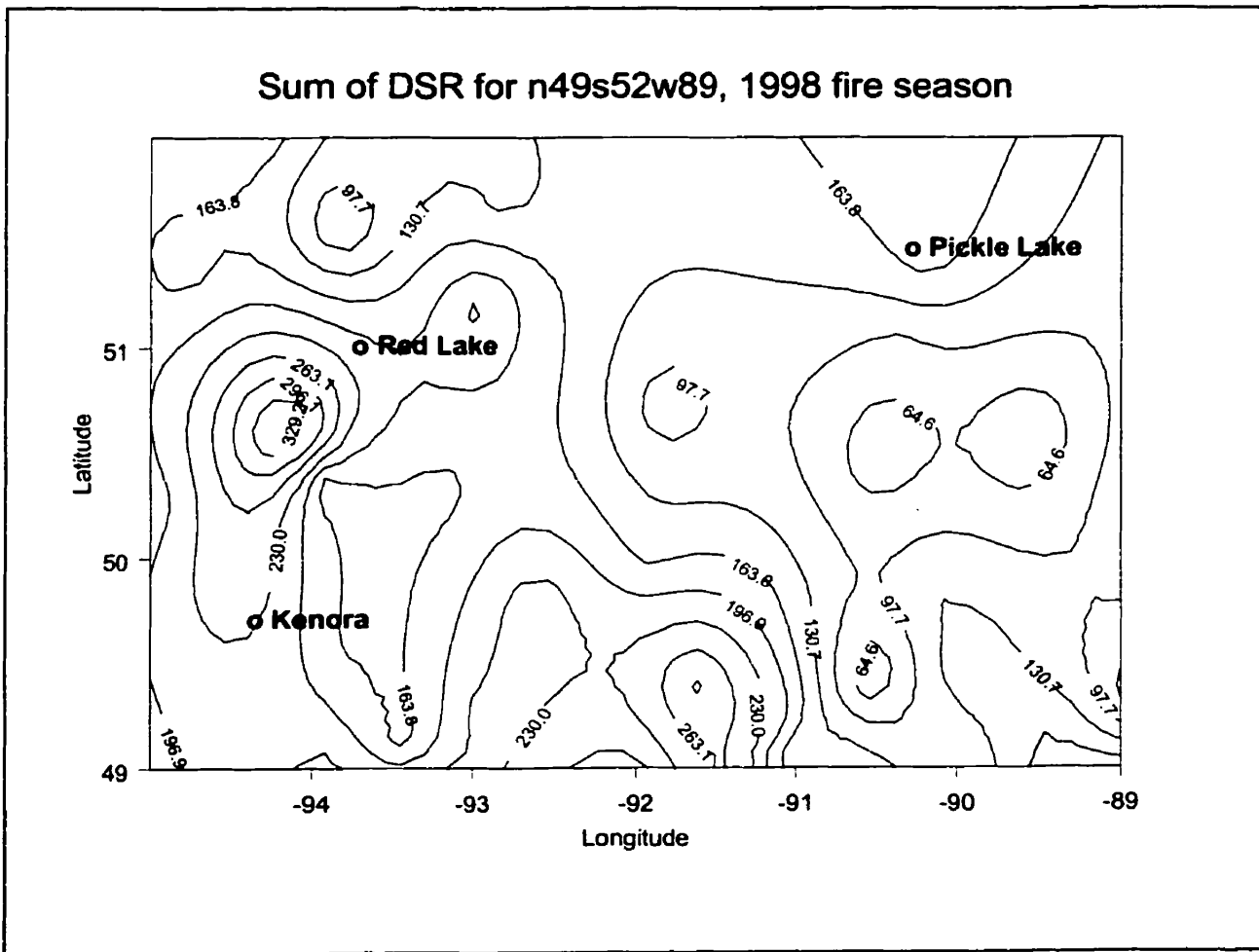


Figure 3.28 Interpolation of the sum of the Daily Severity Rating over the 1998 fire season for the same study region.

## fire density for n49s52w89, 1998

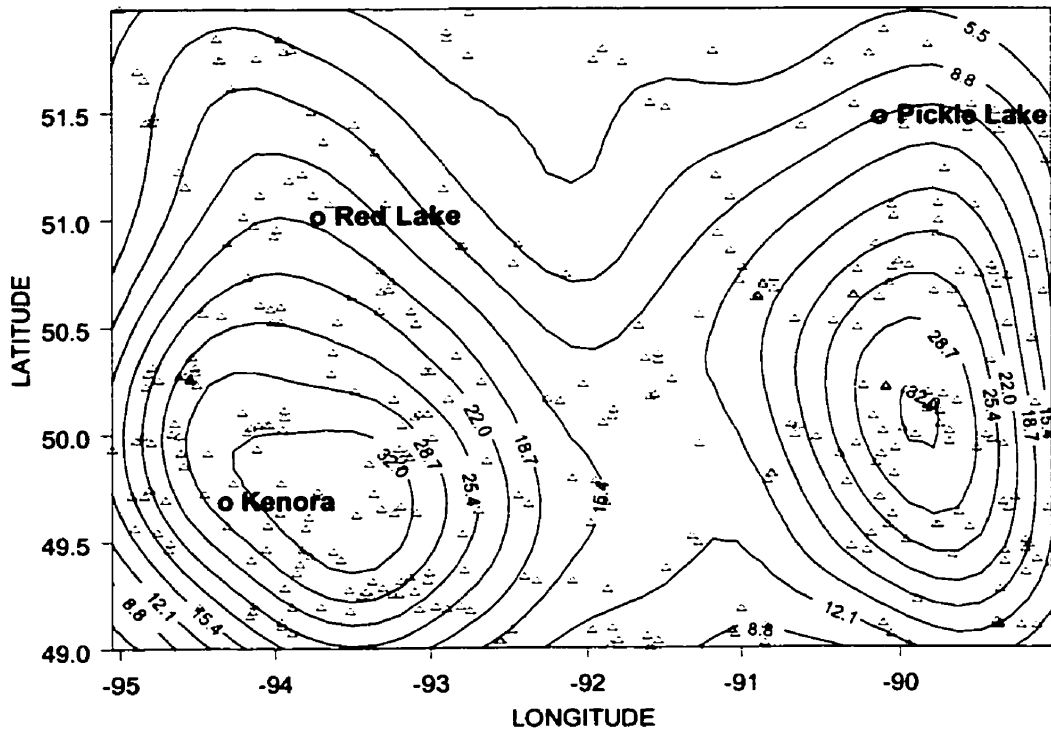
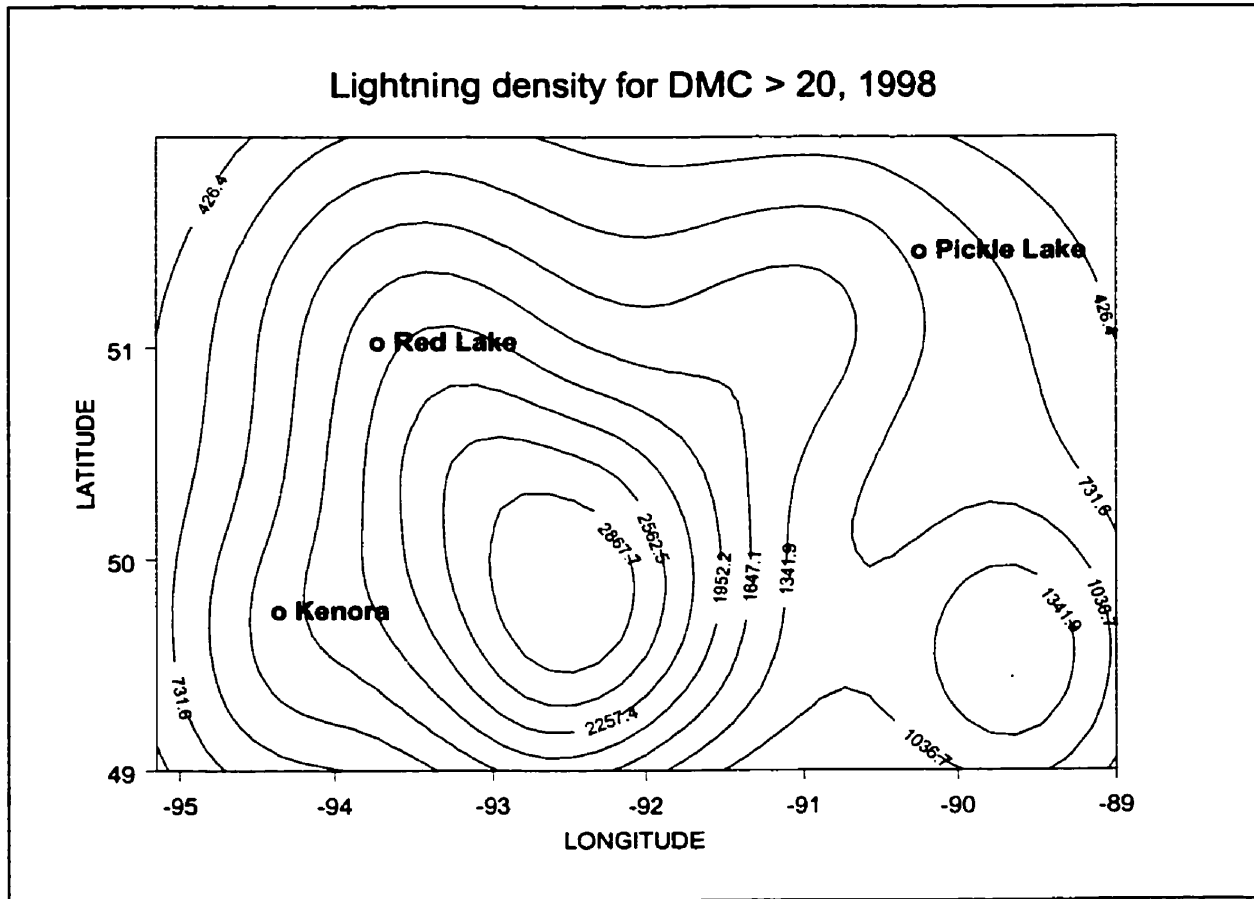


Figure 3.29 Spatial intensity of lightning-ignited fires in the northwest region for 1998.



**Figure 3.30** Spatial intensity of lightning strikes in the northwest region for 1998 on days when the Duff Moisture Code exceeded a value of 20.



## Chapter 4: Time Series Analysis of Canadian Forest Fire Statistics

### 4.1 Abstract

Time series analyses were conducted of the annual number of fires and area burned in Canada and Ontario for the periods 1918-2000 and 1917-2000 respectively.

Autoregressive models were fitted to the number of fires, which exhibited significant serial correlation at a lag of one year. Annual area burned in Ontario exhibited significant serial correlation at a 14-year time lag. The annual area burned in both Canada and Ontario, however, were best modeled as purely random processes.

### 4.2 Introduction

#### *4.2.1 Fire Management Records*

In Canada, forest fire management is largely the responsibility of the provincial and territorial governments but the federal government is responsible for fire management in national parks. Most Canadian forest fire management agencies were established early in the 20<sup>th</sup> century in response to fires that killed hundreds of people and destroyed property and industrial timber supplies. The timing of the introduction of organized fire management, the policies that governed their activities, and the resources at their disposal varied considerably from agency to agency. There is no comprehensive documentation of the history of fire management in Canada but Lambert and Pross (1967) described the

development of fire management in the province of Ontario and Murphy (1985) did so for Alberta.

Each year Canadian fire management agencies compile historical summaries of fire activity on the land under their jurisdiction. The agency responsible for compiling the provincial summaries to produce national figures has varied over time and annual fire statistics are now compiled by Natural Resources Canada and made publicly available on the internet<sup>4</sup>

#### *4.2.2 Weather and Climatic cycles*

Forest fire activity is driven by weather and by climate. Time series analyses of weather and climate have found cycles and trends in those series. Saunders (2001) conducted a time series analysis of temperature and precipitation data from 1916-1998 in northwestern Ontario and found both significant warming trends and cycles. Strong cycles were found with periods of 2.1 years, 3-5 years, and 16.5 years. There were overall warming trends in the mean temperature from 1916-1944, and again from 1970-present, with the period 1944-1970 classified as 'relatively benign'. Saunders (2001) lists some natural cycles which could influence northwestern Ontario's climate, including the ENSO (El Nino/Southern Oscillation), the QBO (Quasi-Biennial Oscillation), and the PNA (Pacific North American). Schindler et al. (1990) found lakes in northwestern Ontario had warmed by 2° C between 1969 and 1987. Corti et al. (1999), modeling the climate system as a nonlinear dynamical system with a chaotic attractor, generated results

suggesting that climate change may project itself on natural patterns in complex ways. This means that finding the ultimate source of climate changes in anthropogenic activities or in natural variation could be impossible. This study is an attempt to find the existing temporal patterns in forest fire activity. The patterns found were similar in length to weather cycles described in the literature just reviewed, as the results below show. Time series analysis of fire activity identifies cycles of similar lengths as weather cycles. This is evidence of weather's influence on fire activity.

#### *4.2.3 Time Series Analysis*

Time Series Analysis methods are statistical methods used to detect cycles, trends, and probabilistic structure in random time series (Chatfield 1996). The structures detected are typically used to model the process underlying the time series, and the model is then used for forecasting. The richer the underlying process and the better the model describes it, the better the forecast will be. This chapter is an attempt to use time series methods to model annual area burned and number of fires in Canada and Ontario using the longest time series available.

### **4.3 Data**

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<sup>4</sup> [http://nfdp.ccfm.org/cp95/text\\_e/tab31e.htm](http://nfdp.ccfm.org/cp95/text_e/tab31e.htm)

The statistics on Canada's annual area burned (Figure 4.1) and number of fires (Figure 4.2) were taken from Kayll (1995).

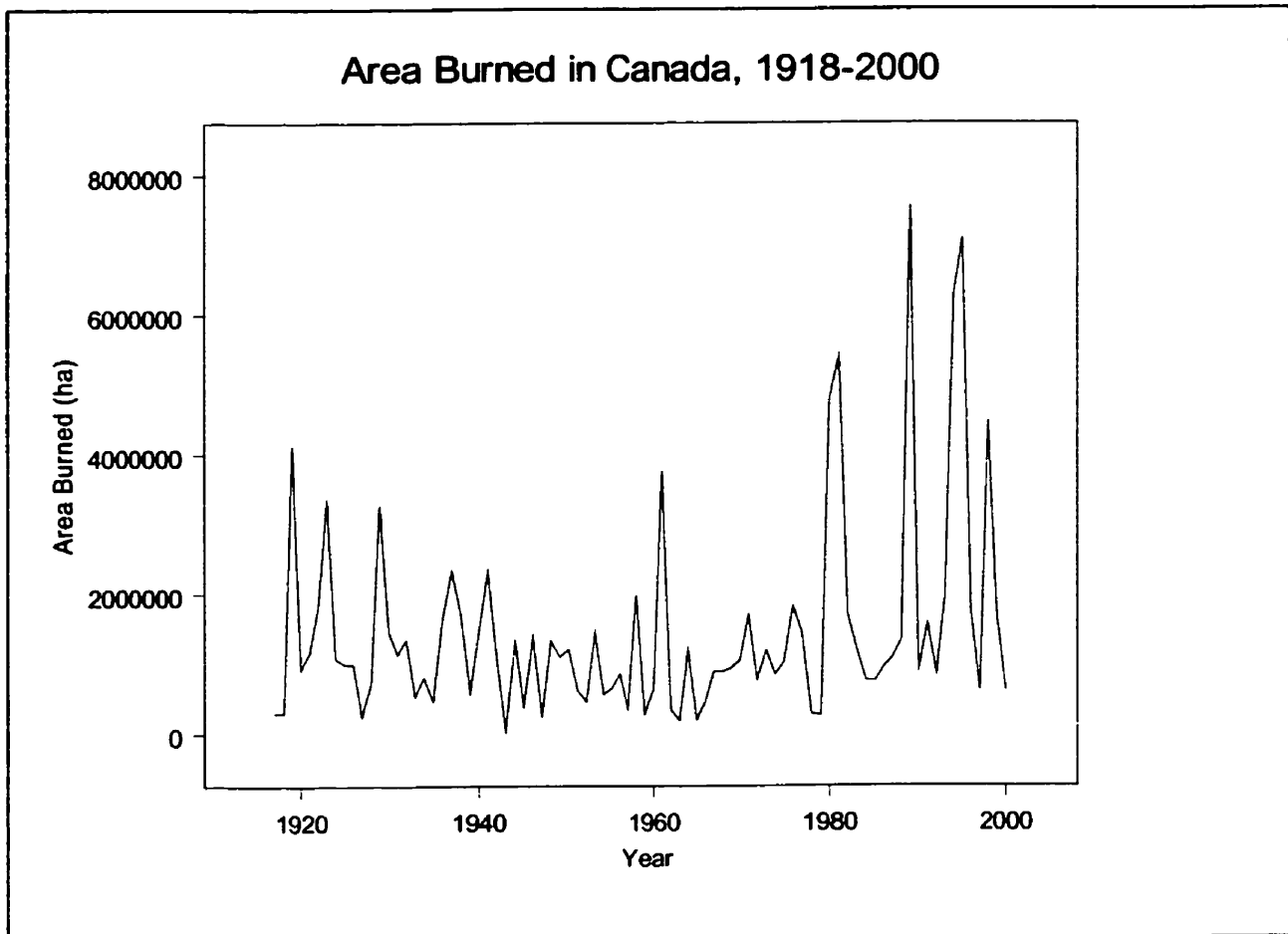


Figure 4.1 Annual Area Burned in Canada, 1918-2000

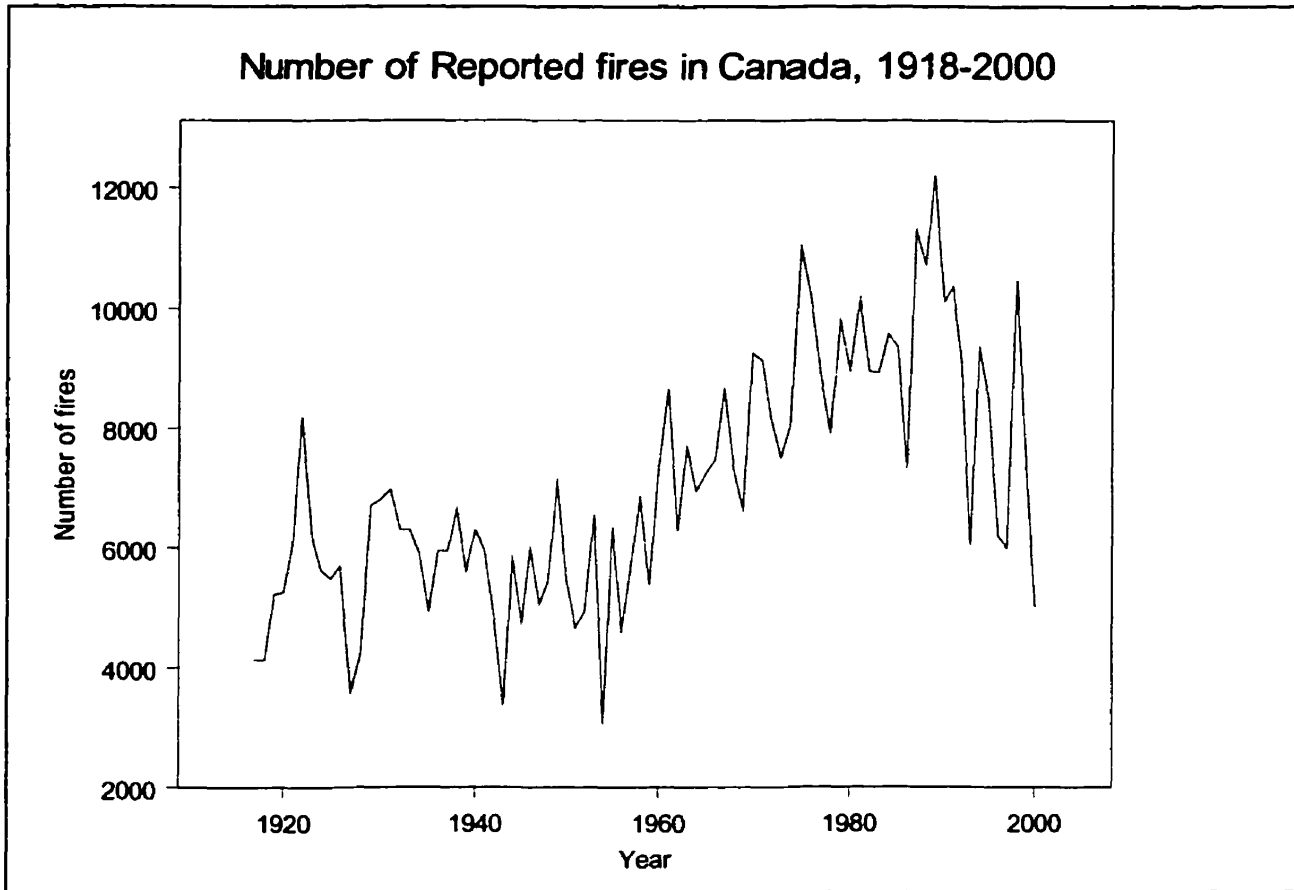


Figure 4.2 Annual Number of Fires in Canada, 1918-2000

Kayll recognized that the Canadian statistics would be biased downward in early years because the Northwest and the Yukon territories were not included in the record until 1947 and Newfoundland and Labrador were not included until 1949. Attempting to compensate for this, Kayll calculated what portion of Canada's annual area burned and number of fires these areas accounted for in the years when they were included in the record (35% of area burned and 6% of number of fires), and added these percentages to the years when they are not present. Van Wagner (1988) used similarly adjusted data for his study of historical patterns of area burned in Canada. These adjustments introduce large problems with the accuracy of the data. The statistics on Ontario's annual area

burned (Figure 4.3), and Ontario's annual number of fires (Figure 4.4), 1917-2000, were provided by the Ontario Ministry of Natural Resources (OMNR 1986, OMNR 2000).

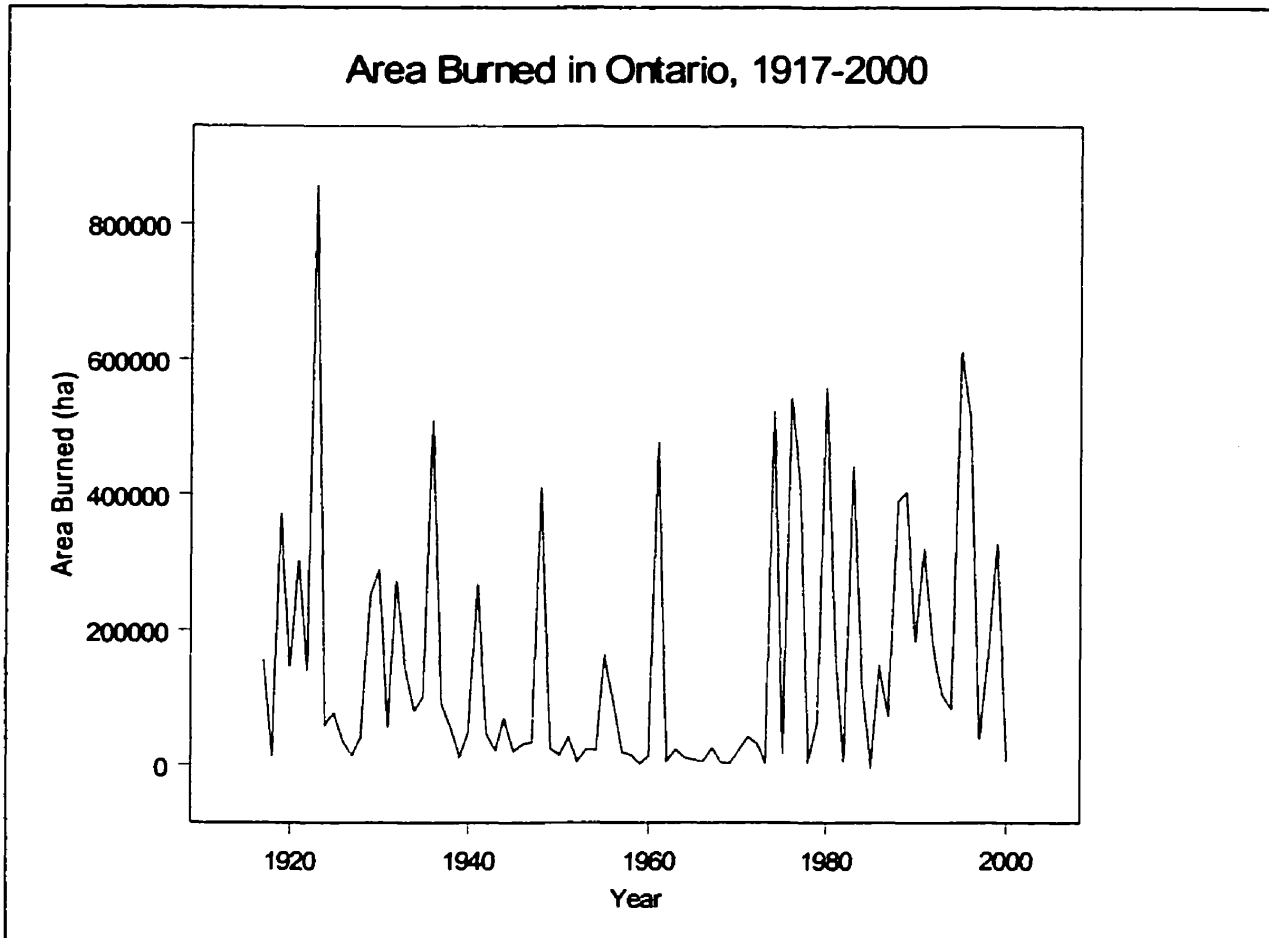


Figure 4.3 Annual Area Burned in Ontario, 1917-2000

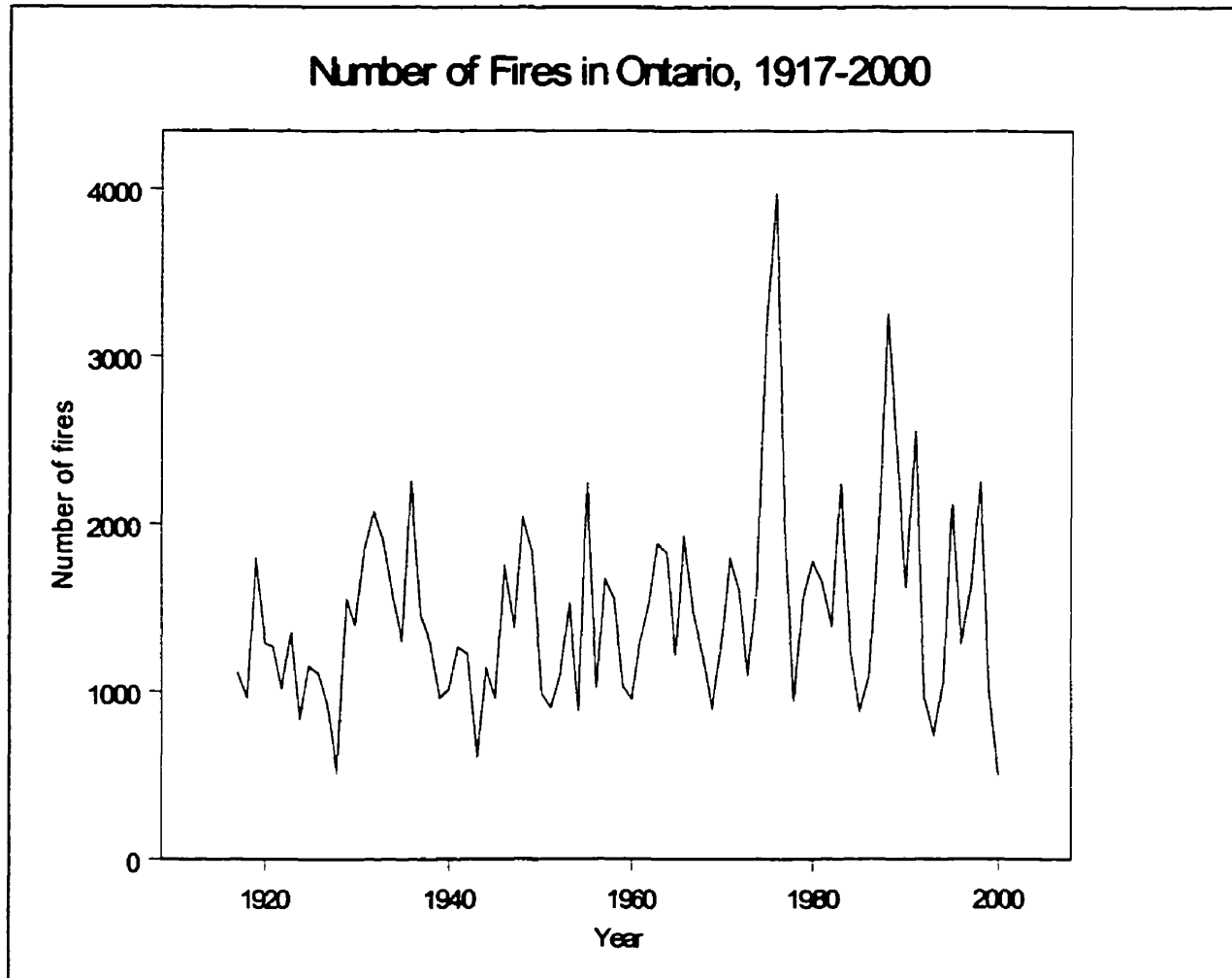


Figure 4.4 Annual Number of Fires in Ontario, 1917-2000

Murphy et al. (2000) reported on the quality of fire data and outlined many serious problems with provincial and national level fire statistics, primarily because of inconsistent and expanding detection systems. They concluded that in general, the national data can only be thought to be consistent after 1975. The flaws they identified are so serious that their effects could confound any attempt to understand historical patterns. Fire records are incomplete in the northern regions 1) of British Columbia prior to 1960; 2) of Saskatchewan and Manitoba prior to 1950; 3) of Quebec prior to 1980.

Only fires around communities were reported in the Northwest territories prior to 1964. Newfoundland, Labrador, and the Northwest and Yukon territories were not included in the National database until 1949 (for Newfoundland and Labrador) and 1946 (for the territories). There are also a number of documented fires not included in the national statistics. (Murphy et al. 2000) Finally, prior to 1975 (later in some provinces) most provinces did not report fires occurring in areas that were not under intensive fire protection. These fires are estimated to contribute approximately 2/3 of the overall area burned. (Simard, personal communication)

These flaws explain why identifying patterns in the fire time series is difficult. They do not, however, justify not attempting to identify such patterns. Although the series are noisier and more biased than is optimal, analysis might identify patterns in spite of this. Time series analysis, a set of techniques for identifying patterns in noisy time series, is well suited to this problem and was utilized in this study.

#### **4.4 Descriptive Analysis and Modeling**

Descriptive time series analysis utilizes the autocorrelation function (ACF) (Chatfield 1996). For a time series  $X(t)$  with mean  $\mu$ , the autocovariance at lag  $\tau$  is

$$\begin{aligned} \gamma(\tau) &= E\{[X(t) - \mu][X(t + \tau) - \mu]\} \\ &= \text{Cov}[X(t), X(t + \tau)] \end{aligned} \quad [4.1]$$



The autocovariance is a measure of the serial correlation between points in a time series. Because its magnitude depends on the units of  $X(t)$ , it is standardized to produce the autocorrelation function, defined as

$$\rho(\tau) = \gamma(\tau) / \gamma(0) \quad [4.2]$$

For an actual time series the autocorrelation function can be estimated and its properties used to model the underlying stochastic process of which the time series is a specific realization (Chatfield 1996). A given time series can be modeled as a realization of many different kinds of stochastic processes. Three such processes (white noise, autoregressive, moving average) are described below. The particular process or composition of processes to be used is suggested by examining the autocorrelation function. Three types of stochastic process suggested themselves for the series in this study. For other processes the reader is referred to a time series text such as Chatfield (1996).

Another important function is the periodogram. Any time series can be thought of as a superposition of periodic functions at different frequencies. The periodogram is a measure of the relative weight of each of these frequencies in a time series, or the spectral decomposition of a time series. For a more detailed description see Chatfield (1996).

***Purely random processes:*** A purely random, or white noise process is one consisting of a sequence of mutually independent, identically distributed random variables. Such a process has the autocorrelation function

$$\begin{aligned}\rho(k) &= 1 \text{ if } k=0, \\ \rho(k) &= 0 \text{ otherwise}\end{aligned}\tag{4.3}$$

There are a number of formal statistical tests for white noise (Box and Jenkins 1970). We chose to use the Bartlett test (Chatfield 1996, p. 61). This test plots the cumulative periodogram which, for a white noise series, is close to a straight line with slope 1.

***Moving average processes:***  $X(t)$  is a moving average process of order  $q$  [MA( $q$ )] if

$$X(t) = B_0Z(t) + B_1Z(t-1) + \dots + B_qZ(t-q)\tag{4.4}$$

where the  $B$ 's are constants and  $Z(t)$  is a white noise process. It has autocorrelation function

$$\rho(k) = 1 \text{ if } k=0\tag{4.5}$$

$$\rho(k) = \frac{\sum_{i=0}^{q-k} B_i B_{i+k}}{\sum_{i=0}^q B_i^2} \text{ if } k=0, 1, \dots, q$$

$$\rho(k) = 0 \text{ if } k > q$$

*Autoregressive processes:*  $X(t)$  is an autoregressive process of order  $p$  [AR( $p$ )] if

$$X(t) = a_1X(t-1) + \dots + a_pX(t-p) + Z(t) \quad [4.6]$$

where the  $a$ 's are constants and  $Z(t)$  is a white noise process. For studying an autoregressive process, the partial autocorrelation function (PACF) is more useful than the autocorrelation function. The partial autocorrelation at lag  $k$  measures the excess correlation at lag  $k$  which is not accounted for by an AR( $k-1$ ) model. (Chatfield 1996)

With the knowledge of the time series gleaned from examination of the autocorrelation, partial autocorrelation, and white noise tests, a time series can be modeled as an AR( $p$ ), MA( $q$ ), a white noise process, or one of a host of other types of models, most generally called ARMA or ARIMA models. Fitting and estimation of parameters is described in Chatfield (1996) and is computationally straightforward using statistical software packages such as Splus which was used for this study.

An important tool in fitting models is Akaike's Information Criterion or the AIC. The AIC is defined as

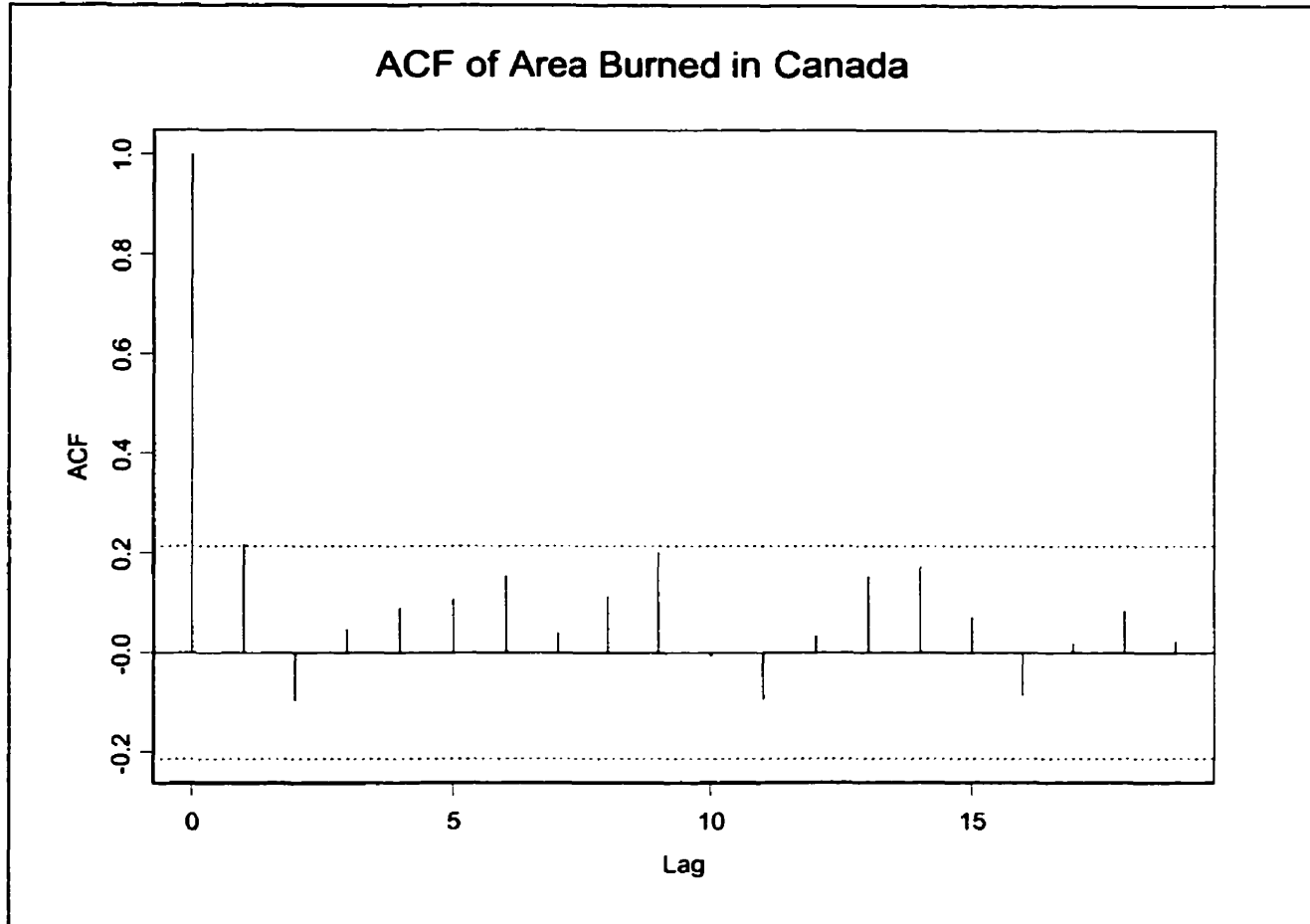
$$-2\ln(\text{maximized likelihood})+2(\text{number of independent parameters estimated}) [4.7]$$

One method of fitting a model to a time series (the method employed in this study) is to fit maximum likelihood estimates of models with different parameters to the series, compute the AIC for each model fit, and choose the model with the minimal AIC.

## **4.5 Results and Discussion**

### *4.5.1 Descriptive Analysis*

The Canadian burned area series (Figure 4.1) shows a barely significant autocorrelation at lag 1 in the ACF (Figure 4.5) and the PACF (Figure 4.6). The white noise test (Figure 4.7) for this series shows that the white noise hypothesis cannot be rejected. For this reason no attempt was made to model the autocorrelation in the data by fitting an autoregressive model.



**Figure 4.5 Autocorrelation Function for Annual Area Burned in Canada.** The dashed lines show the confidence limits. Correlations above the dashed lines are deemed statistically significant. The y-axis plots correlation, while the x-axis is the lag over which the correlation takes place. The correlation of 1 at lag 0 is explicable because each point in the series is perfectly correlated with itself.



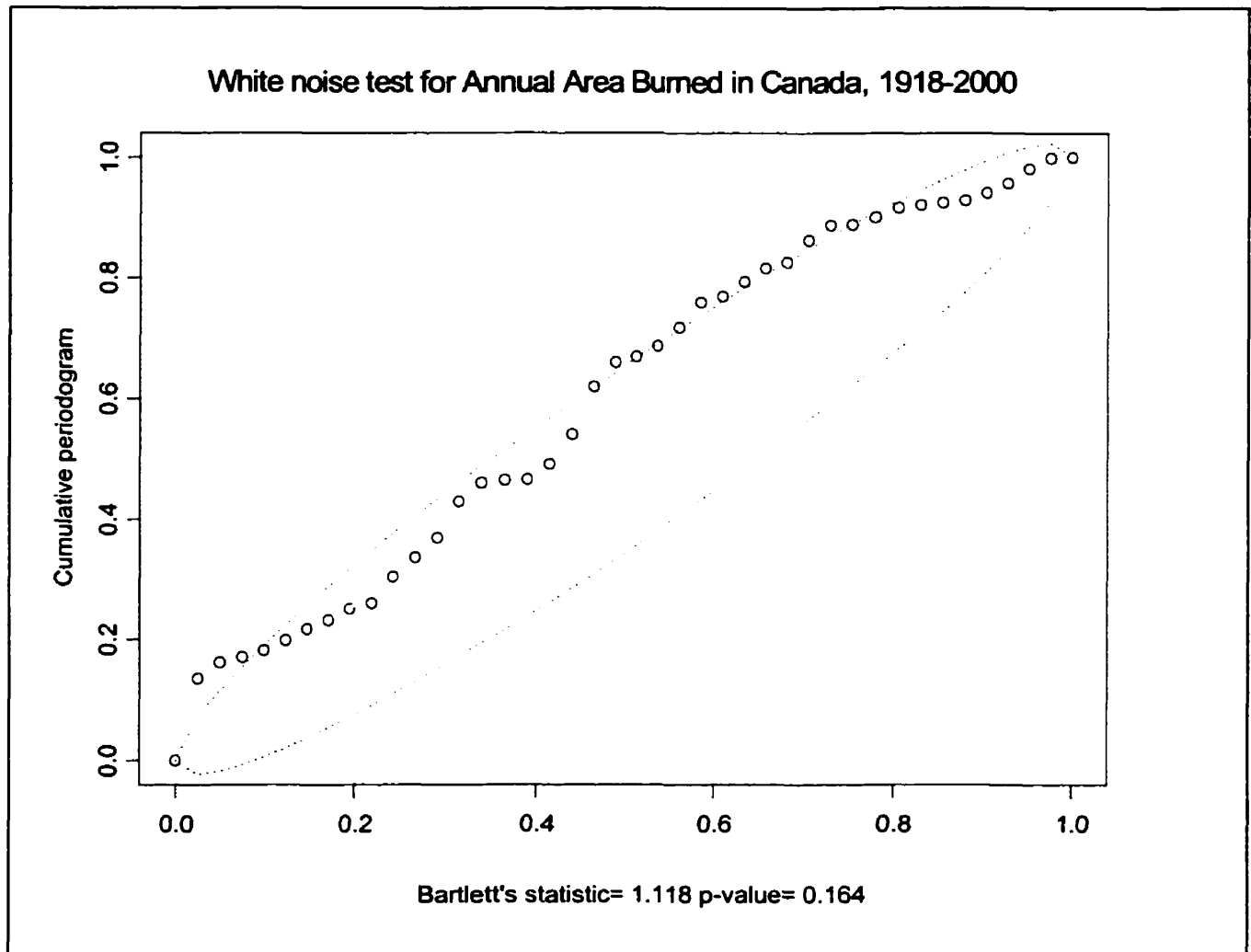


Figure 4.7 White noise test for Annual Area Burned in Canada. The dashed line envelope indicates the confidence limits. If the points in the cumulative periodogram fall within this envelope, the white noise hypothesis cannot be rejected.

The Canadian number of fires series (Figure 4.2) had a decaying autocorrelation function (Figure 4.8) and significant partial autocorrelations at lags 1, 2, and 3 (Figure 4.9).

Because the white noise hypothesis can be rejected for this series (Figure 4.10) an autoregressive model was fitted. An autoregressive model of order 3, or AR(3) model gave an AIC of 1409.23, while an AR(1) model performed quite well as well, with an AIC of 1461.43. The AR(1) model seemed a good choice because the partial autocorrelation at lag 1 was so much greater than that at lags 2 and 3.

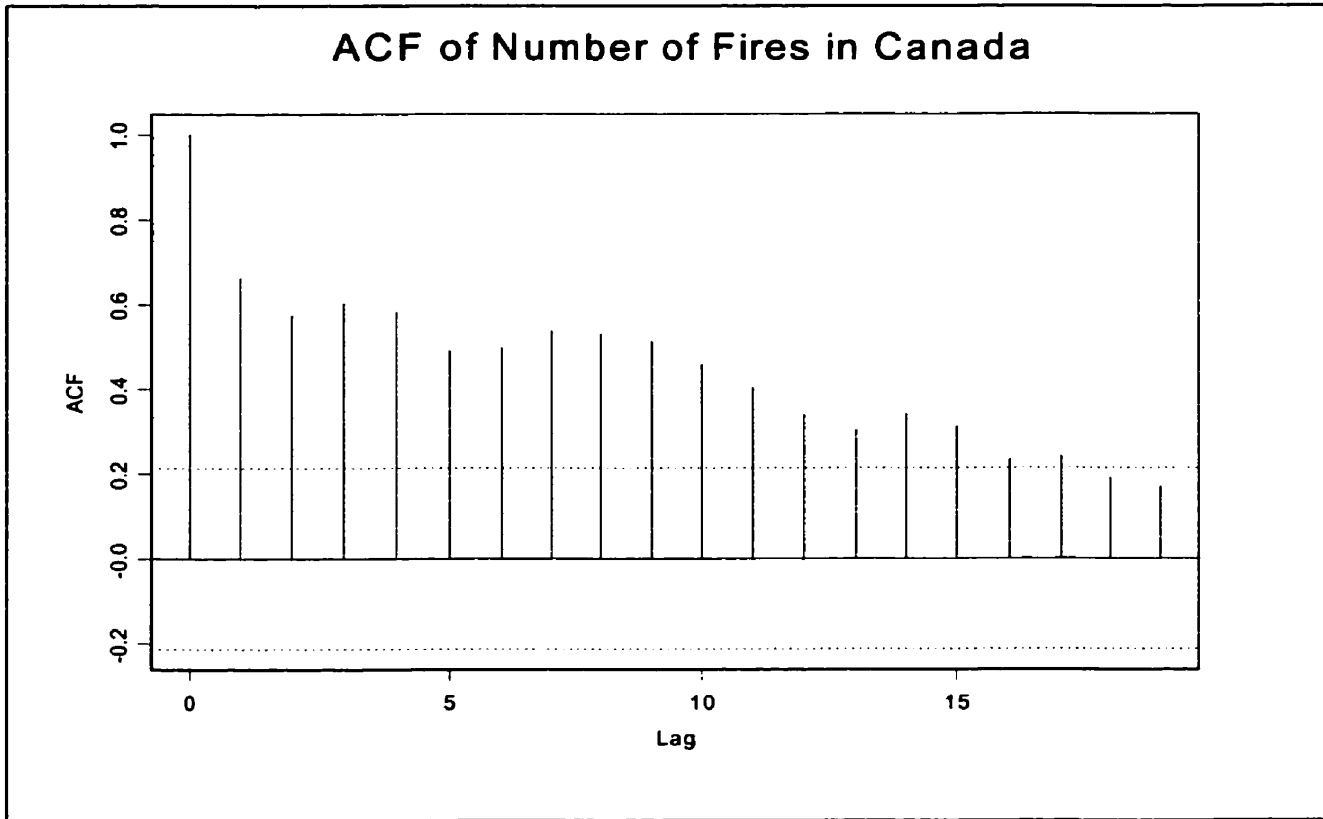


Figure 4.8 Autocorrelation Function for Annual Number of Fires in Canada

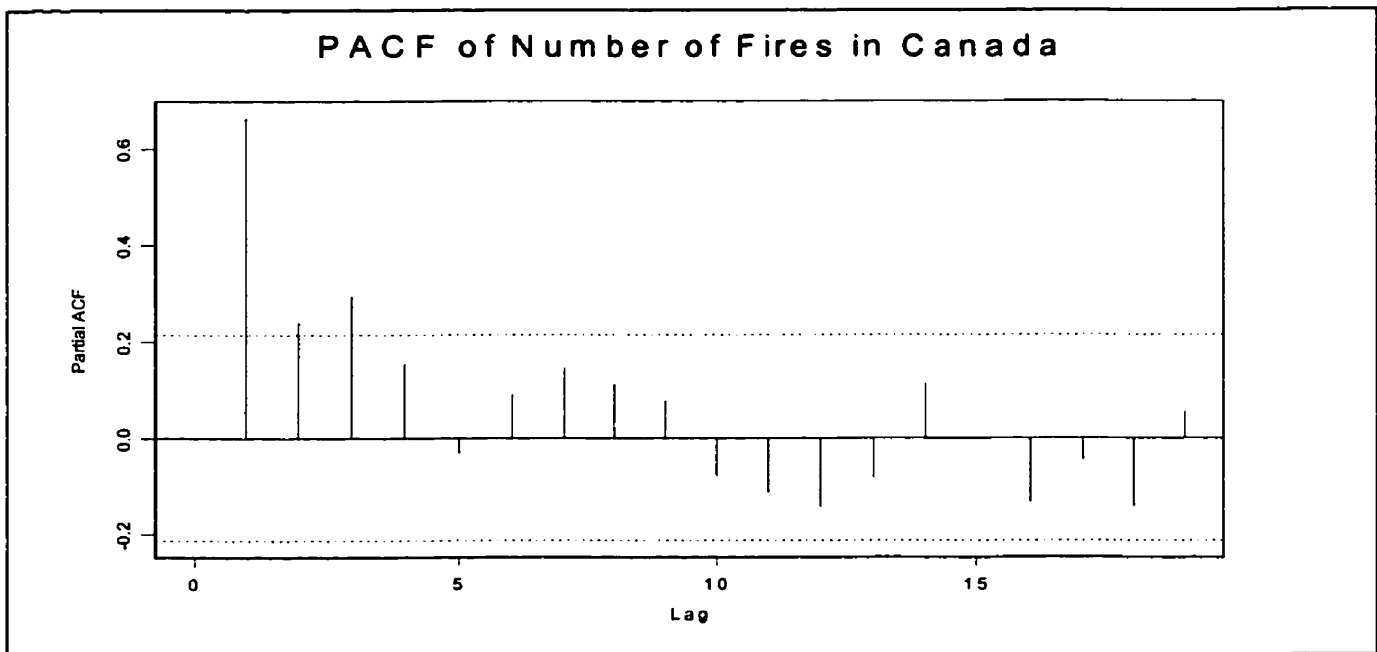


Figure 4.9 Partial Autocorrelation Function for Annual Number of Fires in Canada



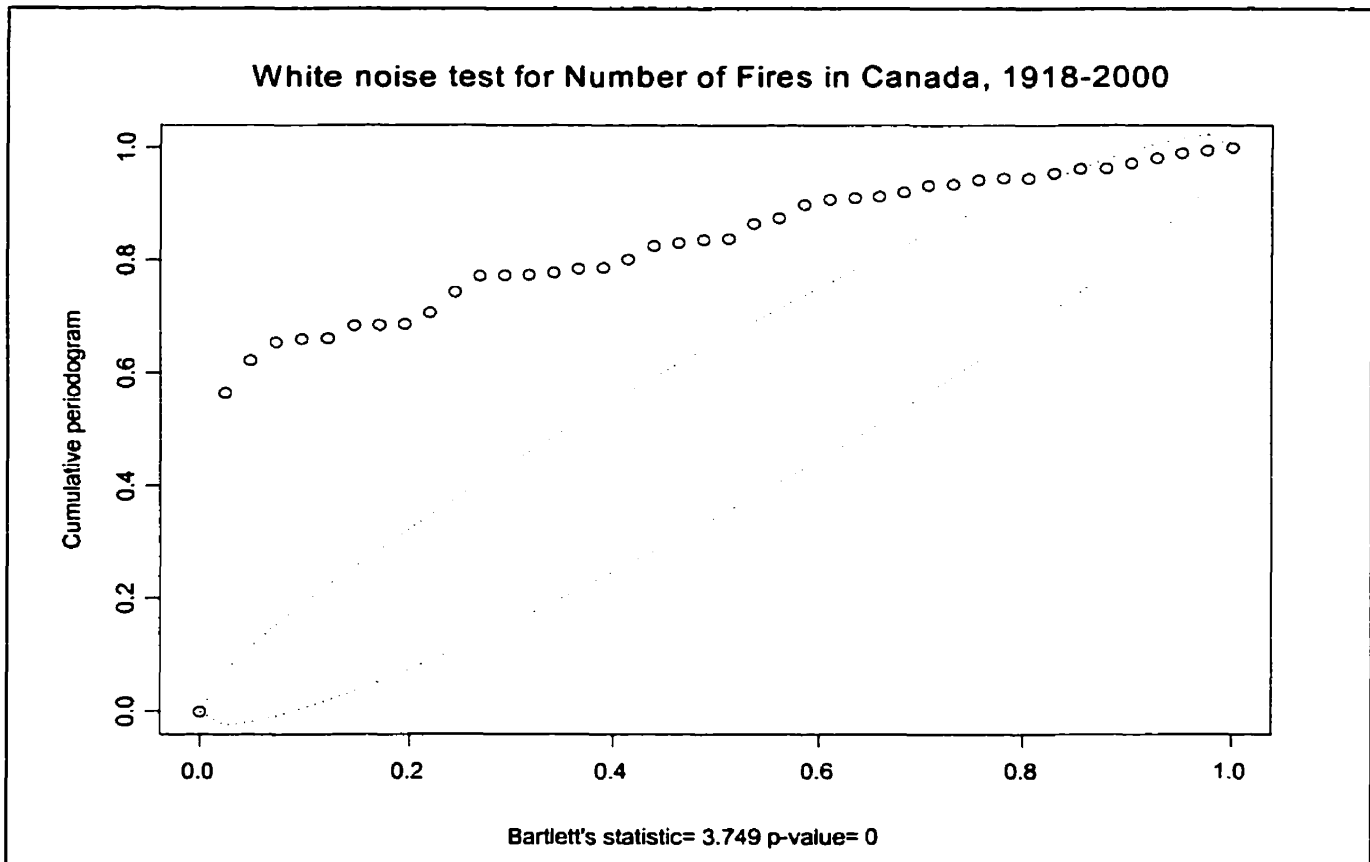


Figure 4.10 White noise test for Annual Number of Fires in Canada

The ACF for the Ontario burned area series (Figure 4.11) shows a statistically significant correlation at lag 13. Since there is no obvious physical phenomena to account for this, it is noted but attributed to chance, but we should note that attempts have been made for decades to correlate annual area burned with sunspot cycles, one of the earliest in Canada by Wright (1940). The Ontario area burned series shows no significant correlations in the PACF (Figure 4.12) and the white noise hypothesis cannot be rejected for it (Figure 4.13). The Ontario number of fires series shows a slow decay of the ACF (Figure 4.14) and a significant correlation in the PACF at lag 1 (Figure 4.15). Like the Canadian number of fires series, it is not white noise (Figure 4.16). This suggests that an autoregressive model of order 1 is appropriate. The AIC of this model is 1312.63.

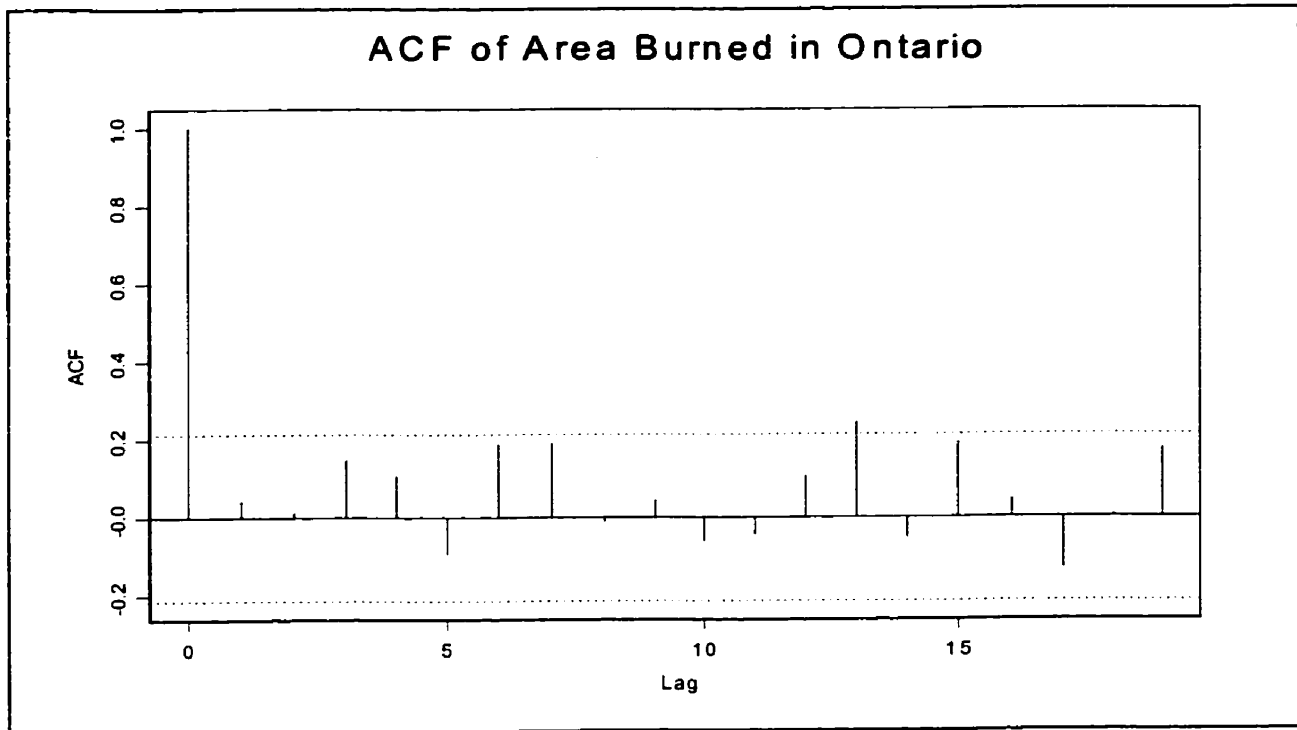


Figure 4.11 Autocorrelation function for Annual Area Burned in Ontario

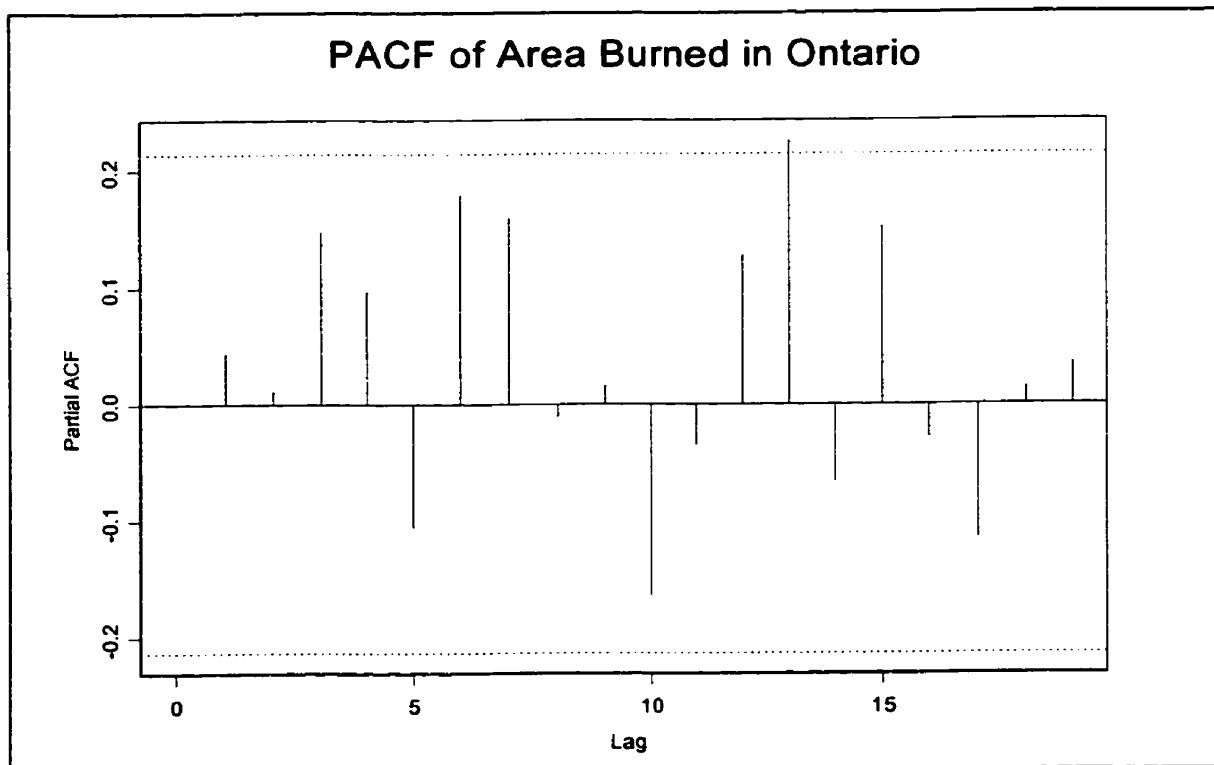


Figure 4.12 Partial Autocorrelation Function for Annual Area Burned in Ontario

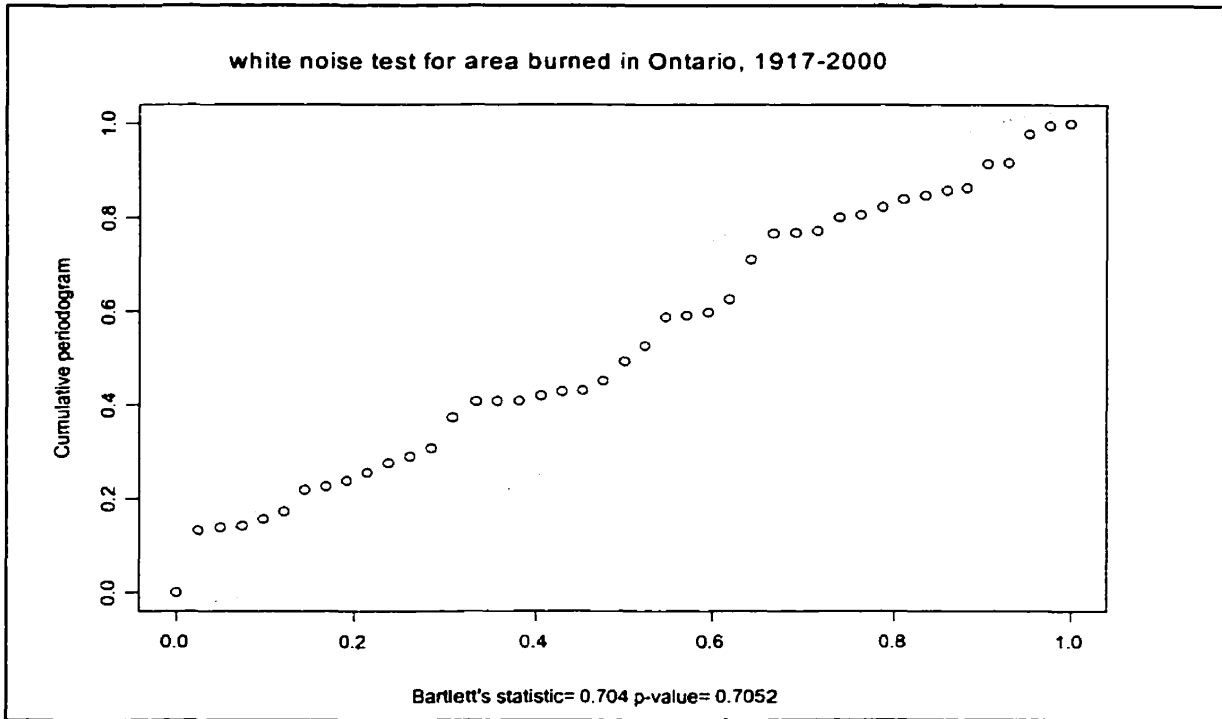


Figure 4.13 White noise test for Annual Area Burned in Ontario

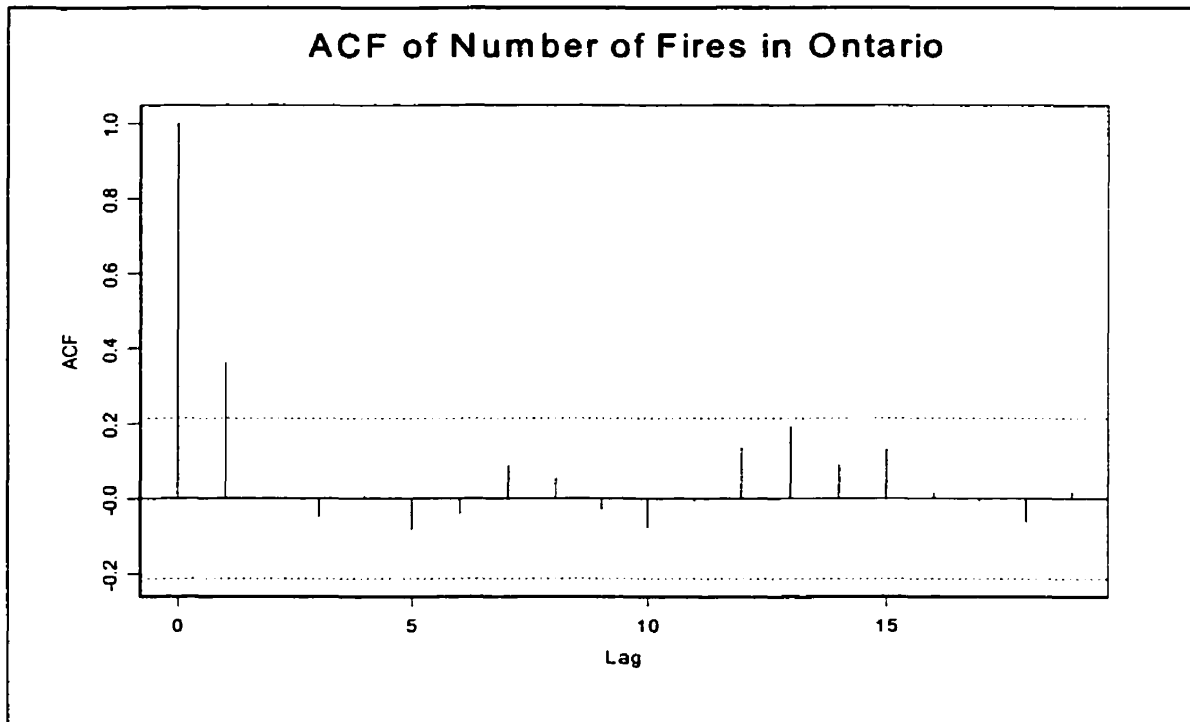


Figure 4.14 Autocorrelation Function for Annual Number of Fires in Ontario

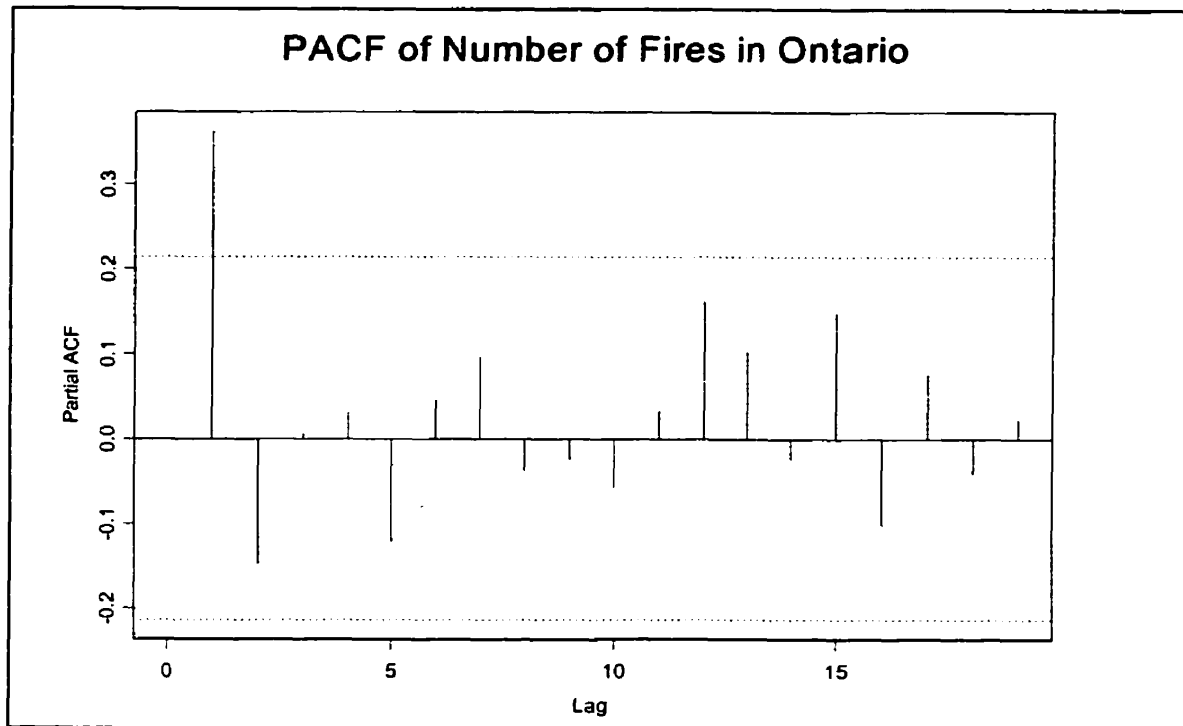


Figure 4.15 Partial Autocorrelation Function for Annual Number of Fires in Ontario

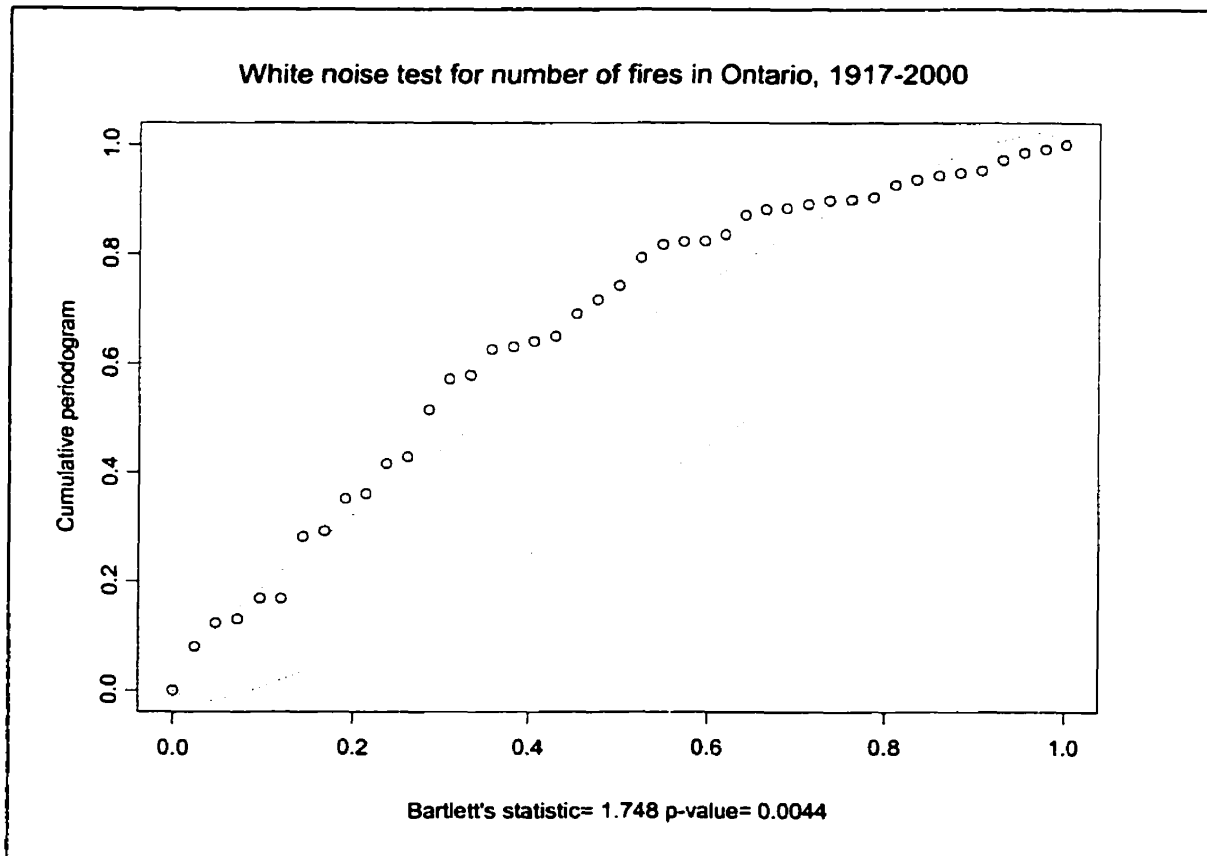


Figure 4.16 White noise test for Annual Number of Fires in Ontario

The periodograms of the datasets did not reveal any significant frequencies. No cyclic or periodic behaviour was detectable by an examination of the periodograms.

In summary, the descriptive analysis based on correlograms and periodograms suggest that annual area burned in Ontario and in Canada are white noise series, and that annual number of fires is an autoregressive process of order 1. In contrast to annual area burned, which shows no serial correlation, number of fires shows serial correlation between years.

#### *4.5.2 Modeling*

Since the Ontario area burned set was judged to be white noise, 'model-building' for it consisted of specifying the mean and variance. The mean was 149 382, variance  $(184\ 968)^2$ . The Canada area burned set mean was 1 489 524, variance  $(1\ 493\ 584)^2$ . The number of fires series for Canada and Ontario were best modeled as AR(1) processes.

The area burned series are highly variable. Year to year variation is so high that a trend or cycle in area burned was not detectable. For this reason quality control methodologies, described in Chapter 5, were used to look for long term increases in mean area burned.

#### *4.5.3 Discussion*

Annual area burned in Canada and Ontario are white noise series with very high year to year variability. Since its year to year variation is high, and its variance also varies, annual area burned is very difficult to predict. The very low area burned and number of fires reported in Ontario in 2000 is a vivid illustration of this difficulty<sup>5</sup>.

The number of fires is best modeled as an autoregressive process of order 1.

This means that this year's number of fires is a function of last year's number of fires plus some random noise factor. Knowledge of the previous year's number of fires gives some ability to predict this year's number of fires. It is likely that area burned is more variable and less predictable by weather than number of fires because it is more sensitive to human intervention than fire occurrence. The number of fires reported, however, is more sensitive to level of protection than area burned, as the public detects and reports large fires even in remote areas. Most of the area burned is due to fires that escape control due to fire behaviour and the inability of the fire management organization to cope with the fire load.

## **4.6 Summary and Conclusions**

### *4.6.1 Summary of Results*

The following are the results of the time series analysis:

- A significant autocorrelation at a lag of 14 years was found in Ontario's area burned, but the white noise hypothesis could not be rejected. Annual area burned in Ontario was best modeled as a purely random process.
-

- Annual area burned in Canada was best modeled as a purely random process.
- Annual number of fires in Ontario was best modeled as an autoregressive process of order 1. There is significant serial correlation from one year to the next in annual number of fires in Ontario.
- Annual number of fires in Canada was also best modeled as an autoregressive process of order 1. There is significant serial correlation from one year to the next in annual number of fires in Canada.
- The 1-year and 14-year time scales for serial correlation of number of fires and area burned in Ontario suggest that weather patterns are the most likely cause.

#### *4.6.2 Future Work*

The conclusions of this study apply for the coarse spatial scales of Ontario and Canada. Applying the same methods to fire data for finer spatial scales, single fire regions or districts, might be instructive and yield different temporal patterns. Comparison of time series results for different regions and provinces over the same time period could be instructive as well.

## Chapter 5: Quality Control Analysis of Annual Area Burned in Canada and in Ontario

### 5.1 Abstract

Quality control methods were used to detect significant changes in the mean and variance of the series. Small significant increases in annual area burned in Canada, Ontario, and northwestern Ontario were detected.

### 5.2 Introduction

#### *5.2.1 Rationale for study*

Although it is widely accepted that the world's climate is now warming (Watson et al 1998) and there is a widespread belief that a warming climate will have significant impacts on Canada's forests, it is not clear that Canada's forests have been experiencing an increase in fire activity. Given the potential impact of global warming on Canada's forests it is essential that fire activity, and other processes which could well be changed by global warming, be carefully monitored.

#### *5.2.2 Data Quality*



It is difficult to disentangle the effects of fire suppression, urbanization and changes in land use, and climate and climate change on fire activity. This task necessitates a long, accurate, and detailed record over a national spatial scale. The record must be long because any changes are likely taking place over long time scales. It must be accurate or any conclusions drawn from it will be invalid. In order to determine whether perceived changes are due to land use, climate, or suppression and detection changes, the record must have sufficient detail on these possible causes of changes in fire activity. Finally, in order to make conclusions about changes in Canada's fire activity, the record must be national in spatial extent.

Such a record does not exist and in practice it is necessary to trade off detail, length, accuracy, and spatial scale. Generally, the farther back the record goes, the less detail and accuracy, and the finer the spatial scale for which data is available.

### *5.2.3 Factors influencing fire activity*

The number of fires and area burned varies significantly from year to year and although there is no detailed understanding of all the parameters that govern fire activity at provincial and national scales, it is widely accepted that the number of fires and area burned each year are largely determined by weather, forest vegetation, land use activities, and fire management activities.

Weather certainly varies from year to year and a growing literature discusses how climate change could have affected the forested regions of Canada over the 20<sup>th</sup> century (Hengeveld 1994). Maps of forest cover type and land use activity show that people have left their mark on the forest landscape and the level of fire protection has certainly varied from province to province, within some provinces, and over time.

Observers often point to Canadian forest fire statistics to support their belief that the national fire record reflects underlying changes in Canada's climate (Flannigan and Van Wagner, 1990) but with the exception of Van Wagner (1988) the scientific literature contains no detailed investigations of the extent to which aggregate national forest fire statistics vary over time. The objective of this chapter is to present the results of using quality control analysis procedures to investigate the extent to which Canadian fire activity has varied since the early part of the 20<sup>th</sup> century. The specific questions to be investigated are: 1) has the annual area burned changed? 2) has the annual number of fires changed? 3) has the variability in these series changed?

#### *5.2.4 Possible Biases in the data*

The quality of forest fire statistics varies over both time and space. Forest fire management agencies have traditionally focused their efforts in areas where they judged fire might have its most significant impact on public safety and forest resources.

Detection efforts were concentrated in those areas and it is widely accepted that not all the fires that occurred in lower priority areas were detected, reported, and included in the annual fire statistics. This problem is compounded by the fact that when forest fire

management was first introduced it was concentrated near population centers and gradually spread into more remote areas. The size of the protected area, the area that was effectively under fire management, is therefore a non-decreasing function of time in most provinces. The effective size of the protected area is therefore one other factor, in addition to weather, vegetation, land use, and level of fire protection, that may influence annual fire statistics.

#### *5.2.5 Approach of this study*

The record available is therefore:

- Biased due to changing measurement techniques and technologies and the extension of protected areas;
- A record of a highly complex process influenced by natural and human activities, whose interactions are poorly understood;
- Of insufficient detail at a coarse scale to facilitate the disentanglement of the role of climate, suppression activities, and extension of protected area.

Even with all these caveats, there is something to be learned from a careful analysis of the data using quality control methodologies. In particular, by looking at time series at different spatial scales (Canada, Ontario, northwestern Ontario), it is possible to make some qualified conclusions about the temporal variation of fire activity. The current study is an attempt to make such conclusions. The analysis is also used as an opportunity

to identify the limitations of the record itself and what conclusions can be drawn from it, as well as to identify some future research directions.

### **5.3 Methods**

#### *5.3.1 Data*

The statistics on Canada's annual area burned (Figure 4.1) and number of fires (Figure 4.2) were taken from Kayll (1995). Problems with these data are discussed in section 4.3.

#### *5.3.2 Quality Control Analysis*

Detecting changes in the mean and variance over time of a highly variable white noise process requires techniques other than those offered by the ARMA/ARIMA modeling of time series analysis. Statistical Quality Control charts were employed to determine if the mean and variance of the area burned dataset were within some 'control limits'. The standard Shewhart and Cusum  $\bar{X}$  chart for the mean and Shewhart S chart for the standard deviation were used. These charts specify statistically significant limits as functions of the mean and standard deviation, aggregate points into three-to-four year cohorts, and thus enable testing of whether the mean or variance of a process has changed significantly. (Derman and Ross 1997) A control chart approach to fire occurrence was previously used by Nickey (1980).

### $\bar{X}$ Chart (Shewhart)

Use of the  $\bar{X}$  chart begins by dividing the chart into rational subgroups. Rational subgroups are n-point groups where n is chosen so that it yields uniformity of data values within individual subgroups, and so that when a shift in distribution occurs it will occur between and not within subgroups. n is typically between 3-5. We chose n=4 for this study. The parameters of the control limits (n and k) are left to the discretion of the user, within limits. The parameters are typically set by studying and modelling the process when it is known or assumed to be 'in control', and then applying the found 'control limits' to the rest of the process to determine whether or not changes have occurred.

Control limits are set as follows:

$$\text{Lower Control Limit} = \mu - k\sigma / \sqrt{n} \quad [5.1]$$

$$\text{Upper Control Limit} = \mu + k\sigma / \sqrt{n} \quad [5.2]$$

$\mu$  = Mean of subgroup means

$\sigma$  = Mean of subgroup standard deviations

k = usually 2 or 3.

### $\bar{X}$ Chart (Cusum)

The Cumulative Sum chart for changes in the mean is prepared as follows. Rational subgroups are used just as in the Shewhart chart, and  $\mu$  and  $\sigma$  are calculated the same way. Choose positive constants  $d$  and  $B$ . Let

$$Y_i = X_i - \mu - d \cdot \sigma \quad [5.3]$$

Where  $X_i$  is the  $i$ th subgroup.

When in the series is in control,

$$E[Y_i] = -d \cdot \sigma \quad [5.4]$$

Let

$$S_0 = 0 \quad [5.5]$$

$$S_{i+1} = \max\{S_i + Y_{i+1}, 0\}, \quad i \geq 0$$

The Cu Sum chart with constants  $d$  and  $B$  plots  $S_i$  and declares the system out of control when

$$S_i > B \cdot \sigma \quad [5.6]$$

Here the parameters  $d$  and  $B$ , as in the Shewhart chart, are determined by studying the process when it is thought to be under control. For more details see Derman and Ross (1997).

### *S Chart (Shewhart)*

This test detects changes in the standard deviation. The estimate of a sample standard deviation for the  $i$ th subgroup is:

$$E[S_i] = c(n) \sigma \quad [5.7]$$

the variance is therefore,

$$\text{Var}[S_i] = \sigma^2 (1 - c(n)^2) \quad [5.8]$$

Limits of the chart are usually given by:

$$\text{Lower Control limit} = E[S_i] - k \sqrt{\text{Var}[S_i]} \quad [5.9]$$

$$\text{Upper Control limit} = E[S_i] + k \sqrt{\text{Var}[S_i]} \quad [5.10]$$

And  $c(n)$ , for  $n=4$ , is 0.94.

## 5.4 Results and Discussion

### 5.4.1 Results

The control charts were calibrated by assuming the system was under control during the first 40 years and testing if it went out of control afterwards. For Canada's area burned, both the  $\bar{X}$  charts (Figs. 5.1-5.2) and the S chart (Figure 5.3) show the area burned to be out of control—above the control limits—in recent years, but under control until then. There has been a statistically significant upward change in both the mean and the variance of annual area burned in Canada.

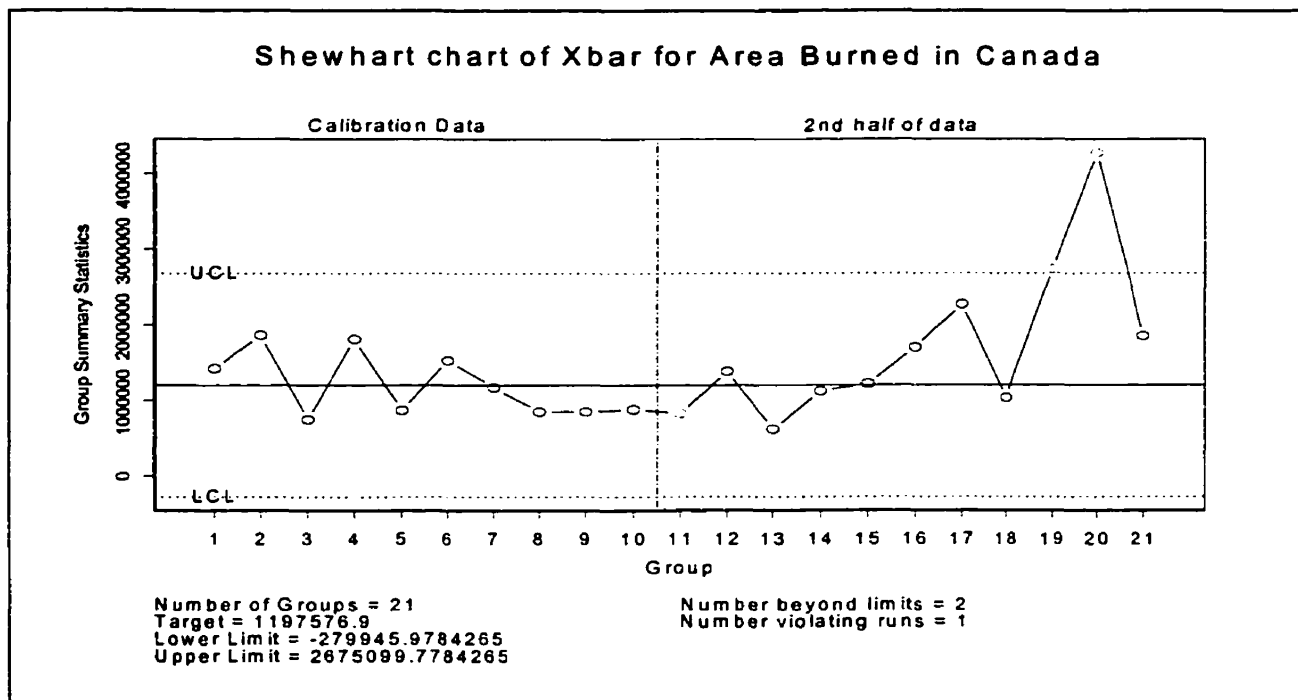


Figure 5.1 Shewhart  $\bar{X}$  Control Chart for Annual Area Burned in Canada. The y-axis plots the means of the 4-year subgroups. The dashed lines are the control limits. The vertical dashed line divides the dataset in half. The first half of the data were used to calibrate the control limits which were applied to the second half of the dataset. This way it was possible to test whether there has been a change in recent years from past years.





The Shewhart  $\bar{X}$  chart for Ontario's area burned (Figure 5.4) show that the mean did not go out of control-- but the more sensitive Cusum test (Figure 5.5), showed that the mean did go out of control during the 1990s. To control for the increasing area under fire protection, area burned in only the northwestern region (north of 49, south of 52, west of 89) was examined. In the resulting series (Figure 5.6) the Cusum test (Figure 5.7) still showed a significant increase in area burned.

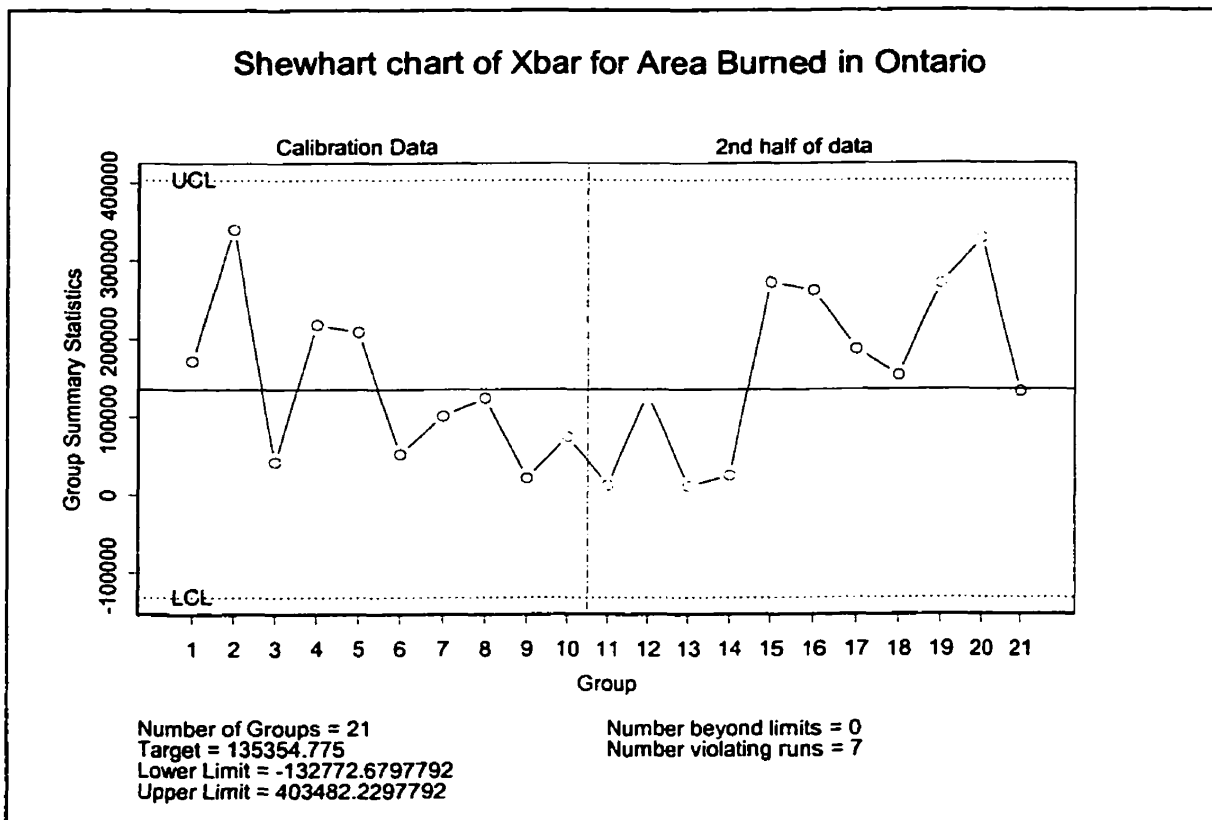


Figure 5.4 Shewhart  $\bar{X}$  Control Chart for Annual Area Burned in Ontario



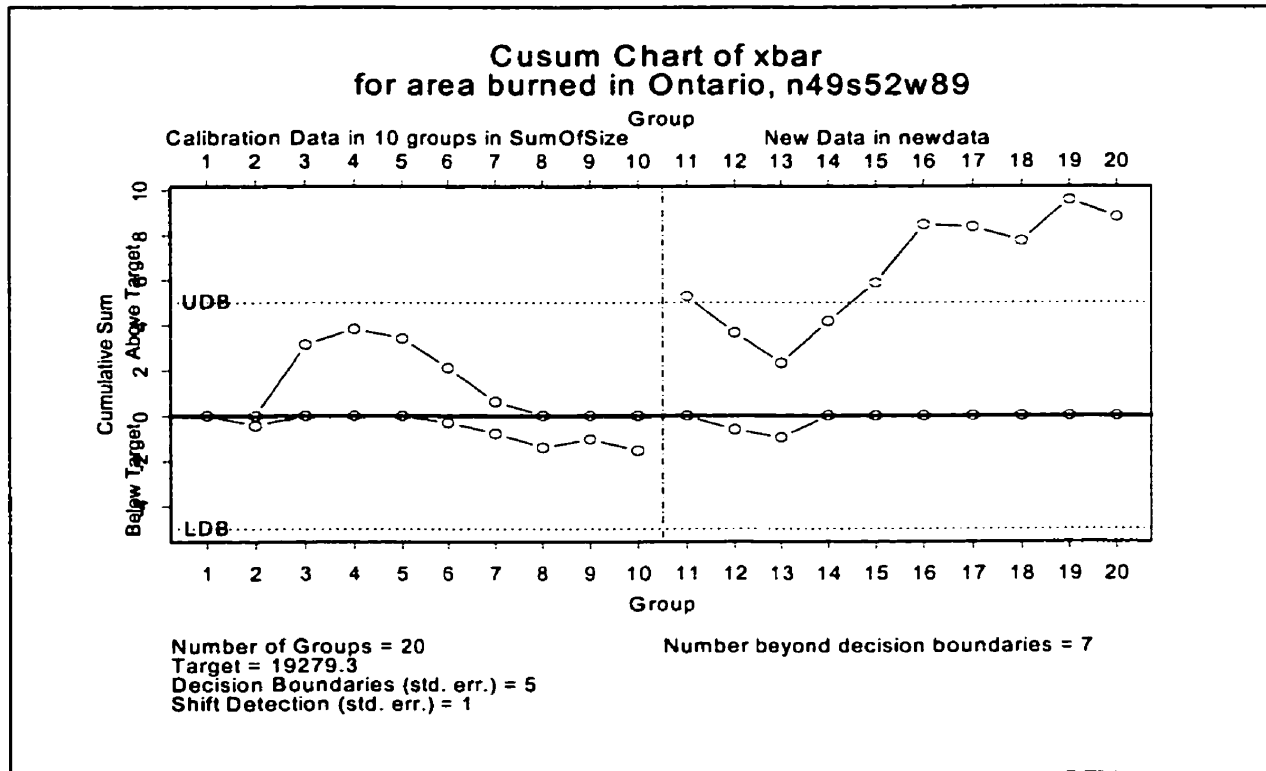


Figure 5.7 Cusum  $\bar{X}$  Control Chart for Annual Area Burned in northwestern Ontario

The S chart for Ontario's annual area burned (Figure 5.8) shows the system to be out of control, below the control limits, in the late 1960s. The variance of Ontario's annual area burned is not constant.

$\bar{X}$  charts and S charts for the number of fires in Canada (Figs. 5.9-5.11) show significant increases in both the mean and the variance of the number of fires in recent years. These results are repeated for the number of fires in Ontario (Figs. 5.12-5.14).

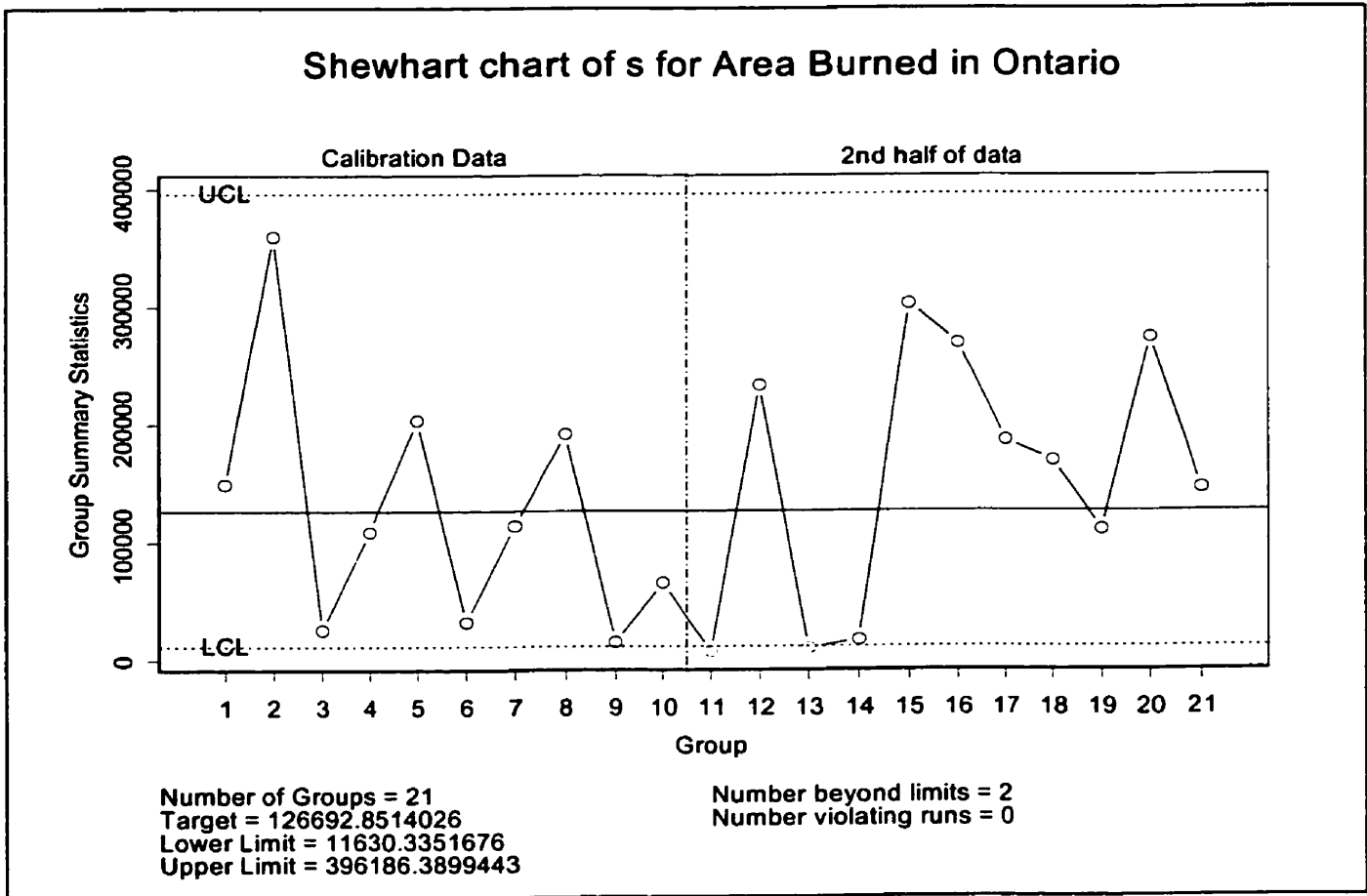


Figure 5.8 Shewhart S Control Chart for Annual Area Burned in Ontario

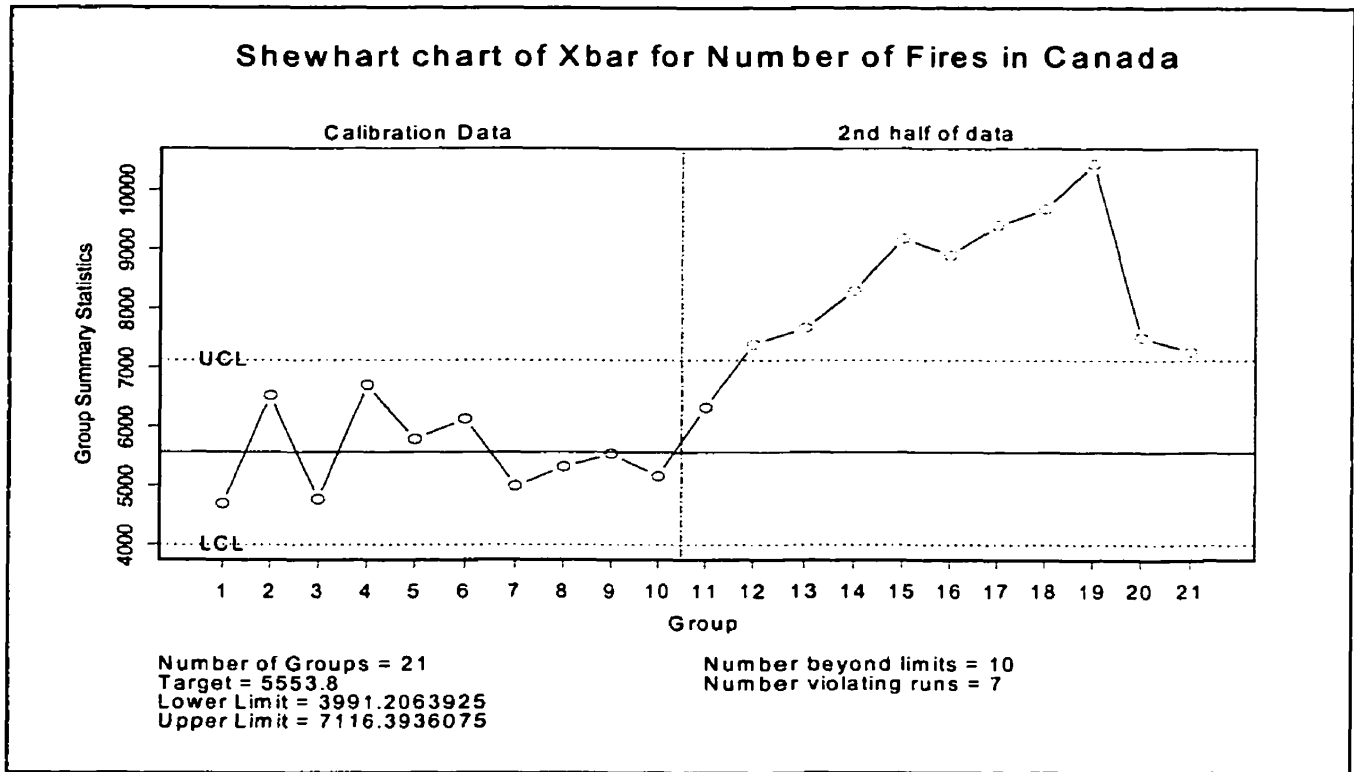


Figure 5.9 Shewhart  $\bar{X}$  Control Chart for Number of Fires in Canada

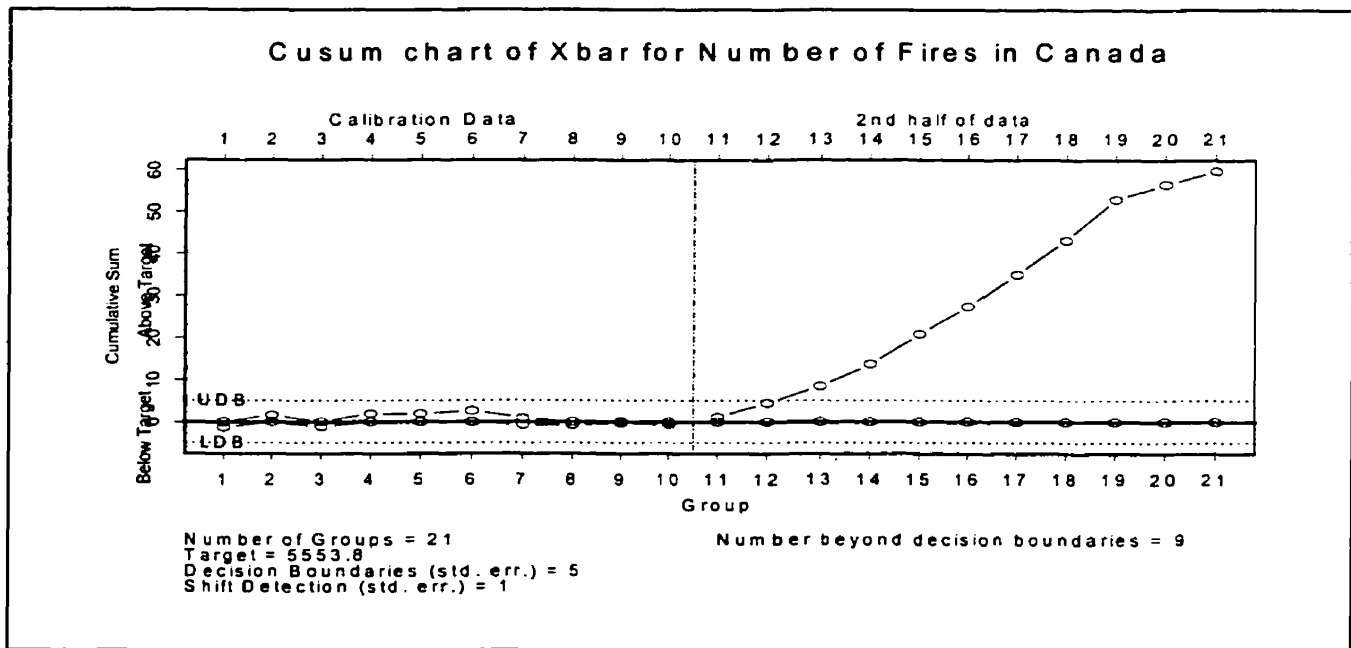
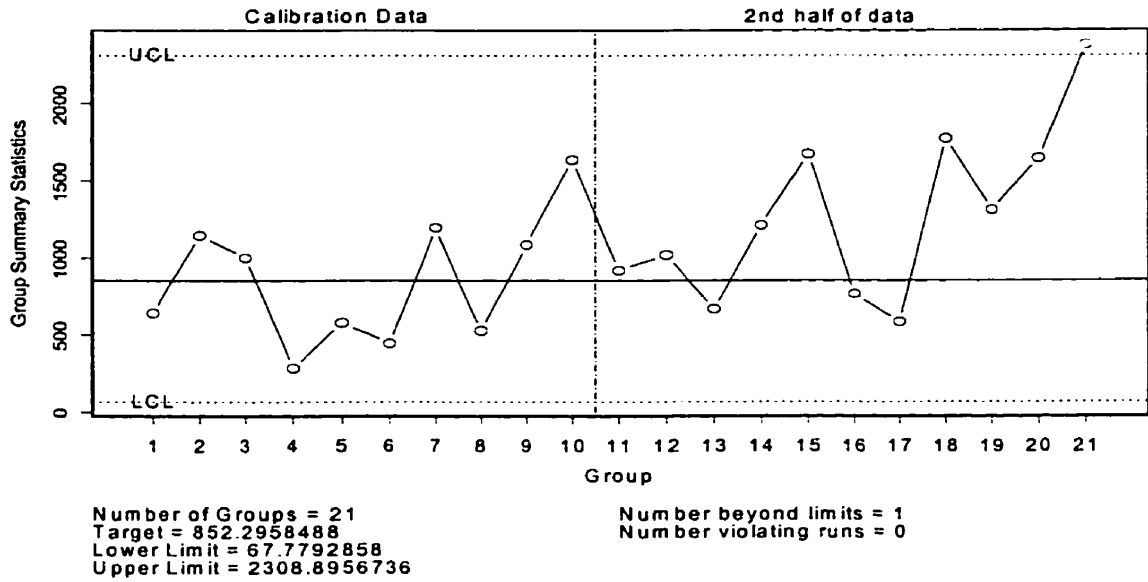


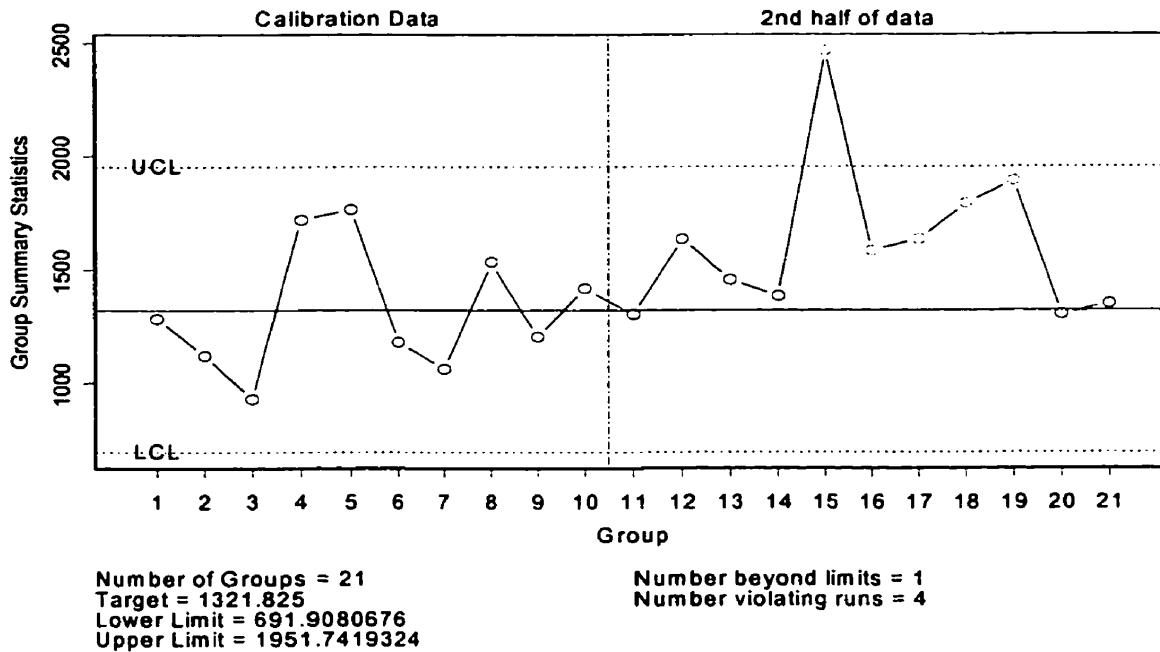
Figure 5.10 Cusum  $\bar{X}$  Control Chart for Annual Number of Fires in Canada

**Shewhart chart of s for Number of Fires in Canada**



**Figure 5.11 Shewhart S Control Chart for Annual Number of Fires in Canada**

**Shewhart chart of Xbar for Number of Fires in Ontario**



**Figure 5.12 Shewhart  $\bar{X}$  Control Chart for Annual Number of Fires in Ontario**

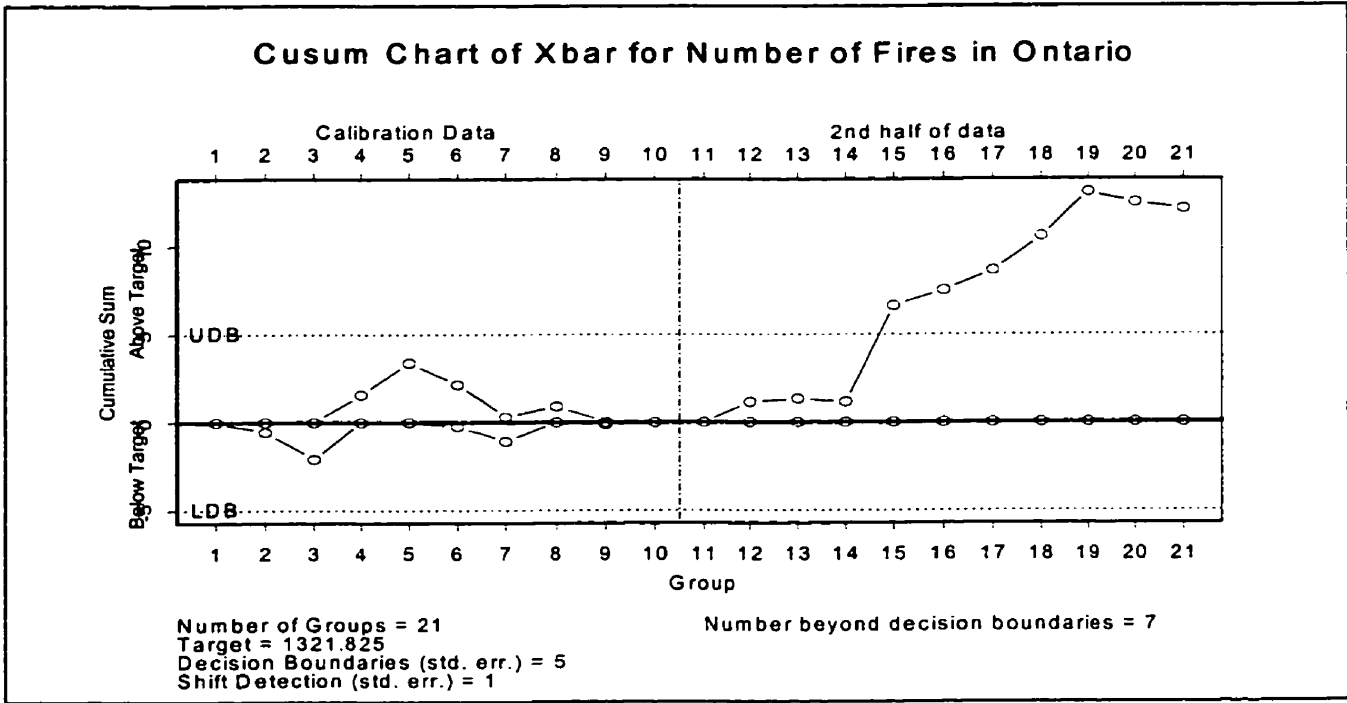


Figure 5.13 Cusum Chart of  $\bar{X}$  for Annual Number of Fires in Ontario

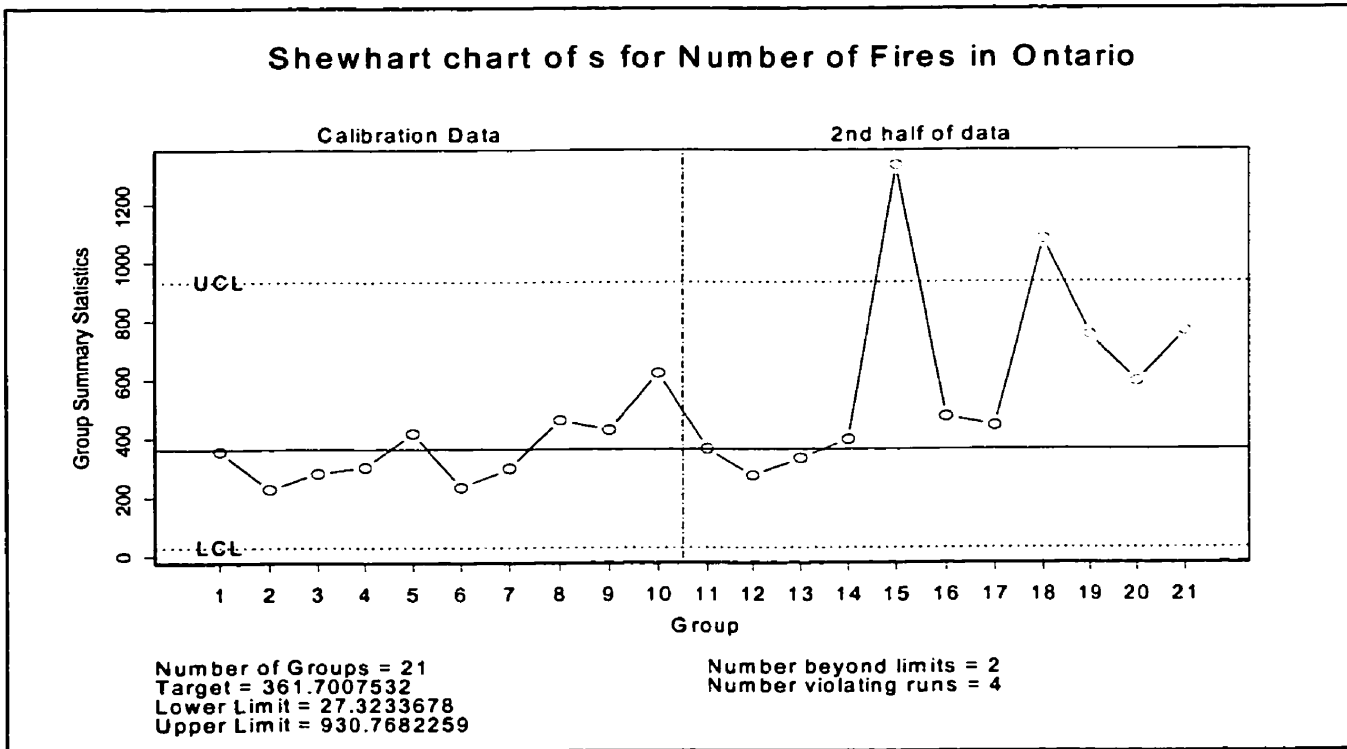


Figure 5.14 Shewhart S Control Chart for Annual Number of Fires in Ontario



#### *5.4.2 Discussion*

Quality control tests on Ontario's area burned indicate its mean just escapes control in the most recent years. The same tests on Canada's area burned dataset shows its mean and variance to be out of control, above control limits, in recent years. Because of the flaws in the record however, very little can be concluded from this except that more fires are being detected and reported as the area in which fires are detected and reported increases. The more effective the detection system and the more area under protection, the more fires will be detected, the higher annual number of fires and area burned will be. That the same test on northwestern Ontario's area burned show the same out of control result, however, is suggestive that there may be a long term increase in mean and variance of area burned, since that study area is thought to have had relatively consistent fire protection<sup>6</sup>.

#### **5.5 Summary and Conclusions**

This study revealed that the mean and variance of annual area burned has changed significantly over time, and have increased recently. The increases correspond in time to the inclusions of new areas into the record. The largest increases in burned area, for example, come after 1975, when the areas outside intensive protection began to be included in the records of several provinces. Significant increases were detected even for northwestern Ontario, however, from 1921-2000, an area which does not suffer the same

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<sup>6</sup>This region was under fire protection from the beginning of fire protection in Ontario.

biases as the national or even the all-Ontario record. Whether increases in mean and variance of annual area burned would be detected in a comprehensive national or even provincial series is unknown, since no such series is currently available. Before any changes can be detected in national-level annual area burned, however, such a series must be assembled. The series would consist of the largest possible area for which comprehensive records are available dating back to the early 20<sup>th</sup> century. The evidence of the tests conducted in this study suggests that fire activity has increased significantly in recent years.

## **Chapter 6 Conclusions: Spatial and Temporal Patterns of Fire Activity in Ontario and in Canada**

### **6.1 Spatial Point Pattern Analysis of Lightning-Caused Fires in Ontario**

A spatial statistical analysis of lightning-caused fires in Ontario from 1976-1998 was conducted using Spatial Point Pattern (SPP) analysis. A nearest-neighbour statistic, the K-function, showed fires to be found in clusters at a scale of approximately 150-200km. Kernel estimates of the spatial intensity show that these clusters are located in the northwest and in the north eastern regions of Ontario.

### **6.2 Causes of Spatial Patterns in Lightning-Caused Forest Fires in Ontario**

Attempts at using linear regression and regression tree analyses to explain the spatial clustering of lightning-caused fire occurrence in terms of fraction of lakes, rivers, roads, a number of weather variables, the density of lightning strikes, failed to yield stable or significant correlations. Kernel estimation of the spatial intensity of lightning strikes on days when the DMC exceeded 20 yielded a spatial pattern quite similar to that of lightning-caused fires. This result confirms the rule of thumb used by the OMNR, which is to predict daily lightning-caused fire occurrence based on lightning strikes in areas where DMC exceeds 20.

### **6.3 Time Series Analysis of Ontario and Canada Forest Fire Statistics**

Descriptive time series analysis of the annual area burned and number of fires in Ontario and in Canada found that the annual area burned series were best modeled as purely random, and that the annual number of fires can be modeled as an AR(1) process. Serial correlation in number of fires from one year to the next is an unexpected result. It may be caused by long term weather patterns, fuel conditions, fire suppression decisions, or some combination of these.

### **6.4 Quality Control Analysis of Forest Fire Statistics**

This study revealed that the mean and variance of annual area burned has changed significantly over time, and have increased recently. The increases correspond in time to the inclusions of new protected areas into the official record. The largest increases in burned area, for example, occur after 1975, when the areas outside intensive protection began to be included in the records of several provinces. Significant increases were detected even for northwestern Ontario, however, from 1921-2000, an area which does not suffer the same biases as the national or even the all-Ontario record. Whether increases in mean and variance of annual area burned would be detected in a comprehensive national or even provincial series is unknown, since no such series is currently available. Before any changes can be detected in national-level annual area burned, however, such a series must be assembled. The series would consist of the

largest possible area for which comprehensive records are available dating back to the early 20<sup>th</sup> century.

## **6.5 Discussion**

Kernel estimation of the spatial intensity of lightning fires in Ontario showed two areas of high fire activity—one in the northwest, the other in the northeast of the province. At a finer spatial extent, using only northwestern Ontario, the spatial intensity of annual lightning fire occurrence was similar to the spatial intensity of annual lightning strike occurrence when DMC exceeded 20. For the northwestern Ontario study area, however, the spatial intensity of annual lightning fire occurrence was quite different from spatial intensity of lightning strike occurrence over all days. This suggests that the spatial pattern of fires is caused by weather patterns of dryness and lightning that recur annually.

Time series analysis of the annual forest fire statistics for Canada, Ontario, and northwestern Ontario showed a 2-year autocorrelation in the annual number of fires. This, too, is likely caused by weather patterns. Annual area burned was found to be uncorrelated white noise, with a weak 14-year autocorrelation which, if it is not chance, is most likely due to a weather cycle as well.

Quality control analysis of the same annual forest fire statistics for the same regions showed an increase in the mean and variance of number of fires and annual area burned over the century. This too, could be caused by weather, which in northwestern Ontario

was characterized by a warming trend to 1944, followed by a benign period from 1944-1970, followed by another period of rising temperature from 1970 onward. (Saunders 2001) If the increase in fire activity is a result of climate change, then the expansion of fire suppression and increases in suppression productivity have likely made the increase smaller than it could have been. This raises an interesting question of how much area would have been burned each year in the absence of fire suppression, or put differently, how to quantify the effectiveness of fire suppression.

## **6.6 Conclusions**

The objective of this study was to use spatial statistics and time series techniques to investigate patterns in the forest fire records of Canada and Ontario. The study was successful in identifying a number of spatial and temporal patterns:

- Areas of high annual lightning-caused fire occurrence in the northwest and northeast of Ontario;
- Clustering of lightning-caused fires on a spatial scale of 150-200km;
- Areas of high annual lightning-caused fire occurrence coincide with areas of high lightning strikes on days when Duff Moisture Code exceeds a value of 20;
- Annual number of fires in Ontario and Canada has a 2-year autocorrelation;
- Annual area burned is uncorrelated white noise but in Ontario has a 14-year autocorrelation;

- The mean and variance of the annual area burned in Canada, Ontario, and northwestern Ontario has increased in the second half of the century.

The study also attempted to identify the causes of the observed patterns in weather and topographical properties such as lakes, roads, and forest type. Weather was found to be the most likely cause of the observed spatial and temporal patterns<sup>7</sup>.

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<sup>7</sup> Weather was the most likely cause of the spatial and temporal patterns found in Chapters 2, 3, and 4. If the importance of weather holds for Chapter 5, then climate change could be responsible for the long-term changes in annual area burned and number of fires. This is offered as speculation.

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