Water-Level Change in Boreal Lakes as an Indicator of Area Burned and Number of Ignitions in the Canadian Prairie Provinces

by

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Abstract.

The relationship between water-level fluctuations of lakes and fire activity has never been elucidated in great detail. The majority of scientific research on wildfire-hydro-climate-vegetation dynamics examines patterns of traditional climatological variables such as temperature and precipitation and their influence on fuel moistures and fire risk at localized spatial scales. The study of lake-level changes in relation to fire was assessed to determine whether lakes are representative of broad scale environmental conditions, and are capable of explaining variability in fire activity (number of fires and area burned) in the western portion of Canada's Boreal ecozone. This study used mean monthly water-levels of 25 naturally regulated lakes in the Boreal regions of Alberta, Manitoba and Saskatchewan and determined the statistical correlation they exhibited with annual area burned and rates of fire occurrence. The findings from the study suggest that water-level fluctuations are correlated strongly with area burned and number of ignitions and that lake level departure values were able to match or exceed the predictive capability of traditional fire indices in multiple linear regression models.

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Table of Contents.

List of Tables.

List of Figures.

Glossary of Terms.

AOB: Area Burned.

CNFDB: Canadian National Fire Database.

CFS: Canadian Forest Service.

CWFIS: Canadian Wildland Fire Information System.

DC: 95th Percentile Drought Code Values for the months of June-August.

DMC: Duff Moisture code.

ENSO: El Nino Southern Oscillation.

Fire Regime: Characteristics of fire activity in a region which include the number of fires, the size of fires, the fire type, the severity of a fire event, the seasonality and the intensity of a fire event.

FFMC: Fine Fuel Moisture code.

FWI: Canadian Forest Fire Weather Index.

GIS: Geographic Information Systems.

Ha: Hectare.

HYDAT: Hydrological database of daily and monthly means of flow, water-levels and sediment concentrations.

IGN: Number of Ignitions

JJA: Measurements for the months of June, July and August.

LL_{DEP}: Percent departure of lake levels in relation to historical averages.

PSUM: Summed precipitation for the months of June-August by year.

SSR: Seasonal Severity Rating.

TEMP: 95th percentile mean monthly temperature values for the months of June-August by year

CHAPTER 1. Introduction.

North American Boreal forests are prone to disturbance events. Droughts, ice storms, insect infestations, flooding and wildfires occur episodically, altering the landscape at different spatial scales (Dale *et al.,* 2001). One of the most common and influential disturbances on the Canadian Boreal landscape is wildfires. Wildfire directly shape the structure, productivity, and composition of forest systems within the Boreal biome (Fauria and Johnson, 2008; Tymstra and Flannigan, 2007). Fire events influence vegetation succession, as well as the presence and success of specific tree species that can determine the biodiversity and ecological functioning of forest systems on both a biotic and abiotic level (Johnson, 1996; Ryan, 2002). Each wildfire event is unique in terms of the energy generated, the consumption of vegetation and the effects on soil characteristics (Burton *et al.,* 2008). The Boreal landscape is affected by fire in many different ways and a great deal of effort has been made to quantify the amount and cause of wildfire, and the effects of changes to Boreal fire dynamics (Flannigan *et al.,* 2000; Gralewicz, 2012; Kelly *et al.,* 2013).

There are approximately 8000 wildfire ignitions per year in Canada, which results on average in 2.1 million hectares burned (Stocks *et al.,* 2002). Each fire event requires fuels to be available for consumption, weather that is conducive to fire spread and a source of ignition. In years of high fire activity, extreme weather conditions, an overabundance of fuels, or increased human-caused ignitions are often to blame. These abnormalities can lead to the investment of considerable financial resources and increased suppression efforts to limit the impact of these fires. Fires that reach a size of 200 ha or larger are often those of greatest concern in Canada. These large fires result in large amounts of area burned (Stocks *et al.,* 2002) and mostly burn at high intensity. Fires 200 ha or larger are representative of only 3 % of all ignitions in Canada, yet they are responsible for 97% of the total area burned (Stocks *et al.,* 2002). These large fires are also responsible for shaping landscape characteristics far more than smaller fires (Johnson *et al.,* 1998). The impact, final size and influence of each individual fire event in the Boreal region is difficult to assess at the onset of an ignition. This is due to the large number of influencing factors specific to each area burned. Fires size, spread and intensity are a function of the vegetation available for consumption (Hély *et al.,* 2001; Johnson *et al.,* 1998), differences in the rate of rate of fire frequency (Bergeron *et al.,* 2002) and the composition of plant and tree species present in the region (Pojar, 1996). To better understand and quantify the patterns and effects of wildfire, scientists have used the fire regime concept as a means to better understand the boreal landscape.

Fire regime is defined as specific elements of fire size, intensity, frequency, seasonality, severity and type (Flannigan, 1993). By classifying fires in the Boreal region using fire regimes, researchers are better able to characterize and understand where and when fires burn.This information can also be used to evaluate how the ecosystem will recover post-fire and can act as an indication of how areas with specific fire regimes will respond to climatic abnormalities. Fire size is a determinant of landscape patchiness and can influence the successional pathway of the system through the dispersion of propagules. Fire size can differ considerably depending on fuel availability and other meteorological variables such as wind speed and relative humidity (Amiro *et al.,* 2001; Bond-Lamberty *et al.,* 2007). Fire size is also a determinant of the fuel build up on the landscape as years with large fires can considerably reduce the fuel load for subsequent years. Fire intensity is a reflection of the available fuel loading and is easily influenced by weather conditions before and during a fire event. High-intensity fires consume large amounts of fuel, have high rates of spread and impact the landscape much differently than lower-intensity fires (Spichtinger *et al.,* 2004). Fire severity corresponds to the depth of burn in the surface organic layer and has implications on plant tissue, root systems, seed banks and forest floor microbial populations. Deeper burns result in the system requiring a longer time to recover and can result in the death and replacement of forest stands (Romme, 1982). Fire type refers to whether the fire is a ground fire, surface fire, crown fire, or a mixture of these. Crown fires are more characteristic of stand-replacing fires, whereas surface fires tend to be lower intensity and can result in short-lasting impacts on biodiversity and plant structure in a forest stand (Scott and Reinhardt, 2001). The seasonality of the fire refers to the season in which the fire occurs. Seasonality plays a role in fire intensity, type and size as different seasons result in different weather conditions influencing fire and vegetation responses during a fire event. Fire regime is directly influenced by climate, and periods of drought coupled with high temperatures can result in considerable changes to the patterning and biodiversity of the system (Kirschbaum *et al.,* 1995; Chapin *et al.,* 2000).

Drought events are common in the Boreal region of western Canada due to its semi-arid climate. These events can lead to increased tree stress or tree mortality (Allen *et al.,* 2010; Michaelian *et al.,* 2011; Peng et al., 2011). Droughts increase crown fire behaviour (Keeley and Fotheringham, 2001) due to the limited water availability leading to an increase in the flammability and greater connectivity of fuels for fire spread. Drought events are highly variable in the Boreal landscape with localized soil characteristics, the life stage of the forest stand, and the frequency, intensity and severity of the drought event all playing a role in how the system is affected. Globally, droughts have been shown to affect the net primary productivity (NPP) and water usage of plants as vegetation undergoes changes in stomatal conductance (Zhao and Running, 2010). Future climate predictions suggest an increase in abnormal weather patterns, which has the potential to considerably affect the health and productivity of Boreal forest stands and the susceptibility and impact of wildfires.

Multiple independent data sets have shown a trend in warming of combined ocean and land surface temperatures of 0.85 °C between the years of 1880 to 2012 within Canada (IPCC, 2014). Climate change is expected to introduce variability in rates of precipitation, evapotranspiration and has the potential to change the species type and numbers of trees in Boreal forest stands. These changes may increase the frequency of fire in the Boreal region (Flannigan and Van Wagner, 1991; Flannigan *et al.*, 2009). Models that have included climate change conditions have forecasted a shift in the fire season to an earlier start date (Flannigan and Van Wagner, 1991; Wotton and Flannigan, 1993; Weber and Stocks, 1998), an increase in the occurrence of human and naturally caused wildfires (Wotton et al., 2003), an impact on the sustainability of water resources (Rosbjerg, 1997), greater lightning activity (Price and Rind, 1992; Price, 2009) and a changing rates of insect outbreaks and other natural disturbances (Kasischke *et al.*, 1995; Girardin and Mudelsee, 2008).

Boreal forest ecosystems are directly responsible for ecological services that influence global-scale processes and are vital in the mitigation of greenhouse gas emissions through the sequestration of carbon through photosynthesis (Harden *et al.*, 2000). An increase in the presence of fire has the potential to drastically change the ability of the Boreal system to sequester carbon and introduces uncertainty into the continuation of the boreal forest as a carbon sink (Kurz *et al.*, 2008). Biomass that is consumed in a fire event also changes the albedo of the Boreal forest, which can lead to the introduction of new plant species or result in heat- and sun-tolerant species dominating the landscape (Lyons et al., 2008). Presently, the Boreal forest contributes to global temperature patterns through the interception of shortwave solar radiation and influences major hydrological cycles through rainfall interception, species diversity, topography and evapotranspiration (Pomeroy *et al.*, 1999). In order to better understand the connectivity between wildfire and hydrological systems, lakes and streams present in the Boreal region are being considered in relation to fire activity to determine whether linkages are present.

Research into lake- and stream-system fluctuations in relation to wildfire activity is limited. The biogeochemical and ecological responses of rivers to low precipitation events and droughts are well documented throughout the United States (Dahm *et al.,* 2003; Malamud *et al.,* 2005), Australia (Bond *et al.,* 2008) and Canada (Sharma and Panu, 2008); however, very few studies exist that examine the connectivity between river discharge, climate and wildfire at the Boreal scale with even fewer examining lake levels in this context. Variability in stream flow discharge (Milly *et al.,* 2005), yearly snowpack (Mote, 2006), and stream flow timing (Stewart *et al.,* 2005) have become a highly useful method of understanding the connectivity between climate, drought and hydrology in North America. These studies provided the context for pursuing further research into the connection of hydrology and wildfire. Lake-based studies have lagged considerably behind those of rivers and the high level of connectivity between climate and wildfire observed in river-based analyses suggests that an exploratory analysis specific to lake systems may be highly valuable.

Most studies linking wildfire to Boreal climatological processes focus on weather patterns (Flannigan and Harrington, 1988; Flannigan and Van Wagner, 1991; Bergeron *et al.,* 2002), and large-scale climatic interactions such as mid-tropospheric ridges (Johnson and Wowchuk, 1993), and Pacific Decadal Oscillation/El Nino Southern Oscillation patterns (Fauria and Johnson, 2008), and their effects on wildfire activity and area burned. Water quality has been evaluated in relation to fire activity but often is only valuable for a specific water body or requires landscape, water-quality and fuel observations surveys to exist for comparison (Carignan *et al.,* 2000). Fire history reconstructions using fire-scarred trees (McBride, 1983), charcoal and lake sediment analysis (Smol *et al.,* 2001; Gavin *et al.,* 2007) and climate conditions through dendrochronology (Larsen, 1996) are all currently in practice and have been useful tools in quantifying fire activity.

To date, there exist no studies that evaluate the relationships present between multiple Boreal lakes and wildfire at a broad spatial scale. The incorporation of lake-level fluctuations as a source of data for comparison has the potential to add considerable information to traditional studies of fire activity. Lakes incorporate landscape conditions of precipitation, evapotranspiration and runoff and are well-defined features on the Boreal landscape. The advantage of developing a field of research that uses lakes systems in place of river data are that lakes are representative of larger-scale catchment-level processes and are less easily influenced by changes on the local landscape. This allows for a measurable response that is buffered from the impacts of short-term weather patterns, which is more representative of long terms climate trends, landscape level processes, and fuel flammability. Lake-level information offers a more complete and broader-scale understanding of the Boreal region in relation to fire activity than traditional fuel moisture measurement and could be highly useful to fire management agencies throughout Canada.

To evaluate whether Lakes were capable of capturing climate processes influencing wildfire, three hypotheses were tested:

I. Does the water-level fluctuations (LL_{DEP}) of naturally regulated lakes in the Boreal shield and Boreal plain ecozone, located within Alberta, Manitoba, and Saskatchewan, exhibit a relationship with area burned (AOB) and number of ignitions (IGN)?

LL_{DEP} will be evaluated against AOB and IGN using three different-sized buffers (circular areas extending from the lake gauges of each station) to determine whether variations in the spatial scale of analysis had an effect on the correlation values that exist between LL_{DEP} and AOB/IGN. The relationship between LL_{DEP} and fire variables of AOB and IGN has not yet been assessed in the literature and there is no research currently available that examines whether LL_{DEP} is associated with variability in the rates and size of wildfires across a multi-provincial scale. Relationships that exist between the variables of LL_{DEP}, AOB and IGN will be tested for the snow-free months of June, July and August (JJA) between the years of 1980-2011.

II. Does a hydrologic time lag of 1 and 2 years on lake levels influence fire activity in the Boreal region?

This hypothesis will test whether lake level change exhibits a multi-year influence on AOB and IGN and quantify the strength of those relationships. The time-lag hypothesis will test if changes in LL_{DEP} influences landscapes 1-2 years after lake level fluctuations have occurred and the degree of connectivity between past hydrological changes and wildfire activity.

III. Can lake level information be incorporated into predictive models to supplement or replace traditional climate variables and how do these models perform?

This hypothesis will determine how LL_{DEP}, when incorporated into predictive models was able to capture variability in fire activity. The study will test 95^{th} percentile temperature values of JJA (Temp), 95^{th} percentile drought code from JJA (DC), and summed JJA precipitation (PSUM) for each station by year in relation to LL_{DEP} values. This will determine how much variability in AOB and IGN can be explained by lake levels and how well it functions as a predictive variable as compared to traditional climate variables.

The investigation of these three hypotheses will determine whether a relationship between lake levels and annual fire activity exists in the Boreal region. The ability to determine whether this LL_{DEP} is associated with fire activity and how lake-level change across multiple years influences fire activity has the potential to advance the field of fire science in regions where lake level data is being monitored. This will be the first study examining natural lakes level changes in relation to wildfire activity in the Boreal region of Canada. The uncertainty and stochasticity of fire is a major obstacle in the prevention and management of fire in Canada and lake-level information, when used as supplementary data source, may reduce the level of uncertainty.

CHAPTER 2. Relevant literature review.

2.1. Canadian fire prediction and management systems.

The earliest attempts to understand fire dynamics in a scientific context was the fire danger rating work of Wright and Beall (1938). Their work examined fire risk as a function of fuel type and seasonality. This was used almost exclusively by fire scientists and practitioners until the release of the Canadian Forest Fire Weather Index (FWI) system (Van Wagner, 1987). Today, fire management is guided by the Canadian Forest Fire Danger Rating System (CFFDRS). Fire danger is a term which refers to the biotic and abiotic conditions within an environment, which contribute to rates of ignition, spread rates and management efforts required to control or suppress an ignition. The CFFDRS system uses four systems to determine the daily fire danger throughout Canada: the Fire Weather Index System (FWI), the Fire Behaviour Prediction (FBP) System, the Accessory Fuel Moisture System (AFWS) and the Fire Occurrence Prediction (FOP) System. The two main systems used in Canadian fire management are the FWI and the FBP. The FWI System uses inputs of noon LST temperature, relative humidity, 24-hour precipitation and wind speed to categorize the effects of fuel moisture and wind on fire behavior in a standardized fuel system. The FBP System uses FWI outputs and spatially specific landscape information, such as topography, to predict fire behavior in the major Canadian fuel types (Stocks *et al.,* 1989).

These indexes and systems are useful in predicting specific elements of fire occurrence and area burned; however, there is no standard method for estimating wildfire probability across Canada. Much of the predictive capability of these systems is supplemented by fire manager experience or utilizing records of disturbance and climatic events. These, along with fuel patterns, and the understanding of the connectivity between ecological elements, allows for greater understanding of how the system will react to an ignition event. These measurements can be used to evaluate post-fire influence of residence time of fires, the depth of burn and the vegetation removed (Kasischke *et al.,* 1993). Wildfires can be both beneficial and detrimental to sites in which they occur. Wildfires can remove old and decaying plant materials, control the spread of insects and disease, release nutrients back into the soil, and allow for cone opening and seed germination of fire-dependent species (Weber & Flannigan, 1997; McRae *et al.,* 2001).

Conversely, wildfires can disrupt the natural cycles of forest composition through the removal of native plant species and can result in the increased runoff and erosion of soil material. Ecological processes can occur simultaneously in the same area and it is important to develop new methodologies for evaluating the influence of fire on the Boreal landscape, and whether a fire in a region was influenced by changes in climate or other environmental processes.

2.2. Hydrology of the Boreal shield and Boreal plains.

Hydrological systems in the Boreal forests of Canada are highly complex (Figure.1). Presently there is considerable literature that is presently available that examines the role of climate in influencing hydrologic systems and of river ice (Lacroix *et al.,* 2005) and stream flow (Zhang *et al.,* 2001) but very little evaluating other systems, such as lakes. Future predictions are that the prairie regions are set to become warmer and drier and a number of hydrological and ecological systems might be at risk under future climate conditions (Gan, 1998). One concern is that variability in climate has the potential to impact vegetation and soil interactions, and could change the size and presence of wetlands and water bodies on the landscape (Woo and Rowsell, 1993; Hayashi *et al.,* 1998; Pomeroy *et al.,* 1999). Boreal plain and Boreal shield ecozones are unique as they experience considerable amounts of fire and while maintaining abundance of permanent lakes (Gunn *et al.,* 2001).

The Boreal plain ecozone is characterized by thick glacial sediments overlying bedrock that can be between 20-300m thick (Vogwill, 1978; Fenton 1994). The Boreal plain is characterized as having a sub-humid climate in which the annual average temperature is 1.7◦C (EcoRegions Working Group, 1989). The region is dominated by numerous shallow lakes and wetlands storing large amounts of water and carbon (Kuhry et al.1993, Krinner 2003) Surface water runoff in the region is typically low and ground water inflows into lakes systems range from low to high depending on the surface geology (Sass *et al.,* 2008; Ireson *et al.,* 2015). Hydrological connectivity is driven by mineral soil groundwater inputs in sub-regions with coarse textured soils (Beckers *et al.,* 2009). In regions with fine textured soils, near-surface flow is the process by which water movement occurs. The organic soils present in peatlands on the landscape allow water to move throughout the region and act as important sources of water for lakes (Winter, 2001; Ferone and Devito, 2004). The spring snowmelt within this region is responsible for over

50% of the annual water flow with summer precipitation being the major driver of hydrological processes (Devito *et al.,* 2005). In addition to snow melt, the region is highly dependent on summer precipitation for its yearly water budget and to maintain the wetlands that cover nearly 50% of the landscape (Vitt *et al.,* 1995). Wetlands are abundant across the Boreal plain and are found in low lying areas or depressions on the landscape. The hydrologic connectivity of the system and the runoff of water to lakes are influenced by land cover, watershed morphology and permafrost thaw, with varying levels of influence across multiple spatial and temporal scales (Winter, 1991; Gibson *et al.,* 2015).

The hydrology of the Boreal shield ecozone is influenced by the depth of the coarse textured soils and rocky areas throughout. The hydrologic connectivity and runoff rates within the region may not be controlled by topography but instead can be driven by climate patterns and regional geology which can differ significantly throughout the ecozone (Devito *et al.,* 2005; Oswald *et al.,* 2011). The elevation of the region is low and characterized by rolling hills and relatively thin glacial deposits overlain by predominantly coniferous and northern mixed wood forests. Containing 22% of all of Canada's freshwater surface area, it has an abundance of both wetlands and lakes (Keller, 2007). Roughly 10 % of the Boreal shield landscape is wetlands even though the region receives between 300 mm of precipitation in the semi-arid grasslands and 700 mm of precipitation in regions of central Manitoba each year (Carignan *et al.,* 2000). The infiltration rate of the soils in the region is very high, as are the rates of runoff, as compared to the Boreal plain.

The provinces of Alberta, Manitoba, and Saskatchewan span a large geographical area and each have major river systems which determine the availability of water resources. Alberta has two major rivers contributing to the total available water and rates of river flow. They are the Peace-Athabasca as the southern headwaters of the Mackenzie River basin and the Saskatchewan River. The Peace-Athabasca River represents nearly 80% of Alberta's river water and flows to the Arctic Ocean. The Saskatchewan River system is responsible for 15% of Alberta's river water but supplies water to the majority of the population of Alberta and its industry. Saskatchewan is also fed downstream by the Saskatchewan River, which accounts for nearly half of all river flows within the province. Manitoba's major rivers that contribute to its watersheds are the Churchill River and the Winnipeg River.

2.3. The relationship of Boreal hydrological systems to natural disturbances.

In recent years, the risks to water resources and the reliance of the Prairie Provinces on groundwater has increased (Wheater and Gober, 2013). In the provinces of Alberta, Saskatchewan, and Manitoba, 27%, 45% and 24% of the population, respectively, depends on ground water for domestic use with the highest use being for irrigation and agricultural purposes (Government of Canada Census, 2011). Water resources are critical in maintaining ecological functioning of Boreal systems as many are directly linked with processes that control fuel flammability and the vulnerability of the system to disturbance events. Examples of this connectivity can be seen in the work done by Westerling *et al.,* (2006) in which earlier snow melt in the western United States corresponded to large increases in wildfire activity and wildfires of increased duration. Hydro-climatic variables in the Boreal region of the Prairies are expected to experience an increased frequency of abnormal events and magnitudes which far exceed historical conditions (Tebaldi *et al.,* 2006; PaiMazumder *et al.,* 2013). Hydrologic instability or periods of reduced precipitation increase fuel flammability and the susceptibility of forests to disease and insect disturbances through dieback and reduced productivity (Hogg and Bernier, 2005). The fuel moisture in a region is correlated with the occurrence of large fires (Luce and Holden, 2009) and prolonged periods of reduced precipitation can lead to decreased fuel moistures and increased flammability (Balshi *et al.,* 2009). Drought events are highly variable in severity, duration and onset event and affect the Boreal region differently. These differences are caused by site specific soil structures, age of forest stands, tree species composition among many others.

Historical records of lake-level changes have illustrated their potential value at identifying hydrologic impacts of climate change and past conditions. Data from Boreal lakes within Canada are often used for reconstructing fire histories (Chara *et al.,* 1991), calculating runoff and sedimentation following harvesting and fire (Lamontagne *et al.,* 2000), researching the effects of fire on aquatic biota (Prepas *et al.,* 2001) and exploring the impacts of fires on water quality in forest catchments (Smith *et al.,* 2011). A commonality between many of these studies is the spatial scale used. Individual lake systems or a small sample size of lakes with homogenous characteristics are preferred to larger-scale analyses. However, small spatial scales fail to capture the heterogeneous nature of water bodies and wetlands present within the Boreal region and the large scale climatic, environmental and disturbance events that affect the landscape. Lakes in the Boreal region are sensitive to landscape-level changes and are reflective of climate processes occurring on the local environment (Pham *et al.,* 2008; Adrian *et al.,* 2009). Lake levels reflect the evapotranspiration, precipitation, landscape-level conditions and temperatures within the catchment basin (Ferone and Devito, 2004; Williamson *et al.,* 2008). Lake water-levels respond to environmental changes at a much slower rate than river systems. These attributes make lake information less sensitive to day-to-day variability than river discharge values that can easily be influenced by one large precipitation or ice melting event.

2.4. The presence of Wildfire on the Boreal Plain and Boreal Shield ecozones

Pattern of fire activity are a function of weather, climate, anthropogenic influence, fuel loading, and landscape characteristics (Bessie and Johnson, 1995; Johnson *et al.,* 2001). They are highly variable across the boreal forest of Canada (Boulanger *et al.,* 2012). On average, 1,000,000 ha of area burns each year within the Boreal Plain and between 0.7 – 7 million hectares in the boreal shield. The annual average area burned for the region is 2.9 million hectares burned. Through the assessment of a previously untested hydrological variable such as $LL_{DEP,}$ changes in the Boreal landscape in wildfire activity can be better understood. Precipitation, temperature, relative humidity and wind speed are the weather variables responsible for determining the Fine Fuel Moisture Code (FFMC) (Van Wagner, 1987). Lake levels are representative of landscape level conditions and are a measurable output that can be easily recorded and monitored over time. LL_{DEP} when evaluated in a historical context may offer additional information in explaining IGN and AOB. LL_{DEP} provides an index which evaluates changes in surface waters, patterns of precipitation on the landscape and fuel conditions at a spatial and temporal scale that is larger than traditional river and stream studies.

CHAPTER 3. Methods and Data.

3.1. Study area.

The study area was located in the Boreal shield and Boreal plain ecozones of the prairie provinces of Alberta, Manitoba, and Saskatchewan in Canada (Figure 2). Within these ecozones, 25 naturally regulated lakes were chosen to as data sources in relation to fire activity. The attributes from each lake system were tabulated for reference (Table 1). For the purposes of this study, naturally regulated lakes were defined as those in which there were no dams, weirs or outlets present and no manipulation or control over water levels occurred. There were eight lakes located within the province of Alberta, six in Saskatchewan and eleven lakes within Manitoba. Eight of the twenty five lakes were located on the Boreal shield ecozone and seventeen were on the Boreal plain ecozone. Ecozones were defined using the classification system developed by the Ecological Stratification Working Group (1996).

3.2. Hydrology of the Study Area

The climate of the Boreal region is semi-arid. Under this climate classification, rates of evapotranspiration are equal to or exceed rates of precipitation during many parts of the year. This results in the region experiencing periods of water scarcity and drought frequently. The average precipitation is 300-600 mm for the Boreal plain and 400-550 mm for the Boreal shield. The Boreal plain has considerably fewer lake systems than the Boreal shield due to the underlying Precambrian bedrock found in the boreal shield region. This bedrock prevents water from draining from the surface as easily as the Boreal plain. The permeability of this substrate is low resulting in considerable run-off rather than soil water storage. This results in the presence of considerable surface water and the pooling of water in water bodies and wetlands (Lafleur *et al.,* 1997) Both regions are highly reliant on groundwater recharge from spring snow melt and precipitation events that occur outside of the growing season and are highly vulnerable due to their limited ability to access and to store water (Redding and Devito, 2011). The vulnerability in the Boreal plains is caused by the majority of precipitation events occurring outside of the summer months, when fire activity is the greatest. Vulnerability in the Boreal shield stems from low soil water storage and less hydrological memory with surrounding hydrological features.

3.3. Boreal plain and Boreal shield ecozone characteristics.

The Boreal plain is characterized as having fertile soils which are the result of glaciofluvial, glaciolacustrine, and moraine deposits between 20-240m in thickness (Pawlowicz and Fenton 2002). The climate of the region is continental with mean annual temperatures ranging between -2 and 2.5 degrees Celsius. 84% of the ecozone is covered by forest. The dominant coniferous tree species in the region are white spruce (*Picea glauca*), black spruce (*Picea mariana*), tamarack (*Larix caricina*) and jack pine (*Pinus banksiana*). Patches of broadleaf species of white birch (*Betula papyrifera*), trembling aspen (*Populus tremuloides*) and balsam poplar (*Populus balsamifera*) are seen in the transitional zone between the Prairie region and the Boreal plain. The Boreal plain occupies an area of 668,664 km^2 (Statistics Canada, 2012). The total forested area within the region is 580,577 km^2. Human land use in the Boreal plain is predominantly agriculture, oil and gas, forestry, and tourism.

The Boreal shield is 1,640,949 km^2 in size. The total area forested within the Boreal shield is 1,382,690 km^2 (Canadian Encyclopedia, 2015). The climate of the Boreal shield is classified as continental with an average annual temperature range between -5.5 and - 4 degrees Celsius. The region experiences annual precipitation between 400mm in the west with as much as 1000 mm in some of the eastern regions of Ontario. The geology of the region is thin soils which are highly acidic soils and which are nutrient poor. The region is dominated by highly resilient and adaptable tree species being the most prevalent. These include black spruce (*Picea mariana*), white spruce (*Picea glauca*), jack pine (*Pinus banksiana*) and balsam fir (*Abies balsamea*). The mean fire return interval for the region is 150 years, dependent on tree types and site specific differences (de Groot *et al.,* 2013). Land usage in the Boreal shield is primarily forestry and mining with some limited agricultural activity in the southern region.

3.4. Lake selection methodology and the relationship between IGN, AOB and lake-level variability

The detection of trends within a natural system, and in particular those which examine time series relationships of hydrological variability, are difficult due to the highly complex nature of hydrologic systems. In order to standardize the data sets implemented in the study, the use of established monitoring stations was employed. The lake level data was provided by the hydro climatological data retrieval program (HYDAT) https://www.ec.gc.ca/rhc-wsc/default.asp?lang=En&n=9018B5EC-1. The HYDAT database is a part of the national water data archive and contains real time, automated and historical records of water-levels and stream flows for many Canadian river and lake systems. The database provided measurements of daily, monthly and yearly hydrological information, as well as minimum and maximum flow of river systems. Monthly mean lake levels were chosen as the data set and measurements for the months of June, July, and August (JJA) were tabulated. These months were chosen as they reflect months when they are free of ice and in which fire activity is the greatest in the study area. Monthly mean water-levels of the study lakes varied between 7.83 meters above sea level (msl) at Sturgeon Lake near Prince Albert, SK and 849.91 msl at Pigeon Lake, AB. The aim of this study was to determine key landscape-level interactions between wildfire and lakes systems at a provincial scale, and the month mean measurements of each lake for JJA contained the most consistent and reliable data to meet the goals of the study.

The HYDAT database allowed hydrometric data to be filtered based on a series of user-defined criteria. The HYDAT data was refined to include only the monthly mean measurements for JJA between the years of 1980-2011. The choice to limit the data to 1980-2011 was made as it was the most recent information and the most complete source of data for analysis. Prior to 1980, area burned/ignition data was inconsistent making it difficult to assess the relationships between the data sources effectively. The second criterion required that the lake station have greater than nine years' worth of data for JJA. This was done to assure a data record that could be compared against the fire database information and for the time lag analysis which required continuous data to test the hydrological memory of the lake. The hydrologic memory refers to the multi-year influence that lake level change has on AOB and IGN and whether specific trends could be seen on the landscape that influenced fire activity across multiple years. The third criteria for the study was that the station had to be classified as naturally regulated with no outlets or dams controlling the water level of the lake. Many of the lakes that were monitored in the HYDAT database were regulated or had some type of weir, dam or other control. As the study aimed to test the relationship between LL_{DEP} of naturally regulated lakes, the removal of human influence where possible was a necessary step in the analysis. Including lakes with human water level control would have introduced variations in the measurement of lake water levels that were not the result of surrounding environmental influence or climate. A correlogram, which is the statistical method that evaluates correlation values between data points, determined the approximate distance that was needed between lakes within the study to properly avoid autocorrelation. The results of the correlogram determined that an average distance of 200 km between lakes was adequate to remove most, if not all, of the spatial autocorrelation. Using these results, the initial 54 lakes were further refined to include only those in which the most complete data record was available while achieving the best spatial coverage. The resulting 25 lakes meeting these criteria became the lakes for the study.

Lake size was determined through the data extraction tool from the CanVec database accessible at "http://geogratis.gc.ca/site/eng/extraction/". The CanVec database is a set of vector data produced by Natural Resource Canada. The data available within the database is at a scale of 1/50,000. The CanVec information served two purposes, the first was to calculate the size of each lake and the second was to cross reference the coordinates of each lake listed in the HYDAT database to make sure that the locations were accurate. Elevation and drainage areas were also included into the data sheet to better understand the hydrology of each lake. The smallest lake that was included in the analysis was Childs Lake near Boggy Creek with a total area of 8.243 km^2, and the largest lake was that of Island Lake which had a total area of 1,230.19 km^2. The variability in lake size and drainage basin area allowed the study to be comprehensive and inclusive of all lakes in which hydrological information was available. Lakes that did not have size information available in the CanVec database were determined through the use of supplemental sources such as estimations from aerial photographs, remote sensing and other online sources. The minimum number of yearly values for lake level available was nine and the maximum was thirty four (median= 16 years). Water levels in the study were considered as the independent variable with AOB and IGN at the varying buffered scales acting as the dependent variable.

3.5. Number of Ignition and total Area burned data for fires greater than 200 Hectares.

Wildfire data were acquired from the Canadian National Fire Database. The CNFDB consists of fire ignition point information (IGN) and area burned polygons (AOB) for all reported fires that occurred in Canada from 1959-2014 that grew to 200 ha in size or greater. Fire information was limited to 1980-2011 as data prior to 1980 tended to be under reported and the metadata collected had inconsistencies (Table 1). This data was summarized and placed into a dataset which would later be evaluated against $LL_{DEP.}$ To evaluate the influence of spatial scale on AOB and IGN, a series of areal buffers were created. There were three standardized sized buffers of 10,000 km^2, 100,000 km^2 and 1,000,000km^2. The smallest buffer of 10,000 km^2 contained 722 ignitions and accounted for 1,697,857 km^2 in area burned. The 100,000 km^2 buffer contained 22,045,518 km^2 of area burned and 8,336 total ignitions over the period of 1980-2011. The AOB polygons were clipped using the three buffers and the total number of fires and area burned within each of the three was summarized for analysis. The largest buffer of 1,000,000 km^2 had the greatest number of ignitions with 61,039 and the largest area burned, 214,971,710 km^2.

3.6. The influence of different scales of spatial buffers on the fire activity in the study area.

The spearman correlation values of LL_{DEP} in relation to fire activity at the three buffer scales were calculated to determine the spatial scale that displayed the strongest connection with AOB and IGN. Three buffer sizes were created from the lake centroid at each lake station and were compared against fire data information of IGN and AOB. The creation of circular buffers that extended from the centroid of each of the final twenty-five lakes was done in Arc GIS 10.0. The use of three standardized buffers allowed for us to explore whether a spatial relationship existed between the HYDAT lake level information and the CNFDB fire data for IGN and AOB. The buffers contained all annual AOB and IGN for fires that were greater than 200 ha in size and were calculated for each year. The three buffers occupied areas of 10,000 km^2 (56.42 km radius), 100,000 km^2 (178.42 km radius) and 1,000,000 km^2 (564.20 km radius). IGN and AOB data which fell within each of these buffers was tabulated for each lake using the intersect function. Standardizing the buffer size for each lake allowed for enough pertinent information to be included while still being able to capture the variability among lakes. For the purposes of this analysis statistical significance was defined as a spearman correlation value in which the p values was ≤ 0.05

3.7. Deviation of mean monthly lake water-levels from historical averages.

Water-level variations were determined through the averaging of historical seasonal monthly values of JJA and comparing them to annual measurements. These values were used to estimate the inter-annual variability between lake levels in the study and identify years of lower levels. A series of calculations were performed to determine how the lake level information compared to historical averages. The historical average refers to the mean value of JJA values over the course of the historical record. JJA values were calculated for each lake for each year. JJA values for all years for each of the lakes were averaged for a historical average. These acted as reflection of how the water-level traditionally responded to the influence of climate and whether lake levels in a particular lake experienced greater susceptibility to climate patterns than others. To calculate the percent departure of each of the lakes, the equation below was used:

Yearly JJA refers to the average of monthly mean lake level measurements for June, July and August for each of the study lakes. The mean of these three months was used as the yearly JJA value pertaining to the specific year in which the measurements were taken (i.e. 1980). The historical JJA was the mean of all available June, July and August measurements for all available years by station. For the purposes of the study, only data between the years of 1980-2011 was analyzed. The historical average of mean lake levels functioned as a standard to which yearly fluctuations were compared. Differences between the yearly and historical JJA lake levels were divided by the historical average to determine how the levels during a specific year compared to historical measurements. This numerical value was then multiplied by 100 to provide a percentage value. Using percentages, allowed lakes within the study area which varied considerably in terms of size and drainage area to be compared using a common variable. Lake level percent departure (LL_{DEP}) was an effective measurement of mean water-level changes from averages of historical normalized values.

3.8. Lake Level Departures and Area Burned/ Number of Ignitions by buffer size.

The statistical analysis for each of the buffers was performed using the Spearman rank test. This method calculated the correlation coefficients for LL_{DEP} as a function of AOB and IGN for the three buffers. The Pearson method was also attempted in the initial stages of analysis. This method resulted in similar correlations but overall were weaker than the spearman method and was not used for the further stages of analysis. In order to evaluate the relationship of current year change in lake water-levels and area burned, the correlation analysis was limited to the same year for $LL_{DEP,}$ IGN and AOB. The aim was to evaluate whether a relationship was present between LL_{DEP} and AOB or IGN during a given year, and the strength of that relationship. The test was used to refine in the spatiotemporal scale of analysis and increase the overall strength of later statistical models.

3.9. Temporal lags in relation to AOB and IGN.

To test the hypothesis of whether antecedent hydrological conditions of a lake system have the capacity to affect the flammability of fuels and total area burned one to two years later, lags were implemented on LL_{DEP} values in relation to fire. JJA seasonal LL_{DEP} values were lagged behind fire activity for the buffered areas. The comparison of LL_{DEP} from previous years in relation to fire activity was incorporated to determine the strength of the connection between changes in lake levels on the landscape fuel flammability across numerous years. The implementation of a one and two-year lag was then evaluated against buffered AOB and IGN values of the year being tested. To calculate the correlation coefficients, the Spearman correlation method was used and the results for AOB and IGN were tabulated. The output from this analysis would be used to determine the presence and extent of any synoptic connections and ecological relationships with wildfire that existed at a multi-year scale.

3.10. Linear Models of AOB/IGN as a function of climate and LL_{DEP}.

The final analysis involved the creation of multi-variable models of fire activity. This was done through the creation of multiple linear regression models using the lm function in the R Statistical software. The packages of Mass and QuantPsyc were also installed for the purposes of the analysis. The climate variables of TEMP, PSUM and LL_{DEP} were evaluated in relation to AOB and IGN and the calculated variances were calculated. DC was initially included as a fourth variable in the models to determine whether it resulted as an improvement in the determination of fire activity. Initial testing determined that multi-linear regression models that were the most capable of explaining variance in fire activity did not include DC. This was likely due to the fact that DC was highly correlated with PSUM. This was determined through a pair wise correlation test of all variables included in the study. The remaining variables of TEMP, PSUM and LL_{DEP} were chosen for analysis in relation to variability in IGN and AOB.

The process for creating the multi-variable models involved a series of statistical analyses to determine the best fit for our model. The first step was the evaluation of the univariate statistics for AOB, IGN, TEMP, PSUM and LL_{DEP}. This was done to evaluate the distribution of each of the data sets. The distribution of data within AOB and IGN were both improved when a log transformation was implemented. Next bivariate relationships between individual variables were examined for logged AOB and IGN data and each climate variable. This information determined the correlation between LL_{DEP}, TEMP and PSUM and AOB/ IGN and allowed for a preliminary evaluation of which of the three climate variables was likely to have the strongest correlation with changes in AOB/IGN. The final stage of analysis was the creation of linear models of AOB and IGN as a function of TEMP, PSUM and LL_{DEP}. The outputs of these models were then used to create standardized coefficients. Using these values, a statistic of the total variance explained by each climate variable was determined.

The equation used in the analysis was as follows:

$$\sum_{n=1}^{t=n} (\log(\text{AOB or IGN}) = \text{P}_t + \text{T}_t + \text{LL}_{DEP})$$

Where, AOB=Area burned, IGN= Number of ignitions, P_t= summed seasonal precipitation, T_t= 95th percentile temperature for JJA and LL_{DEP}= Lake water-level departure from historical average.

Variable importance from each model was calculated using standardized coefficients and the outputs from the multi-variable modelling were recorded. The first model used the inputs of TEMP, PSUM and LL_{DEP} to explain variance in IGN. These models were created to determine the strength of LL_{DEP} at explaining variance in AOB and IGN as compared to traditional climate variables. Temperature and precipitation were included as they are the climatological variables that most directly influence the amount of available water on the Boreal landscape which can influence the flow of water into catchments and corresponding lake sizes. The use of the 95th percentile values of these two climate variables was that they corresponded to danger classes that were between very high and extreme and represented landscape conditions that were the most conducive to large fires and area burned. 95th percentile maximum mean JJA temperature and 95th percentile maximum drought code were chosen as they both coincided with the abnormally high fire risk and were often the periods of the fire season most conducive to ignition and total area burned. The summed precipitation by season was included as it is a contributing factor to lake levels, fuel moistures and landscape connectivity for lakes in the Boreal region. The TEMP, PSUM and DC data was made available from Environment Canada using weather observations from stations throughout the provinces. The data was obtained from the Canadian Forest Service. It was interpolated between stations using inverse distance weighting (IDW) with an exponent of 2 to generate daily grids with a 3x3 km cell size. Temperature values were adjusted for elevation using a lapse rate of -6.5°C/km. The weather grids were then used to calculate the DC on a cell-by-cell basis.

The multivariable models were designed to examine and evaluate the degree of variability in AOB and IGN that could be explained by the inputs of PSUM, TEMP and $LL_{DEP.}$ Standardized coefficients were determined through the use of multiple-regression analyses and evaluated against changes in yearly AOB and IGN. Standardized coefficients were used as they allowed for the comparison of the independent variables within our study despite differences in the scale of units between the variables. The outputs from the models will determine whether LL_{DEP} provides any additive predictive power to current metrics for fire prediction and fire modeling and the variance explained by the three climate variables. The analysis also was useful in determining which variable was most capable at capturing variation in annual values of AOB and IGN.

CHAPTER 4. Results.

4.1. Buffer size in relation to AOB and IGN.

The analysis of LL_{DEP} in relation to AOB and IGN resulted in predominantly inverse correlations values that were fairly strong. Figure 3 and Figure 4 were created to display the variability that was present in the buffers. The size of buffer extending from the lake stations appear to be a determinant of the level of correlations between fire activity and LL_{DEP}. The 10,000 km^2 buffer performed the worst with only 6 lakes that resulted in significant values with IGN and 6 that were significant with AOB. The average correlation value for this buffer was also the lowest of the three tested. The 100,000 km^2 buffer had 12 lake station that were significant for IGN and 13 for AOB. This buffer was determined to be the spatial scale which was the most capable at capturing the relationship of fire activity and area burned. The 1,000,000 km^2 buffer resulted in 8 correlations that were significant for IGN and 7 that were significant for AOB.

4.2. Influence of LL_{DEP} variability in relation to fire activity.

Correlations between LL_{DEP} and IGN were listed in Table 2. Correlations ranged between and between -0.86 (05KG004) and 0.13 (05LH008). The mean correlation value of the twenty five lakes was -0.44. The lake which had the strongest correlation with IGN was 05KG004. The correlation value for this lake was-0.86 and the p value was 0.001. The analysis of the relationship between LL_{DEP} and AOB had a range in correlation values. The strongest inverse correlation was -0.83 (05KG004) and the strongest positive correlation was 0.14 (05LH008). The mean correlation value for AOB and LL_{DEP} for all lakes was -0.49, with 13 lakes displaying a p value of $\leq$0.05. The lake with the strongest correlation was also 05KG004 with a p value of 0.001. IGN was positively correlated with LL_{DEP} for two of the lakes: 06AD001 and 05LH008 with a correlation value of 0.01 and 0.13 respectively. AOB and LL_{DEP} was only positively correlated for the lake 05LH008. The correlation value for this lake was 0.14.

Inverse correlation values of -0.50 or stronger were present in 10 of the 25 lakes for IGN and displayed a correlation that was significant at $p \leq 0.05$. There were 12 correlations of at least -0.50 for AOB with 11 of the 12 correlations being significant at a value of $p \leq 0.05$. The average correlations values of shield lakes with a significant relationship was -0.655 for IGN and 0.66 for AOB. 8 of 17 Boreal plain lakes displayed a significant relationship with AOB and 6 of 17 were significant in relation to IGN. The average correlation of LL_{DEP} for lakes that were significant in the Boreal plain ecozone was -0.62 for IGN and -0.59 for AOB. To better understand and visualise the strength and distribution of relationships between AOB and IGN and $LL_{DEP,}$ correlation values were representing using bubble size to represent the strength of correlation relationship and color to represent whether the relationship was a positive (red) or negative (blue) correlation in Figure 5.

4.3. Time lag analysis.

Implementing a one- and two-year lag on lake level information in relation to AOB and IGN weakened the level of correlations that was seen in the same year analysis (Table 4 and Table 5). The majority of the lakes displayed little to no correlation with lagged lake level. There was only one lake which displayed a significant relationship between LL_{DEP} and IGN/ AOB when implementing a one-year lag (Figure 6). This lake, 05LA007, had a p value of 0.02 and an inverse correlation with both AOB and IGN of -0.67. 10 of the 25 lakes correlated positively with AOB and 12 correlated positively with IGN at the one-year lag. There was one lake station that displayed an inverse correlation but only with IGN, 05MD804 (p=0.01, r=0.48). Incorporating a two year lag exhibited even weaker correlation values with both AOB and IGN. Only one lake exhibited a correlation between LL_{DEP} and IGN with a p value ≤0.05. This lake was 05MD804 with a p value of 0.001 and a correlation value of 0.59. The correlation test between LL_{DEP} and AOB resulted in the lake station 05LN005 having a p=0.05. The correlation value of this lake was 0.53. The majority of the lakes evaluated using the one and two year lag were not significant, suggesting that lagged lake levels resulting in a weakening of the correlation with AOB and IGN.

4.4. Multi-variable models of AOB and IGN using climate variables.

The results from the Correlation matrix suggested that DC values were highly correlated with temperature and precipitation (Table 6). The inputs for the multi-variable two final models were TEMP, PSUM and $LL_{DEP.}$ IGN and AOB both resulted in significant models using these inputs as seen in Table 7 and Table 8. The model for IGN resulted in ten lakes that were significant at a p value ≤0.05 in relation to IGN. A box plot of the correlation values by climate variable is shown in Figure 7. Five out of the ten significant models found that LL_{DEP} explained the largest amount of variance in the number of ignitions. The variance explained by LL_{DEP} ranged from -0.46 (Station 05RE002, p value of 0.04) to -0.81 (Station 05KG004, p value of 0.01). The multiple R^2 values of the significant models ranged from 0.28 (Station A6AF002) to 0.67 (Station 05KG004). For the models that were significant, LL_{DEP} explained 39.2% of the variance on average in IGN as compared to 29.4% for PSUM and 31.5% for TEMP.

The model explaining variance in AOB using the inputs of TEMP, PSUM and LL_{DEP} resulted in ten models which were significant at a p value of ≤0.05. In six of the ten models that were significant, LL_{DEP} explained the highest amount of variability in AOB. The range in variance explained by LL_{DEP} was between 0.80 (Station 05KG004, p value of 0.02) and 0.25 (Station 06DA001, p value of 0.03) and the degrees of freedom for significant models were between 8 and 27. In significant models, LL_{DEP} explained on average 46.3% of the variance on average as compared to 22.7% for PSUM and, 31.1% for Temperature.

CHAPTER 5. Discussion.

The purpose of the study was to evaluate three hypotheses relating wildfire activity and LL_{DEP} values of naturally regulated boreal lakes. Each hypothesis was developed to test whether differential spatial and temporal resolutions affected the correlation values between lake level information and fire activity. Through the incorporation of spatial buffers, the lagging of lake level information through a time series analysis and the creation of multiple variable models, LL_{DEP} was comprehensively examined to see whether it was a capable and useful indicator of fire activity. The results from this study have shown that a strong relationship between LL_{DEP} and fire activity exists for data in the same year, but that the relationship was weakened when LL_{DEP} values were lagged by 1-2 years. The multiple variable models suggested that $LL_{DEP,}$ when considered as an input with traditional climate information, performed well and was capable of explaining variance in AOB and IGN better than traditional models. These finding suggest that LL_{DEP} may capture important information influencing fire activity that is not seen in other climate variables. The ability of LL_{DEP} to capture environmental information that is difficult to measure directly through tradition climate methodologies suggest that LL_{DEP} could present a new direction in the field of fire science.

5.1. Same year analysis and the relationships of LL_{DEP} with IGN and AOB.

The Boreal region of Canada is heavily affected by fire and strong relationship between climate and fire activity are known and well documented. Periods of drought and decreased precipitation have been linked within the increased presence of fire ignitions and fuel flammability (Peterson *et al.,* 2010), and it appears that lakes within the study area are capable of reflecting this fire potential effectively. The high correlation values that were seen may be due to the fact that the boreal region experiences a large amount of fire, and lake systems in the region capture climate processes which influence vegetation and fuel flammability. The 100,000 km^2 areal buffer responded the strongest of the three buffers most likely due to the watersheds of lakes capturing the environmental response of the system to climate most effectively (Pham *et al.,* 2008; Williamson *et al.,* 2008; Adrian *et al.,* 2009). Boreal lakes are dependent on precipitation events, run off and snowmelt to maintain consistent water levels and lake levels fluctuations are representative of the sum of all interacting environmental factors within a lake system and their influence on forest stands. As the buffer size increased, the degree of influence from these localized processes would have decreased and the widest buffer, which had the weakest correlation values of all the buffers, may have been incorporating multiple localized influences, outside noise, and environmental processes.

The relationships that exist between lake levels and AOB/IGN may also be a function of the ecozone in which the lakes were situated on the landscape. The Boreal shield and plain are different in terms of the underlying surface and bedrock geology. The Boreal plains have permeable glacial soils that promote regional flow and result in watershed boundaries that are complex and varied across the landscape. Conversely, the Boreal shield is less permeable to precipitation events and the drainage of water within the system is described as disrupted and disorganized and is characterized by more localized water movement within the system (Schindler, 1998). The deeper soils present on the Boreal plains as compared to the Boreal shield also meant that the water storage potential was higher during periods of drought than lakes on the Boreal shield. Therefore, lakes on the Boreal shield may have been less able to deal with extended periods of drought and appear to have been more susceptible to extremes in temperature, reduced precipitation, or both.

In the Boreal region, evapotranspiration and soil water storage are also most directly linked to the water balance of the region and display this relationship at regional and local scales. Decreases in lake levels may have been signaling a decrease in the soil water storage of surrounding areas and increases in evapotranspiration, both of which would suggest climate patterns favoring wildfire activity and the increase in AOB and IGN. The spatial distribution of lakes in the study revealed spatial patterns on the landscape. Lakes that were located on the Boreal shield ecozone were more strongly correlated with AOB and IGN than those on the Boreal plain. 6 of the 8 lakes located on the Boreal shield displayed a significant relationship with both AOB and IGN. These findings may warrant further analysis but was beyond the scope of this project.

5.2. One and two year lags on lake level information and the hydrological memory of Boreal lakes.

The lagging of lake level information weakened the correlations between LL_{DEP} and AOB and LL_{DEP} and IGN considerably. This finding was somewhat surprising following the strong associations that were discovered in the current-year analysis. Lagging of lake levels at a time period of one or two years does not capture the carry over effects of drought and low water-levels from previous years on future fire activity. The cause of this may have been that the influences on system hydrology between years are influenced by groundwater fluxes and complex inter-year variability of temperature, precipitation and evapotranspiration rates. The lack of response may have been the result of drought conditions of antecedent years that were later rectified with increases in precipitation or winter snow fall the following year. This may require further investigation and study in future analysis. The lagging of $LL_{DEP,}$ may have introduced inaccuracies of the landscape-level conditions that were present, thereby failing to take into account the recovery of the system to hydrological disturbance. Wildfire is more closely correlated with monthly changes in weather and climate whereas lake levels take a much longer time to reflect climate patterns and long term changes. Wildfires in the boreal region are occur episodically in the boreal region and are influenced by a number of environmental processes and climatic patters (Burton *et* al. 2008). Lakes are inherently slow changing and static features that are supported by complex underlying hydrological system. Although the study was unable to discover a correlation between lagged LL_{DEP} data and AOB and IGN, the methodologies that were used may be appropriate for analysis at a more localized study area or for an individual lake.

The study also only examined climate information for the months of June, July and August. Climate events that occurred outside of these months may have caused considerable changes to the connectivity of LLDEP and fire activity but was not specifically addressed within the study. Snow pack and the timing of the snowmelt specific to each may have been one example of a climate event that was not properly captured using lagged LL_{DEP} information.

5.3. Multi-variable analysis and the proportioning of variable importance in relation to fire activity by lake station.

The use of TEMP, PSUM and LL_{DEP} as inputs in our models were successful at explaining variance in AOB and IGN. As the results showed, there were a large number of linear models in which LL_{DEP} was the most capable variable at explaining inter-annual variability in fire activity. Traditional climatological variables, namely temperature and precipitation, although useful, did not have the same explanatory power. The cause of this may have been due to the fact that lake levels are the reflection of the dynamic balance between inputs of precipitation and run off, and evaporation losses (Van der Kamp, 2008). They are also influenced by vegetation, topography and land use changes surrounding the watershed and capture captures more environmental processes and landscape-level conditions than climate variables alone. LL_{DEP} values provide insight into the relationship lake levels and fire activity by more comprehensively associating landscape conditions with fire activity in a given year.

Lake level measurements are simple to record and are available for many lakes the Boreal plain and Boreal shield ecozones. This information has been shown to be a capable supplementary proxy for climate conditions that favor wildfire activity. In situations where climate data availability is low or the connectivity of the system to climate patterns is unknown or underdeveloped, lake level information may be allow for a knowledge gap to be filled or act as another set of information to monitor for change. The success of LL_{DEP} as a new predictor of fire activity has the potential to increase the effectiveness of management objectives in the Boreal region through development and refinement of the methodologies introduced in this study.

CHAPTER 6. Conclusion

In summary, this thesis supported the hypothesis that LL_{DEP} exhibits a statistical relationship with AOB and IGN for the Boreal region when evaluating data from the same year. The high level of correlation between LL_{DEP} and fire activity and the level to which the two data sets were correlated suggest that LL_{DEP} has the potential to be developed as a data set for future fire prediction and measurement studies in the boreal region. The study was capable of discovering a hydro- fire trend across a large spatial scale with very few parameters or filters imposed on the data evaluated. Mean lake level information requires very little information to gather and is capable of capturing more landscape level conditions of drought better than

Our results were unable to support the hypothesis that a relationship between one and two year lags and AOB/ IGN existed. This was likely the result of the hydrological systems being representative of landscape conditions of the same year and the inability of the one- and two-year lags to capture complex interactions between the hydrological systems of the Boreal ecozones. River watershed snowpack (MacDonald *et al.,* 2012), long-term multi-year climate influences of PDO and ENSO processes (Fauria and Johnson, 2008) or feedbacks with the global system by peatlands and other vegetation (Waddington *et al.,* 2015) may have influenced the relationship between LL_{DEP} and fire activity, that may not have been captured in the LL_{DEP} values. Directed analysis that include information on inter-year variability in climatic and hydrological processes that mitigated fire activity in subsequent years may have improved the results and lead to significant values. The final hypothesis that lake levels were able to capture as much, or more variation in AOB and IGN was confirmed. The results of this thesis suggest that LL_{DEP} may become a highly implemented data source that outperforms traditional climate datasets used in fire management in the future.

6.1. Limitations, caveats and future directions.

The success of the study at finding a link between LL_{DEP} and fire activity will allow for future studies to implement and further develop this field of research into other areas of wildfire research in the Boreal region. In order to do so, limitations and caveats within the study needed to be addressed for the purposes of avoiding them in future studies. The first limitation that was apparent was that LL_{DEP} calculation did not take the overwintering processes and precipitation in the form of snowfall into account. LL_{DEP} is an average of the lake level values for only the months of June, July and August. The influence of all other months is assumed to be captured in the variation seen in the mean lake levels. This is an important assumption as the mean monthly averages in lake level for the months of JJA are the constructs of not only the precipitation and temperature inputs within the months themselves but also the months leading up to them. Timing of the snowpack melt and the amount of snow that accumulated on the boreal landscape during the winter months influence the available water on the landscape and the timing of streamflow into forested areas throughout the Boreal region. Lake-level information may act as an indication of the precipitation events and the effect of overwintering on forest fuels and lakes systems at a very basic level but it cannot fully replace direct measurements of snowfall and landscape-level conditions that lead to increased flammability and greater occurrences of fire.

The second issue within the study were lake stations which did not contain measurements for each of the three months evaluated in the study. The seasonal focus of June, July and August meant that values for each of the months were required for a seasonal average to be created for the lake station. If a station did not have monthly measurements for each of the three months, a seasonal measurement for that year could not be analysed in relation to fire activity. Attempts to limit this were made by identifying which stations had the longest and most complete records from the data provided by the HYDAT database and included them in our analysis. The HYDAT database is the most reliable and up to date information for lake stations that was available but still contained considerable gaps in the monthly and yearly data record for lakes. Furthermore, this made the time series analysis difficult and may have been one of the reasons that such a weak response was discovered when implementing a one-year or a two-year lag.

There were few northern lakes included in the study area due to limited data availability or discontinued monitoring for northern lakes. This meant that the majority of the lakes which were included within the study area were located centrally in the ecozones and were sometimes within proximity to urban developments in the central and southern region. This may have had some influence on the outcomes, as industry heavily influences water availability in these regions. The availability of data points that were located in the northern regions of the prairies may have assisted in the improved accuracy of our findings. Northern regions are those in which wildfires are most common and reach the greatest size. The availability of these data sources may have allowed for a study that was free from anthropogenic influences and mimicked the natural processes of wildfire and LL_{DEP} more closely.

The percent of each buffer burned by year would also have been an interesting data source to consider for inclusion in the study. These values would have helped in providing a secondary spatial scale with which to evaluate fire. Fuels on a landscape require a specific amount of time to regenerate and reach a maturity in which they can sustain a fire event and years in which high amounts of the buffer area were consumed may have led to subsequent years of lower areas burned as there was less available fuel for consumption. The higher number of ignitions and area burned from previous years may have influenced the amount of area burned and the number of ignitions in subsequent years (Higuera *et al.,* 2009, Johnstone *et al.,* 2010, Krawchuk and Cumming 2011). Similarly, the inclusion of vegetation and fuel maps for the study area may also have improved the results of this study. Vegetation is known to have an influence on the connectivity of the landscape during a fire by determining the flammability and moisture content of fuel on the landscape. The buffered areas surrounding lakes, in this study, did not include a consideration of the types of forest fuels. This information could be implemented through the use of remote sensing data or pre-existing fuel maps for the region. This information could help to explain why certain landscapes exhibited specific patterns of area burned and which buffered regions were most susceptibility to fire due to the fuels present on the that landscape being more flammable as compared to other forest fuels.

In conclusion, this study was able to prove the hypothesis that natural lake level fluctuations were correlated with area burned and total number of ignitions within the Boreal region by year. This study was the first to evaluate these two data sets and provides evidence for the inclusion of LL_{DEP} in future studies of fire probability and occurrence as an important and highly valuable source of information. Through the refinement of methodologies which evaluate fire and lake level relationships at a localized scale, LL_{DEP} data is a highly implementable and useful source of data.

6.2. Tables and Figures

Table 1. List of the 25 lakes used within the study and associated attributes.

Lake ID	Lake Station w/ Province	Latitude	Longitude	area (km^2)	Drainage Basin area (km^2)	Surface Elevation (m)
04AA002	Oxford lake, MB	54.94	-95.29	420	8,790	186
04AC002	Island lake, MB	53.87	-94.67	1,230	14,000	225
05FA013	Pigeon lake, AB	53.02	-114.13	84	283	849
05GF003	Sturgeon lake near Prince Albert, SK	53.42	-106.16	13	1,490	458
05KF004	Big Sandy lake, SK	54.46	-104.18	78	434	398
05KG004	Schist lake, MB	54.76	-101.83	30	505	322
05LA007	Kipabiskau lake, SK	52.57	-104.18	5	1,040	520
05LC003	Red Deer lake, MB	52.89	-101.46	240	14,200	265
05LH008	Waterhen lake, MB	51.97	-99.59	213	55,000	250
05LN005	Dog lake,MB	51.04	-98.61	161	993	245
05MD804	Childs lake, MB	51.58	-101.11	8	67	643
05MF019	Clear lake, MB	50.66	-99.98	30	146	615
05RD006	Family lake, MB	52.03	-95.46	170	17,600	297
05RE002	Weaver lake, MB	52.77	-96.76	100	6,840	232
05SA801	Gull lake, MB	50.42	-96.52	81	4	254
06AD012	Chitek lake, SK	53.75	-107.74	32	871	570
06AF002	Cold lake, AB	54.47	-110.17	308	6,515	533

06DA001	Wollaston lake, SK	58.48	-103.28	2,711	16,400	395
07BB008	Chip lake, AB	53.63	-115.39	86	1,211	792
07BE002	Baptiste lake, AB	54.74	-113.53	9	305	578
07BJ006	Lesser slave lake, AB	55.31	-115.77	1,086	13,567	654
07CE906	Christina lake, AB	55.63	-110.77	17	1,265	550
07GH003	Sturgeon lake near Valleyview, AB	55.12	-117.56	45	638	683
07JA002	South Wabasca lake, AB	55.94	-113.81	54	1,600	545
07LD001	Cree lake, SK	57.33	-107.17	1,371	6190	488

Metadata for the lakes within the study area and province in which they are located. MB= Manitoba, SK=Saskatchewan, AB= Alberta. Drainage basin area measurements provided by HYDAT. Area and surface elevations were from the CanVec database.

Table 2.Total area burned and number of ignitions by buffer size between the years of 1980-2011.

Buffer Size (in area)	1,000,000 km^2	100,000 km^2	10,000 km^2
Number of Ignitions	61039	8336	722
Area Burned (ha)	214,971,710	22,045,518	1,697,857

Summary statistics of the total number of ignitions and area burned by buffer size.

Table 3.Spearman correlation values of the three buffered scales for AOB and IGN in relation to LL_{DEP}.

Lake ID	IGN 1,000,000 km^2	AOB 1,000,000 km^2	IGN 100,000 km^2	AOB 100,000 km^2	IGN 10,000 km^2	AOB 10,000 km^2
05KG004	**-0.86**	**-0.68**	**-0.86**	**-0.83**	**-0.61**	**-0.61**
04AC002	-0.54	-0.36	**-0.64**	**-0.75**	**-0.68**	**-0.72**
05FA013	-0.09	0.03	**-0.60**	**-0.74**	NA	NA
04AA002	-0.53	-0.45	**-0.82**	**-0.72**	-0.50	-0.58
07JA002	**-0.50**	**-0.56**	**-0.67**	-0.69	**-0.47**	**-0.45**
06AD012	-0.36	-0.44	-0.49	**-0.67**	0.52	0.53
05LC003	**-0.53**	-0.48	**-0.80**	**-0.66**	**-0.60**	**-0.59**
07CE906	-0.05	-0.12	-0.40	-0.65	0.17	0.29
06AF002	0.06	-0.07	**-0.67**	**-0.65**	**-0.46**	**-0.46**
05RD006	**-0.54**	**-0.59**	**-0.52**	**-0.60**	**-0.41**	**-0.44**
05RE002	**-0.42**	**-0.36**	**-0.60**	**-0.56**	-0.31	-0.28
05SA801	**-0.56**	**-0.50**	**-0.49**	**-0.52**	-0.24	-0.18
05GF003	0.04	-0.17	-0.39	**-0.49**	0.04	0.00
05KF004	**-0.53**	**-0.62**	**-0.44**	**-0.48**	-0.21	-0.24
07BJ006	-0.39	-0.30	-0.38	-0.47	-0.16	-0.15
05LN005	-0.29	-0.15	**-0.57**	-0.45	-0.42	-0.43
07LD001	-0.06	-0.09	-0.33	-0.44	-0.45	**-0.51**
07BB008	-0.10	-0.20	-0.38	**-0.39**	-0.33	-0.33
05LA007	-0.35	-0.45	-0.38	-0.38	NA	NA
05MF019	-0.29	-0.03	-0.22	-0.37	-0.40	-0.43

07BE002	**-0.51**	**-0.50**	-0.14	-0.23	-0.28	-0.27
07GH003	-0.14	-0.05	-0.15	-0.22	0.05	0.04
05MD804	-0.15	-0.29	-0.11	-0.20	-0.12	-0.14
06DA001	0.03	0.01	0.01	-0.15	0.01	-0.02
05LH008	-0.09	0.08	0.13	0.14	-0.23	-0.17

Correlation coefficient between LL_{DEP} and AOB/IGN from in ascending order for the 100,000 AOB buffer. The three buffers examined to quantify the differences which existed between the three buffer scales and examine correlation patterns among the three scales for individual lakes across the buffers. AOB=Area burned, IGN=Number of ignitions within each buffer. NA's within the 10,000 km^2 buffer were caused by a lack of fire information present for analysis within this buffer. Bolded values represent correlations with a p value of ≤ 0.05.

Table 4.Spearman correlation values of LL_{DEP} in relation to AOB and IGN when implementing a 1-year hydrologic Lag.

Lake ID	IGN 1,000,000 km^2	AOB 1,000,000 km^2	IGN 100,000 km^2	AOB 100,000 km^2	IGN 10,000 km^2	AOB 10,000 km^2
04AA002	-0.26	-0.15	-0.29	-0.36	-0.34	-0.13
04AC002	0.07	0.02	0.18	0.30	-0.13	-0.06
05FA013	0.04	0.06	-0.23	-0.39	NA	NA
05GF003	0.09	0.02	0.07	-0.26	0.40	0.41
05KF004	-0.20	-0.13	-0.10	-0.21	0.05	0.05
05KG004	-0.20	-0.20	-0.37	-0.20	-0.31	-0.31
05LA007	**-0.65**	**-0.70**	**-0.67**	**-0.67**	NA	NA
05LC003	0.04	-0.12	0.08	0.23	-0.05	-0.08
05LH008	0.19	0.18	0.35	0.33	0.24	0.22
05LN005	0.27	0.42	0.15	0.23	0.16	0.17
05MD804	**0.52**	0.02	**0.48**	-0.03	**0.47**	**0.49**
05MF019	0.04	0.41	-0.18	-0.35	-0.25	-0.27
05RD006	-0.06	0.02	0.08	0.09	0.17	0.13
05RE002	-0.04	-0.07	-0.02	0.03	-0.14	-0.16
05SA801	-0.17	-0.18	-0.13	-0.15	-0.03	0.00
06AD012	-0.53	-0.55	0.01	-0.17	-0.01	0.02
06AF002	0.18	0.07	-0.07	-0.10	-0.05	-0.10
06DA001	0.20	0.18	0.01	0.06	0.02	0.15
07BB008	0.15	0.13	0.24	0.35	0.13	0.13
07BE002	0.15	0.09	0.29	0.17	0.41	0.27

07BJ006	0.19	0.13	0.11	0.13	-0.09	-0.05
07CE906	0.17	0.08	0.30	-0.07	**0.82**	**0.66**
07GH003	-0.03	-0.23	-0.28	-0.30	0.25	0.23
07JA002	0.03	0.03	-0.13	-0.11	0.07	0.11
07LD001	0.04	-0.11	0.32	0.26	0.32	0.10

Correlation coefficient between LL_{DEP} and AOB/IGN after implementing a 1 year lag. The three buffers were left in the figure to highlight the differences which existed between the three buffer scales and examine correlation patterns across the three scales for each of the lakes. AOB=Area burned, IGN=Number of ignitions within each buffer. Bold values refer to correlations in which the p value was ≤ 0.05

Table 5.Spearman correlation values of LL_{DEP} in relation to AOB and IGN when implementing a 2-year hydrologic lag.

Lake ID	IGN 1,000,000 km^2	AOB 1,000,000 km^2	IGN 100,000 km^2	AOB 100,000 km^2	IGN 10,000 km^2	AOB 10,000 km^2
04AA002	0.26	0.10	0.25	0.35	0.41	0.27
04AC002	-0.11	0.07	-0.06	-0.22	0.31	0.13
05FA013	-0.01	-0.16	-0.10	0.02	0.00	0.00
05GF003	0.00	-0.04	0.16	0.05	-0.06	-0.01
05KF004	-0.10	-0.06	0.10	0.26	-0.02	-0.02
05KG004	0.30	0.25	0.11	0.17	0.10	0.12
05LA007	-0.38	-0.36	-0.36	-0.36	NA	NA
05LC003	0.07	0.08	0.04	0.09	-0.06	0.00
05LH008	-0.02	-0.19	-0.41	-0.40	-0.24	-0.19
05LN005	0.41	0.50	0.47	**0.53**	0.39	0.38
05MD804	**0.57**	0.01	**0.59**	0.17	**0.42**	0.33
05MF019	-0.34	0.02	-0.10	0.03	-0.06	-0.11
05RD006	-0.04	-0.04	-0.01	-0.09	0.13	0.18
05RE002	0.19	0.22	0.07	0.06	0.07	0.10
05SA801	-0.05	-0.07	0.16	0.16	0.24	0.23
06AD012	-0.07	0.01	0.35	0.40	0.34	0.21
06AF002	0.08	0.09	0.03	-0.11	0.18	0.15
06DA001	0.08	0.19	0.19	0.20	-0.01	0.06
07BB008	0.17	0.26	-0.13	0.01	0.17	0.17
07BE002	-0.03	-0.11	0.03	-0.02	-0.05	0.09
07BJ006	0.00	0.07	0.29	0.20	0.24	0.17

07CE906	-0.40	-0.52	-0.18	-0.31	0.01	-0.16
07GH003	0.45	0.24	-0.13	-0.05	-0.45	-0.45
07JA002	-0.07	-0.02	0.10	0.14	0.05	0.12
07LD001	-0.01	0.08	0.05	0.14	0.41	0.44

Correlation coefficients between LL_{DEP} and AOB/IGN after implementing a 2 year lag. The three buffers were left in the figure to highlight the differences which existed between the three buffer scales and examine correlation patterns across the three scales for each of the lakes. AOB=Area burned, IGN=Number of ignitions within each buffer. Bold values represent correlations in which the p value was ≤ 0.05. NA values were for stations in which the availability of lake and fire information was too limited to perform the appropriate analysis.

Table 6. Spearman correlation matrix for the climate variables used within the multi-variable modelling analysis.

Variable	Number of Ignitions	Area Burned	95th Percentile Temperature	JJA Precipitation	95th Percentile Drought Code	Lake Level Departure
Number of Ignitions	1.00					
Area Burned	**0.92**	1.00				
95th Percentile Temperature	0.18	0.17	1.00			
JJA Precipitation	-0.08	-0.12	-0.25	1.00		
95th Percentile Drought Code	0.11	0.16	0.35	**-0.76**	1.00	
Lake Level Departure	**-0.36**	**-0.41**	-0.10	0.15	-0.25	1.00

Degree of correlation between climate variables used in the multi-variable analysis. Negative values represent an inverse correlation and positive values represent a positive correlation. For the purposes of the study 95th percentile drought code was excluded for the multi-variable analysis due to the considerable cross correlation it exhibited with JJA precipitation.

Table 7. LL_{DEP}+PSUM+TEMP variable contribution for IGN at the 100,000 km^2 areal buffer.

Lake Id	DF	Multiple R2	Model P Value	Temp Percentage	PSUM Percentage	LL_{DEP} Percentage
04AA002	5	0.58	0.2	0.27	0.08	0.65
04AC002	9	0.53	0.07	0.55	0.16	0.29
05FA013	10	0.6	**0.02**	0.12	0.31	0.57
05GF003	12	0.15	0.57	0.36	0.32	0.32
05KF004	9	0.24	0.45	0.34	0.46	0.20
05KG004	10	0.67	**0.01**	0.16	0.03	0.81
05LA007	7	0.18	0.69	0.00	0.43	0.57
05LC003	10	0.43	0.12	0.32	0.17	0.51
05LH008	10	0.61	**0.02**	0.57	0.11	0.32
05LN005	8	0.69	**0.02**	0.41	0.33	0.26
05MD804	26	0.04	0.81	0.12	0.24	0.64
05MF019	11	0.25	0.36	0.38	0.19	0.43
05RD006	25	0.45	**0.00**	0.32	0.20	0.49
05RE002	26	0.28	**0.04**	0.40	0.14	0.46
05SA801	18	0.50	**0.01**	0.46	0.31	0.23
06AD012	6	0.25	0.60	0.04	0.40	0.56
06AF002	25	0.25	0.06	0.18	0.20	0.62
06DA001	27	0.58	**0.00**	0.10	0.71	0.20
07BB008	21	0.12	0.45	0.37	0.08	0.56
07BE002	15	0.15	0.48	0.21	0.46	0.33

07BJ006	27	0.20	0.11	0.09	0.14	0.77
07CE906	5	0.88	**0.01**	0.35	0.58	0.07
07GH003	11	0.09	0.77	0.23	0.32	0.45
07JA002	24	0.49	**0.00**	0.26	0.22	0.51
07LD001	11	0.29	0.26	0.07	0.83	0.10

Variance explained by each of the Climate variables used within the Multi-Variable analysis and the associated model P values. Models of Temperature, Precipitation and Lake-Level departure were analyzed in relation to the Ignition frequency with the 100,000 km^2 buffer. Bold values refer to models with P values that are ≤ 0.05. The sum of all the climate contributions within the model is equal to 1.

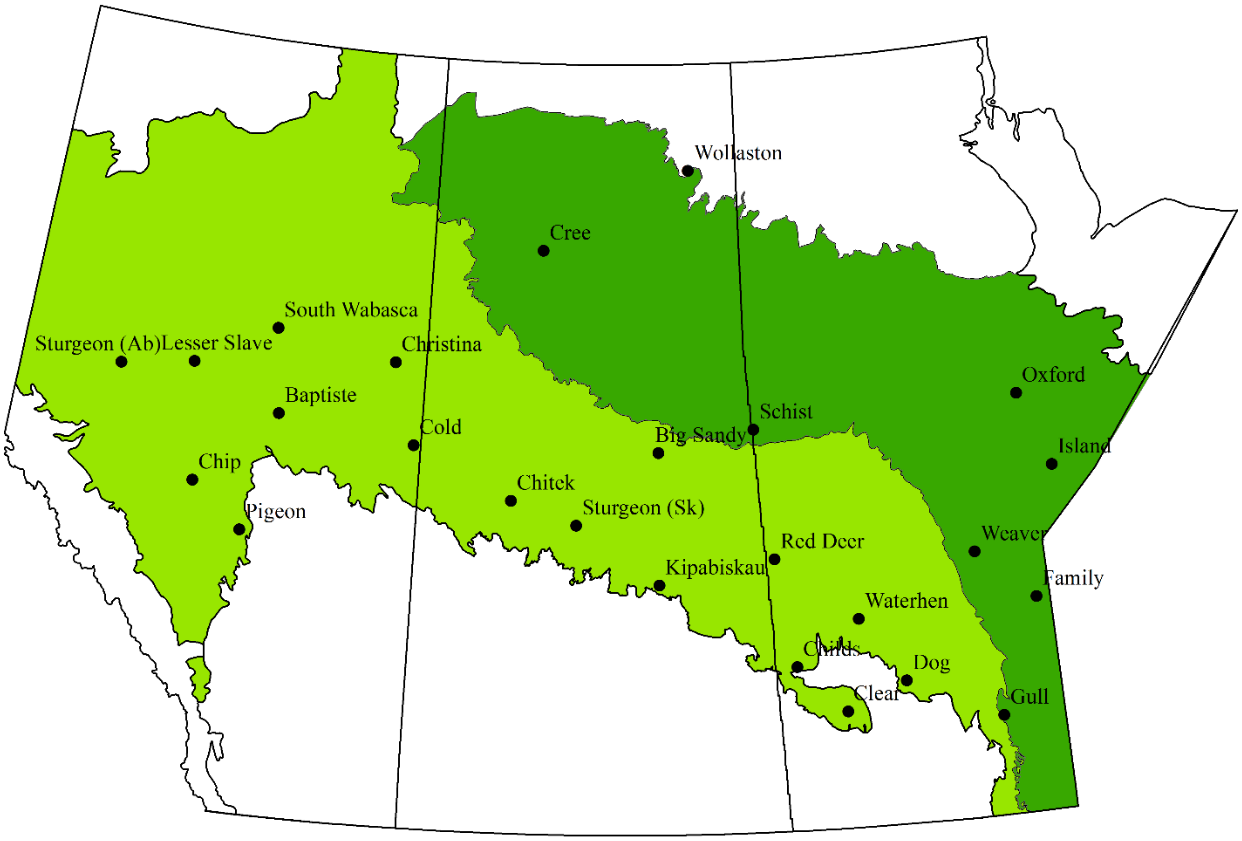
Table 8 LL_{DEP}+PSUM+TEMP for AOB variable contribution at the 100,000 km^2 areal buffer.

Lake Id	DF	Multiple R2	Model P_Value	Temp Percentage	PSUM Percentage	LL_{DEP} Percentage
04AA002	5	0.58	0.19	0.37	0.13	0.50
04AC002	9	0.66	**0.02**	0.48	0.03	0.49
05FA013	10	0.58	**0.03**	0.01	0.22	0.77
05GF003	12	0.17	0.50	0.36	0.30	0.34
05KF004	9	0.23	0.48	0.36	0.46	0.18
05KG004	10	0.62	**0.02**	0.17	0.03	0.80
05LA007	7	0.20	0.64	0.03	0.41	0.57
05LC003	10	0.34	0.22	0.35	0.10	0.55
05LH008	10	0.60	**0.02**	0.55	0.11	0.34
05LN005	8	0.65	**0.03**	0.46	0.32	0.22
05MD804	26	0.06	0.68	0.12	0.22	0.66
05MF019	11	0.25	0.34	0.42	0.09	0.49
05RD006	25	0.48	**0.00**	0.28	0.19	0.53
05RE002	26	0.29	**0.03**	0.38	0.18	0.45
05SA801	18	0.51	**0.00**	0.42	0.31	0.27
06AD012	6	0.56	0.15	0.04	0.35	0.61
06AF002	25	0.22	0.09	0.14	0.21	0.65
06DA001	27	0.59	**0.00**	0.10	0.65	0.25
07BB008	21	0.09	0.59	0.25	0.05	0.70
07BE002	15	0.14	0.52	0.22	0.44	0.35
07BJ006	27	0.21	0.08	0.04	0.14	0.82

07CE906	5	0.69	0.09	0.39	0.34	0.27
07GH003	11	0.08	0.81	0.16	0.37	0.47
07JA002	24	0.51	**0.00**	0.26	0.23	0.51
07LD001	11	0.44	0.08	0.17	0.75	0.08

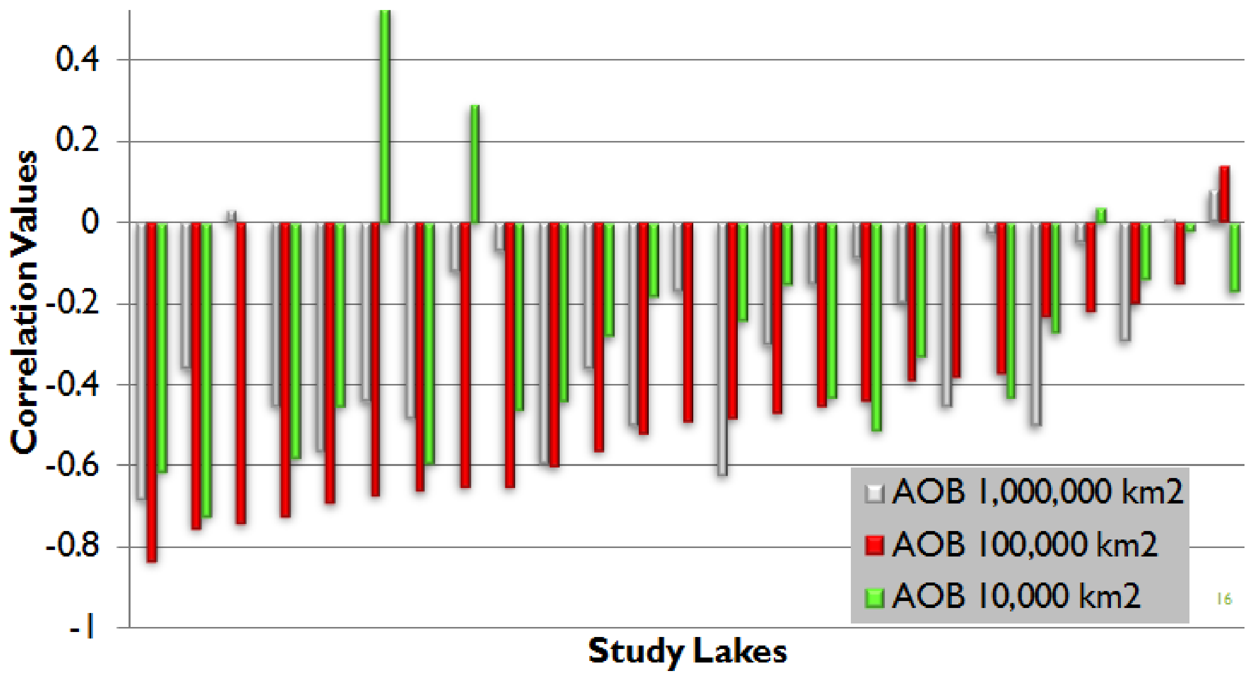
Variance explained by each of the Climate variables used within the Multi-Variable analysis and the associated model P values. Models of Temperature, Precipitation and Lake Level departure were analyzed in relation to Area burned with the 100,000 km^2 buffer. The sum of the climate variable contributions within the model is equal to 1.

Figure 1. Study area and lake locations throughout the Western Boreal region of Canada.



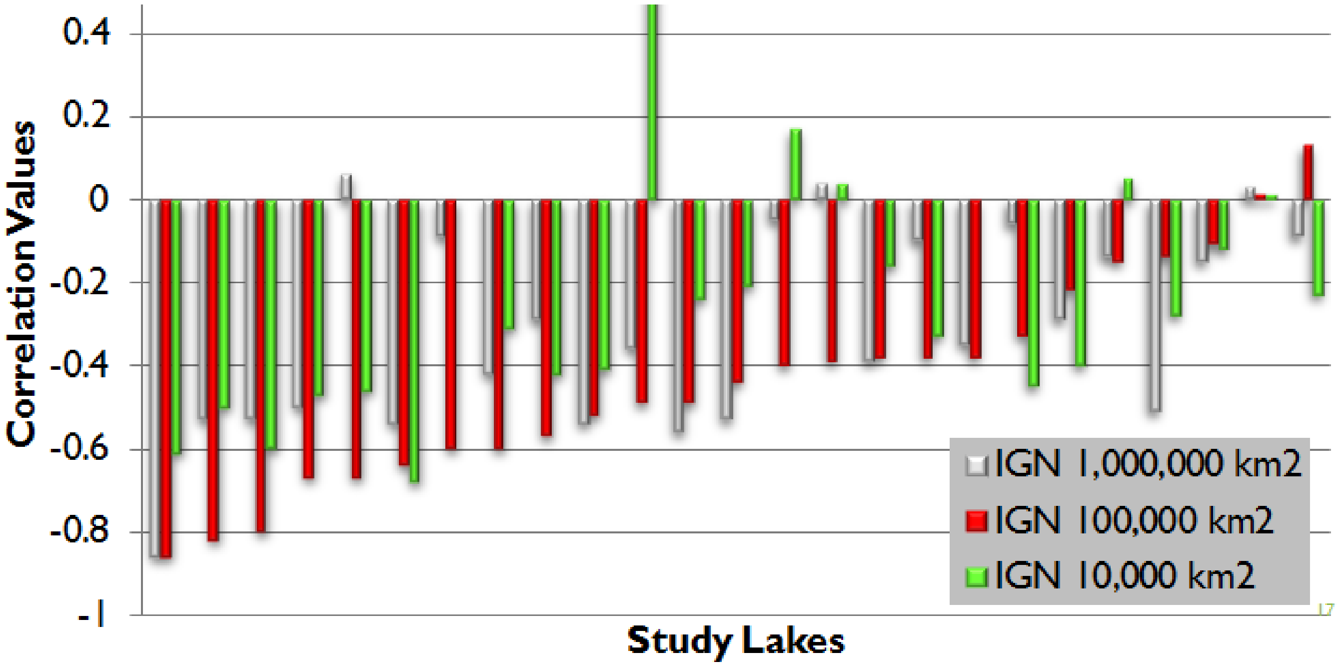
The dark green section in the figure is the Boreal shield ecozone and light green is the Boreal plain. Seven lakes are located on the Boreal shield and eighteen are located on the Boreal plain. Lakes within other ecozones were excluded in order to make the study specific to the Boreal region.

Figure 2. Correlation values of the study lakes in relation to the three incremental buffer sizes used to assess area burned.



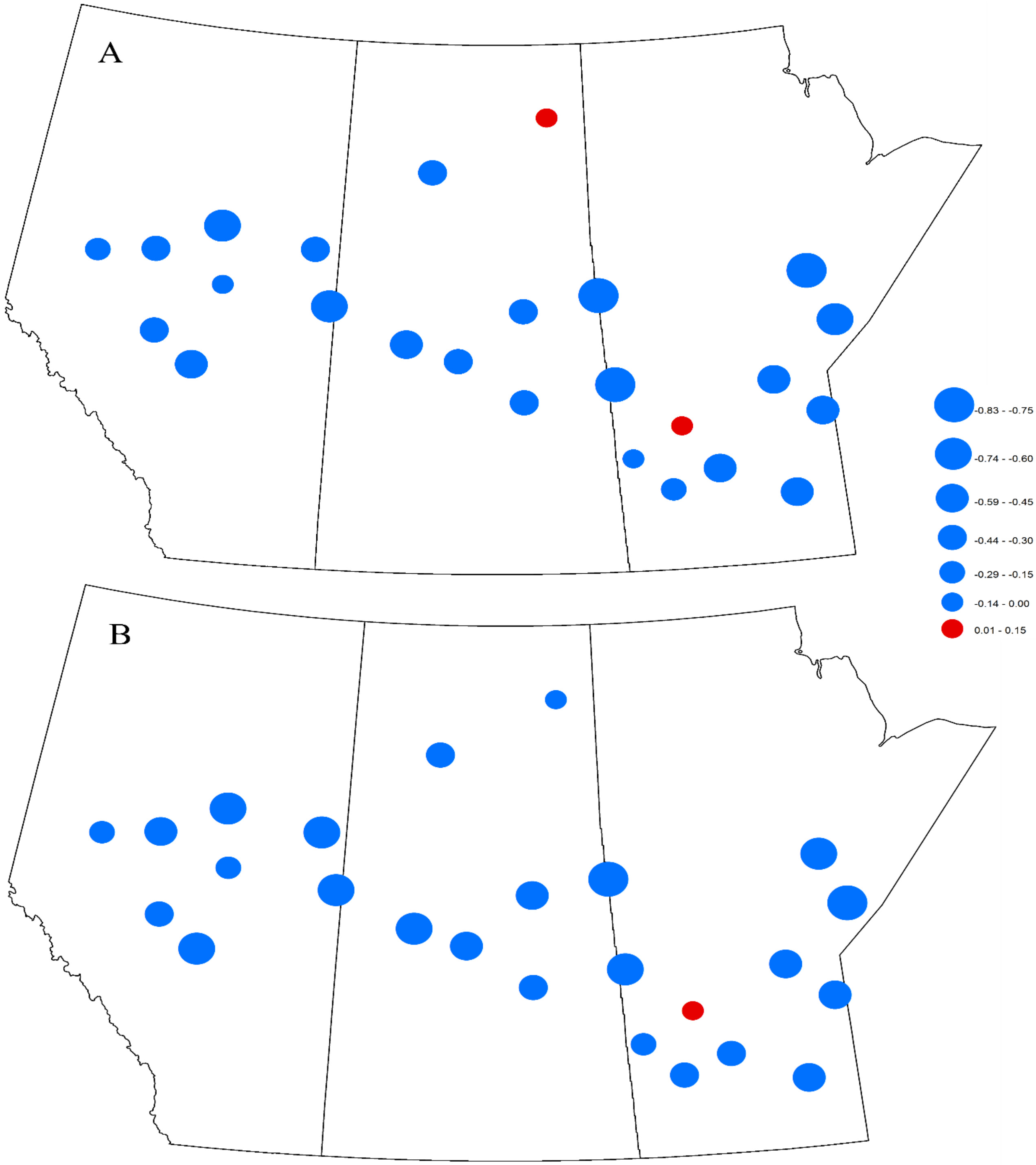
Correlations of each of the three buffer sizes in relation to area burned. The values used are in the same order as those seen in Table 3. They were predominantly negatively correlated with the middle buffer of 100,000 km^2 corresponding with values which consistently displayed the strongest inverse correlation. .

Figure 3. Correlation values of the study lakes in relation to the three incremental buffer sizes for number of ignitions.



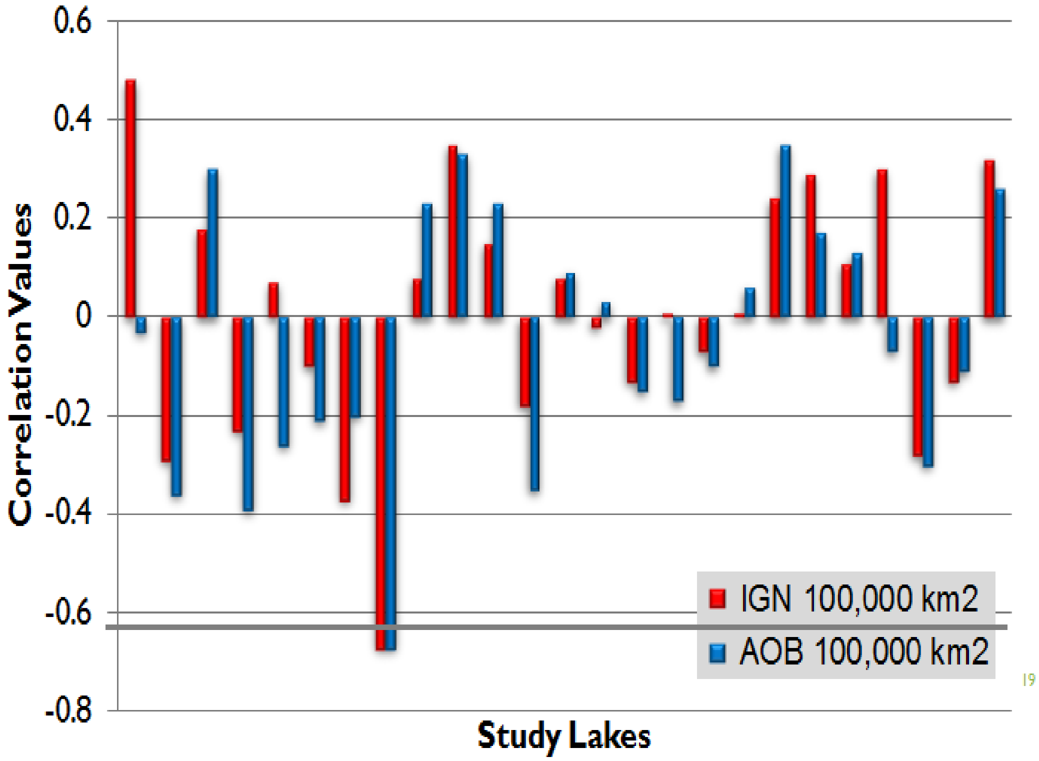
Correlations of each of the three buffer sizes in relation to number of ignitions. The values used are in the same order as those seen in Table 3. They were predominantly negatively correlated with the middle buffer of 100,000 km^2 corresponding with values which consistently displayed the strongest inverse correlation.

Figure 4. Bubble size as a function of correlation between LL_{DEP} and AOB and LL_{DEP} and IGN



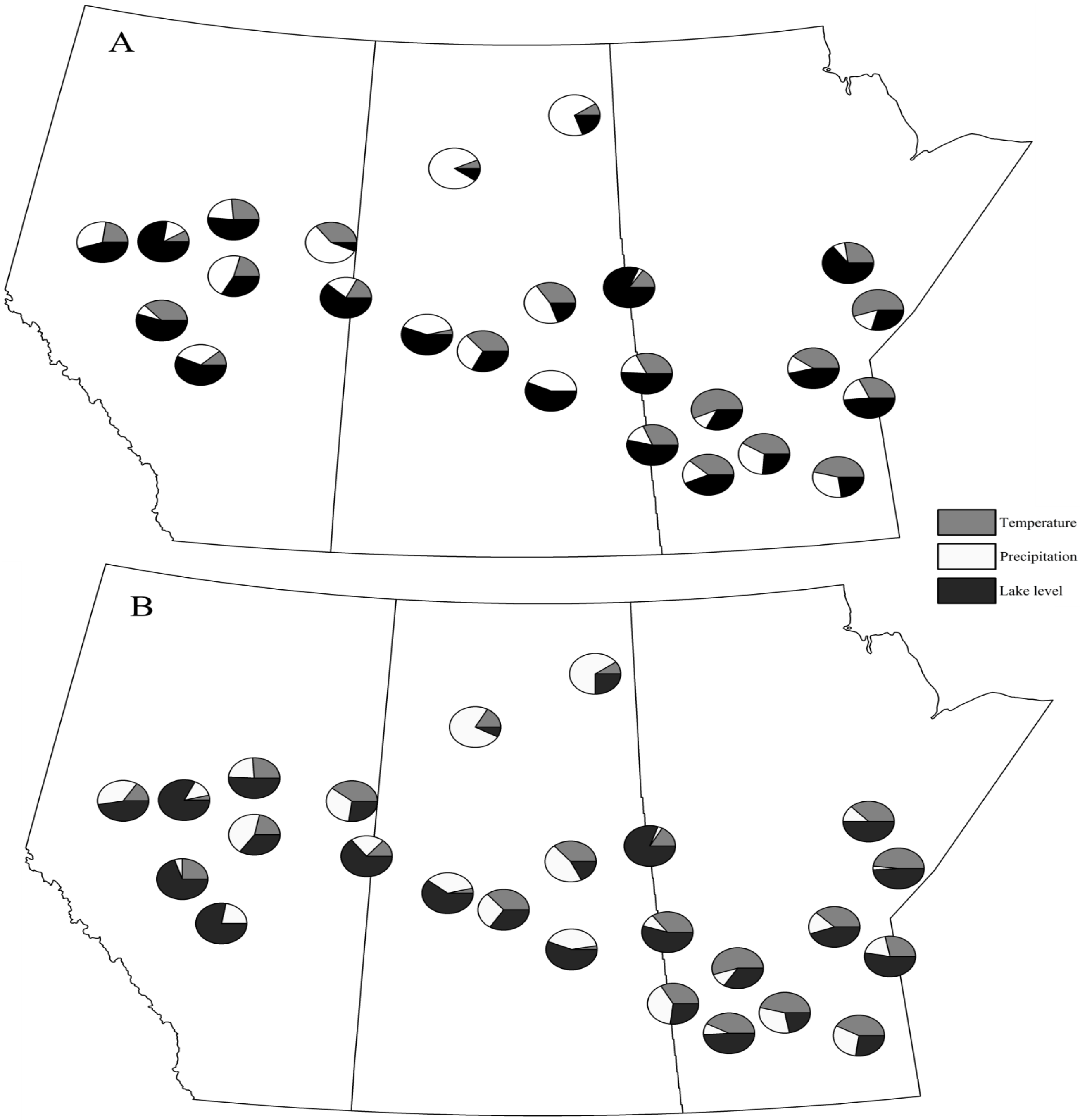
Map A) refers to the relative correlation of ignition count with LL_{DEP} and map B) refers to Area burned as a function of LL_{DEP}. The corresponding bubble size represents the associated value of correlation. Red values on the map indicate a positive correlation and Blue represents an inverse correlation.

Figure 5. Influence of a one year lag on the correlation values of area burned and number of ignitions.



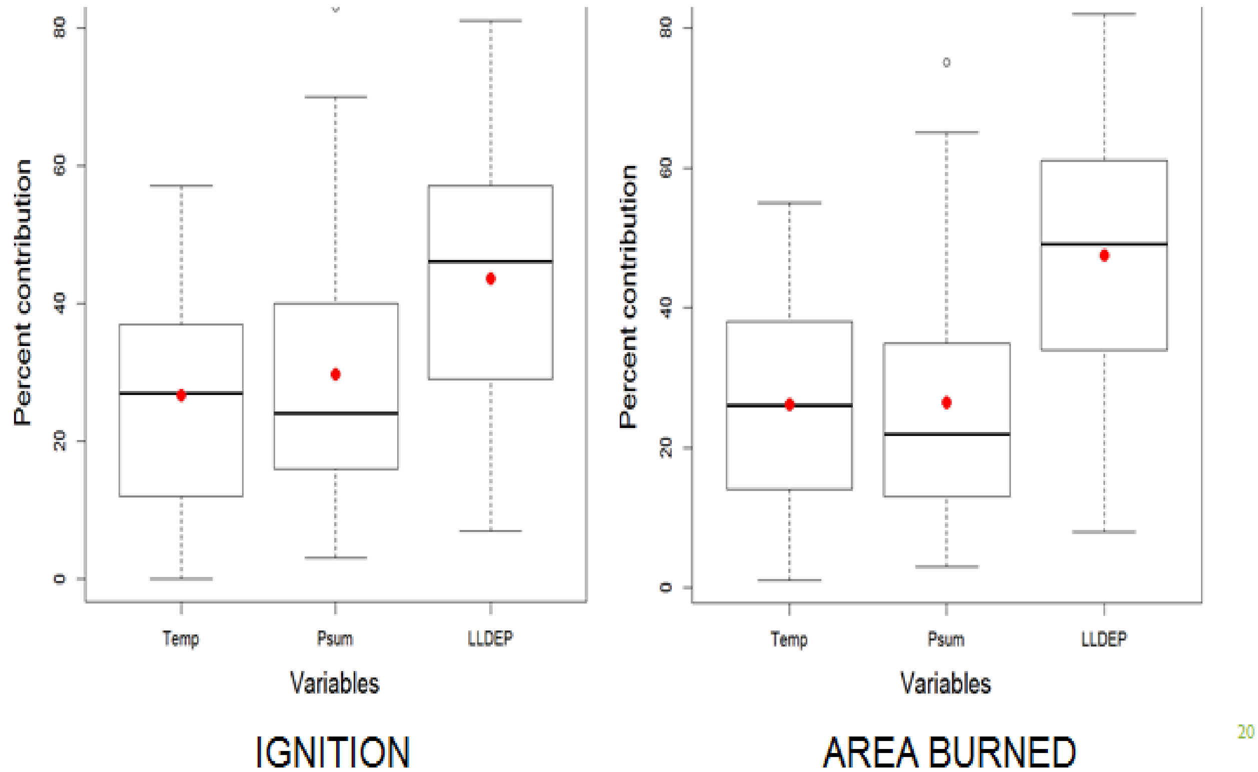
Correlation values of each of the 25 lakes in the study in relation to area burned and number of ignitions at the 100,000 km^2 buffer. Level of significance for the inverse correlations is the grey bar which represents the approx. significant correlation values at -0.62.

Figure 6. Variable importance by lake for each of the climate variables included within the study area.



Map A) Refers to area burned as a function of the climate variables and B) is the ignition count.Temperature in the legend refers to the 95th percentile temperature measurement of max seasonal temp. Precipitation is the summed seasonal precipitation for JJA. Lake level refers to LL_{DEP} and the amount of change experienced by the lake system by each of the lakes in relation to the fire information.

Figure 7. Box plots of the variance explained by each of the climate variables included within the multi-variable models



Box plots representing the percent contribution of variance for Temperature, Precipitation and LL_{DEP} within the models for AOB and IGN. Within the figure, the box defines the 25th and 75th percentiles, the dark line represents the median for the data and the 5th and 95th percentiles are shown by the whiskers, and red point for the mean.

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