Seminar series nr 228

# Fire in boreal forests

## Climatic influences on the number and sizes of fires in recent Canadian forests and the size-area relationship in a Swedish site over the last 800 years.

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2011
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Master degree thesis in the Division of Physical Geography and Ecosystems Analysis,
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# Abstract

To assess if the fire regimes in Sweden before the strong human intervention are comparable to the recent Canadian fire regime I compared two datasets of fire numbers. A likeness could be found when comparing the Swedish and Canadian fire regimes, but due to the differences in study area (Canada: the whole state; Sweden 608km$^2$) and time span (Canada: 41 years, Sweden: 800 years), no significant result could be determined. The effective fire size (definition p. 27) were calculated for the four forest types in Canada (coniferous, broadleaf, mixed and transitional), a significant difference in the effective fire size is present when assessing the broadleafed and the coniferous forests with the other forest types.

The weather is often used to predict the fire danger, using fire indices such as the Nesterov fire index. In this analysis the correlations between the daily weather and the number of fires and the fire size were assessed over Canada. No relationship between the fire size and the weather was detected. An envelope pattern was assessed, in which the weather limits the maximum size of the fires but has no effect on the minimum size. This is most probably due to a number of additional factors limiting the spread of the fires (e.g. fire barriers).

A GLM regression model was carried out to assess if a more significant result was detected when not using a linear correlation for the correlation between the burnt area and the fire indices, but no good correlation could be found.

To test whether large scale climate pattern influence the fire pattern, a correlation was carried out between the teleconnections NAO, PNA, TNH, PT, AO, ENSO and the effective fire size, standard mean fire size, number of fires and total burnt area per year. A significant correlation was found between the standard mean fire size and the teleconnections NAO and TNH. When assessing the whole of Canada there is no correlation between the teleconnections in the northern Hemisphere and the effective fires size, number of fires and total burnt area.

Compared to other areas (e.g. Africa), the link between fires and large scale weather conditions is rather weak due to the randomness in the ignition pattern, which cannot be assessed using the available climate data.

Keywords: Geography, Physical geography, forest fire, weather, climate, teleconnection

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Degree-project 30 credits in Physical Geography. Spring 2011. Seminar series nr 228
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## Sammanfattning

För att se om brand regimerna i Sverige före större antropogena påverkningar skett år jämförbara med nutida Kanadensiska brand regimer jämförde jag två datasets av brand storlek och antal bränder. Man kan se likheter när Kanada och Sveriges brand regimer jämfördes, men eftersom sökarean varierade mycket (Kanada: hela landet, Sverige: 608km$^2$) och den temporala upplösningen (Kanada: 41 år, Sverige: 800 år), inget signifikant resultat fanns. Den ’effektiva brand storleken’ (definition s. 27) räknades ut för fyra skogstyper i Kanada (barrskog, lövskog, blandskog och övergående skog), en signifikant skillnad i den effektiva brand storleken kunde ses för barrskogen och lövskogen mot de andra skogstyperna.

Vädret används ofta för att förutse brandfara, brand indexer som till exempel Nesterov brand index. I analyserna som genomfördes här, korrelerades det dagliga vädret med antalet bränder och med brand storlekarna i Kanada. Inget samband hittades mellan vädret och brand storlekarna. Ett brev mönster kunde ses, där vädret begränsar maximum storleken men inte har någon effekt på minimum storleken. Detta beror troligtvis på att det finns många orsaker till att utbredningen av en brand skulle bli begränsad, så kallade brand barriärer.

En GLM regression modell kördes för att se om ett mer signifikant resultat var möjligt om man inte använder sig av en linjär korrelation mellan brandstorlekarna och vädret, men ingen bra korrelation hittades.

För att testa om brand mönster beror på storskaliga klimat variationer, gjordes en korrelation mellan NAO, PNA, TNH, PT, AO, ENSO och den effektiva brand storleken, standard medel brand storleken, antal bränder och total bränd area per år. Ett samband fanns mellan standard medel brand storleken och NAO och TNH. Om man tittar på hela Kanada som en helhet så kan man inte finna någon korrelation mellan NAO, PNA, TNH, PT, AO, ENSO och den effektiva brand storleken, antal bränder och total bränd area per år.

Jämför med andra områden (t.ex. Afrika), så är länken mellan bränder och storskaliga väderfenomen svag eftersom eld startnings mönstret är mycket slumpmässigt, vilket inte kan ses när det tillgängliga klimat data använts.

Nyckelord: Geografi, Naturgeografi, väder, klimat, skogsbrand, Kanada

Handledare: Veiko Lehsten, Igor Drobyshev
Masterexamensuppsats i Naturgeografi och Ekosystemanalys (30hp). Vår 2011. Seminarieuppsatser nr 228
Institutionen för Naturgeografi och Ekosystemanalys, Lunds Universitet.

## Acknowledgment

I would like to thank my supervisor Veiko Lehsten for all the help and support that he gave me, especially with the great mystery known as Matlab®. I would also like to thank Mats Niklasson for agreeing to let me use his collected fire data for Sweden. Hongxiao Jin is also given big thanks for letting me use the slope data that he had calculated for Canada. For ideas and support I would like to give thank to Igor Drobyshev for taking a critical look at the project and giving advice about how to make it better.

## Table of content

# Introduction

The Boreal forest contains 33% of the Earths forests, and is thereby the second largest biome in the world. The boreal region exists in a circumpolar with approximately the same taxa across the whole range. Approximately 20300 identified species exists in the boreal forest regions (Ruckstuhl, et al. 2008). Unlike other ecosystems large parts of the boreal ecosystems are still only sparsely populated by humans, which make it largely intact from anthropogenic influences. The Canadian boreal forest for example still consists of approximately 80% forest which is unfragmented by settlements or roads (Ruckstuhl, et al. 2008). The fact that the boreal forest is left undisturbed by humans allow large-scale natural disturbances such as fires and epidemic insects to occur with natural frequencies and patterns (Ruckstuhl, et al. 2008).

Fires are a natural part of the boreal ecosystems disturbance regimes (Granström and Schimmel 1993). Re-occurring fires are believed to be of evolutionary significance for the boreal forest (Granström, et al. 1993).

Forest fires are a major driver in the global carbon cycle and the atmospheric chemistry. It is also very important for the terrestrial ecosystem functions and the biodiversity (Girardin, et al. 2009a). About 9% of the global pyrogenic emissions of carbon come from boreal forests. The emissions from Asia’s boreal forests are almost 2.5 times higher than the emissions from Northern America’s boreal forests (van der Werf, et al. 2010).

From a anthropogenic point of view, fires can be either advantageous or disadvantageous depending on the viewpoint as well as on the nature of the fire. Low intensity fires decrease the fuel load and make access to the forest products easier, but high intensity fires destroy valuable resources, transferring large amounts of carbon to the atmosphere and pose a hazard to humans and animals (Landsberg 1997). Fire management has become more and more important as the demands on the land increases. There are many forms of fire management. Those that totally suppress the fires (plantations of thin-barked threes), those that don’t suppress the fires at all (wilderness, national parks) and those that have an integrated fire management as an integral part of the society (Landsberg 1997).

The multifaceted importance of wildfires in boreal forests shows the interest in explaining and predicting wildfire occurrence in the past as well as projecting it into the future.

### Hypothesis

Many attempts have been performed during the past to figure out the role of local meteorology, topology, climate, and land use regarding the boreal fires (Peterson 2010). Flannagan and Harrington (1988) have described how the fire size correlate with prolonged dry and warm periods. Peterson et al. 2010 have shown that it is the dry lightning that is the most important ignition cause in boreal forests. Skinner et al. (1999) have shown that regions in Canada that are under a positive 500hPa height anomalies have above average fire seasons. For the positive anomalies to have an effect they must be present for at least 10 days according to Fauria and Johnson (2006).

Three hypothesizes were tested in this project.

1. The first hypothesis of this thesis is that forest fire regimes in Canada at present and in Sweden over the last 800 years are similar with respect to the relationship between fire size and fire numbers. If such a relationship could be identified, one could predict how a natural fire regime would look like in Sweden (given the fact that Sweden has a highly advanced firefighting system).
2. The second hypothesis is that large scale climate (at 2.5 degree latitude) is a major driver of fires in boreal forests and hence a determinant of the fire size and fire number distribution. The reasons for choosing such a coarse resolution is that climate projections are typically performed at that scale. Hence if such a relationship is found, boreal forest fires can be predicted using climate projections. Such a relationship could furthermore be used in global vegetation models, i.e. LPG-GUESS.
3. If a relationship can be found on the 2.5 degree scale it would be interesting to assess if the same relationships is valid on an even larger scale. To check this, a third hypothesis is performed, that the aggregated fire characteristics over the whole of Canada correlate with large scale teleconnections affecting the northern hemisphere.

# Background

### Fire size and frequency

The fire size and frequency are parts of the fire regime, which is a part of the areas disturbance regime. The fire regime describes the fire's characteristics, such as the fires intensity, hardness, frequency, size and size distribution.

The fire size and frequency are important, as the burning of biomass has a large impact on the atmospheric chemistry which affects the climate. In Canada there are many small fires but very few large ones, but the large fires contributes much more to the total burnt area than the many small fires do. Only approximately 3% of all fires in Canada exceeds 200 hectare but they stand for 97% of the burnt area (Stocks, et al. 2002).

The frequency of fires depends strongly on the vegetation in the area (Niklasson and Nilsson 2005), i.e. a spruce forest has a fire cycle of approximately 100 years while a Jack Pine forest has a fire cycle of only 28-54 years (Larsen 1997). The fire frequency also depends on the topology and wetness of the location, the fire frequency will be higher in dry flat areas than in topographically varied and wet areas (Larsen 1997).

How large a fire will become depends much on the wind and dryness. The ideal conditions for a big forest fire would be a windy day after a long time without any precipitation (Niklasson, et al. 2005). Other factors that will influence the fire size are the extent of forest, topology, lakes and roads, fuel characteristics, season, latitude, fire management, fire site accessibility, and the number of simultaneous fires. The fire size determines the landscape patchiness and the regeneration distances (Stocks, et al. 2002). It is not only climatic factors that will affect the spread of fires but also the landscapes morphology, a variable landscape will prevent the spread of large fires by natural fire barriers. Human influence can also affect the spread of the fire by the infrastructure, i.e. roads will work as fire barriers (Archibald, et al. 2009)

### Fire cause

There are many reasons to study the ignition causes of fires in boreal forests i.e. the need for accurate assessment of the fire impacts, the development of mitigation strategies. As the boreal forests are large and remote, the fires are often left to burn without human interference (Peterson 2010). Most of the fires in Canada are ignited by lightning. In the Northern part of Canada lightning constitute nearly the only ignition cause while further south there are more human caused ones. Most of the large forest fires in Canada are lightning caused (Stocks, et al. 2002).

Different types of lightning (i.e. wet lightning and dry lightning) have different effects. Wet lightning occurs during a precipitation event, while the dry lightning occurs without. Accordingly, dry lightning are  most often the cause of fire (Peterson 2010). A forest fire very seldom starts directly when the lightning strikes, the few lightning strikes that reach the humus layer can smolder for days before the fire starts in earnest. It is normal with a delay of a couple of days after the lightning strikes to the start of the forest fire. This of course makes it hard to decide on the fire cause (Niklasson, et al. 2005).

The higher the human density the more fires will occur (Archibald, et al. 2009), which fits well with the spread of the fires in the south of Canada where the human populations are. This is probably because not only there are the natural lightning ignited fires but also the human caused fires (Stocks, et al. 2002). In Canada about 50% of the burnt area comes from fires that aren't suppressed as their locations are remote or because of efforts to let the natural role of fire in the forest ecosystems take place (Stocks, et al. 2002).

### Fire weather

Since the beginning of the 1920's researchers in Canada started to use the weather to rate the day to day danger of wildfires (Girardin and Wotton 2009b).

There are some extreme weather conditions which have been associated to the occurrence of large fires. For example droughts are associated with large fires, other weather conditions that effects the annual burnt area are the temperature, wind speed and the relative humidity (Drever, et al. 2008). Many of the large fires occur when there have been a mid-tropospheric (500 hPa) ridge over the area for more than 10 days, as these conditions gives higher temperatures and drier weather (Fauria and Johnson 2008). No precipitation over a long time will increase the fire risk as the fuel has had time to dry. If the relative humidity are over 60% the fire fuel will start to absorb the water and therefore become less flammable (Flannigan and Harrington 1988). The wind are also important for the spread and intensity of the fire (Chandler, et al. 1983).

Human caused fires are most abundant in the beginning and end of the fire season while most lightning caused fires occur in the middle of the season (Stocks, et al. 2002).

### Teleconnections effects on fires

Teleconnections are weather anomalies that stretch out over large areas (Rodionov 1994). There are several teleconnections affecting the northern hemisphere (cpc.ncep.noaa.gov, 2011-04-11). Anomalies in the mid-troposphere are a part of the teleconnections resulting from atmospheric and coupled sea/air dynamics. Fauria and Johnson (2006) and Fauria et al. 2008 report that large lightning started fires in Canada often occur when a positive mid-tropospheric height anomalies (500hPa) that persists over at least ten days during the fire season occur (Skinner, et al. 1999).

A positive Pacific North American teleconnection (PNA) has been reported to give years with many large fires in the southern Canadian Rocky Mountains (Fauria, et al. 2008).

During the last four decades large fires in Canada and Alaska have also been linked with the Arctic Oscillation (AO) and the Pacific Decadal Oscillation/El Niño Southern Oscillation (PDO/ENSO). The warm phases of PDO often produce high-pressure anomalies over North America that will stay there for long periods of time. The PDO affects the climate over long time periods (decades) while the AO and ESNO affects the climate over shorter time periods (months to a few years) (Fauria, et al. 2008).

### Boreal forests and fires

The boreal forests are located in the belt between the Arctic Circle and approximately 50° north. The forests in these regions hold more than three fourths of the world's coniferous trees and represent one third of the world's total forest area (Chandler, et al. 1983). The boreal forests are an important part of the world's carbon balance, and are present in large areas in the northern hemisphere (Amiro, et al. 2001). The Boreal forests are located in the latitudes where the highest effects of the global warming are expected. Since it is estimated that the boreal forests stores more carbon than the temperate and tropical forests together, it is important to know how the forests will react to climate change because that can change the carbon balance on a large scale (Ruckstuhl, et al. 2008).

The climate for the boreal forests is characterized of a long cold winter and a short cool summer. Freezing periods are present in the soil for the most parts of the year with a frost free period less than 120 days per year. The precipitation is low (250-600mm) but since the evapotranspiration is also low there are few water limited periods in the area. Soil moisture below one meter remains relatively constant over the year. Bogs and swamps are common in areas where the drainage is poor (Chandler, et al. 1983).

The most effective disturbance in Boreal forests is fire (Niklasson, et al. 2005). Approximately 0.7% of Canada's forested areas burn annually (Stocks, et al. 2002, Xiao and Zhuang 2007). In populated areas, this disturbance is often suppressed while its importance can still be assessed in areas where the human influence are low (Niklasson, et al. 2005). In Canada the man-caused fires are most often found in the south, in the proximity of the human settlements, while in the north the lightning caused fires dominate and stands for 80% of the total areas burnt (Stocks, et al. 2002).

A considerable amount of large fires with a size of more than 200 hectares take place in areas with dry forest fuels, strong winds and high temperatures. These fires often increase fast under favorable conditions. The fire conditions are even more favorable if there have been droughts in the forest for at least ten days but preferably longer. Droughts like this are driven by blocking high-pressure areas which leads to air subsidence, warming and drying over large areas (up to 1000km$^2$) (Girardin, et al. 2009a).

The fire frequency in the boreal forests varies depending on the forest sites. Moist boreal forests have typically a fire frequency of 200-250 years. Fires there have a high intensity (often crown fires) and cover large areas. The fire frequency is much lower if the forest is dry, typically 40-65 years. These fires are normally of low intensity (i.e. ground fires) leading to a survival of some trees of the fire.

Boreal forests are considered to be fire-prone ecosystems. Boreal forests are dynamic evolving forests that are renewed after every disturbance (Amiro, et al. 2001). The succession after a fire event in the moist areas are often even aged as large proportions of trees die in high intensity fires, while in the dry areas the successions are more mixed due to a higher tree survival caused by the lower intensity of the fire (Chandler, et al. 1983).

Many of the tree species growing in boreal forests require fires for reproduction (Niklasson, et al. 2005). Trees that are specialized "fire types" often dominate forests with dry conditions. Fire types are trees that require fires to reproduce. An example of this type of tree is the jack pine (*pinus banksiana*), the cone from this tree require fire before it releases the seeds. The cone can withstand high heats so that there are many seeds released directly after a fire (Chandler, et al. 1983).

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### Boreal forest fires with a changing climate

Climate changes also changes the weather in the fire seasons, which could change the forest fires regime, i.e. the fire frequency, size and intensity (Ruckstuhl, et al. 2008). The years with many large fires, thus large areas of burnt forests have probably increased under the last four decades of the 20th century (Fauria, et al. 2008). The increase in the number of large fires has been partially attributed to a warming climate (Fauria, et al. 2008).

The burning of large areas of forests has not only a large impact on the surface albedo but also on the emission of particles and gases such as carbon monoxide, carbon dioxide, methane, and other trace gases (Amiro, et al. 2001, Peterson 2010). An increased emission of these gases will result in a positive feedback. If the predicted climate change occur it will probably result in an increase in the fire frequency and severity in the boreal zone (Stocks, et al. 2002). These fires will release more greenhouse gases that will warm the climate more, which will give more fires (Amiro, et al. 2001). The area burnt in the northern latitudes are predicted to increase with up to 118% from today to the end of the twenty-first century if the $CO_2$ scenarios are doubled and tripled (Fauria, et al. 2008).

Also the fire severity might change if the drought regime changes due to by the climate change. If the new drought regime increases the fire severity it will impact the post-fire ecosystem structure and functions. Fires, burning deep into the soil might destroy roots, reproductive tissues and soil seed banks. A new drought regime can therefore change the forest succession pathways which can change the forest composition, structure and biodiversity (Girardin, et al. 2009b). The increased temperatures that are predicted will not only increase the fires severity and size, but also increase the length of the fire season (Fauria, et al. 2008).

## Fire indices and other fire parameters

Fire danger ratings were first developed in countries with a growing forest industry in the beginning of the 20th century where fire control systems were most needed (Chandler, et al. 1983).

There are at present a number of indices that can be used to calculate the fire risk in a location, i.e. Nesterov, Drought code, Angstrom and the Canadian forest fire weather index (Chandler, et al. 1983, Wagner 1987), of which the first three are purely based on climatic conditions. A couple of the most commonly used fire indices will be examined closer to assess which ones are the best fire predictors regarding the boreal forests.

Four fire indices have been used in this study, the number of dry days, Nesterov index, drought code and Angstrom index. Other parameters which will be considered are the growing degree day (GDD), the annual temperature and the slope.

### Angstrom index

The angstrom fire ignition index was developed in Sweden for Scandinavia. It is solely based on temperature and the relative humidity and is therefore the simplest of all the different fire danger systems considered here. A lower value indicates a higher fire risk. Values between 0 and 4 indicate some fire danger, while values above 4 indicate no risk of fire ignition (see table 1; (Chandler, et al. 1983)).

**Table 1**. The fire danger depending on the angstrom ignition index.

| Class | Ignition index |
|---|---|
| Fire occurrence unlikely | >4.0 |
| Fire conditions unfavorable | 2.5-4.0 |
| Fire conditions favorable | 2.0-2.5 |
| Fire conditions very likely | <2.0 |

### Nesterov index

The Nesterov ($Nest_d$) index is related to the fuel dryness and was developed for boreal areas. It cumulates (increases) over dry days and depends on the daily precipitation ($p_\mathrm{d}$) and the mean dew point temperature ($t_\mathrm{mean}$ and $t_\mathrm{dew}$). It will be reset to zero if the temperature is below zero degrees or if the precipitation is above 3mm/day (Lehsten, et al. 2010). The values for the fire danger from the Nesterov can be assessed in table 2 (Chandler, et al. 1983).

**Table 2.** The fire danger depending on the Nesterov fire index.

| Class | Ignition index |
|---|---|
| No fire danger | 0-300 |
| Moderate fire danger | 301-1000 |
| High fire danger | 1001-4000 |
| Extreme fire danger | 4000+ |

### Number of dry days

The more days with no precipitation following each other, the drier the fire fuel will become. This makes it easier for a fire to start (Chandler, et al. 1983). The number of days in a sequence with no precipitation (<1.5mm) will also affect the area burnt by wildfires. The 1.5mm threshold stands for the canopy interception, the amount of precipitation that would not affect the fire fuel (Flannigan, et al. 1988).

### Daily drought code

The daily drought code (DC) is widely used in Canada and has recently begun to be used in other countries too (northern Europe and northern Asia). The DC is today one of the moisture indices that many forest practitioners in the boreal area rely on (Girardin, et al. 2009a).

The drought code was first developed as a daily index for the water stored in the soil. It tracks the moisture variations in deep compact duff layers and is most often used as an indicator for the moisture content in deep layers of the forest floor. Drought in the deep organic materials is an important factor of fire severity since dry conditions there will facilitate deep burning and smoldering (Girardin, et al. 2009b).

No specific values are currently known to relate this index to a fire danger, but there are some general guidelines. A DC under 200 is considered a low value and therefore indicates a low fire risk, while a value of 300 will give a moderate risk. A drought code of 300 or more indicates that the fire will involve a burning of the deep sub-surface and heavy fuels (Girardin and Mudelsee 2008).

### Slope

The slope may have impacts on the occurrence and spread in the landscape (Jin 2010). The rate of the fire spread depends on the steepness of the slope and the packing ratio of the fuel bed. The slope will affect the fire spread more in loosely packed fuel such as grass while the slope will have a lesser effect on the dense duff which as are present in forests (Chandler, et al. 1983). If the slope ascend before the fire, the fire dry the fuel better than if there were no slope at all or if the slope is descending, this effect is most noticeable if wind is also present (Butler, et al. 2007).

### Growing-degree day (GDD) and annual temperature

The temperature is considered as one of the most important drivers of wild fires. Moderately high temperature will act as a positive factor for the vegetation growth which leads to fuel accumulation. A high temperature will also increase the flammability of the fuel (Jin 2010).

The growing degrees are the number of temperature degrees above a certain threshold temperature. This threshold temperature is the temperature below which the vegetation growth is negligible. The daily mean temperature minus the threshold temperature is calculated for every day resulting in the growing-degrees. The growing-degrees day is the accumulated growing degrees from the previous days added to the present day, this way all the days contribute to the GDD as the season progresses (Womach 2005).

# Data

### Fire data Sweden

Fire data of a Swedish forest with fires dating from 1232-1901 were used in this project.

The data is collected by Mats Niklasson (Niklasson, et al. 2000) in an area in northern Sweden (fig. 1). The collection is performed through the analysis of tree rings and their fire scars. The study area is 608 km$^2$, and 19x32km large, the center of the area is located at 63°56’N, 18°48’E.

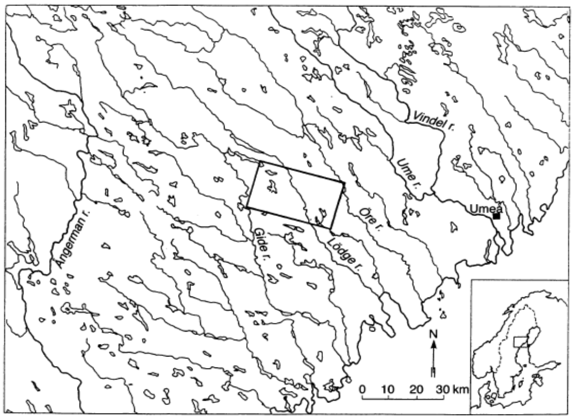


**Figure 1.** The fire search area in Sweden 63°56’N, 18°48’E, the map was used with permission of the author (Niklasson and Granstrom 2000)

203 sample points is established for the dating of the past fire events. Each sampling point represents an area of approximately 3.0 km$^2$ with an average 1.7 km between the points. Totally 1152 samples are collected, on average 5.7 samples per sample point. From living trees 147 samples are taken and 1005 samples are from dead trees (Niklasson, et al. 2000).

The area has a river (Lögde) running through the central part of the study area. There are many lakes in the area, most of them are small, but they cover about 5% of the area. Peatlands cover about 15% of the area. The elevation ranges from 200-500 m above the sea level. Scots pine (*Pinus sylvestris L.*) and the Norway spruce (*Picea abies* L. Karst.) are the dominant tree species in the area. There were also some broadleaved tree species. The birch (*Betula pendula, B. pubescens*) was the most common, but Aspen (*Populus tremula*), Sallow (*Salix caprea*) and Alder (*Alnus incana*) were present (Niklasson, et al. 2000).

### Fire data Canada

I used the fire data from Canadian Large Fire Database (LFDB cwfis.cfs.nrcan.gc.ca). In this database, all fires larger than 200 hectares within Canada are potentially recorded. The data used are from 1959-1999. The database contains information on location, burnt area, fire start date, ignition source and eco zone of fire origination.

The development of the database began 1989. Wild fire reports are collected from all Canadian fire management agencies for the period after 1980. The fires was then digitized and mapped in a Geographical Information System (GIS). The LFDB have since then been expanded to include all large fires as far back as the agencies have records for them. All these fires have not been digitized as polygons yet but they can be found as attribute information from 1959-1997. It was decided to only have the fires larger than 200 hectares, because even if only approximately 3% of the fires reaches 200 hectares, these fires still represent 97% of the burnt area (Stocks, et al. 2002).

The data in the database from 1959-1970 are incomplete to a larger extend than the remainder of the data. This makes analyses over that time period uncertain.

Other limitations with the database are that the burnt areas are estimated from the analysis of satellite images, more recent fire size estimates are thought to be more accurate. (Stocks, et al. 2002). The database can also be biased due to the forest management practices, forest fires in low priority areas may not be as well documented as the fires in high priority areas, where the fires may have a greater impact on the public safety, property and forest resources (Xiao, et al. 2007).

### Land cover data for Canada

The land cover data over Canada was taken from geogratis.cgdi.gc.ca and is present as the vegetation cover map included in the fifth edition of the National Atlas of Canada.

The data was derived from the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA satellites which have a resolution of 1.1km. From the AVHRR dataset twelve different land cover types were classified. The data was performed using approximately 45 satellite images spanning four years, only images taken during cloud free conditions were suitable for the interpretation and classification. The classification of the data was performed using a combination of supervised, automated, “maximum likelihood”, and manual classifications. After this first classification a filtering process was then carried out to reduce visual noise. This was carried out by only keeping areas that have a minimum of four contiguous pixels, some exceptions to this rule was performed. Some manual editing was performed to complement the automatic techniques. 11 land cover types were classified (Appendix A1) where four forest types can be assessed in table 3.

The raster data was then converted to a vector with a polygon topology structure coded with the thematic values of the raster. A generalization of the vector data was performed and all areas smaller than 50 square kilometers was eliminated for the 1:7 500 000 scale map (Palko, et al. 1996).

**Table 3.** The definition of the four forest types according to Palko et al. 1996

| Forest type | Definition |
|---|---|
| Coniferous | 76-100% of the canopy is composed of coniferous trees |
| Broadleaf | 76-100% of the canopy are composed of broadleaf trees |
| Mixed | 26-75% of the canopy are composed of coniferous or broadleaf trees |
| Transitional | Tree cover is discernable but forest land occupies less than 50% of the area |

### Climate data Canada

The climate data (precipitation, temperature, humidity and convective rainfall) were taken from the National Center for Environmental Prediction (www.ncep.noaa.gov). The climate data was in the format lat/long 2.5 x 2.5 degree grid cells with the daily values for the years 1959-1999 (Kalnay, et al. 1996).

### Slope data Canada

The Canadian slope data used was given in a lat/long 2.5x 2.5 degree grid cells over the same areas as the climate data. The slope data were derived from Hongxiao Jin using the global digital elevation model (DEM) *GTOPO30 dataset*, with 30 arc-seconds (i.e. 1˚/120) resolution and with 90˚N to 60˚S spatial coverage. The dataset is available electronically at the USGS Earth Resources Observation and Science (EROS) Data Center. The data was used to calculate the slope from the height data in the DEM the mean and the 95% slope in the 2.5x2.5 degree grid cells. The used Matlab®-script is attached in appendix 2 part 1.

### Teleconnection over the Northern hemisphere

The monthly value of four teleconnections in the northern hemisphere, North Atlantic Oscillation (NAO), Pacific/ North American Pattern (PNA), Tropical/ Northern Hemisphere Pattern (TNH), Pacific Transition Pattern (PT), Arctic Oscillation (AO) and for the El Niño southern Oscillation (ENSO) were downloaded from the web site NOAA, National weather service center, Climate prediction center (www.cpc.ncep.noaa.gov).

# Method

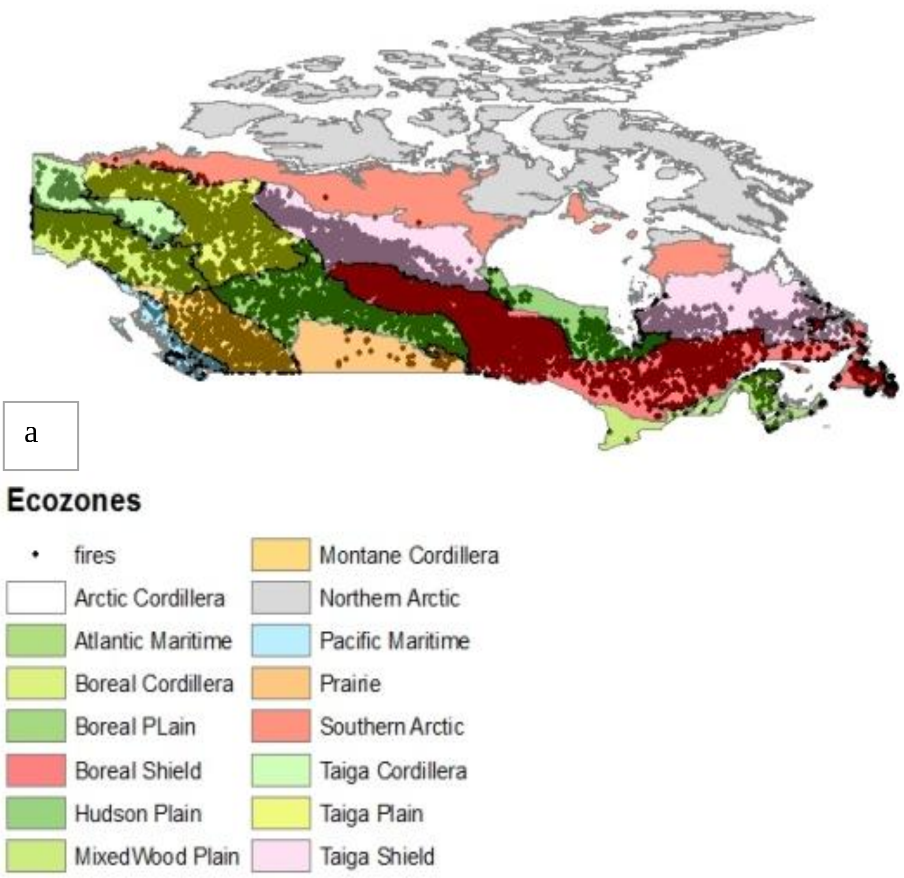
### Canadian fire data

First the data was downloaded from the Canadian large fire database and examined to perform some exploratory data analysis. A linear correlation between the total burnt area and the number of fires per year was calculated to assess if the relationship was significant.

The total burnt area and the number of fires per month were used to assess the difference in fire activity over the year (the fire seasonality). Only the fires with a known starting date were used. The fire season was visualized in a diagram where seasonality easily could be detected (Fig. 11).

After the relationships were displayed, the Canadian fire data was imported in ArcGIS® to get a better overview of the spatial fire distribution. There were large areas of Canada with no fires and some areas with many fires. Canada was then divided in fifteen ecozones to test if there was a relationship between the ecozones and the number of fires (see Fig. 2a). The ecozones where most of the fires were present in are the Taiga plain, Taiga shield, Boreal shield, Boreal plain and the Boreal Cordillera (sis.agr.gc.ca). Visual inspection showed that the spatial fire distribution in Canada seemed to relate to some of the ecozone borders but not to all of them. Therefore another approach was performed, where the fire distribution was related to the land cover type. The fire distribution regarding the land cover followed the border of the land cover classes better than the borders in the eco zone map (Fig. 2b), therefore the following analyses will be performed with respect to the land cover types instead of the ecozones.  An overlay was used on the land cover and fires to combine them.

**Canada divided in ecozones showing the fire distribution**



**Canada divided in landcovers showing the fire distribution**

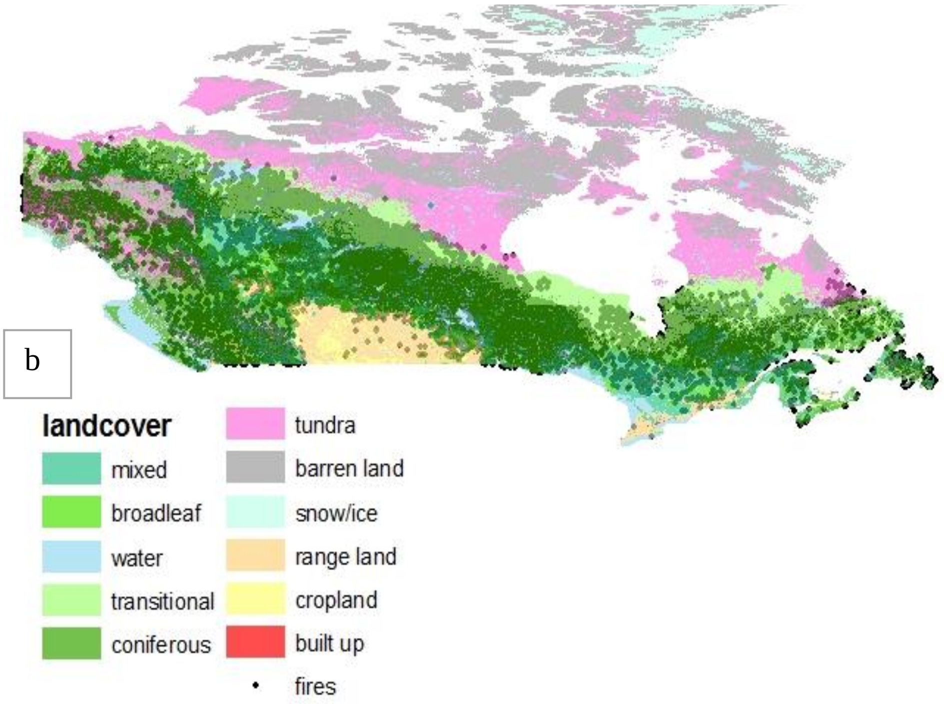


**Figure 2.** The spatial distribution of the forest fires in Canada. The map in panel **a** is divided by the ecozones and the map in panel (http://sis.agr.gc.ca/cansis/nsdb/ecostrat/gis_data.html), **b** is divided according to the land cover (geogratis.cgdi.gc.ca).

**The effective fire size**

All the following calculations were made in Matlab® and can be found in the Matlab script in appendix 2 part 2. I defined the effective fire size as the fire size which mostly contributed to the total burned area. The distribution of fires size versus number of fires shows that the smaller fires are the most frequent ones (Fig. 3). However, this does not allow to directly asses the contribution of fires of a certain size class to the total burned area. The distribution of the fires seemed to be following an exponential curve.

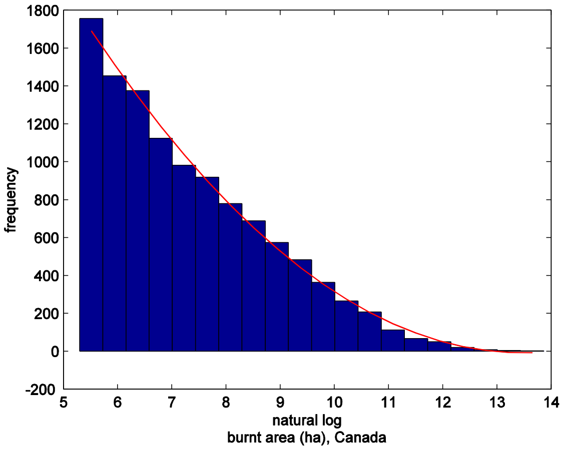


**Figure 3.** A frequency histogram with the fire size in natural logarithmic hectares. The line shows an exponential curve in red.

The frequency (y bars in figure 3) was multiplied with the burnt area (x values for the bars). The resulting density distribution histogram resembles a normal distribution curve (fig. 4). A fit with the normal distribution curve (red line resulted in an r-square value of 0.97). From the density distribution histogram the mean size of the fire sizes could be calculated. The mean shows which fire size class will contribute most to the total burnt area, i.e. the effective fire size. The effective fire size was calculated using a Gaussian normal distribution formula, where μ stands for the effective fire size.

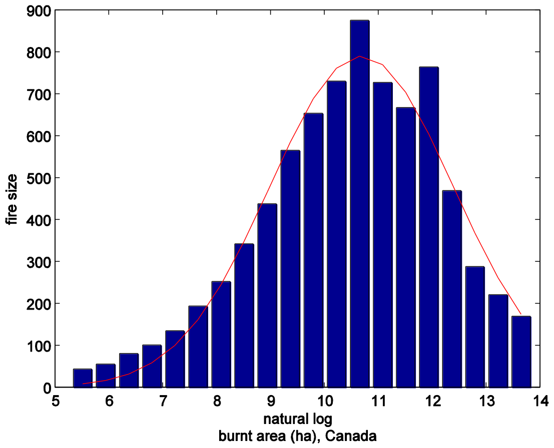


**Figure 4**. A density distribution of the burnt area with a normal distributed curve in red

Additionaly the standard mean was calculated using the Normfit function in Matlab®.

The effective fire size and standard mean were calculated for each year. It could then be assessed if the effective fire size changed on a yearly basis, and if there was a changing trend present during the time period that was examined. When using just one year at a time the histograms do not fit very well to the functions as there are less fires to use. In some of the years the distribution did not drecease towards large fires, which lead to a difference in the effective fire size and the standard mean which otherwise have approximately the same value (fig 5).

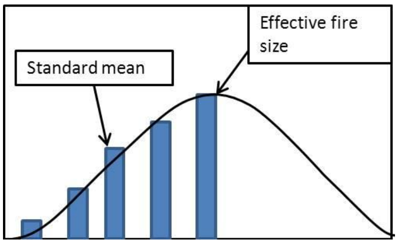


**Figure 5.** The difference between the effective fire size and the standard mean

The effective fire size and standard mean were calculated for the four forest types (coniferous, broadleaf, mixed and transitional). A box plot was created to assess if there was a significant difference between the forest types. To assess if the effective fire size changes over the time a time series was performed from the yearly data.

### Weather data

The fire indices that depend on the weather were calculated to assess if a relationship existed between the number of fires, the fire sizes and the weather. The climate data was downloaded for the precipitation, cumulative rainfall, relative humidity and for the air temperature as daily data over 41 years in 284 grid cells (2.5x2.5 degree) all over Canada.

The temperature and precipitation had to be re-scaled before they could be used in the equations for the fire indices, since in the equations for the fire indices they were in a different format. The temperatures in the climate data were in degrees Kelvin but all the fire index functions were calculated using degrees Celsius, therefore the temperature was converted to Celsius. The precipitation also had to be converted as it came in the precipitation rate kg/m$^2$/s and it was needed in the format mm/day.

The “drizzle effect” is an effect that is present when assessing precipitation on a large scale. When a large grid cell has one precipitation value that stands for the whole cell, there will almost always be some local precipitation somewhere in the cell which will affect minimum precipitation. By subtracting the total precipitation with cumulative rainfall the drizzle effect is at least partially circumvented. The cumulative rainfall was converted from kg/m$^2$/s to mm/day before it was used.

### Calculation of the fire indices

#### *Angstrom ignition index*

The Angstrom fire ignition index was calculated according to equation 1.

$$I = \left(\frac{R}{20}\right) + \left(\frac{27 - T}{10}\right) \qquad \text{Eq. 1}$$

The R stands for the relative humidity in percent and the T is the air temperature, and the I for the angstrom fire index (). Here the minimum of the relative humidity and the maximum of the temperature were used (Chandler, et al. 1983).

#### *Nesterov fire index*

Before the Nesterov could be calculated the dew point temperature had to be calculated using the dew point equation. The Nesterov index was then calculated based on the equation 2 (Foken 2003, Lehsten, et al. 2010).

$$Nest_d = \begin{cases} (t_{mean} - t_{dew})t_{mean} + Nest_{d-1} & P_d < 3mm \text{ and } P_d > 0\,°C \\ 0 & P_d \geq 3mm \text{ and } P_d \geq 0°C \end{cases} \qquad \text{Eq. 2}$$

The *Nest*$_d$ are the Nesterov ignition index, the $p_d$ are the daily precipitation and the $t_{mean}$ and $t_{dew}$ are the mean and dew point temperature.

***The daily drought code (DC)***

Before the daily drought code could be calculated some pre-calculations were required. The parameter L, which is the standard day length adjustment factor (Wagner 1987) was imported from Wagner 1987 (appendix A2), but since here only monthly values are given, it was interpolated to daily values.

The daily drought code was then calculated following the equations found in Girardin et al. (2009b). First the potential evapotranspiration (PET) was calculated, then the effective rainfall after interception of the canopy and surface fuel.

Now the moisture equivalent in the layer after interception (Q(r)) could be calculated (equation 3). Here a starting value for the DC is needed. The DC value 15 is often used as a starting value for the first of May according to Girardine et al. (2009b), hence it was decided it would be used here too. Equation 4 was used to calculate the drought code.

$$Q(r) = \begin{cases} 800e^{(-DC/400)} + 3.937R_{EFF}, & r < 2.8 \\ 800e^{(-DC/400)}, & r \geq 2.8 \end{cases} \qquad \text{Eq. 3}$$

Q(r) is the moisture equivalent in the layer after interception, DC is the daily drought code, $R_{EFF}$ is the effective rainfall after interception of the canopy and surface fuel, r is the precipitation.

$$DC = 400 \ln\left(\frac{800}{Qr}\right) + 0.5 * PET \qquad \text{Eq. 4}$$

DC are the daily drought code, Qr are the moisture equivalent in the layer after interception, PET is the potential evapotranspiration.

***Number of dry days***

The number of consecutive dry days was calculated using a precipitation threshold of 1mm/day.

***Slope***

No calculations for the slopes were needed. The mean slope for the whole grid cells was used.

***Annual temperature***

The annual temperatures were calculated by taking the daily mean temperature and calculating the mean per year and grid cell.

### *GDD*

The growing degree days (GDD) were calculated by taking the maximum temperature for each day and adding the temperatures with the previous days. This was carried out only with the days with a temperature between 5 and 30°C.

### *Fire season*

It was decided to only to consider the yearly fire season which was estimated to be between the beginning of April and the end of September (90-273 day of the year; see Figure 6). Only the fire indices for the days between 90 and 273 were included in later analyses. After the fire indices had been calculated for each day, the maximum value for each year and location were calculated.

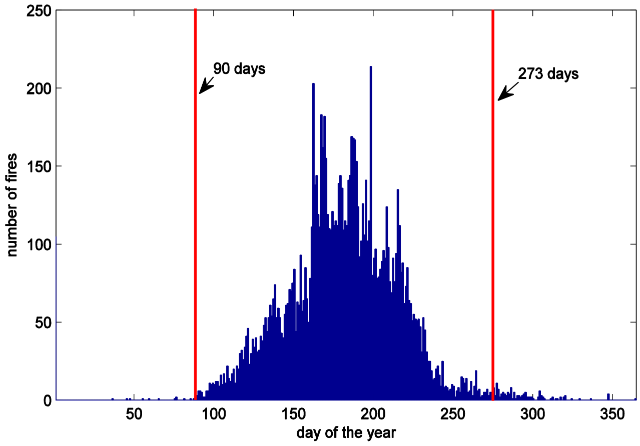


**Figure 6.** The number of fires per day of the year, with red lines where the fire season starts and ends

## Statistical analysis

### *Grid cell correction & proportion*

Before it was possible to compare the fires and the fire indices, the fires had to be divided into the grid cells just as the fire indices. To do that the individual coordinates of the fires were used to identify which grid cell the fire belonged to.

The area for the cells had to be calculated to get the proportion of burnt area per fire in the grid cells. As the Earth is round the grid cells that have the same degrees in grid cell get different areas along the latitude as can be assessed in Figure 7, a change in longitude would not change the grid size. A correction for the size of the grid cells for the latitude was performed with the equation below (badc.nerc.ac.uk) (equation 5). In the equation 5 the λ stands for the longitude, φ for latitude (both are expressed in radians). R is the Earth radius, 6371 km.

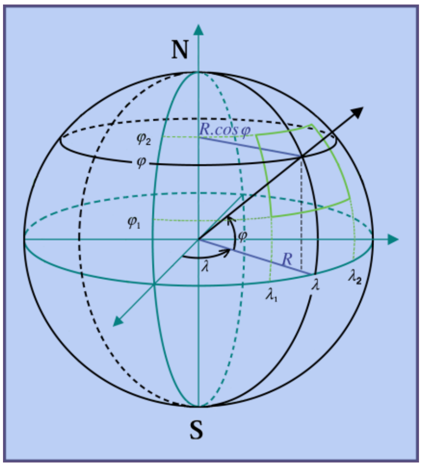


**Figure 7.** a visual picture over how the cell size will change over the latitude

$$S = \int_{\varphi_1}^{\varphi_2} R \left( \int_{\lambda_1}^{\lambda_2} R\cos\varphi \, d\lambda \right) d\varphi = R^2 (\lambda_2 - \lambda_1)(\sin\varphi_2 - \sin\varphi_1) \qquad \text{Eq. 5}$$

The proportion of the fire size was then plotted in a scatter plot. Some fires were larger than 1 and were therefore given the value 1, as that should be the maximum value in a proportion plot. When assessing the proportions of burnt area per grid cells, the fires are smaller than 50% of the grid cells, which seems reasonable, but then there are some anomalies that can be assessed. An explanation to the anomalies is that the fires can be larger than the land area in the grid cell which will give it the maximum proportion value of one in plot (fig. 8).

### *Correlation of the fire indices*

A linear correlation was performed between the maximum fire indices value reached during the fire season and the fire sizes, to assess if a relationship exists between the weather and the fire sizes.

### *Generalized linear model regression (GLM)*

To assess if the fire indices could predict the size of the fires, a generalized linear model regression was used. Before the logistic regression model could be parameterized the burnt area ratio for each grid cell had to be calculated, the ratios were calculated depending on the forest type, and then pooled for all types.

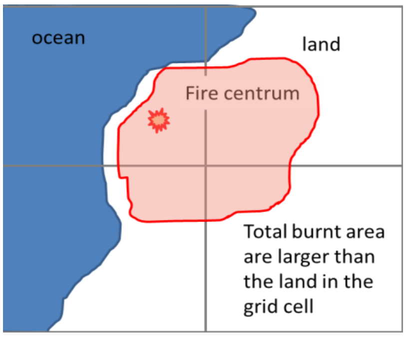


**Figure 8.** This example shows four grid cells and how the fire area can be larger than the land area in one grid cell

This required a vector map of the grid 2.5x2.5 degree grid cells. Thiessen polygons were created using the center coordinates of the grid cells. An edge effect was corrected by manually editing the polygons. To know where the edges of the polygons should be, the coordinates of the grid cells corners functioned as guidelines for where the edges of the grid polygons should be. An overlay between the grid cell polygons and land cover was performed.

The ratio of the burnt area in each grid cell could now be calculated for each land cover type, and be used in the following analysis e.g. in the linear regression model.

The Generalized linear regression model was parameterized using the GLM fit function in Matlab®, with a logit link function. The modeled response curve to follows a unimodal distribution, see equation 6.

$$b_a = \frac{1}{1 + e^{-\left(a + \sum_{i-1}^{5} l_i v_i + l_i v_i\right)}} \qquad \text{Eq. 6}$$

### *Large scale fire correlations, Canada's mean*

To assess if there was a relationship between the climate and fires on a larger scale Canadian mean values were used. A linear correlation was carried out between the maximum teleconnections (table 4) the total burnt area, the number of fires and the effective fire size per year for all of Canada (1959-1999). A correlation between the fires and the fire indices over Canada were also performed to assess if a relationship could be discerned on such a large scale.

# Results

## Overview

When assessing the spatial distribution of the fires over Canada, it followed the land covers better than the eco-zones. The fires occurred mostly in the classes coniferous, transitional, mixed, broadleaf and water (decending order), all of which are forest types, except for the water.

The connection between the number of fires and the total burnt area each year is displayed in Figure 9. A linear correlation between them was tested, as can be assessed in figure 10, the correlation between burnt area and number of fires was good but not very strong, with a $R^2$ of 0.69 and a P-value below 0.001. During the investigation period of 41 years, the total burnt area per year is roughly one to two million hectares, but during six years the burnt area was much larger, over four million hectares. The years with large areas burnt are all present after 1979, that can either mean there are more large fires after 1979 than in the past, or it can depend on the fact that before 1970 the registrations of fires in Canada were much less reliable than today (Stocks, et al. 2002).

From summarizing the fires by the months, it can assess that the fire season in Canada is between April and September (fig. 11). A linear correlation between the number of fires and the total burnt area per month showed a strong relationship between them ($R^2$ = 0.98, P=0.00).

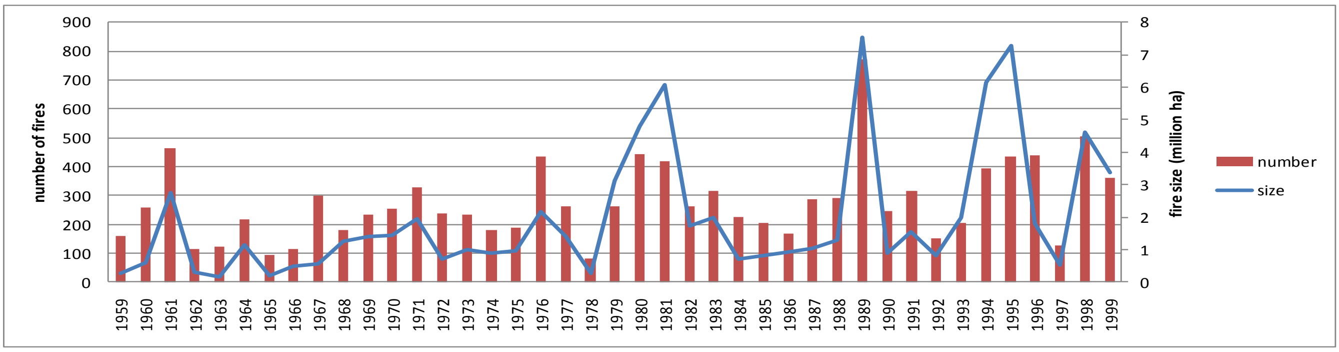


**Figure 9.** The total burnt area and number of fires per year, 1959-1999

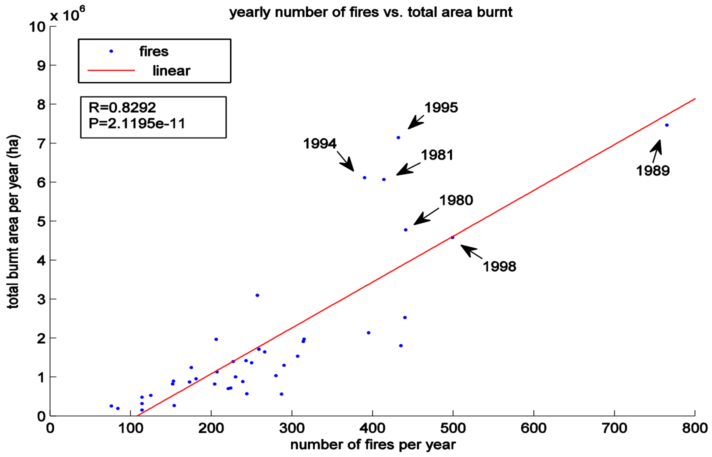


**Figure 10.** Correlation between the number of fires per year and the total burnt area (ha) per year

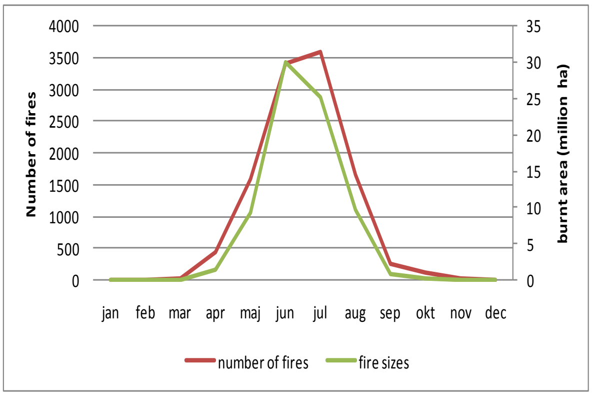


**Figure 11.** Monthly total burnt area (million ha) and the number of fires per month

To assess if a trend was present in the fires over the years a time series analysis was performed (see Fig. 12). It was performed for all the 41 years 1959 to 1999. A positive trend can be assessed over the time period 1959-1999, but if the time period is divided in 1959-1970 and 1970-1999 no trends can be found (table 4). The slope shows the difference in hectare from the start of the time series to the end of the time series.

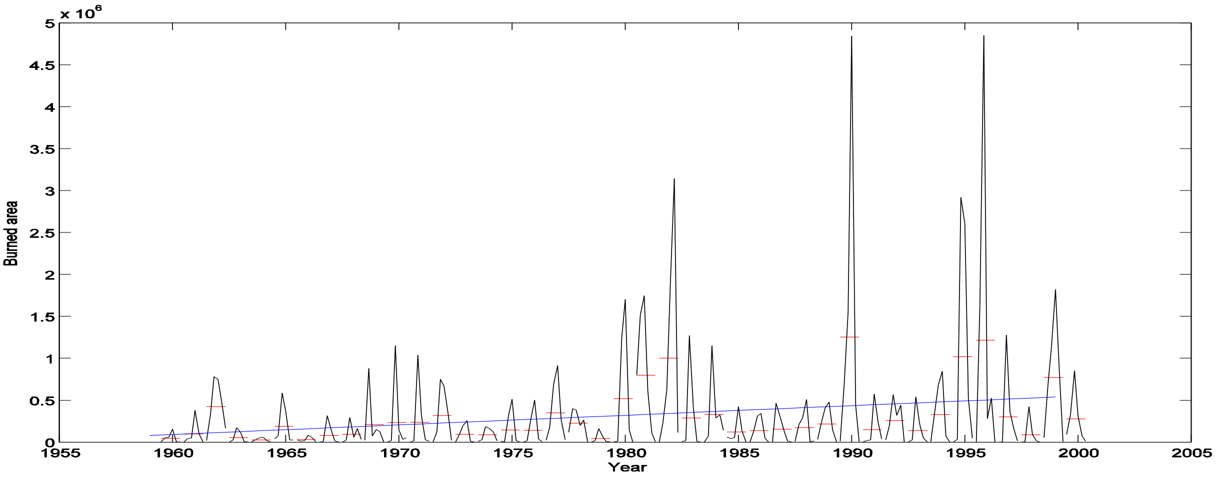


**Figure 12.** Time series where a positive trend can be assessed in the burnt area per year. Blue=trend, Red=yearly mean, Black=fire size

**Table 4.** The $R^2$, p and slope of the burnt area/year

| Time period | $R^2$ | p | Slope (ha/yr) |
|---|---|---|---|
| **1959-1999** | 0.18 | 0.01 | 11441.96 |
| **1959-1970** | 0.05 | 0.49 | 7159.43 |
| **1970-1999** | 0.09 | 0.12 | 11565.47 |

A time series over the months of the fire season was also performed (Fig. 13). During the fire season, the months June and July have a significant positive trend while the other months lack a significant trend (table 5).

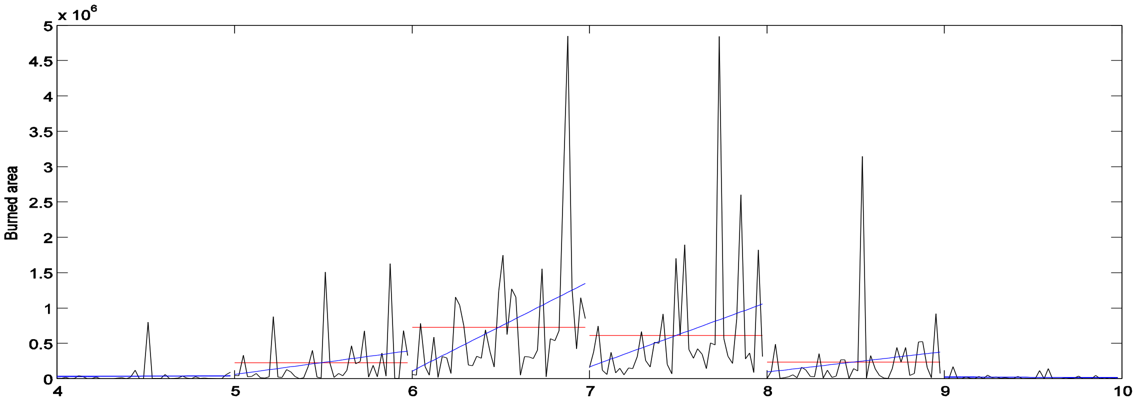


**Figure 13.** Time series that shows the seasonal change over the fire season (April to September). Blue=trend, Red=mean, Black=fire size

**Table 5.** The $R^2$, p and slope for the months present in the fire season

| | 1959-1999 | | | 1959-1970 | | | 1970-1999 | | |
|---|---|---|---|---|---|---|---|---|---|
| | $R^2$ | p | Slope (ha/yr) | $R^2$ | p | Slope (ha/yr) | $R^2$ | p | Slope (ha/yr) |
| **April** | <0.005 | 0.77 | 495.37 | <0.005 | 0.92 | -119.60 | <0.005 | 0.73 | -1094.15 |
| **March** | 0.07 | 0.09 | 8281.30 | 0.02 | 0.63 | 10999.03 | 0.06 | 0.19 | 11218.76 |
| **June** | 0.18 | 0.01 | 30960.61 | 0.26 | 0.09 | 57902.49 | 0.11 | 0.07 | 36643.39 |
| **July** | 0.09 | 0.05 | 22241.72 | 0.10 | 0.33 | -17081.12 | 0.03 | 0.37 | 18761.08 |
| **August** | 0.03 | 0.30 | 7077.67 | 0.04 | 0.55 | -7193.59 | <0.005 | 0.74 | 4115.10 |
| **September** | 0.02 | 0.42 | -404.93 | 0.01 | 0.72 | -1550.63 | <0.005 | 0.72 | -251.33 |

### Swedish vs. Canadian fire regimes

The fire distribution in both Canada and Sweden showed that there are more small fires than large fires present in the two countries.

When comparing the Canadian and Swedish fires some things always have to be remembered like the fact that no Canadian fires less than 200 hectares are part of the data set. Likewise the different scales in data sets have to be considered, both in the area examined and the number of years present. In the histograms below the number of fires can be assessed when the fire size is expressed in a logarithmic scale on the x-axis (figure 14).

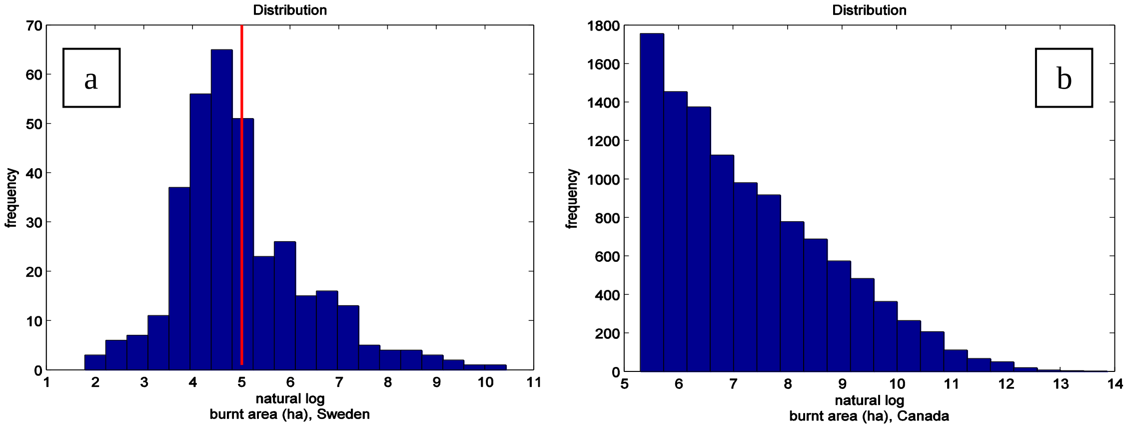


**Figure 14.** The fire frequency in Sweden (panel a) and Canada (panel b), The red line in the Swedish histogram shows the threshold for where the fires are smaller than the fires in Canada

The histograms should only be compared where they overlap. This is because fires smaller than 200 hectares are present in the Swedish but not in the Canadian fire data and the really large fires are only present in Canada. One reason for this is that the research area in Sweden was only 608km$^2$ (19x32km) and the research area in Canada was the whole country (9093507 km$^2$). Since Sweden is smaller than Canada it is impossible to get the same distribution curves for the two countries. An investigation of how the scale effect affects the distribution will not be performed in this work as it is outside the scope of a master thesis.

Assessing the histograms with the x-axis value of five and higher, the same shape can be assessed in the two histograms. This could mean that the number of fires in Canada and in

Sweden follow the same pattern. The histogram for the fires of Canada has a more even shape than the Swedish histogram, and that can be explained by the fact that there are more fires present in the large area of Canada than in the much smaller Sweden, even if the fires in Sweden were occurring over a longer time period.

The Swedish and Canadian effective fire size (Fig. 15) also show a similar pattern when assessing the overlapping parts of the histograms, which also points in the direction that the fire sizes follow the same distribution in the two countries.

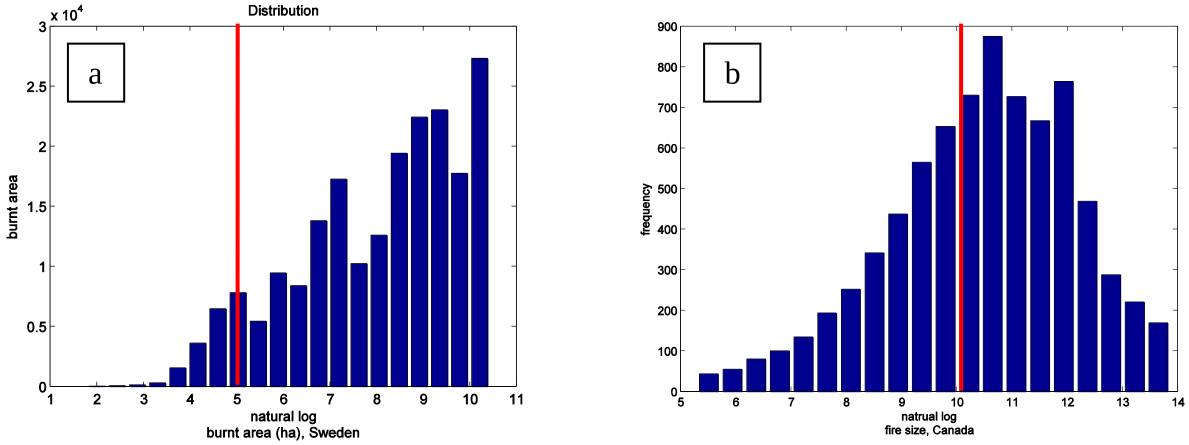


**Figure 15.** Comparing the Swedish (panel a) distribution diagram with the Candian (panel b) frequency diagram. They overlap between 5 and 10 log ha.

The Swedish research area is dominated by mostly coniferous forest. In Canada the fires of four different forest types were examined. The coniferous forest fires were most similar to the Swedish coniferous forest fires while the fire distribution in the other three forest types was different. This means that it is important to have the same type of forest when comparing the fire regimes in different areas. When assessing at the forests all over Canada the coniferous forest is the dominating type.

### Effective fire size

The effective fire size was calculated for all the fires in Canada and for the different forest types. In the density histogram (Fig. 4) it can be assessed that the fires which have the most effect are not the small fires that frequently happen and not the large infrequent fires but the fires with a size between the two extremes.

In figure 14 the effective fire size for the four different forest types in Canada can be assessed. The interpretation of the boxplot are that the red line stands for the median, the boxes stretch from the 25 percentile to the 75 percentile, the whiskers include the extreme points that are present without being a outlier, the red crosses stands for the outliers. When comparing the medians the notches in the boxes are used, they show the 95% confidence interval. If the notches overlap the true medians do not differ significantly (mathworks.com).

Figure 16 shows that the broadleaved and coniferous forests differed significantly from the other forest types that had approximately the same effective fire size. The broadleaved forest had smaller effective fire size than the others forests and the coniferous forest had larger effective fire size (fig. 16).

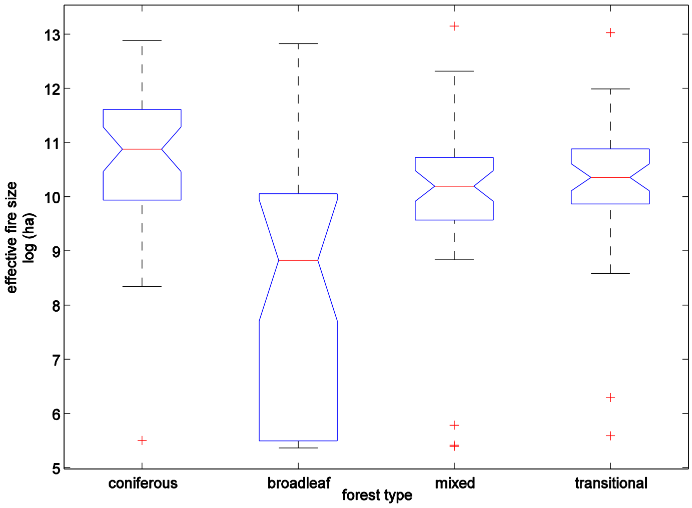


**Figure 16.** A boxplot showing the effective fire size for the four forest types. The Effective fire size is in natural logarithmic hectares.

A time series for the effective fire size for each year was performed, to examine if any patterns or inter-annual variation could be detected (Fig. 17). The coniferous, mixed and transitional forests seem to follow approximately the same pattern. While the broadleaved forest has the same effective fire sizes as the other forest types at the peaks, but the lower values differ much from the other forest types.

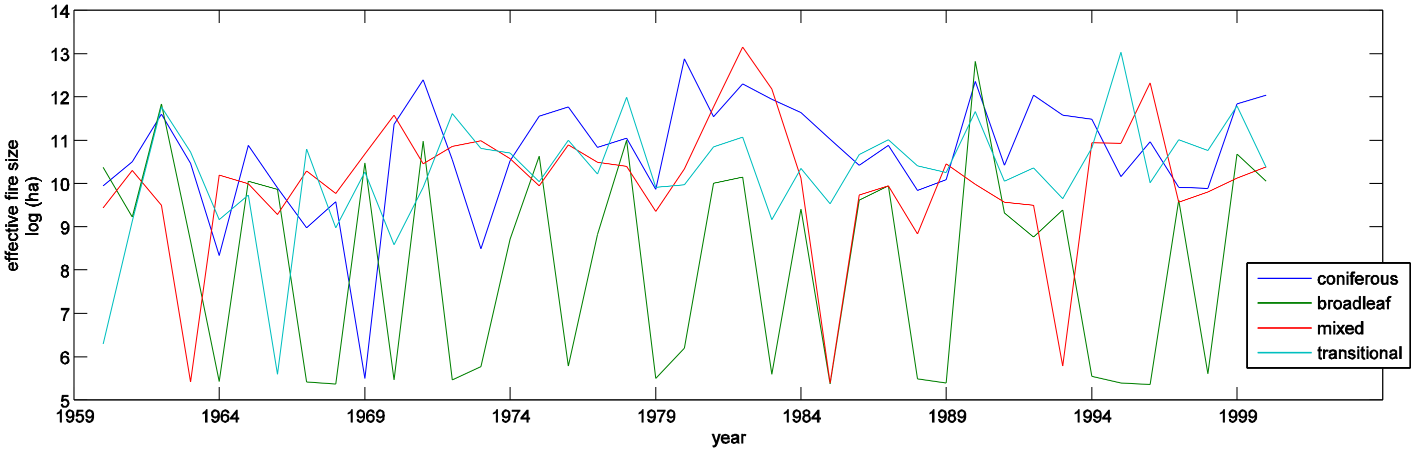


**Figure 17.** The effective fire size during the years 1959-1999. The effective fire size is visualized in the natural logarithm for the hectares.

A time series analysis was performed, to assess if any trends could be found in the effective fire size or the standard mean fire size (fig. in Appendix B1, B2). The effective fire size showed no overall trend, and while the standard mean size showed a significant trend when assessing all the fires and the fires in the coniferous forest areas (table 6). When making the time series with the fires divided into the four forest types, the effective fire size showed significant changes in the coniferous, broadleaf and the mixed forest, while the standard mean fire size show significant changes in the broadleaved, mixed and transitional forest.

**Table 6.** The $r^2$, p and slope of the effective fires size and standard mean trends

| | Effective fire size | | | Standard mean | | |
|---|---|---|---|---|---|---|
| | $R^2$ | p | slope | $R^2$ | p | slope |
| **all** | <0.005 | 0.94 | <0.005 | 0.15 | 0.01 | 0.03 |
| **coniferous** | 0.10 | 0.05 | 0.04 | 0.11 | 0.03 | 0.02 |
| **broadleaf** | 0.01 | 0.63 | -0.02 | <0.005 | 0.67 | -0.01 |
| **mixed** | 0.00 | 0.79 | 0.01 | 0.06 | 0.11 | 0.02 |
| **transitional** | 0.18 | 0.01 | 0.05 | 0.08 | 0.09 | 0.02 |

### The weather as the driver for the fire sizes

When assessing the weather as the determining factor for the fire size, the fire indices for the grid cells in Canada were used, (a maximum value for each year and grid cell was calculated). A visualization of the burnt area per fire versus the fire indices was performed, where no correlation could be found. A envelope pattern could be found for all the fire indices except the slope. The pattern shows that the maximum size a fire can reach depends on the value of the fire index, but just because the fire indices have a high value a fire that occurs does not have to be large it is just as probable it will be small (fig. 18).

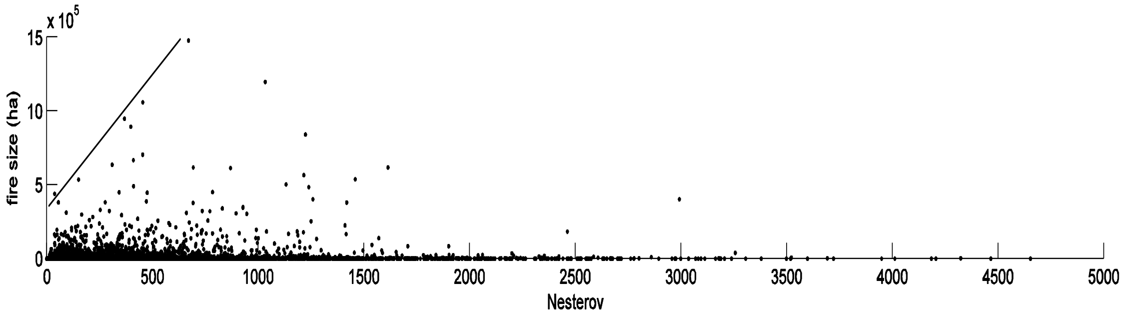


**Figure 18.** The Nesterov versus the fire size (ha), a line was drawn to visualize the envelope

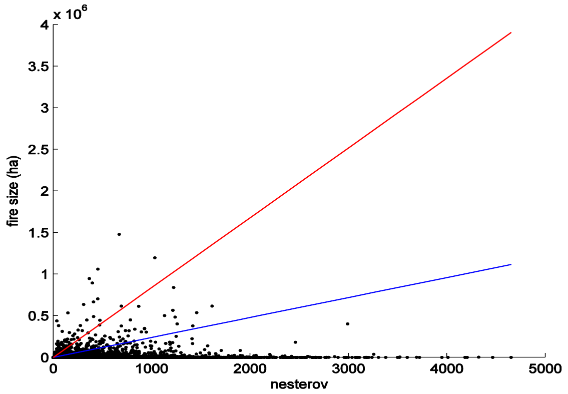


**Figure 19.** A plot over the burnt area (ha) against the fire indice Nesterov. The lines show the envelope present below the 99% (red) and 95% (blue).

It was decided to insert lines in the plots to show where the 99 and 95% threshold were to visualize the envelope (figure 19, Appendix B3).

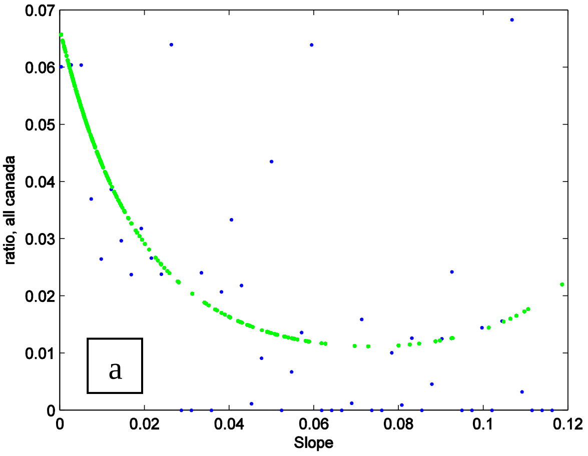
A Pearson correlation was performed between the fire indices and the burnt area, examining if it was true that no correlation existed (table 7). There is a stronger correlation regarding the fire indices and the number of fires than the indices and the fire size. The best correlations can be assessed between the annual temperature and the GDD. The GDD also has strong relationships with the Angstrom, the Nesterov and the DC. There is also some strong relationship between the other fire indices as can be assessed in table 7.

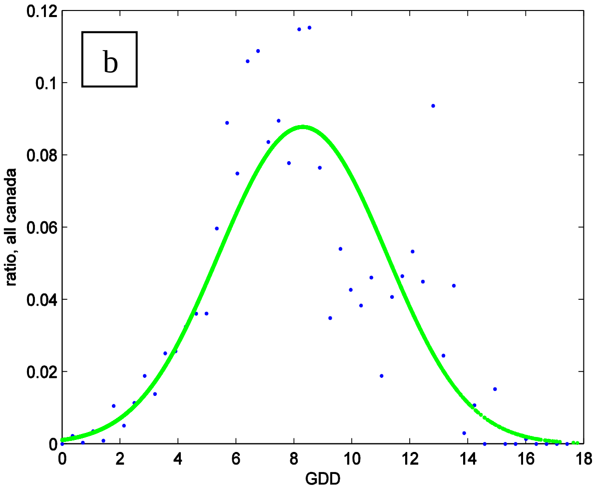
**Table 7.** The correlation coefficient and p-value for the number of fires and burnt area vs. the fire indices (I=angstrom, dd=dry days). $R^2$ on the lower half of the table and the p-value on the upper part of the table.

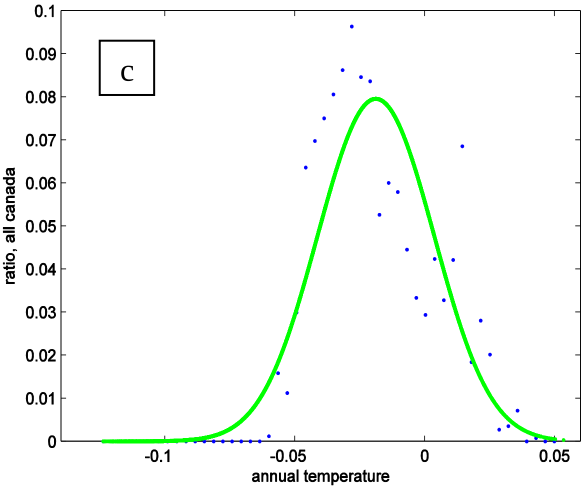
| | nr | size | slope | I | nest | dd | DC | an temp | GDD |
|---|---|---|---|---|---|---|---|---|---|
| **Nr** | - | <0.005 | 0.01 | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 |
| **size** | 0.29 | - | <0.005 | <0.005 | <0.005 | 0.57 | <0.005 | <0.005 | <0.005 |
| **slope** | <0.005 | <0.005 | - | <0.005 | <0.005 | <0.005 | <0.005 | 0.01 | <0.005 |
| **I** | 0.09 | 0.03 | 0.01 | - | <0.005 | 0.33 | <0.005 | <0.005 | <0.005 |
| **nest** | 0.03 | 0.01 | 0.03 | 0.46 | - | <0.005 | <0.005 | <0.005 | <0.005 |
| **dd** | <0.005 | <0.005 | <0.005 | <0.005 | 0.03 | - | <0.005 | <0.005 | <0.005 |
| **DC** | 0.06 | 0.02 | 0.05 | 0.60 | 0.60 | 0.01 | - | <0.005 | <0.005 |
| **an temp** | 0.06 | 0.01 | <0.005 | 0.57 | 0.30 | 0.12 | 0.45 | - | <0.005 |
| **GDD** | 0.08 | 0.02 | 0.07 | 0.73 | 0.48 | 0.02 | 0.69 | 0.79 | - |

### Generalized linear regression

For the GLM analysis a sigmodial as well as a unimodal response was used. In almost all the possible variations the best correlation was found using a unimodal distribution (see table 8 & 9). In figure 20 the model seems to follow the fires well but no significant correlation could be found (table 8). The standard deviation and p-value can be found in the Appendix B4. This is because the displayed blue points represent the mean value of the ratio over a certain range of the fire index. Hence the variability is understated by looking at the plots.







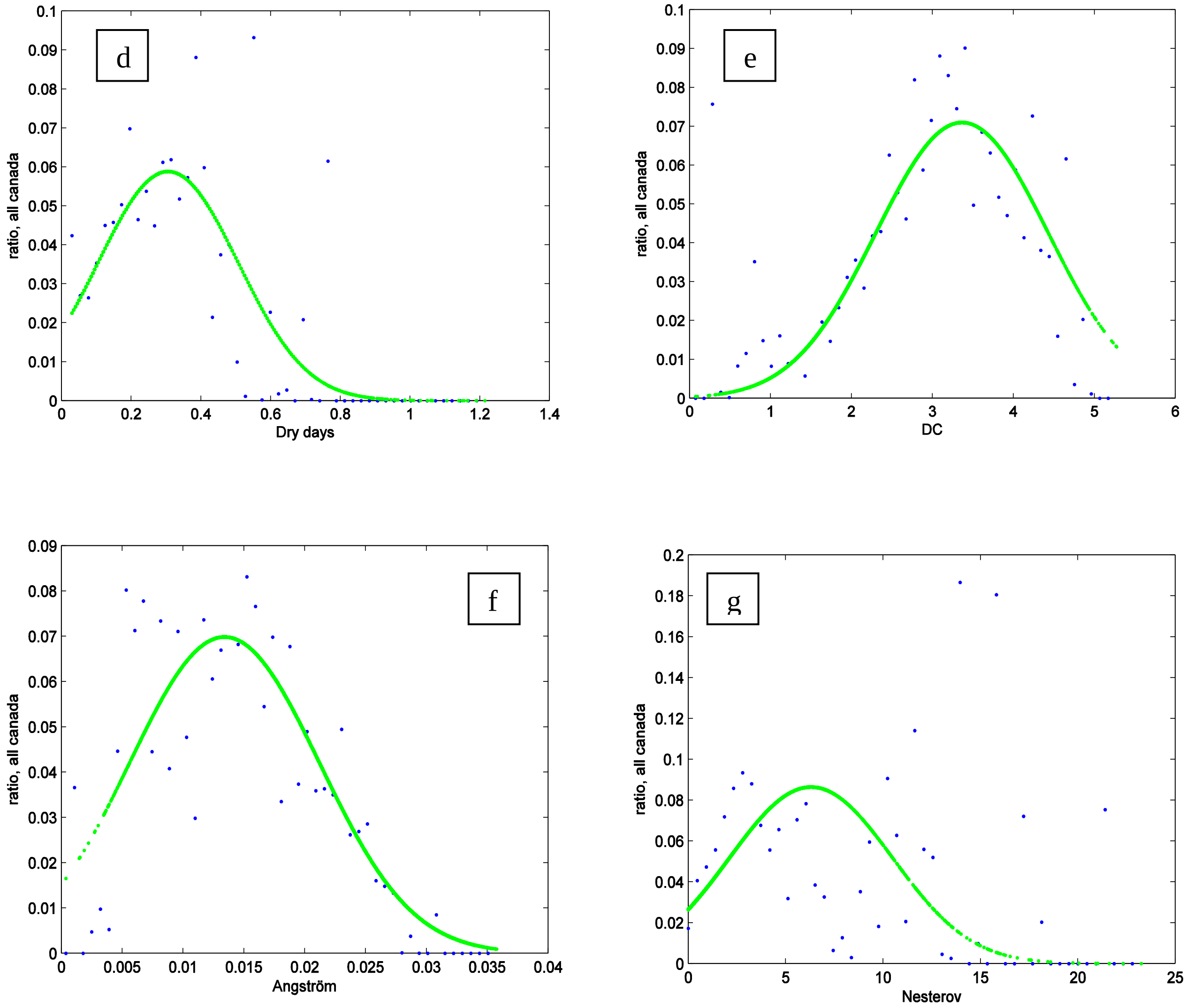


**Figure 20.** The modeled GLM regression in the green points and actual fire values in blue. Especially good fits can be assessed for the annual temperature, the DC and the Angstrom ignition index. **a.** slope, **b.** GDD, **c.** annual temperature, **d.** dry days, **e.** DC, **f.** Angstrom, **g.** Nesterov.

**Table 8.** The correlation coefficient from the unimodal GLM regression

| | all | broadleaf | coniferous | transitional | mixed | other |
|---|---|---|---|---|---|---|
| **solpe** | 0.04 | 0.03 | 0.02 | 0.01 | 0.01 | <0.005 |
| **Angstrom** | 0.04 | 0.03 | 0.03 | 0.01 | 0.01 | <0.005 |
| **Nesterov** | 0.03 | 0.03 | 0.03 | 0.02 | 0.01 | <0.005 |
| **dry days** | 0.03 | 0.03 | 0.02 | 0.01 | 0.01 | <0.005 |
| **DC** | 0.04 | 0.03 | 0.02 | 0.01 | 0.01 | <0.005 |

**Figure 20.** The modeled GLM regression in the green points and actual fire values in blue. Especially good fits can be assessed for the annual temperature, the DC and the Angstrom ignition index. **a.** slope, **b.** GDD, **c.** annual temperature, **d.** dry days, **e.** DC, **f.** Angstrom, **g.** Nesterov.

**Table 9.** the correlation coefficient from the GLM regression when a sigmodial curve is modeled

| | all | broadleaf | coniferous | transitional | mixed | other |
|---|---|---|---|---|---|---|
| **solpe** | 0.04 | 0.02 | 0.02 | 0.01 | 0.01 | <0.005 |
| **Angstrom** | 0.03 | 0.03 | 0.03 | 0.01 | 0.01 | <0.005 |
| **Nesterov** | 0.03 | 0.03 | 0.02 | 0.01 | 0.01 | <0.005 |
| **dry days** | 0.03 | 0.02 | 0.02 | 0.01 | 0.01 | <0.005 |
| **DC** | 0.03 | 0.03 | 0.02 | 0.01 | 0.01 | <0.005 |
| **Annual temp** | 0.03 | 0.02 | 0.02 | 0.01 | 0.03 | <0.005 |
| **GDD** | 0.03 | 0.02 | 0.02 | 0.01 | 0.02 | <0.005 |

### Does the teleconnection effect the number of fires or the fire size

To find if the number of fires and their size depend on large scale climate shifts, such as a change in the teleconnections or the annual temperature, the maximum yearly value of the fire indices, the annual temperature, the total burnt area, the effective fire size and the number of fires that took place in Canada during a year, were used. The teleconnections NAO, PNA, TNH, PT, AO and ENSO were also used (figure 21, table 10).

A correlation could be discerned for the standard mean fire size against the NAO the TNH and PT, with a significant p value for the NAO and TNH. No significant correlation could be found between the teleconnections and the effective fire size, the number of fires or the burnt area.

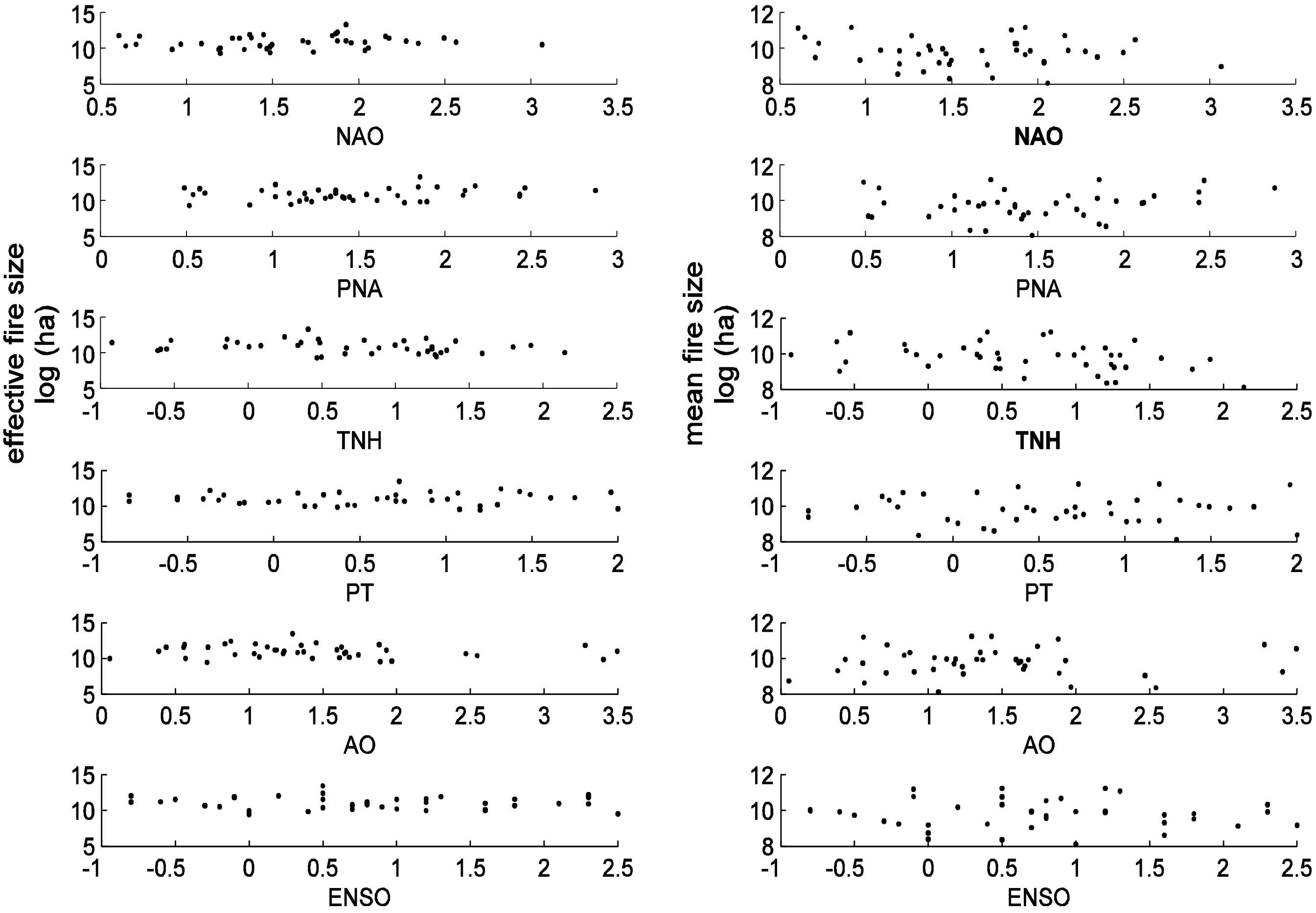


**Figure 21.** The maximum yearly teleconnections versus the effective fire size and the mean of the effective fire size distribution.

**Table 10.** The R and P for the correlation between the teleconnections and the burnt area, number of fires and the effective fire size in Canada

| | NAO | | PNA | | TNH | | PT | | AO | | ENSO | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $R^2$ | P | $R^2$ | P | $R^2$ | P | $R^2$ | P | $R^2$ | P | $R^2$ | P |
| **Area burnt** | 0.0332 | 0.2538 | 0.0040 | 0.6947 | 0.0036 | 0.7109 | 0.0140 | 0.4615 | 0.0111 | 0.5111 | 0.0004 | 0.9033 |
| **Number of fires** | 0.0231 | 0.3432 | 0.0000 | 0.9935 | 0.0069 | 0.6051 | 0.0173 | 0.4118 | 0.0049 | 0.6637 | 0.0113 | 0.5079 |
| **Effective fire size** | 0.0215 | 0.3599 | 0.0438 | 0.1891 | 0.0753 | 0.0825 | <0.0005 | 0.9524 | 0.0015 | 0.3885 | 0.0330 | 0.6935 |
| **Standard mean** | 0.1631 | 0.0088 | 0.0002 | 0.9252 | 0.0954 | 0.0494 | 0.0819 | 0.0697 | 0.0143 | 0.4573 | <0.0005 | 0.9939 |

### The fire weather in Canada

While assessing the Canadian mean, a linear correlation between the weather parameters was performed (table 11). It shows that the correlation between the fire indices DC and Nesterov, dry days and GDD is good on this large a scale. No good relationship could be assessed between the burnt area per year versus the fire indices. When assessing the relationships for the number of fires and the fire indices, a relationship can be detected for the drought code and for the GDD (table 11).

**Table 11.** The $R^2$ and p-value for the fire indices when assessing the whole of Canada. The $R^2$ in the lower part of the table and the p-value in the upper part of the table.

| $R^2$ | size | nr | I | nest | DC | dd | GDD | an temp |
|---|---|---|---|---|---|---|---|---|
| **size** | - | <0.005 | 0.21 | 0.38 | 0.05 | 0.73 | <0.005 | 0.02 |
| **nr** | 0.69 | - | 0.16 | 0.08 | 0.04 | 0.75 | <0.005 | 0.05 |
| **I** | 0.04 | 0.05 | - | 0.02 | <0.005 | 0.02 | <0.005 | 0.64 |
| **nest** | 0.02 | 0.07 | 0.13 | - | <0.005 | <0.005 | <0.005 | 0.75 |
| **dc** | 0.10 | 0.10 | 0.19 | 0.54 | - | <0.005 | <0.005 | 0.73 |
| **dd** | 0.00 | <0.005 | 0.13 | 0.47 | 0.46 | - | 0.11 | 0.50 |
| **gdd** | 0.20 | 0.26 | 0.25 | 0.23 | 0.40 | 0.07 | - | <0.005 |
| **an temp** | 0.14 | 0.09 | 0.01 | <0.005 | <0.005 | 0.01 | 0.27 | - |

## Discussion

To be able to predict when fires will occur and how large they will be are important for the prediction of vegetation distribution, structure and the emissions of greenhouse gases.

### Results

Most authors analyzing Canadian forest fires have divided Canada according to the eco-zones (Skinner, et al. 1999, Amiro, et al. 2001, Stocks, et al. 2002) or by the eco-regions (Girardin, et al. 2008). However in this thesis Canada were divided according to the land cover, as the fires corresponded better to the land cover. This can be because the eco-zones are divided on a larger scale and by using more parameters.

The relationship between the number of fires and the total burnt area per year or per months (pooling all years) have a correlation of $R^2$ 0.69 and 0.98 respectively. That the monthly fires have a much stronger relationship probably depend on the fact that the 41 years were pooled an only the remaining12 values are used, while the yearly fires have 41 values, which will give a larger variation among the values used.

A positive trend for the burned area over the time period 1959-1999 could be found, strengthening the results of previous authors on the subject (Stocks, et al. 2002, Fauria, et al. 2008). But when dividing the time period no significant trend could be found. A reason for this can be because prior to 1970 there were smaller amounts of burnt areas than the later data. This is probably not because a difference in the fire regime so much as a result of expanded forest use and the increased fire monitoring/detection capabilities. Many of the fires in the Canadian ‘Large fire database’ that were present in remote areas are missing from 1959 to mid-1970s (Stocks, et al. 2002).

The effective fire size has not been used before when analyzing the fires in the boreal forests. When assessing the fire sizes effect on the total burnt area previously the fire size distribution has been the most widely used. It is widely believed that while many small fires occur that it is the large fires that contribute the most to the burnt area (Cui and Perera 2008). The effective fire size (the fire size that will contribute most to the total burnt area) is not the fires that are the absolute largest but the fires that have a little more than average area, which means that the previous assumption are incorrect for the dataset that was investigated here.

There is a difference in the effective fire size depending on the forest type. The broadleaved forests have a smaller effective fire size than the others, one possible reason is that they are present in the southern part of Canada where more fire suppression takes place.

That the months of the fire season that show a positive trend are the months in the middle points towards that the fire season is not lengthening but instead becomes more intense over the investigation period.

That no relationship could be found between the fire size and the weather probably depends on the fact that the fire size do not only depend on the weather but also other factors such as fire barriers. While the weather effects the maximum fire size that a fire can reach, the fire barriers will limit the size of the fire so that it does not reach its maximum potential.

The reason that we only investigated a single variable in the GLMs and not a combination of the fire indice is because we were not interested in finding the best model, but to see whether the indices had an effect. These effects were very weak in all cases.

That the teleconnections used in the analyses had no relationship to the burnt area and number of fires and effective fire size per year can depend on the fact that a relationship was tried to be found using Canadian mean values, but teleconnections do not affect the whole of Canada but only certain parts (Fauria, et al. 2008). If Canada had been divided in smaller parts maybe a stronger relationship between the teleconnections would have been found. Over the eastern part of North Americas boreal forests a relationship between a positive AO and large burnt areas have been assessed (Fauria, et al. 2008), but no relationship could be found between the area burnt and the AO. Another possible reason to why no strong correlations could be found for the teleconnections can be because they are stronger in the winter than in the summer when they would need to be strong to affect the fire frequency. NAO is one of the teleconnections that are strong in the winter and weak during the summer (Rodionov 1994).

When assessing if a relationship existed using the Canadian mean values versus the number of fires and burnt area per year no significant correlation could be found. However, a relationship was found between the number of fires and the DC and GDD reflecting the fact that a sufficient fuel production (related to NPP) is required for fires to start, while non was detected for the burnt area.

### Reasons why the hypothesizes couldn't be proven right

All the fires in Canada were used regardless of the cause of the fires. But when assessing the number of fires that occur by different conditions one should also assess the cause. The lightning caused fires might be sensitive to one factor while the human caused fires might be more sensitive to something else. But the error from this will be rather small as 80% of the fires in Canada are ignited by lightning.  When assessing the size of the fires, the suppression action present in the area should also be considered as that will make a large difference in how large the fires is allowed to get. The suppression of the fires will also affect how many fires reach 200ha and thereby the number of fires. One possible reason that the broadleaved forests have smaller effective fire size than the other forest types can be that they are only present in the southern part of Canada where more fire suppression takes place.

Due to the fact that the Swedish and Canadian fire data differed in both the scales and the time periods used, it was impossible to compare the countries statistically. The Swedish fire data was taken during 800 year on a limited research area, while the Canadian data were collected during only 41 years and using the whole of Canada.

The weather is not the only important factor to assess at when analyzing at fire size. One should also use the landscape characteristics, type of forest fuels, ignitions, topography, suppression efforts, abundance of fire breaks such as lakes, roads or agricultural land (Drever, et al. 2008). The fire barriers are probably easier to consider when using a smaller scale than what was used here.

The sizes that a fire can reach depend on the height of the fire index but a high fire index is not always causing a fire to grow to a large extend. The fire size is not only limited by the weather but by other factors like rivers and other obstacles hindering the spread of a fire. There are significant relationships present between the fire indices, the strongest being between the Nesterov, DC, and DC, dry days, which can be explained by the way they are calculated which is relatively similar and uses partially the same weather variables.

### Other parameters that could have been used

The boreal forests could be divided not only by the forest type but also separating the forest in moist (bogs, peats) or dry. This division could have been potentially better since the fire frequency seems to differ much between these two types of boreal forests. A moist forest has a fire frequency of 200-250 years a dry forest have much shorter fire intervals of 40-65 years (Chandler, et al. 1983). There are also a difference in fire intensity in the dry and moist forests (Chandler, et al. 1983). In this thesis only the direct weather was linked to the fires and not the soil water content since no such data was available and a simulation of such data was outside the scope of this work.

Another thing that should be considered when assessing the fires are the fire fuels. How much and which type of fuel is present will affect the fires. The fires fuel consumption depends partly on the fuel type, i.e. the forest type (Amiro, et al. 2001). In some fire prediction models the fuel is used in a combination with the weather, the Canadian fire weather index (FWI) is one of them (cwfis.cfs.nrcan.gc.ca). Only the relationship between the weather and the fires were wanted here, which is why the fire fuel was not a part of the analyses.

The wind is also a very important weather parameter when assessing its influence on forest fires. It dries the fuel by carrying away evaporated moisture. It also helps to keep a fire going by bringing in more air which increases the combustion. The wind will also help the fire in its movement and speed. This makes the wind an important factor when predicting the spread and direction of the fire. That the wind was excluded from the weather factors used in the analysis can have affected the result for the fire size analysis against the weather. The reason for this exclusion was because wind is a local event that would not be represented well on the scale that was used here. The fire spread also creates its own wind (Chandler, et al. 1983), which would still be lost in the analysis.

If a fire is ignited by lightning, the forest fire very seldom starts directly when the lightning hits, as a few of the lightning flashes reach the humus layer that then can smolder for days before the fire stars. It is normal with a delay of a couple of days after the lightning that the forest fire starts. This of course makes it hard to decide on the fire cause (Niklasson, et al. 2005). This in conjunction with the low quality at which currently lightning data is available were the reasons for not including lightning data in this analysis.

### Error sources

There are many factors that contribute to uncertainty in the analyses carried out in this thesis. The collection of the fire data for Sweden and Canada differed, both with their own weaknesses. The disadvantage of the fire data sampling method used in Sweden, was that earlier fire evidences could be destroy by later fires (Niklasson, et al. 2000). The Canadian database reaches from 1959 to 1999 but the quality is better in the years after 1970, while the fire data in the years before are incomplete. The Canadian fire database did not have the starting dates and coordinates for all the fires that were recorded. Therefore the fires were excluded from the analyses where dates or coordinates was used.

The temperature data that was imported from NCEP were re-aggregated mixtures of station and satellite data. The weather data were in a resolution of 2.5x2.5 degrees While using this coarse resolution is good on a global scale the uncertainties are larger than if the resolution would have been less coarse.

The land cover data used were derived from the AVHRR on the NOAA satellites with a resolution of 1.1 km. The raster data were then transformed to polygons in a shapefile, the polygons with a perimeter of less than 50km where merged with a neighboring polygon. This generalization took away some of the original precision of the land cover data. Another thing that should be taken into account is that the same map was used for all the years of the analysis without considering the changes in land cover between the years.

A factor that affects the results is that for every new classification that was performed more fires were lost, as not all had the parameters needed. When doing overlays between different layers, the fires in the edge areas that do not overlap were lost for further analyses. That the different map layers not always overlap perfectly can also affect the results, this can be seen where fires are located in the land cover water thought that is physically impossible.

The effective fire size and standard mean were calculated using only the fires that had coordinates within the land-cover map. The fires with no known land-cover was excluded from the analysis, here a lot of fires close to the coasts were lost. Only the forest types were assessed while the fires in other landcover-classes was not used.

The Nesterov index depend on the Nesterov of the day before which means that the following days values depend on which starting value are given, in this case the starting value was 0, as that are the most used one when calculating the Nesterov index. Just like the Nesterov the Drought code needs a starting value which in this case was given 15 at the first of May, which according to Girardine are the value most used when calculating the Drought code.

That only the fire season and not the whole year was used might also have an effect on the result.

# Conclusion

The first hypothesis that modern Canada and paleo Sweden have a similar fire regime was tested by visually comparing the number of fires and the fire sizes in the two countries. No significance tests were performed but by visually interpreting the distribution histograms a similar main shape was found between the forest fires in the two countries.

The second hypothesis was that the climate is the limiting factor when assessing Canada's fires. To test this hypothesis a number of different fire danger rating systems that depend on the weather were calculated and a correlation between the fire indices and the actual fires were performed. No relationship could be found between the weather and the fire sizes, but a certain climatic value has to be reached before a certain fire size can be reached. When the climatic threshold has been reached, the size of the fire is independent on the weather, the maximum fire size might follow the fire indices but the fire size does not depend only on the weather but on other factors too, like the presence of fire barriers, so small fires are just as common when the fire indices are high as large fires.

A GLM regression was performed to assess if the fire sizes relationship with the weather was sigmodial or unimodal instead of linear, the resulting relationship was a slightly better but still had no strong correlation.

The third hypothesis is that the number of fires and area burnt every year depend on a much larger scale than the daily weather therefore the climate variations as can be assessed in the teleconnection variations every year.

A correlation between the NAO and the standard mean fire size was found but otherwise no relationship to the teleconnections. No relationship between the Canadian mean values versus the number of fires and burnt area per year was found. A relationship can be found between the number of fires and the DC and GDD, no relationship for the burnt area could be detected.

### Outlook

In future works related to fires in boreal forests some things could be done different than here. When choosing how to divide the areas studied, to assess the spatial fire distribution, I would not only divide by the forest type but also by how wet the ground are (soil moisture), as that affects the fire frequency.

It would be interesting to test the fire indices that have been used here could also be used on a more local scale and to assess if a relationship can be found between them if the scale was less coarse.

The fire indices that are used to predict fires should contain more parameters than just the weather, such as the wind, lightning, and fuel type available. If the landscape has many fire barriers (e.i. many rivers) the expected fire size would be less than in areas without any barriers. The effectiveness of fire suppression might also be a parameter to account for.

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Eco-zones (used: 2011-02-12): http://sis.agr.gc.ca/cansis/nsdb/ecostrat/gis_data.html (last updated: 2008-11-27)

Land cover (used: 2011-02-13): http://geogratis.cgdi.gc.ca/geogratis/en/option/select.do?id=C898CC10-3DAE-9BA0-92BC-30E7545342AF (last updated: 2010-05-11)

Teleconnections (used: 2011-04-11): http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml (last updated 2011-02-03)

### Web sites

National weather service, Climate prediction center, (used: 2011-04-11):
http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml last updated 2011-02-03.

Canadian large fire database, (used: 2011-01-17):
http://cwfis.cfs.nrcan.gc.ca/en_CA/lfdb (last updated 2009-12-22).
http://cwfis.cfs.nrcan.gc.ca/background/summary/fwi (last updated 2009-12-22)

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# Appendix

**Data used**

A1. The Canada Vegetation and Landcover definitions
A2. The standard day length adjustment factor

**Results**

B1. Time series, effective fire size
B2. Time series, standard mean
B3. Scatterplots (red line 99%. Blue line 95%)
B4. GLM deviation and P
B5. Teleconnection vs. Burned area and number of fires per year

Appendix 2 with The Matlab®-script used is available from:
www.nateko.lu.se/ex-jobb/Exj_228App2.pdf

### A1. The Canada Vegetation and Landcover definitions

Canada were divided according to these land cover classes here in the analyses performed

**Table 1.** Canadas vegetation and land cover definitions acording to Palko et al. 1996

| **Predominant Plant cover** | **class** | **definition** |
|---|---|---|
| Tree | **forest land** | Land on which trees are the dominant vegetation cover with tree crown cover of 10% or more. Includes land where trees are stunted owing to site limitations, undetectable ownig disturbance, or temporaly absent. |
| | **Continous forest** | Land cover type where forest land occupies more than 50% of the area. |
| | coniferous forest | Continous forest in which 76-100% of the canopy is composed of coiferous trees. |
| | broadleaf forest | Continous forest in which 76-100% of the canopy is composed of broadleaf trees. |
| | mixed forest | Continous forest in which 26-75% of the canopy is composed of coiferous or broadleaf trees. |
| Tree/Shrub/Herb/ Nonvascular* | transitional forest | A mixture of land cover classes where the tree cover is discernable but forest land occupies less than 50% of the area |
| Shrub/Herb/ Nonvascular* | tundra | Low arctic or alpine vegetation with discernible cover. Althought generally located beyond the tree line, low woddy plants (ericaceous shrubs, willows, etc.) and patches of stunted trees may occur. |
| | **agricultural land** | |
| crops | cropland | Cultivated land with crops, fallow, feedlots, orchards, vineyards nurseries, shelter belts, and hedgerows. |
| Non-Cultivated (Shrub/Herb) | rangeland and pasture | Land supporting native vegetation, shrubs, grass, and other herbaceous cover with less than 10% tree cover. Includes improved land dedicated to the production of forage, and upland and lowland meadows. |
| Non-Vegetated | **Non-vegetated land** | |
| | perennial snow or ice | Perennial snow fields and glaciers. |
| | barren land | Land without discernible vegetation cover. May include sand, rock, bare soil, and open pit mines. |
| | built-up area | Cities and towns of sufficient size to be depicted at the scale of mapping |
| | **Water/Sea ice** | |
| | open water | |
| | sea-ice | |

*Plants lacking an internal vascular system (e.g. moss, lichen)

### A2. The standard day length adjustment factor

When using the drought code the standard day length adjustment factor is needed.

**Table 2.** the monthly standard day length adjustment factor (Wagner 1987)

| Month | L | Month | L |
|---|---|---|---|
| January | -1.6 | July | 6.4 |
| February | -1.6 | August | 5.0 |
| March | -1.6 | September | 2.4 |
| April | 0.9 | October | 0.4 |
| May | 3.8 | November | -1.6 |
| June | 5.8 | December | -1.6 |

**B1. Time series of the effective fire size**

To assess if the effective fire size have changed over time, a time series were performed.

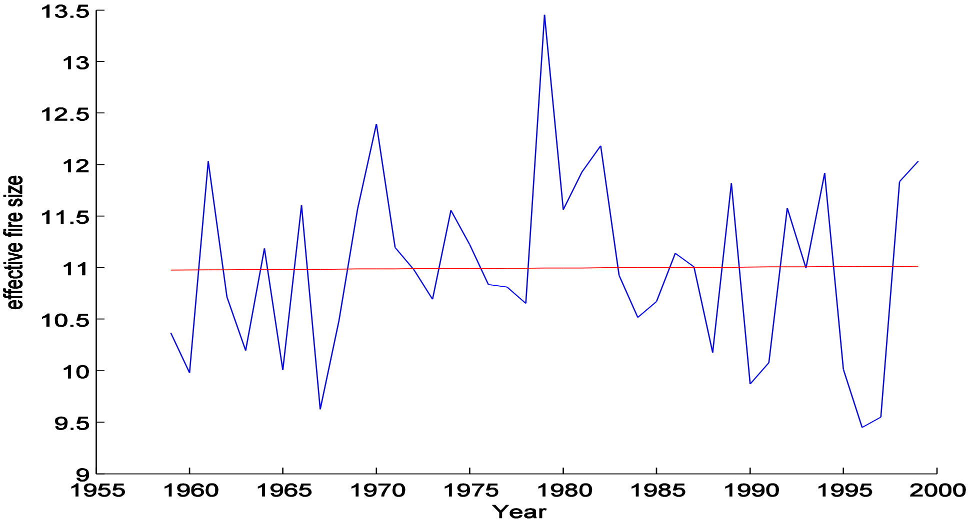
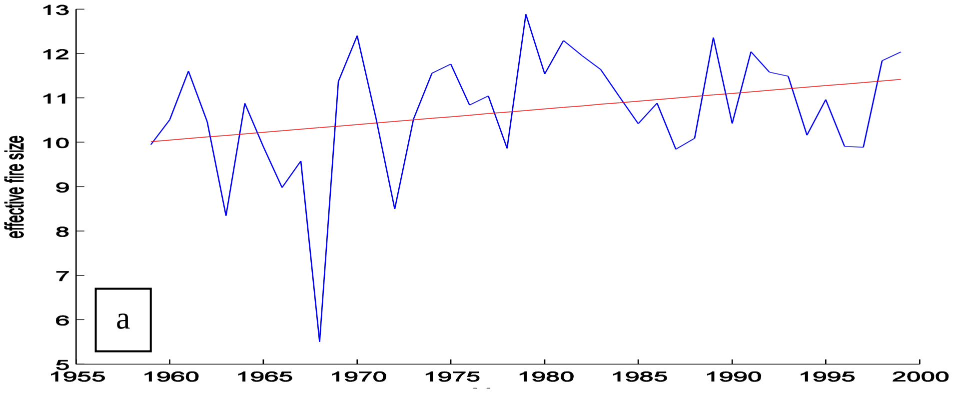
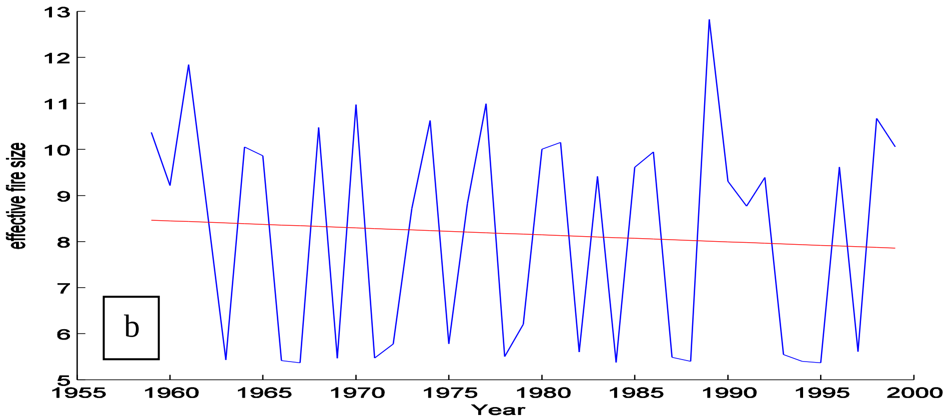


**Figure 1.**Trend in the effective fire size over the period 1959-1999

A effective fire size trend were also assessed acording to the forest types.





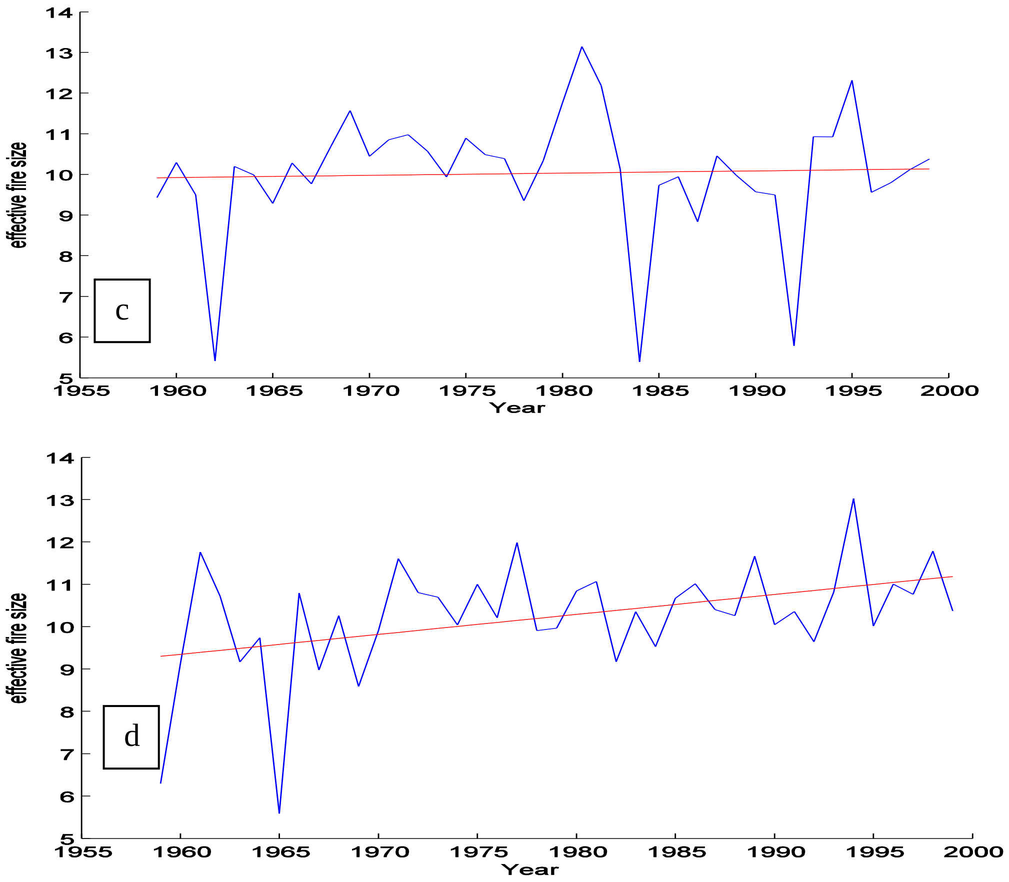


**Figure 2.**Trend in the effective fire size over the period 1959-1999 for the four forest types, **a.** coniferous, **b.** broadleaf, **c.** mixed, **d.** transitional

**B2. Time series of the standard mean fire size**

To assess if the standard mean fire size have changed over time, a time series were performed.

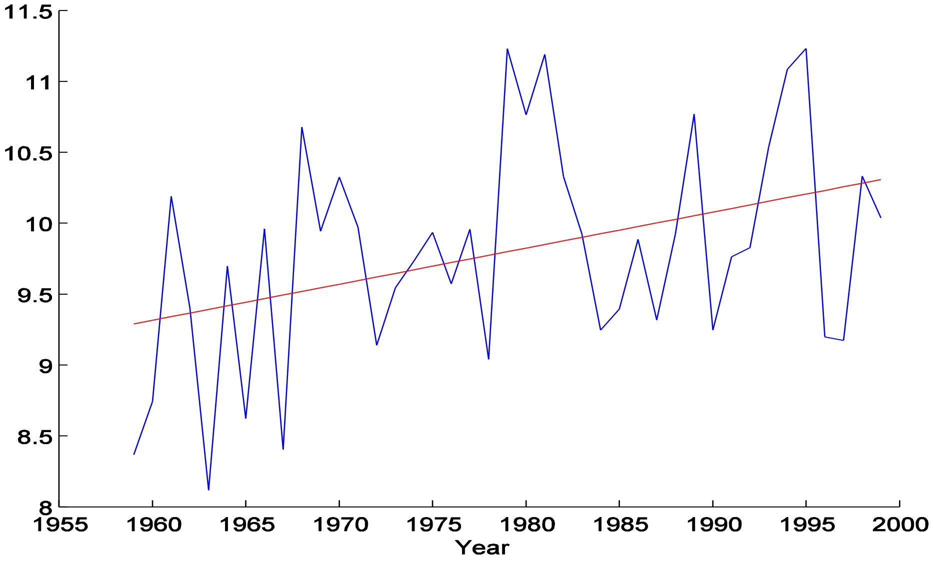
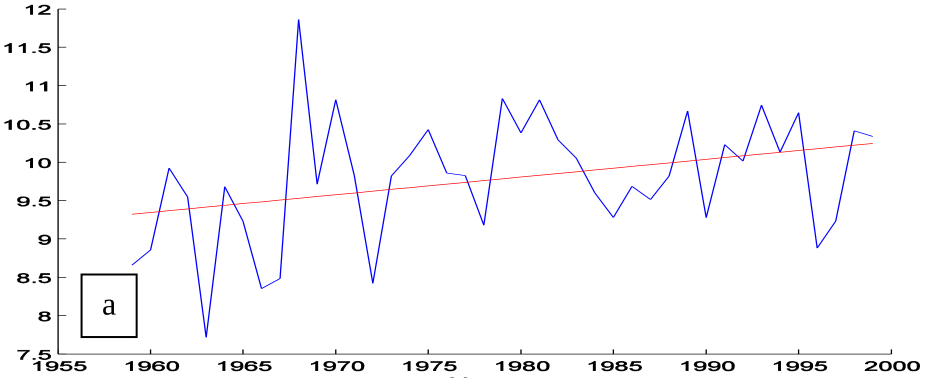
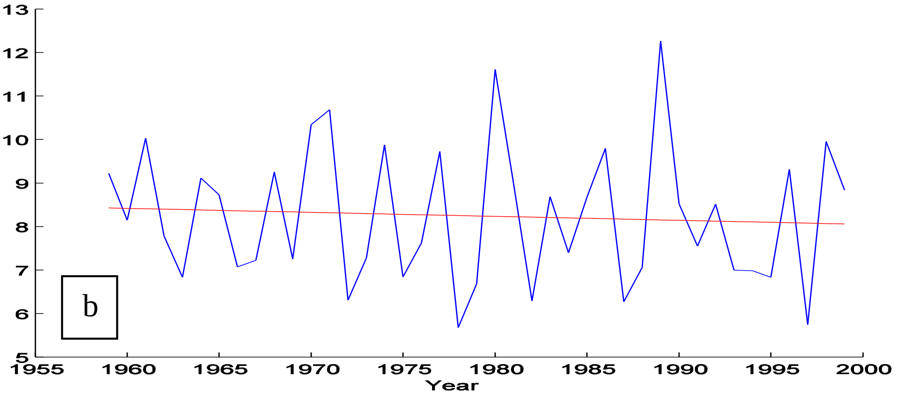


**Figure 3.**Trend in the standard mean fire size over the period 1959-1999

A standard mean fire size trend were also assessed acording to the forest types.





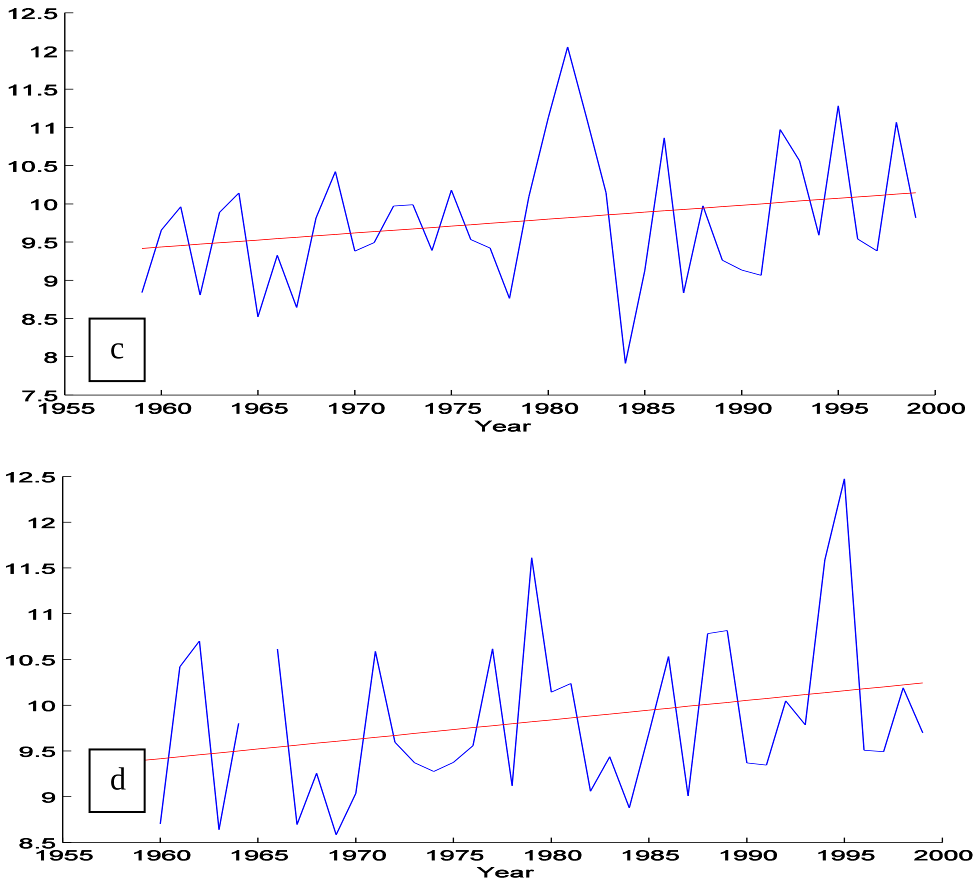


**Figure 4.**Trend in the standard mean fire size over the period 1959-1999 for the forest types, **a.** coniferous, **b.** broadleaf, **c.** mixed, **d.** transitional

### B3. Scatterplots (red 99%, Blue 95%)

To better visualize where the envelope are lines on the 99 and 95 percentile were created.

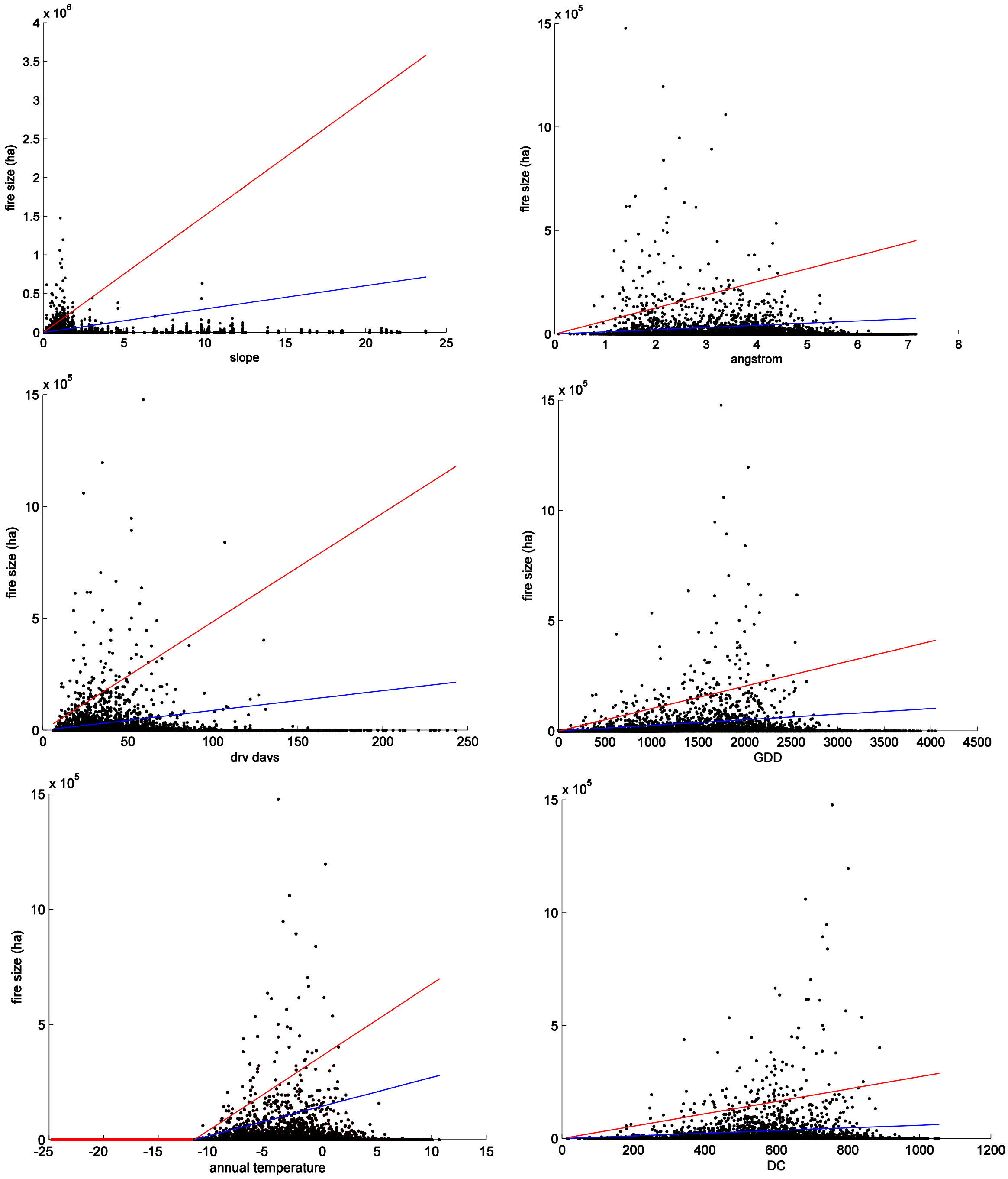


**Figure 5.** The fire indices versus the fire size. The 99% (red) and 95% (blue) envelope were inserted.

### B4. GLM deviation and P

The deviation between the modeled GLM and the actual fires can be assessed in the table below for the sigmodial and for the unimodal models.

**Table 3.** The deviation using the unimodal GLM in hectare

| | all | broadleaf | coniferous | transitional | mixed | other |
|---|---|---|---|---|---|---|
| **Solpe** | 36189642 | 1214236 | 6169361 | 2852692 | 3096500 | 212369 |
| **Angstrom** | 35425528 | 1197082 | 6073098 | 2815302 | 3101572 | 187433 |
| **Nesterov** | 36243265 | 1209174 | 6141466 | 2795378 | 3100100 | 202022 |
| **Dry days** | 36714560 | 1211002 | 6313362 | 2821058 | 3096265 | 220593 |
| **DC** | 35321925 | 1210337 | 6217640 | 2836291 | 3096340 | 210804 |
| **Annual temp** | 33719072 | 1200773 | 6360325 | 2825399 | 2926913 | 179451 |
| **GDD** | 33496142 | 1206421 | 6199037 | 2801916 | 3017141 | 188333 |

**Table 4.** The deviation using the sigmodial GLM in hectare

| | all | broadleaf | coniferous | transitional | mixed | other |
|---|---|---|---|---|---|---|
| **Solpe** | 36359431 | 1216273 | 6233290 | 2852867 | 3099759 | 222178 |
| **Angstrom** | 36138853 | 1198380 | 6081702 | 2825823 | 3101823 | 203318 |
| **Nesterov** | 36910663 | 1213889 | 6214290 | 2831454 | 3101858 | 219977 |
| **Dry days** | 37187964 | 1212680 | 6331047 | 2825537 | 3096902 | 222763 |
| **DC** | 36136042 | 1210357 | 6219693 | 2839959 | 3097174 | 211562 |
| **Annual temp** | 36685689 | 1209665 | 6409747 | 2843927 | 2944429 | 195399 |
| **GDD** | 36080195 | 1221988 | 6216728 | 2808313 | 3053833 | 198811 |

The p-values for the two GLM models, unimodal and sigmodial, can be seen below (table 5 and 6).

**Table 5.** The p using the unimodal GLM, when there is a zero the model do not have a significant relationship whit the real data, where an X is a significant relationship is present

| | all | broadleaf | coniferous | transitional | mixed | other |
|---|---|---|---|---|---|---|
| **Solpe** | 0 | 0 | 0 | X | 0 | 0 |
| **Angstrom** | 0 | X | 0 | X | X | 0 |
| **Nesterov** | 0 | 0 | 0 | 0 | X | 0 |
| **Dry days** | 0 | 0 | 0 | 0 | X | X |
| **DC** | 0 | X | 0 | 0 | X | X |
| **Annual temp** | 0 | 0 | 0 | 0 | 0 | X |
| **GDD** | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 6.** The p using the sigmodial GLM, , when there is a zero the model do not have a significant relationship whit the real data, where an X is a significant relationship is present

| | all | broadleaf | coniferous | transitional | mixed | other |
|---|---|---|---|---|---|---|
| **solpe** | 0 | 0 | 0 | 0 | 0 | X |
| **angstom** | 0 | 0 | 0 | 0 | X | 0 |
| **nesterov** | 0 | 0 | 0 | 0 | X | 0 |
| **dry days** | 0 | 0 | 0 | 0 | 0 | X |
| **DC** | 0 | 0 | 0 | 0 | 0 | 0 |
| **allual temp** | 0 | 0 | 0 | 0 | 0 | 0 |
| **GDD** | 0 | 0 | 0 | 0 | 0 | 0 |

### B5. Teleconnection vs. Burned area and number of fires per year

A relationship between the teleconnections and the fires were tested for, but not found.

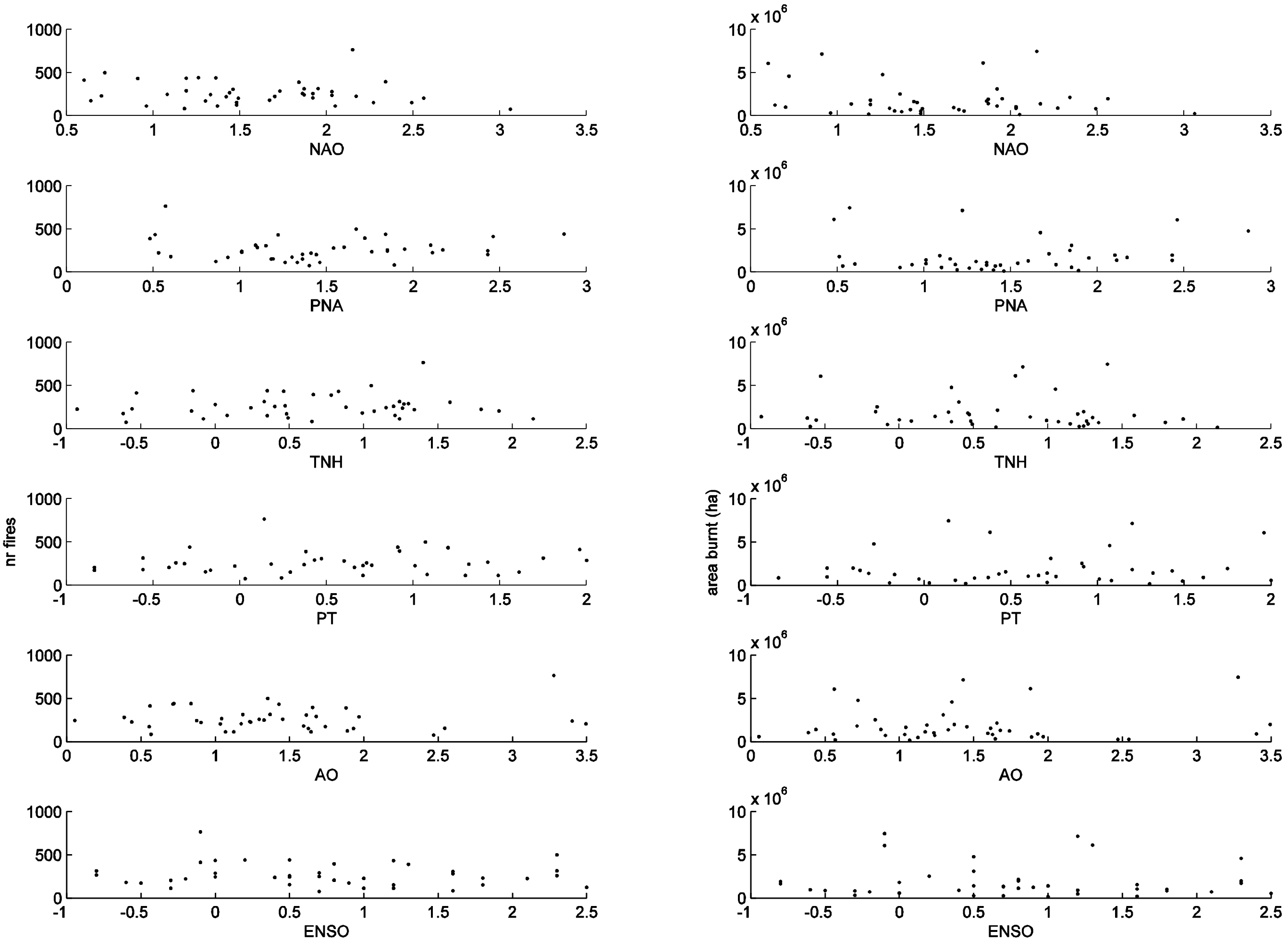


**Figure 6.** The maximum yearly teleconnections against the number of fires and total burnt area per year in Canada

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