Climate trends and anomalies and their impact on forest fire size and frequency from 1986 to 2020 in Canada

by

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Abstract

This study investigates the relationship between climate change, climate anomalies, and forest fire incidence in different regions of Canada between 1986 and 2020. By integrating analyses of temperature and precipitation anomalies and climatic moisture deficits at multiple time scales, the study analyses the association between climatic factors and the frequency, severity, and magnitude of forest fires. The study further aims to quantify the cumulative effects of monthly climate anomalies of up to 6 months preceedign a fire event. The study also aims to identify trends in climate change within Canada's ecozones and explore their links to fire. Findings suggest that rising temperatures and changing humidity are exacerbating the frequency and magnitude of wildfires. Regional analyses indicate that precipitation and temperature trends vary substantially cross Canadian ecozones, but the overall pattern suggests that warmer and drier climatic conditions are escalating fire risks. This analysis highlights the need to develop adaptive fire management strategies that incorporate climate change projections to address the different needs in different regions to effectively mitigate wildfire risk linked to climate change.

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1. Rationale and objectives

Forest fires are a natural part of the forest ecosystem in Canada as one of the natural disturbances that play a key role in forest regeneration (De Grandpré et al., 1993), species composition (Bergeron & Dubue, 1988) and nutrient cycling (Amiro et al., 2001; Bladon et al., 2008; Thiffault et al., 2007). However, Gillett et al., (2004) stated that human emissions of greenhouse gases and sulfate aerosols produce detectable warming effects during the fire season in fire-prone regions of Canada. Some studies also predict an increase in the incidence of forest fires in Canada because of the result of anthropogenically driven climate change (Gillett et al., 2004; Flannigan et al., 2005; Stocks et al., 1998; Wotton & Flannigan, 1993). Therefore, there is a need to understand the relationship between wildfire and Canadian forests in the context of climate change to address the challenges posed by climate change and to ensure the health and resilience of forest ecosystems in the face of anthropogenic impacts. The project aimed to comprehensively analyze wildfire data in Canada from 1986 to 2020, focusing on various crucial aspects. The objectives include examining the patterns of wildfire occurrences and burned areas across different Canadian provinces and ecozones over time. This aims to elucidate shifts in wildfire patterns and to explore the response of different regions and ecozones to wildfire. In addition, I seek to understand changes in climatic variables that may increase fire risk by examining climatic conditions before wildfires and correlating them with changes in climate variables before and after fires, and I also explored the linkages between mega wildfires and individual ecozones and trends in climate indices across ecozones over a 34-year period.

2. Literature Review

2.1 What is known about climate change？

2.1.1 Factors affecting climate change.

Climate change represents long-term changes in the Earth's average weather conditions, which may include changes in the average state of the climate or its variability, over decades or longer (Adedeji et al., 2014). These changes may be due to natural factors such as fluctuations in solar radiation (Nikolov & Petrov, 2014; Speight, 2019), orbital changes (Hays et al., 1976; Lourens, 2021; Lourens & Tuenter, 2009; Pisias & Shackleton, 1984), and volcanic eruptions (Cooper et al., 2018; Marti & Ernst, 2008; Pollack et al., 1976; Stenchikov, 2021; Zhong, 2016), movement of crustal plates (Panwar et al., 2017) and El Niño-Southern Oscillation (ENSO) (Cai et al., 2021; McPhaden et al., 2020; Trenberth & Hoar, 1997; Yang et al., 2018). Perry and Hsu (2000) emphasized solar output as a key factor influencing climate change historically. However, Schurer et al. (2014) concluded that solar forcing may have had a relatively minor impact on Northern Hemisphere climate over the past 1,000 years, whereas volcanic eruptions and changes in greenhouse gas concentrations appear to have been the most important influences during this period. Gilles (2024, March 14) also argued that the regional effects of solar activity on climate are more pronounced, and that anthropogenic factors (greenhouse gases, albedo) are more rightly affecting the global scale, but that solar activity will continue to interact with climate change in certain regions (Ineson et al., 2015). The human factor is a major driver of climate change. For example, since the industrial revolution, fossil fuels such as coal, oil and natural gas have been burned in large quantities, generating additional greenhouse gases (European Commission, n.d.; Government of Canada, 2009). Deforestation for urban and agricultural development has led to a reduction in the area of forests capable of absorbing carbon dioxide, and large-scale livestock breeding has led to methane gas emissions (European Commission, n.d.; Rojas-Downing et al., 2017). All these human behaviors contribute to climate imbalance.

2.1.2 Evidence of Climate Change.

The Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) has unequivocally stated that human activities have been a major driver of climate change since the 1970s, shifting the perception from theory to established fact (Chen et al., 2021). This comprehensive report synthesizes evidence of rapid climate changes, including warming rates unprecedented in the Earth's history, interconnected impacts across the global climate system, and measurable warming indicators (Figure 1). Key findings include (IPCC 2021; Bush & Lemmen, 2019; Trenberth, 2011):

Rise in Greenhouse Gas Concentrations: Since the late 19th century, human activities have significantly elevated greenhouse gas levels, leading to a net increase in effective radiative forcing (ERF), with minimal natural contributions and some offsets by changes in aerosols and land use.

- Temperature Increase: Global surface temperatures have increased significantly since the Industrial Revolution, with the rate of temperature increase particularly accelerating in the past few decades. The global mean surface temperature (GMST) rose by 0.85°C from 1850-1900 to 1995-2014, reaching an increase of 1.09°C by 2011-2020. Projections indicate a further rise of 1.5°C between 2021-2040.
- Changes in Precipitation and Humidity: Without major changes in wind direction, precipitation patterns will not change much, but will cause dry areas to become drier (generally throughout the subtropics) and humid areas to become wetter, especially in mid- and high- latitudes.
- Cryosphere and Sea Ice Changes: Significant reductions in Arctic Sea ice, glacier retreat, decreasing Northern Hemisphere snow cover, rising permafrost temperatures, and mass

loss from the Greenland and Antarctic ice sheets have been documented.

- Rise in greenhouse gas concentrations: Human activities have significantly increased greenhouse gas concentrations since the late 19th century, leading to a net positive and accelerating effective radiative forcing (ERF), with natural factors playing a negligible role, and changes in aerosols and land use providing partial offsets.
- Ocean Changes: Global ocean heat content has increased since 1971, and large-scale near-surface salinity contrasts have intensified. Global mean sea level (GMSL) rise is accelerating, and the report holds high confidence that since 1901, sea levels have risen by 0.20 m. So, GMSL is projected to continue to rise during the 21st century, and cumulative carbon sequestration by the oceans and land is likely to increase.

In Canada, the evidence of climate change is even more pronounced and is expected to intensify in the future. On average, past and future warming in Canada is about twice as great as global warming, and the Canadian Arctic is warming at about three times the rate of global warming (Flato et al., 2019) (Figure 2). The oceans around Canada are already warming, becoming more acidic and hypoxic. By mid-century, Canadian Arctic waters are expected to experience large ice-free periods in the summer. In addition, coastal flooding is expected to increase in many parts of Canada due to local sea level rise and surface changes. Warming will exacerbate some of the extremes of weather in the future. For example, extreme heat will become more frequent and intense, which will exacerbate the severity of heat waves and increase the risk of drought and wildfires. Since 1981, the seasonal snowpack has been decreasing by 5 to 10 percent per decade across most of Canada, and it is projected to be lower across much of southern Canada by mid-century, but with little change in the snowpack in the north. Also, overall, precipitation is projected to increase in the future, but summer precipitation is projected to decrease in parts of southern Canada by the end of the 21st century under the high emissions scenario (Bush & Lemmen, 2019).

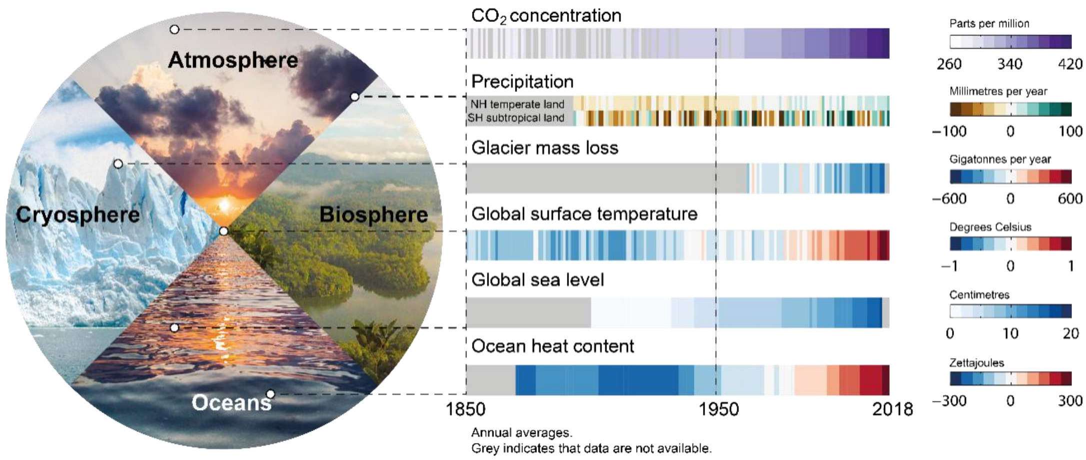


Figure 1. Changes in the atmosphere, biosphere, cryosphere and ocean climate systems from 1850 to 2018 (The annual average is shown as a stripe, with color indicating its value and gray indicating that the data is not available) (see IPCC, 2021, Figure 1.4).

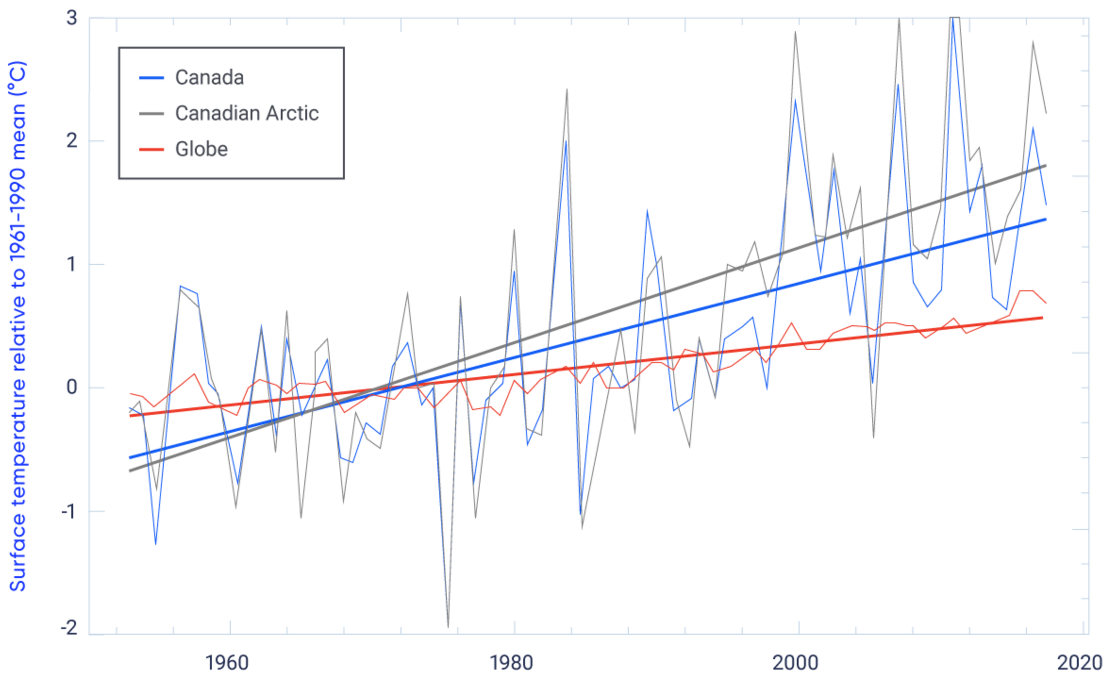


Figure 2. Warming rates for Canada, the Canadian Arctic, and the world (the blue line indicates the rate of surface warming in Canada, the red slope indicates the rate of global surface warming, and the gray slope indicates the rate of warming in the Canadian Arctic) (Flato et al., 2019).

2.1.3 Impact of climate change on forests.

The impacts of climate change on forests are complex, and as the global climate continues to warm, forests are suffering at multiple levels. First, some forests can suffer from successive droughts and high temperatures. The main response of forests to droughts is a reduction in net primary production and water use due to reduced soil moisture and stomatal conductance (Dale et al., 2001), so water stress caused by drought reduces the viability of trees and their ability to withstand disasters (Dale et al., 2001; Kirilenko & Sedjo, 2007; Menezes-Silva et al., 2019). Furthermore, drought and high temperatures may also affect nutrient cycling in forests, as decomposition processes are affected by drought and high temperatures to the extent that they lead to a buildup of organic matter, which further affects the fertility of forest soils and the health of the ecosystem as a whole (Dale et al., 2001). Coastal forests are often affected by hurricanes, such as along the eastern and southern coastlines of the United States (Dale et al., 2001). Secondly, Climate change may also lead to an increase in the frequency and intensity of catastrophic storms, and atmospheric warming may shift the location of prevailing ice storms northward (Dale et al., 2001; Peterson, 2000). These catastrophes can easily lead to direct mechanical damage to forests, and can also affect the structure, composition, and succession of forests in the short or long term. In addition, the survival and reproduction of insects and pathogens can be affected by changing temperature and humidity. For example, one study found that climate change leading to warmer winter temperatures is expected to increase the severity and frequency of forest tent caterpillar outbreaks in areas that have historically experienced cold winters (Haynes et al., 2014). Studies have also mentioned that increased warming is expected to make southern pine beetle outbreaks more likely to move northward, and that insect diversity will increase at higher latitudes (Dale et al., 2001; Ungerer et al., 1999). The prevalence of white pine blister rust requires cool and moist environments, which could lead to fewer infections of this rust as wet periods decrease in the spring or early summer (Kinloch, 2003; Sturrock et al., 2011). Pine blight shows the opposite, with the potential for outbreaks of the disease increasing with warmer temperatures and increased precipitation(Sturrock et al., 2011). An increase in the severity of forest pests and diseases will not only weaken forest health and productivity, but may also affect the overall functioning and structure of forest ecosystems (Dale et al., 2001; Jamieson et al., 2012; Pureswaran et al., 2018; Ramsfield et al., 2016; Sturrock et al., 2011). Additionally, many studies have documented changes in the phenology of plants growing at mid- to high latitudes, such as earlier plant budding and flowering, and delayed leaf discoloration or defoliation, which are likely due to anthropogenic climate change and its associated increase in temperature (Badeck et al., 2004; Beaubien & Freeland, 2000; Bertin, 2008). Tree lines would also be expected to respond to warming by moving beyond their current position, with plant distributions changing more at altitude, e.g. high temperature trends in the Himalayas suggesting an advance of timberlines to higher altitudes as well as a gradual northward shift of timberlines in Canada (Bertin, 2008; Harsch et al., 2009; Schickhoff et al., 2016).

In conclusion, increasing temperatures and changing precipitation patterns are exacerbating various unnatural and natural disturbances in forests and affecting the structure, resource availability and productivity of forest ecosystems. Most importantly, interactions between different disturbances may amplify overall impacts on forests, but this may be balanced by indirect effects such as vegetation changes, notably coniferous forests and boreal biomes are expected to experience the most significant changes (Seidl et al., 2017).

2.2 How climate change affects forest fires?

2.2.1 Amplification of fire weather conditions

As the climate warms, increased fire weather conditions provide conditions for the ignition and spread of wildfires. Weather determines fuel moisture, influences flash ignition, and promotes fire growth through wind(Flannigan et al., 2005). Exacerbated fire weather conditions include longer dry periods, higher temperatures, and increased lightning activity, among other things, which may act synergistically to create landscapes that are more likely to burn. For example, Alencar et al. (2015) highlighted that in the dense forests of the Amazon Basin, changes in fire conditions are closely linked to El Niño Southern Oscillation (ENSO)-related drought conditions. A one-month delay in the end of the dry season led to larger and more severe fires later in the dry season in the Amazon basin. Additionally, in the boreal forests of North America, Whitman et al. (2022) emphasized that warmer and drier conditions directly influence fire dynamics, such as an increase in the number of large wildfires, more comprehensive fire spread, and escalating fire severity. Increased forest fire severity in the western United States has also been attributed to changes in climatic water deficit (CMD), vapor pressure deficit (VPD), evapotranspiration (ET), and fuels (Wasserman & Mueller, 2023). The forest fire-prone environment of Yunnan, China is also attributed to climate extremes that have altered air water storage in the region (Cui et al., 2022). Jain et al. (2022) investigated the global trend of extreme fire weather and its meteorological drivers and found that decreasing relative humidity and increasing temperature were the main reasons for the global increase in extreme fire weather. In addition, lightning-induced fires are the main natural fire initiation method in forest fires, and Price and Rind (1994) found that global lightning activity increases by 30% in warming climates and decreases by 24% in cold climates through modeling. Thus, in the context of a warming climate, there is evidence that large burns occurring within boreal forests in the northern regions of North America are associated with unusually large amounts of climate-driven lightning ignitions (Veraverbeke et al., 2017). In addition to temperature and precipitation, other weather variables such as wind and cloud cover will also change in a changing climate (Flannigan et al., 2006). Overall, the severity of fire weather increases significantly with warming, but it varies from region to region. However, The study from Flannigan et al. (2005) also demonstrated that while there are large regional differences, the area burned will increase significantly in the future, especially in the Boreal Rim forests. There will also be more fire starts and longer fire seasons, but there will also be large spatial and temporal variability in the response of fire activity to climate change (Flannigan et al., 2006).

2.1.2 Balance and dynamics of forest ecosystems.

Climate change affects fire occurrence and spread not only through weather, but also through changes in the balance and dynamics of forest ecosystems that affect fire behavior. Organic matter in forests is affected by warming as part of the dynamic cycles within ecosystems. Studies have predicted that the frequency of extreme weather events over the next seventy years will result in the destruction and death of vegetation, thus accumulating more combustible material for forest fires, and that changes in relative humidity within forests will result in a decrease in plant water (Shao et al. 2023). These changes not only make forests more susceptible to fires, but also make it possible for fires to spread faster and more widely once they do occur. Moreover, climate change will also cause changes in vegetation types, and Gaboriau et al. (2023) projected that in the Northwest Territories (NT) of Canada, in the context of climate change, fire burning rates will decrease in most areas due to a decrease in the proportion of coniferous species by the second half of the 21st century, but an increase in the biomass of coniferous species will enhance fire activity in the southeastern portion of the study area. This implies that forest composition and biomass will be one of the limiting drivers of future burning, as more heat-adapted and less flammable species may inhibit climatic forcing of wildfires, and prolonged droughts may affect the growth of some tree species resulting in open spaces that limit fire ignition and spread (Foster et al., 2022; Gaboriau et al., 2023; Girardin et al., 2013). Additionally, climate change affects the occurrence of wildfires by exacerbating interactions between forest disturbances (Seidl et al., 2017). Climate change contributes to the frequency and intensity of extreme weather events, including the possibility of snapping fragile trees to increase fuel accumulation, and may also directly exacerbate the spread of fires (Cannon et al., 2019). Another major impact is the increased vulnerability of forests to pests and diseases, which are themselves affected by changes in temperature and humidity (Ramsfield et al., 2016; Sturrock et al., 2011). For example, some studies have demonstrated that fires are more likely to occur 3 to 9 years after a spruce budworm outbreak (Fleming et al., 2002). Escalating pest and disease activity can weaken the resistance of trees, resulting in massive tree mortality, which in turn creates large amounts of combustible material that makes forests more susceptible to wildfires (Dale et al., 2001; Metz et al., 2011; Parker et al., 2006).

2.1.3 Feedback loop between forest fires and climate change.

Carbon loss feedbacks from forest fires could become a major factor in climate change, creating a complex feedback loop (Flannigan et al., 2006). As shown in Figure 3, in addition to the large release of greenhouse gases, smoke particles released from biomass burning can directly affect atmospheric radiative transfer by scattering and absorbing shortwave radiation and can also act as cloud condensation nuclei to change the optical properties of clouds, influence precipitation processes, and alter surface temperatures (Liu et al., 2014). In addition, heat and water vapor emissions from fires can affect atmospheric circulation and atmospheric humidity, leading to changes in local climate patterns (Liu et al., 2014). Vegetation removal and surface exposure can also affect the exchange of heat, water, and trace gases with the atmosphere on both short- and long-term scales, thereby influencing weather and climate (Liu et al., 2014). The impact of these interactions on climate change varies regionally. In tropical savannas, for example, there is a positive feedback loop between vegetation fires and climate, with vegetation clearing leading to warmer and drier climates, increased fire frequency, and further vegetation loss (Hoffmann et al., 2002). They also demonstrated that this fire-mediated feedback mechanism may have led to a decline in tree density in the global savanna, and that this feedback loop is expected to become increasingly influential over the next century, potentially exacerbating tree cover loss and altering the global savanna ecosystem. However, in Randerson et al.'s (2006) study of the boreal forest, although there was a warming effect in the first year after fires, this warming effect was likely to be counteracted by a long-term increase in surface albedo. Thus, their study demonstrates that the future increase in boreal fires may not necessarily accelerate warming as previously thought after the interaction of various factors such as greenhouse gases, aerosols, black carbon deposition on snow and sea ice, and changes in surface albedo after fires.

In summary, while forest fires are an integral part of the dynamics of Canada's natural ecosystems, contributing significantly to forest regeneration, species composition, and nutrient cycling, their interactions with anthropogenic climatic factors present complex and urgent challenges.

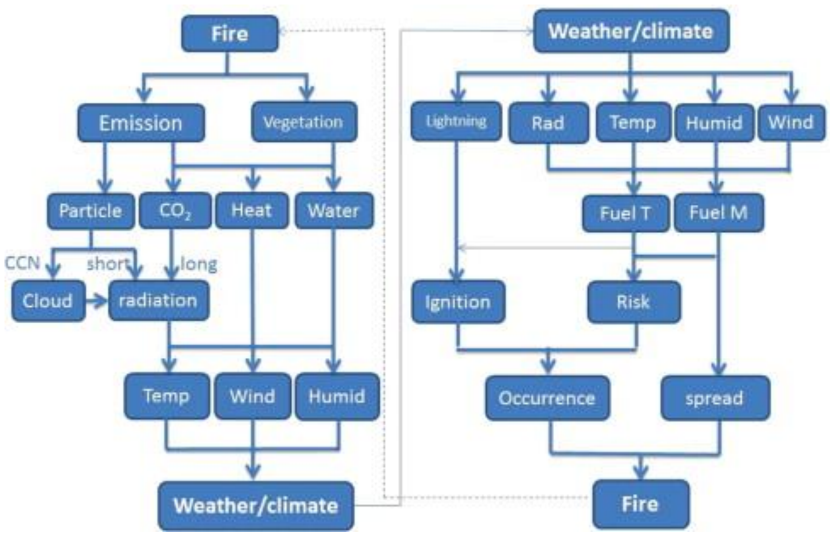


Figure 3. Diagram of physical processes for fire’s impacts on weather and climate and feedbacks (Liu et al., 2014).

3. Methods

3.1 Area of study

This study covers fires that have occurred within Canadian forested areas since 1986. With approximately 362 million hectares of forest area, Canada is the third largest forest landowner in the world (Canadian Forest Service, 2022). These forests are situated within the boreal forest region, predominantly. Because of the significant variations in topography, soil types, climate conditions, and dominant tree species, Canadian forest regions have been categorized into several distinct types: Boreal, Subalpine, Montane, Coast, Great Lakes-St. Lawerence, and Acadian (Thompson & Pitt, 2003) (Figure 4). Canada's forest area has generally been stable, with less than half of 1 percent of the area deforested since 1990 (Canadian Forest Service, 2022). Canada's vast natural landscape encompasses 15 distinct terrestrial ecozones, each characterized by unique geographical features, climate conditions, and biodiversity. However, not all of these ecozones are forested, such as the Arctic ecozones-Arctic Cordillera, Northern Arctic, Southern Arctic- and the James Bay islands in the Hudson Plains ecozone lack significant forest cover (Natural Resources Canada, 2013) (Figure 5). Canada is comprised of 10 provinces and 3 territories (British Columbia [BC], Alberta [AB], Saskatchewan [SK], Manitoba [MB], Ontario [ON], Quebec [QC], Newfoundland and Labrador [NL], New Brunswick [NB], Nova Scotia [NS], and Prince Edward Island [PE]) Yukon Territory [YT], Northwest Territories [NT] and Nunavut Territory [NU]), each province has its own set of protocols and resources dedicated to wildfire management, which includes prevention, preparedness, response, and recovery phases (Tymstra et al., 2020) (Figure 4).

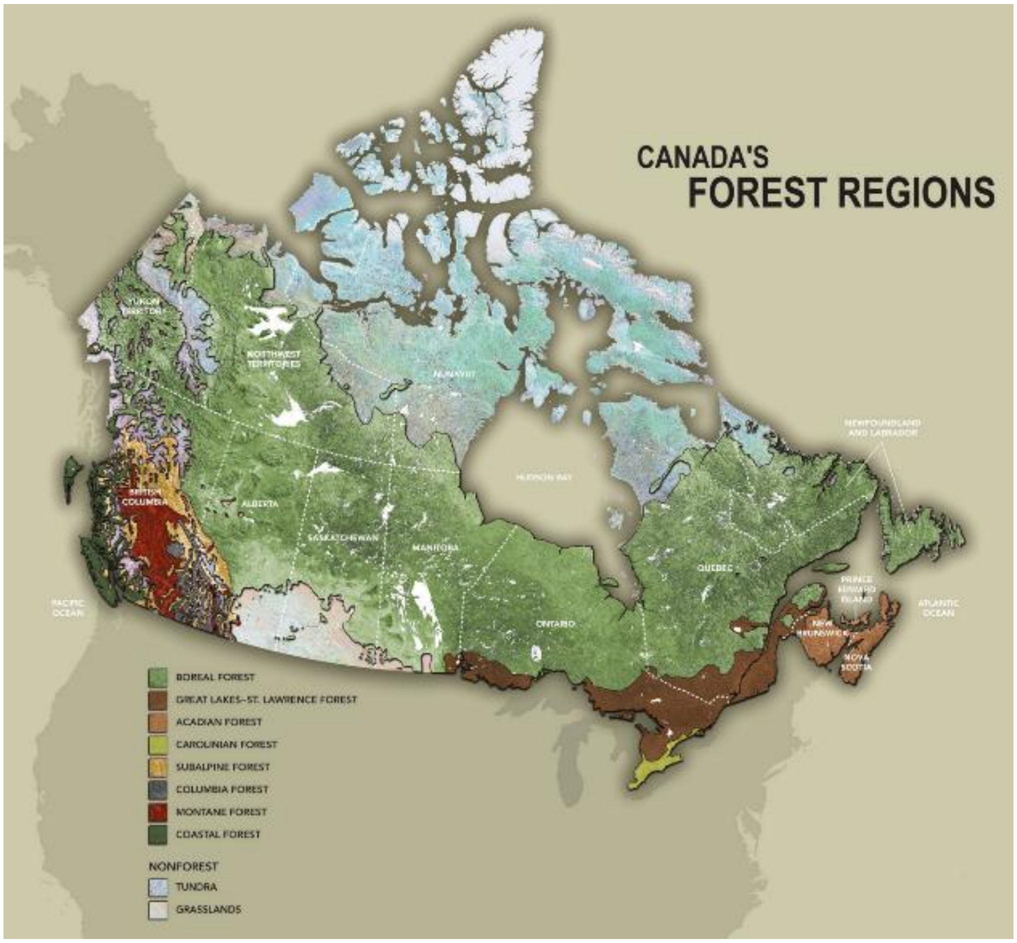


Figure 4. Forest regions of Canada (Natural Resources Canada, 2013).

3.2 Data collection

3.2.1 Preparation of forest fires

The foundational dataset of forest fires employed originates from the National Burned Area Composite (NBAC), a compiled resource managed by Natural Resource Canada, and Provincial, Territorial and Parks Canada agencies (Figure 5). The NBAC depicts burned areas through the use of polygons and stores a large amount of descriptive data on fire events since 1986, such as fire location and area burned, cause of the fire, fire start and end dates, data sources, and mapping methods (Hall et al., 2020).

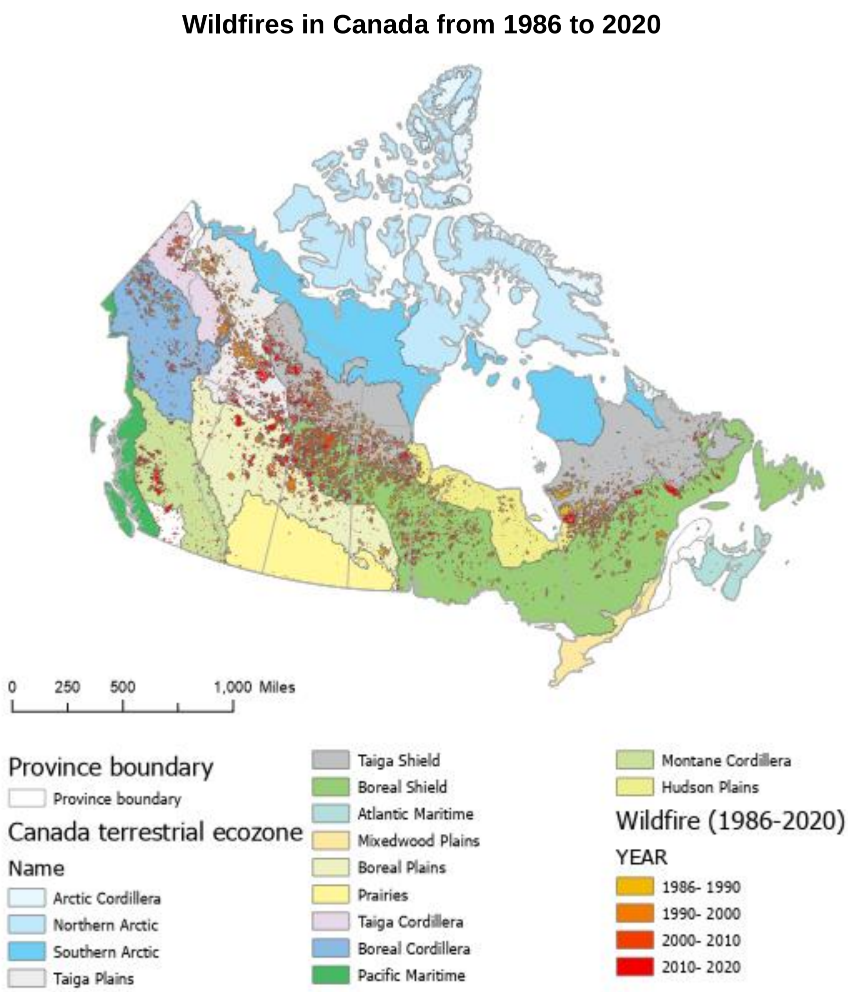


Figure 5. Wildfires distributed across ecozones and provinces in Canada from 1986 to 2020.

3.2.2 Extraction of climate data set

Climate data has been generated with the ClimateNA v6.40b software package, available at http://tinyurl.com/ClimateNA, based on the methodology described by Wang et al. (2016). This choice enables the extraction of detailed climate information pertinent to your fire data locations. To analyze the climate change of the fire site more concretely, I reprojected the raw fire data into a form with a coordinate system, extracted the year, latitude, and longitude, and obtained the climate change of the relevant year through the ClimateNA v6 software. Using this package, three sets of climate data were extracted, namely Current Year Data, Previous Year Data, and Normal Data. The Current year Data is primarily extracted for the current year from 1986 to 2020, and this dataset provides the current year's climatic information for each fire site to analyze the current year's climatic conditions. Previous year data is extracted so that the current year climate data can be compared to the conditions in the previous year, allowing us to examine pre-fire climate conditions and potentially identify the climate factors that led to the fire outbreaks. Normal data are extracted for climate data from 1961 through 1990, the baseline dataset that serves as a reference point for understanding climate variability and change. Comparing recent and historical climate data to this norm can highlight significant climate change over time.

3.3 Data analysis

First, to better visualize these fire data, Figure 6 compares the area burned and the number of fires per year by province from 1986 to 2020, showing interprovincial differences and temporal variations. This allows for the analysis of long-term trends and frequency of major fire events in different regions. In addition, for the analysis of seasonal patterns within provinces, in Figure 7, the 34 years of fire data are divided according to the month in which each fire occurred, to the extent that we can identify the seasonality of fires in each province. Second, to determine the effect of climatic conditions in the month prior to the fire on the conditions observed in the month of the fire, it was necessary to establish a link between the time of the fire and the previous climatic conditions, including average temperature, Hargreaves climate moisture deficit, Hogg's climate moisture index, maximum average temperature, and precipitation. Thus, I first calculated the difference between the climate data for the current year and previous years and the standard 1961-1990 data. Positive differences indicate that climatic conditions in the current year were above average, while negative differences indicate below-normal climatic conditions. Subsequently, the month corresponding to the recorded fire event was extracted to facilitate the analysis of climatic conditions in the month of the fire and the five preceding months. Using the ggplot () function, histograms can be generated that represent the correlation between temperature anomalies (deviations from normal conditions) and fire incidence. This visual approach effectively demonstrates the relationship between anomalous climatic conditions and fire likelihood (Figure 8). In figure 8, the horizontal axis indicates the deviation of the climate index for the month of the fire and the previous 5 months from the 1961-1990 normal, and the vertical axis indicates the number of fires. In addition, to quantify climate change within each ecozone, I plotted trends in climate moisture index (CMI), mean annual precipitation (MAP), and mean temperature (MAT) for each ecozone in Canada from 1986 to 2020 (Figure 9). By visualizing these three variables together, we can identify changes in climate within ecozones. Furthermore, to obtain the number of large-scale forest fires in each ecozone, I defined fire areas as large-scale fires with polygons exceeding 50,000 hectares in size to check the area of fire occurrence (Figure 10). Finally, the study also synthesizes the relationship between the variance of each climate parameter and its time course, thus deepening the understanding of climate parameter fluctuations over time (Figure 12). For a more detailed discussion of the evolution of the climatic parameters, scatter plots were generated using the ggpubr software package and correlation analyses were performed using the ggscatter() function (Figure 13).

4. Results and discussion

4.1 Analysis of fire data

Figure 6 provides a detailed overview of wildfire activity in Canadian provinces from 1986 to 2020, illustrating the number of fires per year and the area burned per year. In Figure 6 we can find a large range of data, so to compress the scale and make visualization easier, I log-transformed the raw data for the number of fires per year and area burned per year for the different Canadian provinces (Figure 10). In terms of the area burned by fires, Manitoba, Yukon, Northwest Territories and Saskatchewan have a relatively high frequency of large fires. The area burned is not always directly related to the number of fires. For example, Manitoba experiences many fires in some years, but the area burned shows very strong fluctuations. This suggests that while fires may be frequent, their size or severity may vary widely. In terms of the number of fires, Newfoundland and Labrador, Ontario, Quebec, and Nunavut have had relatively few fires over the past 34 years, while Alberta, British Columbia, the Northwest Territories, Saskatchewan, and the Yukon have had more frequent fires. Nova Scotia began to experience frequent fires after about 2013. In New Brunswick, there were two peaks in the number of fires around 2005 and 2015. Provinces such as Alberta and British Columbia saw sharp increases in the number of fires, which may indicate extreme fire events or conditions conducive to ignition in those years. The trend line in Figure 10 represents the average area of wildfire burned each year, and the shading represents the variability in the data itself. The rising trend line on this graph indicates that the average area burned or average number of occurrences per year within a province is increasing over the years, such as in Alberta and British Columbia. Conversely, a declining trend line indicates that the average area or number of occurrences of fires burning is decreasing over time. In some provinces, such as Quebec, fires are burning less each year, but are occurring more frequently. In other provinces, such as New Brunswick, the frequency and extent of fires have varied considerably over the 34-year period.

Figure 7 depicts monthly wildfire data for Canadian provinces from 1986 to 2020, with one graph showing the area burned by fire and the other the number of fires. Looking at the number of fires in each month, the timing of the fire season in each province is typically March through October. Certain months that show a higher area burned or number of fires occurring are usually the hot and dry months, i.e., June, July, and August. Large fires are also concentrated in June and July. There is a clear seasonal pattern, with most provinces experiencing more and larger fires in the middle of the year (summer), which is consistent with typically warm and dry conditions. Comparing the provinces, we can see that some, such as British Columbia, Alberta and Manitoba, have more frequent fires during the summer months; in the Northwest Territories, Quebec and Saskatchewan, fires are more severe in the summer months. Manitoba experienced more wildfires in July. In these three provinces, New Brunswick, Nova Scotia, and Nunavut, data on the size of fires were not observed, but fires did occur.

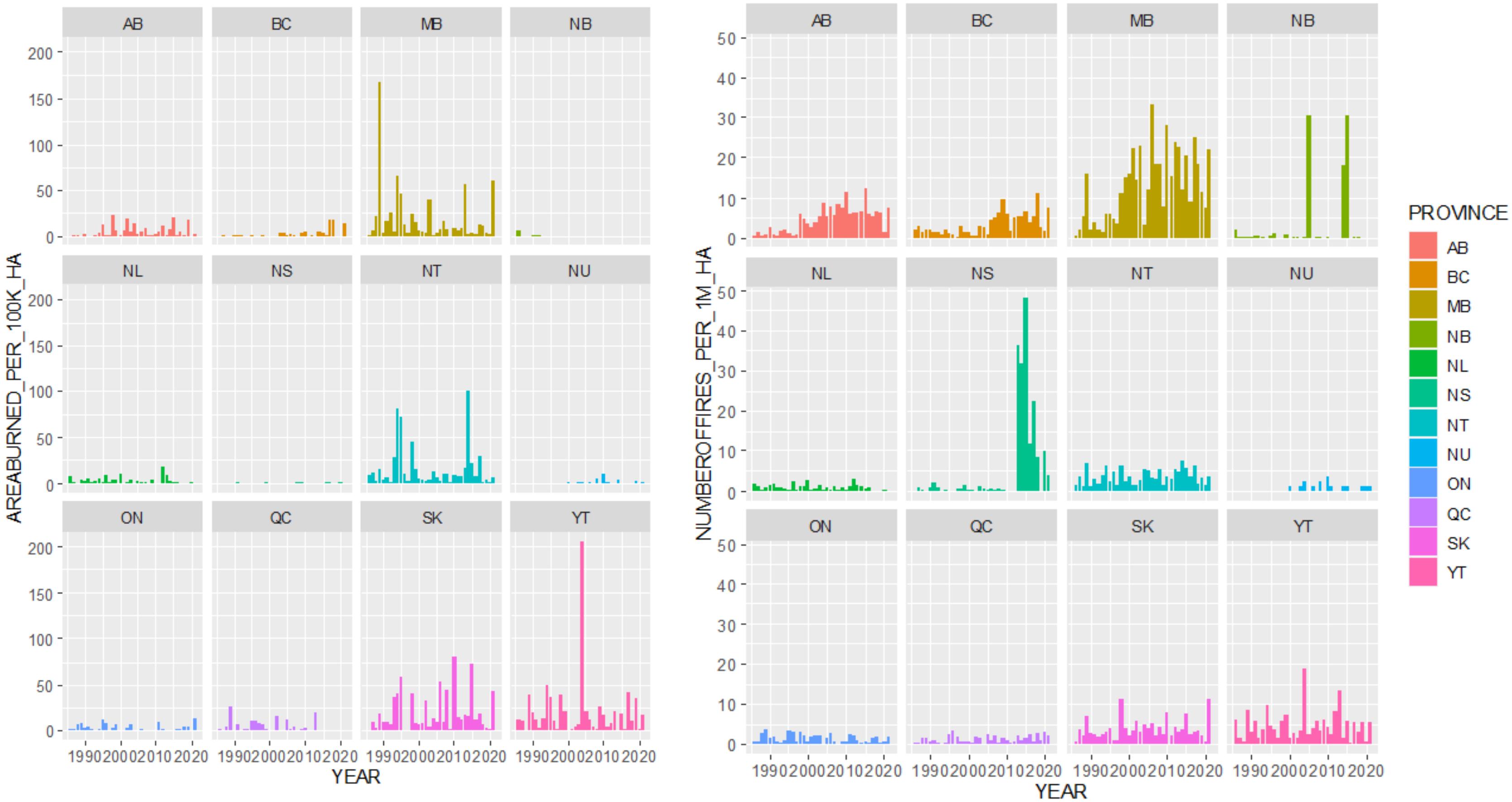


Figure 6. Area burned (left panel) and numbers of fires (right panel) in 12 provinces from 1986 to 2020.

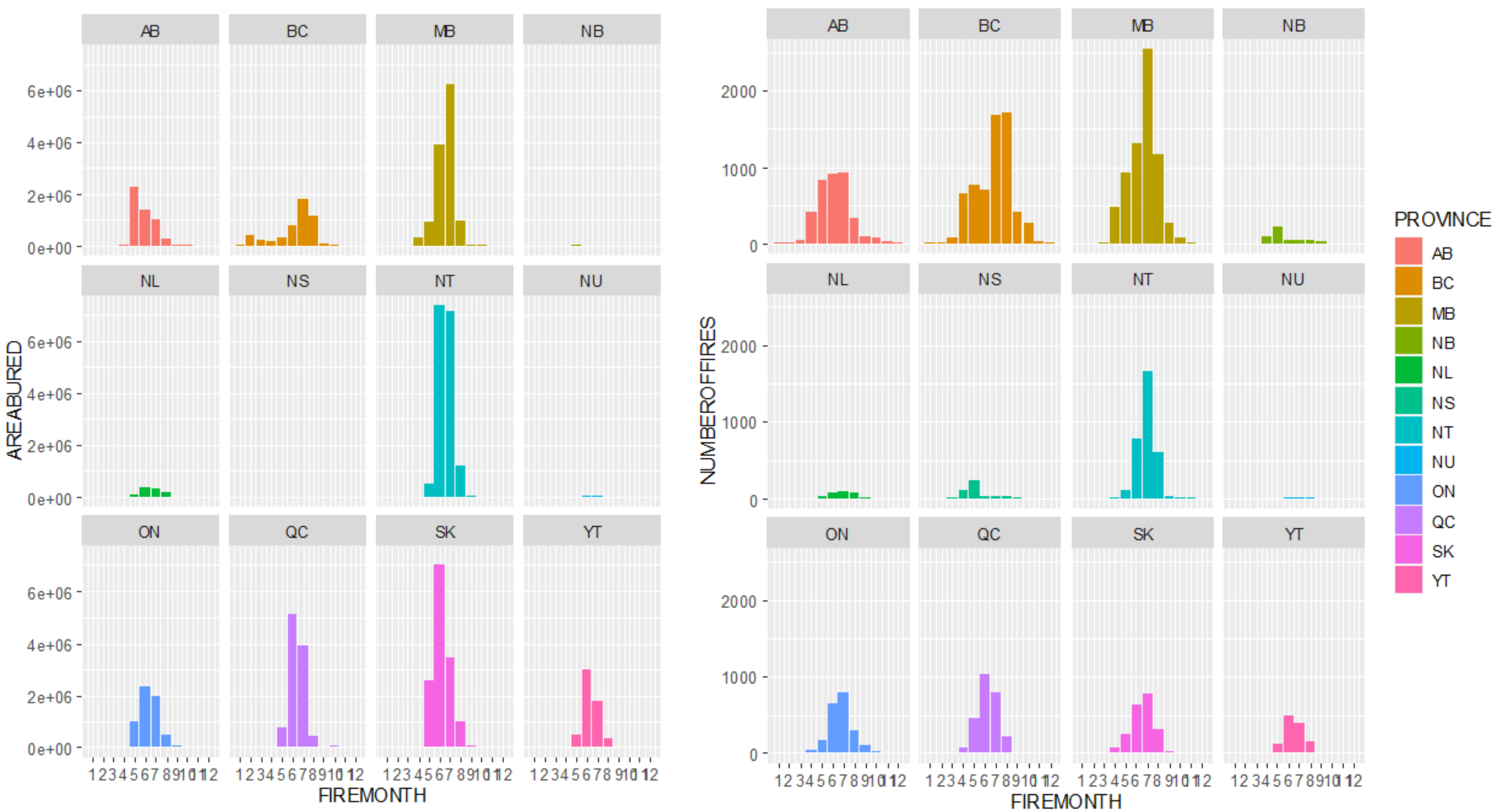


Figure 7. Area burned (left panel) and numbers of fire per month (right panel) in each province over a 34-year period.

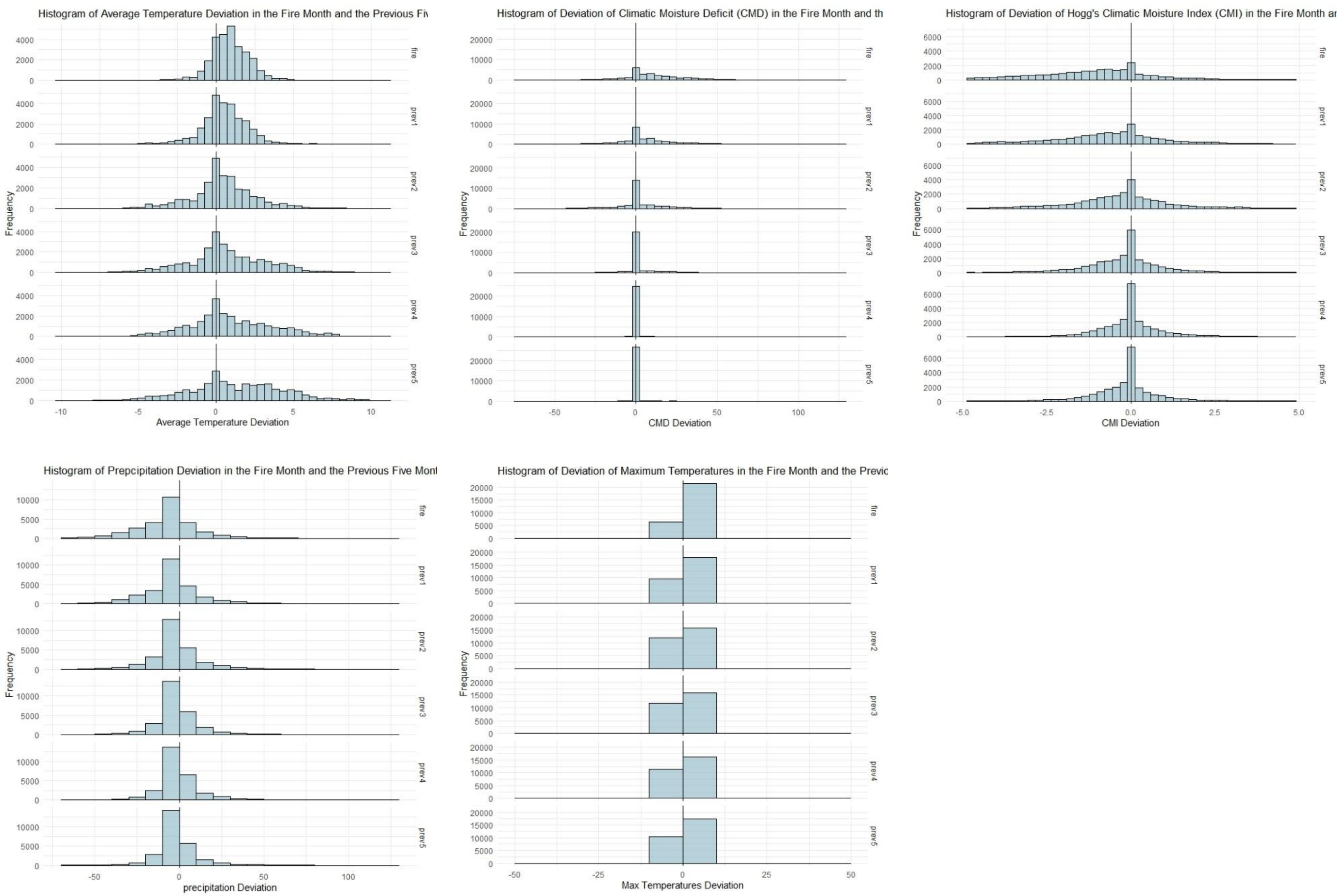


Figure 8. Climate anomalies for the month of the fire and the preceeding five months.

There are significant differences in the frequency of fires and the area burned within and between provinces. This may be due to a range of factors, including differences in climate, topography, vegetation types and human activities across provinces. For example, one study predicts that burn rates will decline across much of the Northern Territory by the end of the 21st century, as tree composition and biomass will limit future burn drivers (Gaboriau et al., 2023). Observed peaks correspond to years or months of particularly high fire activity, emphasizing the significant impact of extreme weather events, such as droughts or heat waves, on the incidence and severity of wildfires. For example, hot and dry temperatures and multiple lightning strikes were recorded in the Northwest Territories of Canada in 2014, British Columbia experienced its worst fire season in at least 50 years in 2017 and 2018 (Gaboriau et al., 2023). Combined with Figures 6, 7 and 10, the Northwest Territories and British Columbia have shown exactly the peak of fire burning in these years. This implies that this climate anomaly is exactly what is causing the anomalous fire behavior.

The map illustrates Canada's ecozones and distinguishes areas such as the Taiga Plains, the Taiga Shield, and the Boreal Shield with color codes, highlighting areas where large-scale forest fires are most prevalent (Figure 11). Large-scale fires are concentrated in Taiga Plain, Taiga Shield, Boreal Shield, Boreal Plain, Taiga Cordillera, Boreal Cordillera, and Montane Cordillera. The boreal forest ecosystem, known for its coniferous forests, covers a large portion of the map. Boreal areas are more prone to large fires due to their specific climatic conditions and vegetation types. One reason for this is that boreal forests, with their ground layer of flammable species such as black spruce, as well as mosses, lichens, and shrubs, are particularly susceptible to intense fires, including crown fires, which are difficult to control (National Park Service, 2021). The boreal forest ecozone has dry, cold winters and wet, warm summers. Lightning strikes are frequent in the summer, with lightning also being a significant cause of fires. For example, Manitoba has the highest number of fires and more frequent large-scale fires. Since about 1995, the number of fires in Manitoba has gradually increased. This may be due to Manitoba's geographic location with ecozones that include the prairie, southern arctic, boreal shield, Hudson plain, boreal plain, and taiga shield. This makes Manitoba cold, dry, windy, and particularly vulnerable to climate change (Halsey et al., 1997). Other ecozones are not prone to large fires due to topography, climate, and ecosystem structure. For example, the Pacific Maritime ecozone has a cool, wet climate and Polar ecozones have cold climates and are dominated by tundra biomes, making it difficult for fires to start (Ecozone and Ecozone Maps and Descriptions, n.d.). Combining this map with the previously discussed figures emphasizes the relationship between fire frequency, area burned, and ecozones characteristics.

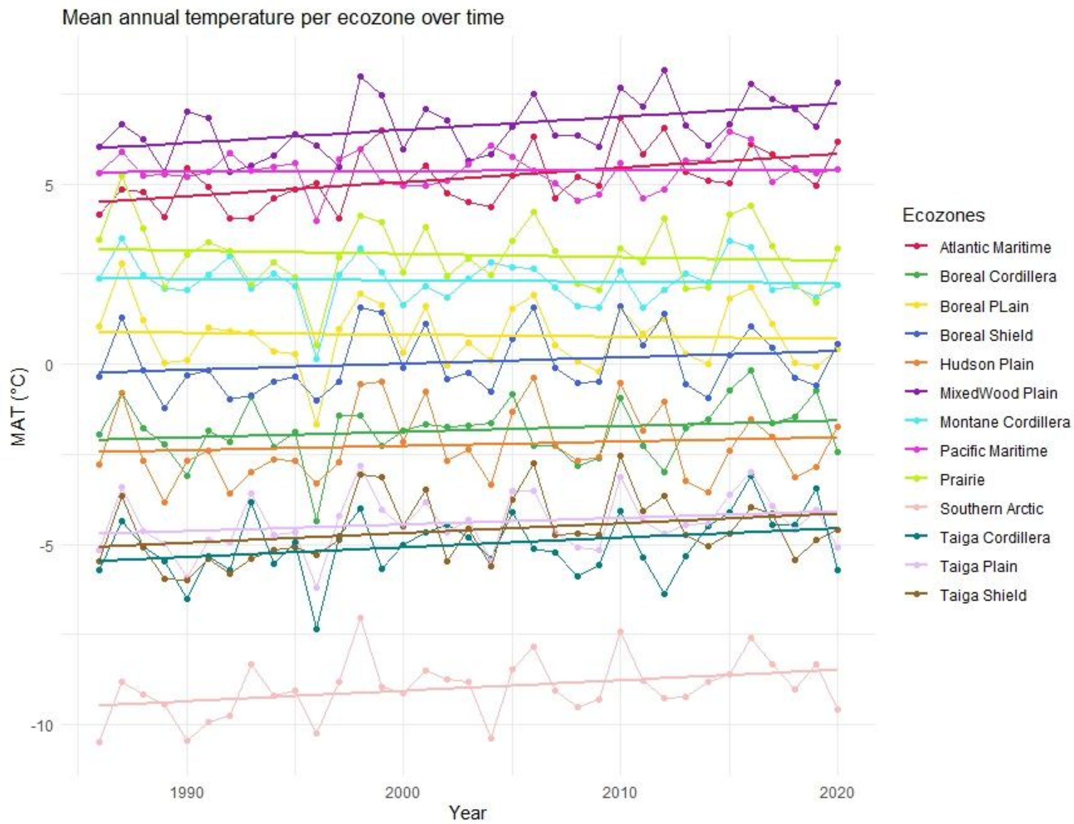
4.2 Analysis of climatic data

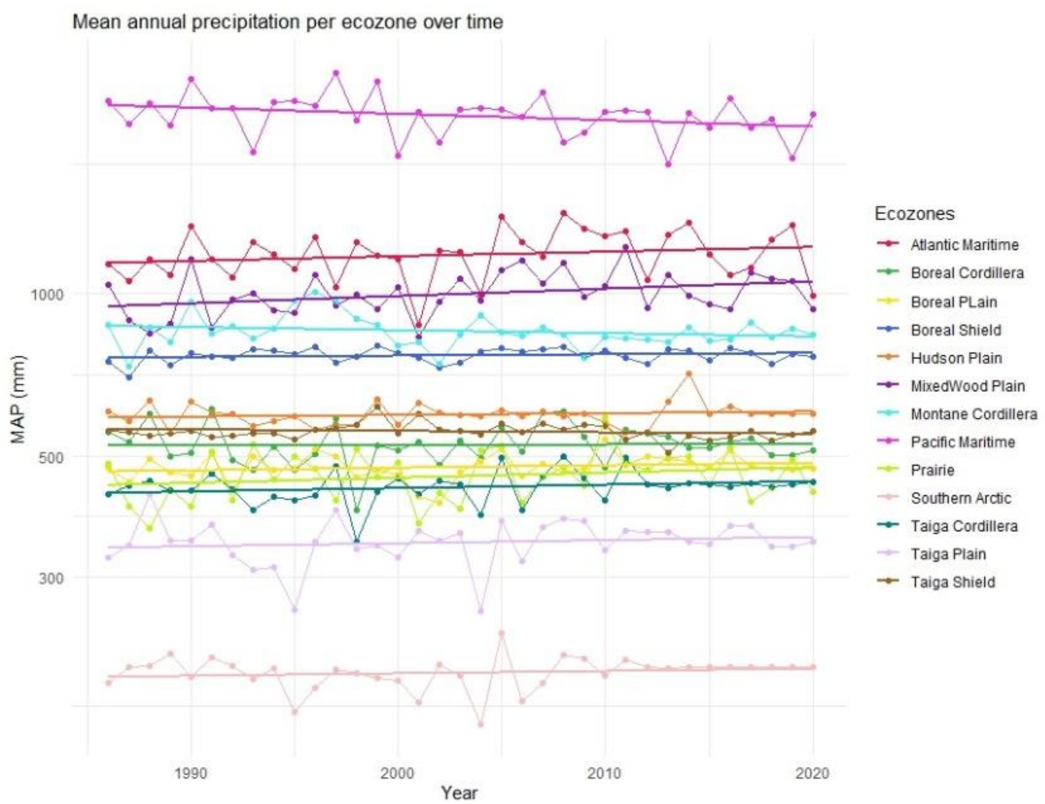
This series of graphs depicts various climatic anomalies before and during a typical fire season, focusing on the differences between this year's climatic data and those of the previous year, as well as those of a normal year. Each histogram represents the monthly distribution of climate anomalies relative to the baseline period (1961-1990) for mean temperature, maximum average temperature, precipitation, Hargreaves Climate Moisture Deficit (CMD), and Hogg's Climate Moisture Index (CMI) and is intended to correlate these with wildfire occurrence. The histogram of average temperature deviations shows that the distribution of mean temperatures in the month of fire occurrence is significantly right skewed compared to the normal distribution. The closer to the month of the fire, the distribution clearly shows a gradual clustering. The width of the distribution narrows gradually from the five months prior to the fire to the month of the fire, and the peak continues to increase. This suggests that warmer-than-average weather is more frequent, which may lead to dry weather and increase the likelihood of fire ignition and spread. The closer to the month of the fire, the CMD distribution appears to widen, and the peak is gradually decreasing. This means that weather conditions are getting drier, which can increase fire intensity and area burned. The CMI distribution extends to the left as we get closer to the month of the fire. This indicates a moisture deficit, which is consistent with conditions that favor fire occurrence. In the maximum temperature deviation histogram, the maximum average temperature for the fire month is distributed to the right of the center line. The peaks become larger and larger the closer to the time of the fire during the six months. For precipitation, the fact that the peak is consistently on the left side indicates that precipitation during the month of the fire and the pre-fire period was below average, leading to dry fuels and increased fire risk.

The patterns observed in these histograms emphasize the close relationship between climatic variables and wildfire activity. The positive deviations observed in the temperature-related graphs indicate a warming trend in climatic conditions during the fire season, which is a key factor in the increased risk of wildfires. Similarly, negative deviations in precipitation indicate a dry climate, another risk factor for wildfires. These data show a clear trend of anomalous increases in temperature and decreases in precipitation prior to and during the fire season. Such conditions can dry out forest fuels, making them more susceptible to fire, often resulting in more extensive fires and more challenging to control. Most notably, climate change may exacerbate these trends and may lead to more frequent and severe wildfire seasons in the future.

Figure 12 represents the variation of climate anomaly bias with year and month. In the months of June, July, August, September, November, and December, the deviations of the maximum temperatures are similar to the deviations of the mean temperatures in that they have mostly positive deviations. This indicates that temperatures in the fire months were above the historical norm. In January, February, and December, the deviation of the CMD is about 0. This means that for three months during the 34-year period, the CMD barely deviated from normal data. However, from August through November, their distributions were more skewed toward positive values, meaning that increased evapotranspiration and decreased precipitation in late summer and fall exacerbated dry conditions conducive to fire. In most months, the bias distribution of the CMI is skewed toward negative values and extreme changes are common. Negative deviations indicate lower than average moisture levels, which is consistent with an environment that is more prone to fire initiation and spread due to dry vegetation. Negative deviations in winter and fall indicate lower than normal precipitation levels, which can lead to longer dry seasons and thus longer periods of fire risk. Persistent patterns of climatic anomalies characterized by increasing temperatures and decreasing humidity are strongly associated with wildfire occurrence and severity. These trends are indicative of broader climate change impacts that exacerbate wildfire conditions. The data suggest that the region may experience longer, and more intense fire seasons as average and maximum temperatures continue to rise, and precipitation declines from historical normal levels.

Figure 9 reveals several important climate trends in Canadian ecozones from 1986 to 2020, namely Hogg's climate moisture index (CMI), mean annual precipitation (MAP) and mean annual temperature (MAT). CMI measures the availability of moisture, and fluctuations in CMI over the years indicate changes in humidity levels. The Pacific Maritime ecozone has a significantly higher CMI compared to other ecozones, suggesting more available moisture historically, but shows a downward trend, indicating that it's becoming drier. The Prairie ecozone has the lowest CMI, possibly reflecting a naturally drier climate, and this trend is upwards, which may indicate increasing moisture availability. The Mixedwood Plains, Atlantic Maritime, and Prairies are experiencing upward trends in CMI, potentially pointing to increased moisture availability. Other ecozones show minimal change, suggesting stable moisture availability. The Pacific Maritime ecozone, despite a historically higher MAP, is experiencing a decreasing trend in precipitation. Some ecozones, like the Southern Arctic, show lower overall precipitation and high year-to-year


Mean annual temperature per ecozone over time
MAT (°C)
Year
Ecozones
Atlantic Maritime
Boreal Cordillera
Boreal PLain
Boreal Shield
Hudson Plain
MixedWood Plain
Montane Cordillera
Pacific Maritime
Prairie
Southern Arctic
Taiga Cordillera
Taiga Plain
Taiga Shield


Mean annual precipitation per ecozone over time
MAP (mm)
Year
Ecozones
Atlantic Maritime
Boreal Cordillera
Boreal PLain
Boreal Shield
Hudson Plain
MixedWood Plain
Montane Cordillera
Pacific Maritime
Prairie
Southern Arctic
Taiga Cordillera
Taiga Plain
Taiga Shield

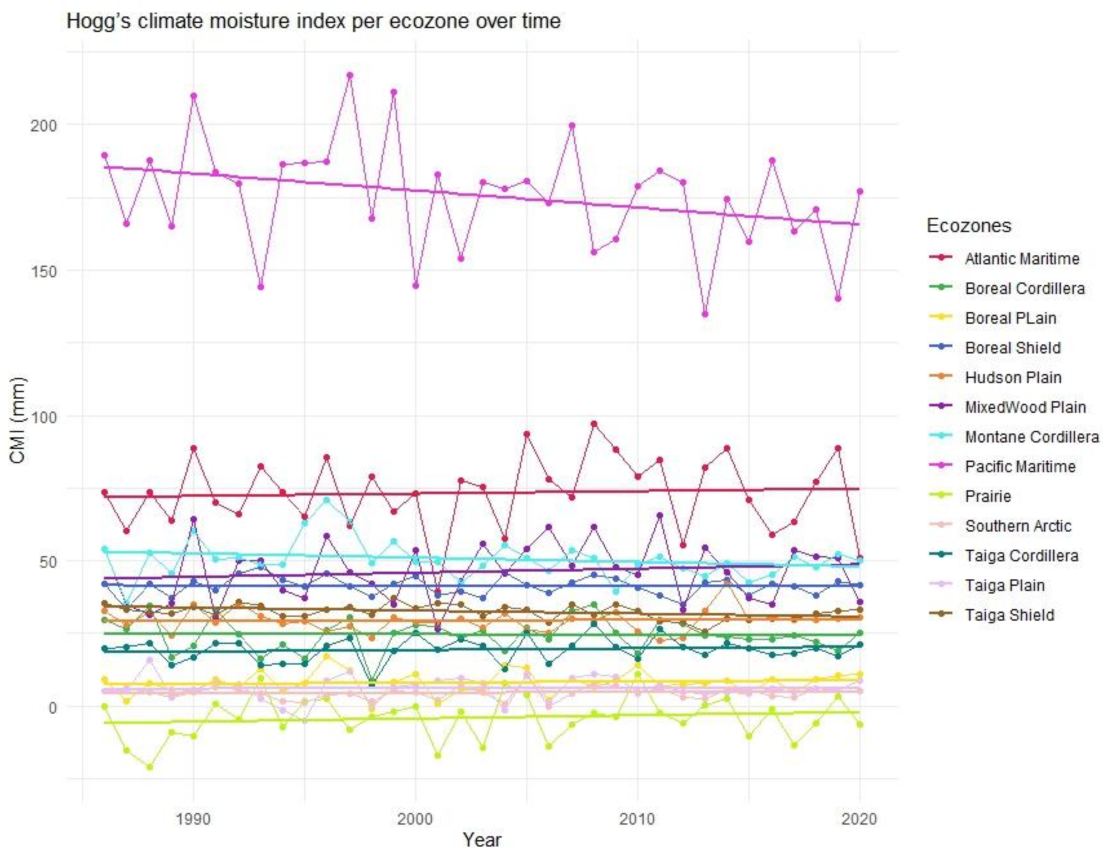


Figure 9. Trends in mean annual temperature (MAT), mean annual precipitation (MAP) and Hogg'e (1999) climate moisture index (CMI) for different ecozones in Canada from 1986 to 2020.

variability, which could make these areas more susceptible to drought and fire under the right conditions. However, overall precipitation levels are rising in this ecozone. Ecozones like the Mixedwood Plain, Atlantic Maritime, Taiga Cordillera, and Prairies show increasing trends in MAP, which could imply a lesser fire risk if the trend continues. There is a warming trend in most ecozones, which aligns with global patterns of climate change. The Prairies, Montane Cordillera, Pacific Maritime, and Boreal Plain are exceptions to this warming trend. Ecozones like the Mixedwood Plain and Atlantic Maritime show higher temperatures and more pronounced warming trends, potentially increasing the risk of fire. Overall, rising temperatures across most ecozones indicate widespread impacts of global warming. However, regional differences in precipitation and humidity indices suggest that local factors are also at play, contributing to differences in climate trends across Canada.

4.3 Correlation Analysis

The graphs show the correlation between the climate parameters for the month of the fire and their mean values for the previous five months (Figure 13). Each plot shows different climate metrics such as mean temperature, Hargreaves Climate Moisture Deficit (CMD), Hogg Climate Moisture Index (CMI), maximum temperature, and precipitation, and how they correlate with fire events. Mean temperature had the strongest correlation with fire month ($R = 0.2$). This suggests that warmer weather in previous months is a strong indicator of increased fire risk. Following mean temperature, maximum temperature was significantly correlated with fire occurrence ($R = 0.16$), emphasizing the effect of extreme heat on fire risk.CMD had an R value of 0.12, showing a moderate correlation. CMI had a lower correlation ($R = 0.078$) compared to CMD. Precipitation had the lowest correlation ($R = 0.066$). This means that changes in mean temperature are most likely to influence fire occurrence.

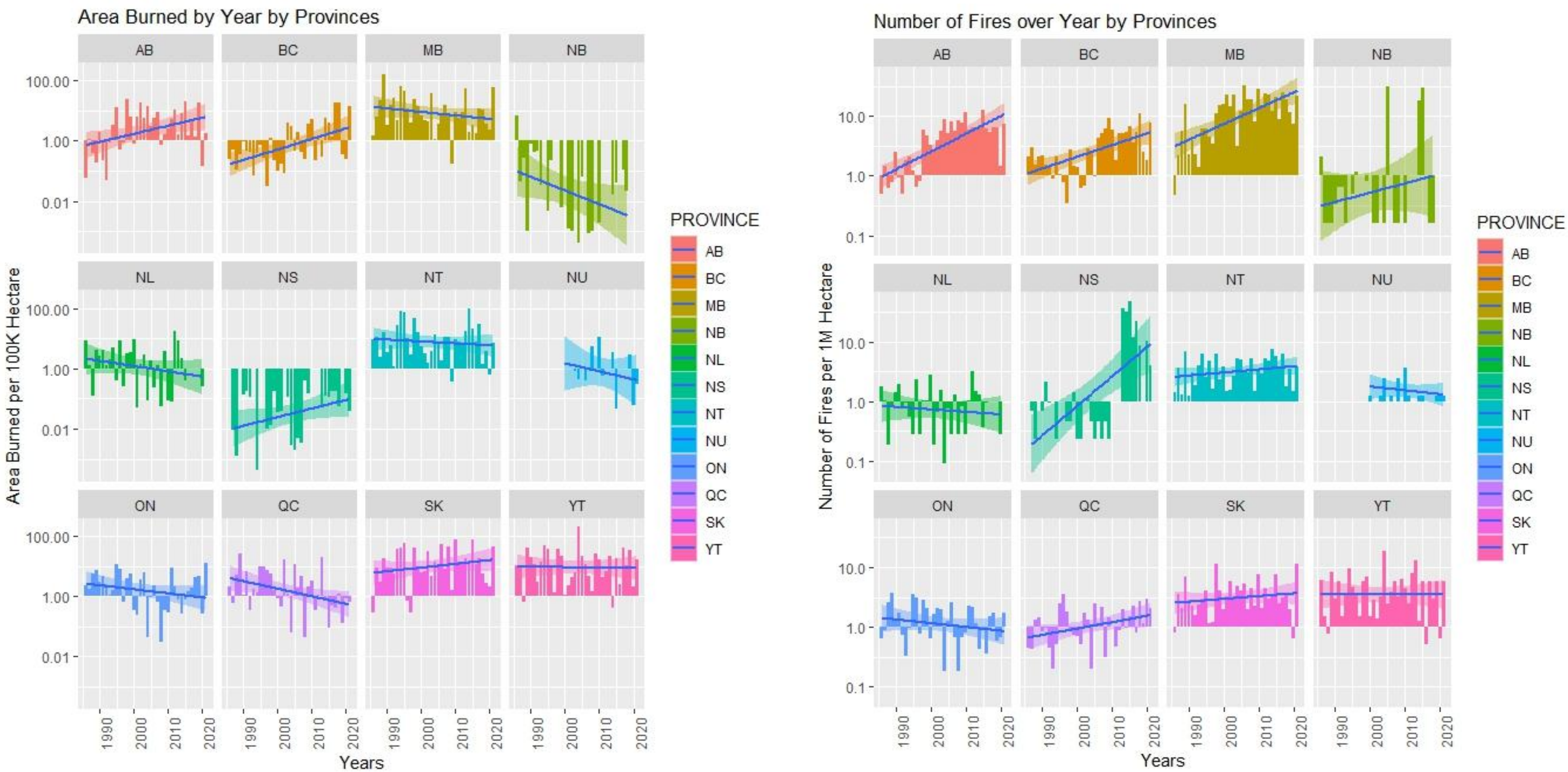


Figure 10. Log-transformed area burned by fire and number of occurrences per year in each province (trend lines and shaded areas represent the mean and standard deviation of the area burned or number of occurrences per year).

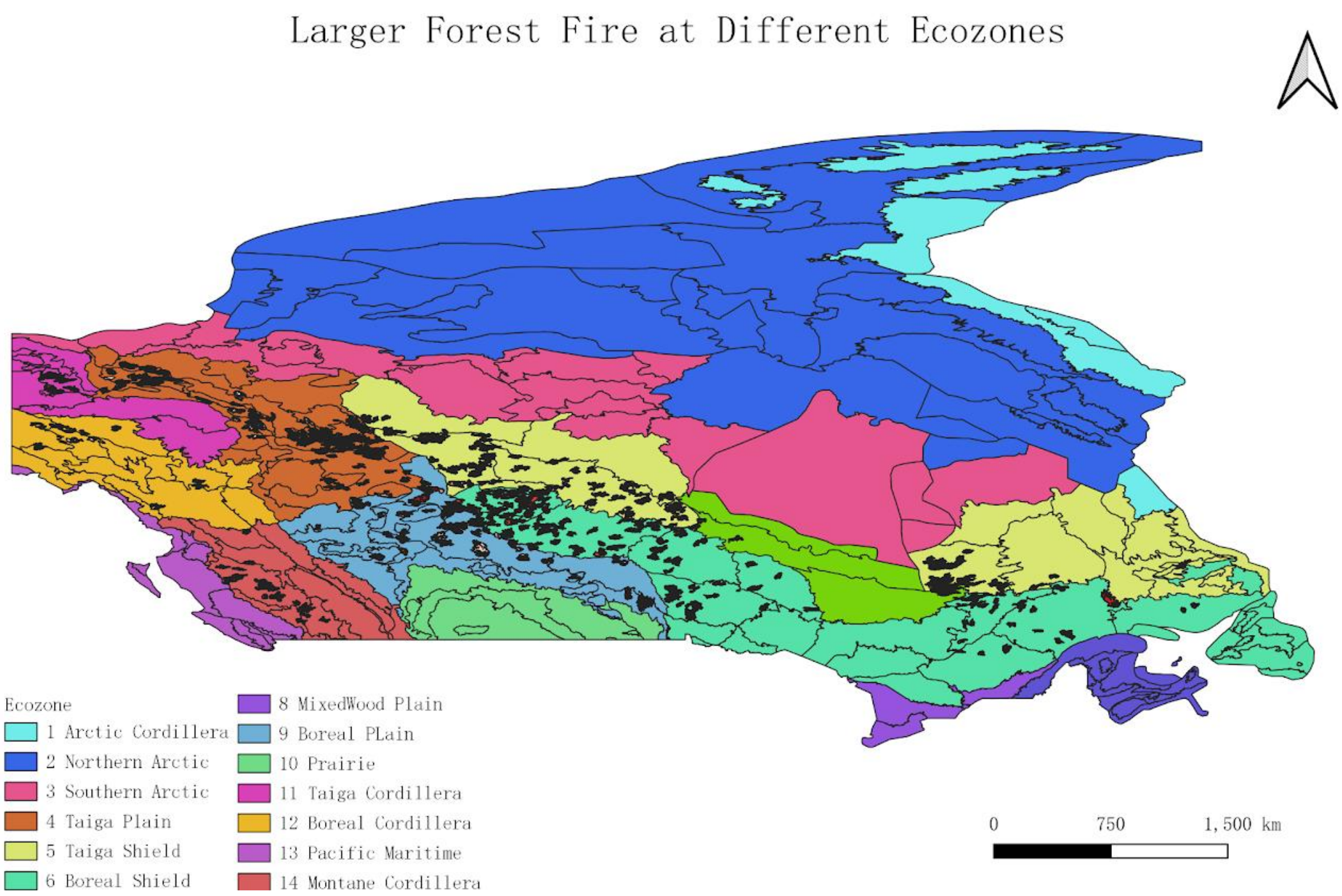


Figure 11. Larger forest fire at different ecozones.

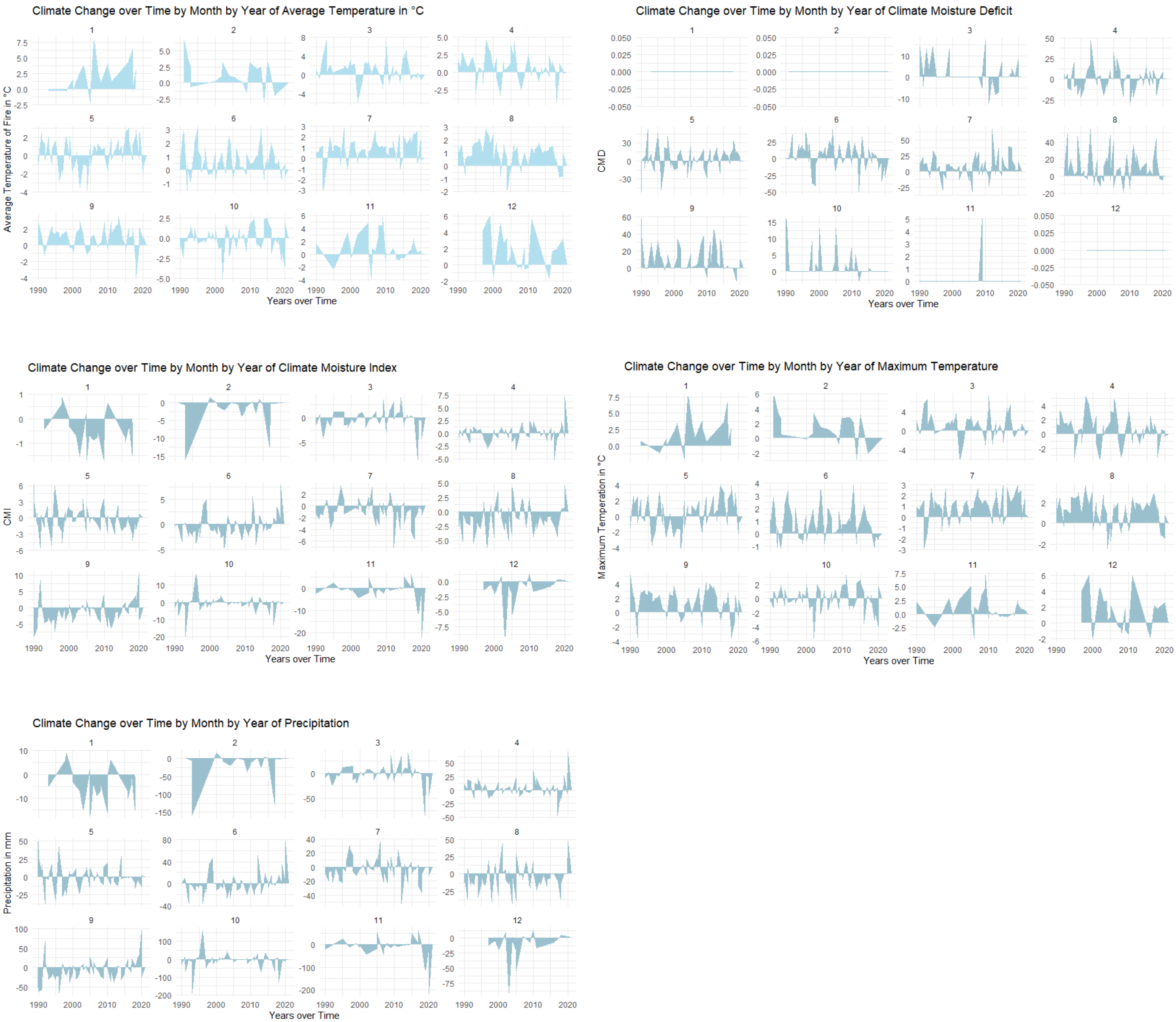


Figure 12. Variation of the climate index with year and month (x-axis represents time, y-axis represents the difference between the month in which the fire occurred and the normal data. Each square represents the month in which the fire occurred, and the blue area represents the number of fires that occurred during the month. It represents how the number of climate anomalies varies with year and month).

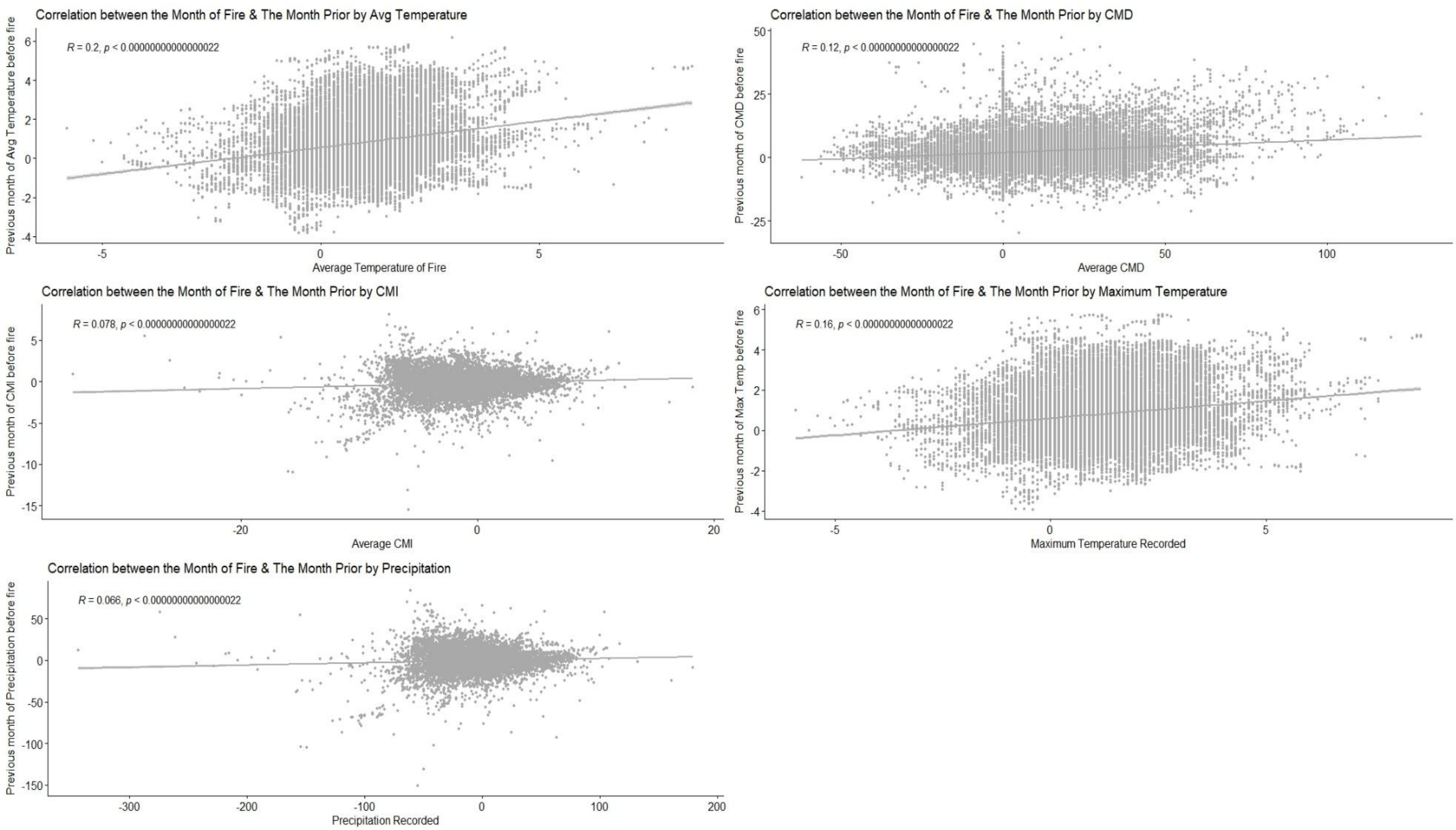


Figure 13. Correlation between the month of fire and the prior months of the fire month (the average temperature, CMD is Hargreaves climate moisture deficit, CMI is Hogg's climate moisture index, maximum average temperature, and precipitation.).

5. Conclusions

A synthesis of Canadian provincial fire and climate data from 1986 to 2020 reveals a significant associations between climatic conditions and wildfire size and frequency. Further, trends in the Climate Moisture Index (CMI) and Hargreaves Climate Moisture Deficit (HCMD) suggest that increasing temperatures and changes in humidity, are associated with an increase in the incidence and size of wildfires, particularly in boreal forest ecosystems. These findings are consistent with expected impacts of climate change, suggesting that as global temperatures continue to rise as a result of greenhouse gas emissions, the frequency and intensity of forest fires will also increase. Although there are regional differences, with some ecozones showing trends of decreasing precipitation and others showing trends of increasing precipitation, the overall pattern suggests that warmer and drier climatic conditions are likely to prevail overall, increasing fire risk. The study also points to the particular sensitivity of northern boreal forests to climate change. There is evidence that these ecosystems are at higher risk, as confirmed by the association of higher temperatures and precipitation patterns with fire occurrence. Correlation analyses indicate that mean and maximum temperatures are significant predictors of wildfire occurrence. While precipitation had the lowest correlation with fire events, the combination of climatic factors highlights the increasing challenge of wildfire management under changing climatic conditions. Despite the limitations, a limited temporal record of 35 years, and regional variability in climate change trends, it can be concluded that incorporating observed climate change trends over the last several decades, as well as future climate change projections into fire management strategies will improve regional resource allocation to mitigate the effects of climate change on wildfire risk wildfire risks.

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