Impact of Climate Change on Area Burned by Large, Lightning-Caused Forest Fires in Northwestern Ontario

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A Major Paper submitted to the Faculty of Environmental Studies in partial fulfillment of the requirements for the degree of Master in Environmental Studies

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Abstract. The dominant contribution to the area burned by forest fires in Canada is from large, lightning-caused fires. Using anomalies calculated from Canadian General Circulation Model (CGCM) climate predictions, we generated future fire weather, fuel moisture and fire danger indices for baseline, 2 x CO_2, and 3 x CO_2 climate scenarios, and used these as the inputs to *Prometheus*: The Canadian Wildland Fire Growth Simulation Model for northwestern Ontario. The goal of this study was to provide a more quantitative methodology to assess the impact of climate change on area burned by large, lightning-caused forest fires in northwestern Ontario, by combining GCM predictions with the fire growth simulation model. Area burned was calculated for a total of 63 individual simulations (21 fires x 3 climate scenarios). Results indicated a 64.75% average increase in area burned by 2040, and a 174.45% average increase in area burned by 2090, from the reference baseline scenario. This represents almost a tripling of area burned by the end of the 21st century. These estimates do not explicitly take into account fire suppression, nor any changes in vegetation, length of the burning period or fire season that may influence area burned. Fire management agencies should consider planning and implementing mitigative and adaptive strategies to prepare for this scenario.

Foreword

This Major Paper is the final document to satisfy the requirements of my Plan of Study in the Master in Environmental Studies Program (MES) at York University. This research began with an interest in studying the impact of climate change on forest fire regimes (i.e. fire frequency, intensity, severity, type, seasonality, and area burned) in Canada. I also became interested in learning about how Canadian forest fire management agencies are using decision-support systems, in particular Geographic Information Systems (GIS) and *Prometheu*s: The Canadian Wildland Fire Growth Simulation Model, for planning and real time decision making. By taking MES Independent Study Courses such as Forest Fires and Fire Management in Canada, and Introduction to Fire Growth Modelling, I became aware that many studies have addressed the impact of climate change on various components of the fire regime such as fire severity and seasonality, yet relatively few studies have quantified the potential changes in area burned due to climate change. This allowed me to narrow down my research, and develop an original study that provides a quantitative methodology to assess the impact of climate change on area burned by large fires in northwestern Ontario, by integrating the use fire growth simulations.

These interests have led me to develop my Major Paper based on the technical skills that I have gained through MES courses, and the academic conversations of my three area of concentration components: the history of forest fires in Canada, forest fires and climate change, and forest fire management in Canada. Our study hopes to provide some insight into the complex relationships between weather, large forest fires, area burned, and suppression. Filled with many challenges and opportunities, my experience with this major paper has been full of enlightenment Overall, I believe that my MES degree will be of great asset in building a career in fire science research, where my university education and field experiences will have valuable application.

Acknowledgements

I would like to start by expressing my sincere thanks to my MES supervisor Dr. Justin Podur of the Faculty of Environmental Studies, for guiding me through my research and encouraging me through the highs and lows of conducting scientific research. Justin provided me with great inspiration and the tools and concepts necessary to succeed. Specifically, he introduced me to The Canadian Wildland Fire Growth Simulation Model (*Prometheus*), which is a complex system intended for sophisticated users that took a lot of patience, perseverance, and enthusiasm to learn; and he enhanced my intelligence of Geographic Information Systems (GIS). He also introduced me to other well-known fire scientists, and gave me insight into future career opportunities. He constantly allowed this to be my own original work, but steered me in the right direction whenever he thought I needed it. I have learned a lot from Justin, and I will take the skills and perspectives he has passed on to me into my career. It has been a pleasure – thank you.

I would like to thank Mike Wotton, who is a Research Scientist with the Canadian Forest Service (CFS), but works out of the University of Toronto (UofT) as an adjunct professor in the Faculty of Forestry. Mike broadened my knowledge of the various methodologies used in predicting the impact of climate change on area burned – specifically focusing on the Canadian Forest Fire Danger Rating System (CFFDRS). Mike also provided me with necessary data (i.e. fire weather data) from the Ontario Ministry of Natural Resources, that I could not have gotten without his help. Without his passionate participation and input, this research could not have been successfully conducted.

I would also like to acknowledge Dr. Gregory Thiemann, who is an associate professor with the Faculty of Environmental Studies, as the second reader of my Research Proposal and final Plan of Study. I am grateful for his valuable advice and comments on my Major Paper.

Throughout my seven years at York University, The Faculty of Environmental Studies (FES) has provided me with a great environment to learn, gain new skills, and meet life-long friends. This research was made possible by a number of grants. I would like to thank FES, The Faculty of Graduate Studies (FGS), and CUPE for offering me GA financial assistance and GA bursaries. I would also like to thank the Han Shan Sih Buddhist Society for offering me a financial bursary.

Finally, I must express my very profound gratitude to my family for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this Major Paper. A special thanks goes to my mother, who has always taught me to be patient, stay strong, work through challenges, and to never give-up on my dreams. This accomplishment would not have been possible without my family. Thank you.

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1. Introduction:

Fire is the dominant disturbance regime in Canada’s vast boreal forest region (Natural Resources Canada, 2014). Fire is a process critical for forest regrowth of primary boreal species such as pine, aspen and spruce which depend on extreme heat to reproduce, and is responsible for the maintenance of the vegetation mosaic in the landscape, and influencing energy flows and biogeochemical cycling (Weber and Stocks, 1998). Forest fire activity is strongly influenced by four factors – weather/climate, ignition agents, fuels, and humans (Flannigan et al. 2009). Climate/weather are dynamic, meaning they are characterized by constant change as a result of changes in the earth’s orbital parameters, atmospheric composition, and solar output (Flannigan et al. 2009). In Canada, weather/climate is the most important natural factor influencing forest fires (Flannigan and Wotton, 2001).

Recently there has been a growing consensus that the earth’s climate has been warming at an unprecedented rate due to increases of radiatively active gases in the atmosphere (carbon dioxide, methane, nitrous oxide etc.), as a result of human activities (IPCC, 2014). According to Warren and Lemmen (2014), the average annual temperature in Canada has warmed by 1.6˚C from 1948 to 2013. This period of rapid climate change that we have entered will have significant impacts on Canada’s forests, and may have a profound impact on fire activity in Canada. Since fire plays such a significant role in the life cycle of Canada’s forests, and fire is dependent on climate, research into the potential impacts of climate change on fire activity in Canada is essential, and needs to be monitored.

Since the late 1980’s, substantial research has been ongoing into the impact of climate change on fire activity (Flannigan and Van Wagner 1991; Wotton and Flannigan, 1993; Flannigan and Wotton, 2001; Stocks et al. 2003; Podur and Wotton, 2010a). Early research focused on the impacts of climate change on the overall length of the fire season, as well as severity. Using the Canadian General Circulation Model (CGCM), Wotton and Flannigan (1993) predicted that not only will the fire season in a 2 x CO_2 scenario start approximately 30 days earlier (an increase of 22%), but the fire season will also likely extend to later in the fall. Similarly, Flannigan and Van Wagner (1991) predicted a 46% increase in the seasonal severity rating (SSR) in a 2 x CO_2 scenario across Canada, translating into a similar increase in area burned.

Most recently, climate change impacts research in Canada has focused on predicting more physically basic characteristics of forest fire activity, such as area burned. This is because it is easily understood by the public and policy-makers, and because of enhanced geomatics intelligence and decision-support systems in fire science research (Flannigan et al. 2005*a*). According to Gillet et al. (2004), the area burned by forest fires has increased over the past four decades as a result of human-induced climate change. Additionally, Flannigan et al. (2005*b*) suggest that temperature is the most important predictor of area burned, with warmer temperatures associated with increased area burned. Most projections of area burned are based on projecting fire danger indices, and although there is some research, relatively few studies quantify the potential changes in area burned due to climate change. To-date, Flannigan et al. (2005*b*) have used historical relationships between area burned and weather/fire danger, coupled with two GCMs, to estimate future area burned in Canada. The results of their study indicate that on average, the area burned could be expected to double (from current averages) by the end of the 21st century. Specifically, in the province of Ontario, Podur and Wotton (2010) use a simplified elliptical fire growth model, as opposed to a spatially explicit model, to predict changes in area burned. They use a combination of GCM predictions, coupled with a fire growth and suppression model to examine the probable changes in future area burned in Ontario. Their results show that there will be more than a doubling of area burned by 2040, and an eightfold increase in area burned by the end of the 21st century.

In North America, forest fires that are in areas under fire management are contained by initial attack forces while they are small. However, the small portion of large fires (greater than 200 ha) that 'escape' initial attack, result in most of the annual area burned (Strauss et al. 1989; Stocks et al. 2003). Today, both human-caused and lightning-caused forest fires ignite and spread across forested landscapes. Current statistics based on the last 35 years, show that human and lightning-caused fires occur in approximately equal numbers in Canada (Stocks et al. 2003). However, an examination of records of area burned by fire, do reveal that lightning fires are the dominant cause of the majority (~80%) of the area burned in Canada (Stocks et al. 2003).

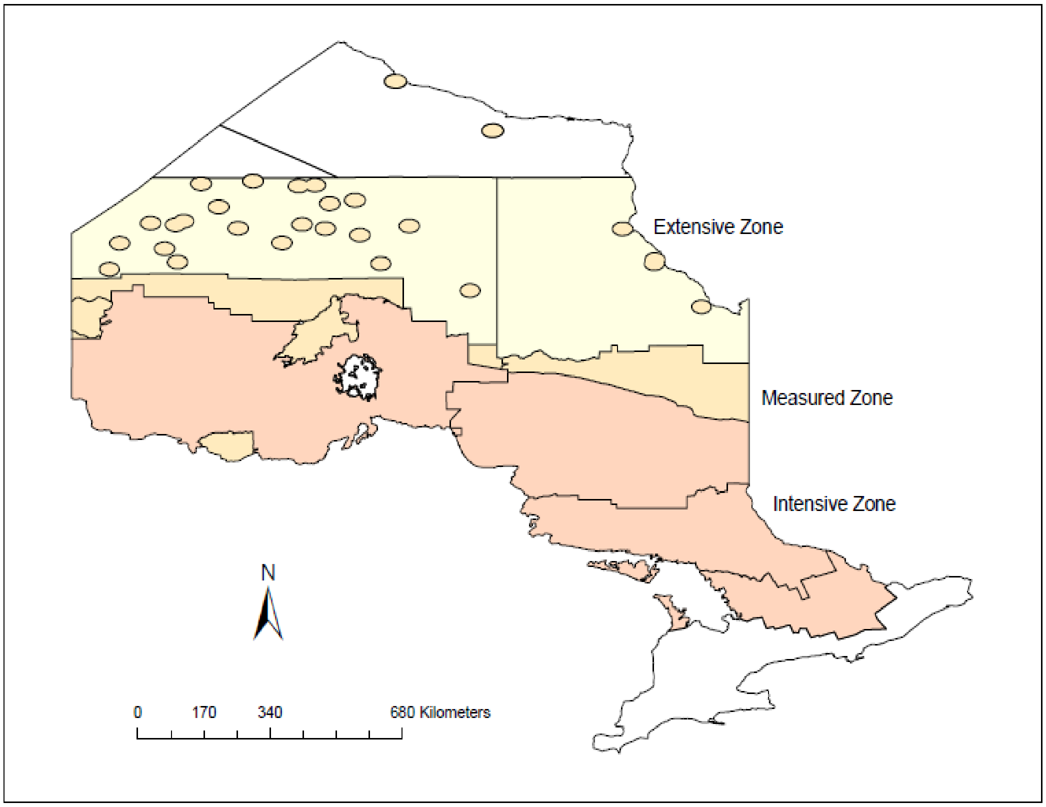


Fig. 1. The province of Ontario forest fire management zones

Specifically, in the province of Ontario, the fire region was divided into several fire management zones up until May 7, 2014 (Martell and Sun, 2008). Each fire management zone fell into one of three levels of protection classified as intensive, measured, or extensive (Fig. 1). According to Podur and Wotton (2010), human-caused fires made up 59% of the forest fires occurring in the intensive and measured zones (where fire suppression is active) over the period of 1976-2004. These forest fires resulted in 33% of the area burned. If the extensive protection zone is included, where fires are not suppressed but monitored, the area burned by human-caused fires drops to 17%. This means that 83% of the area burned in the province, is a result of lightning-caused forest fires. Similar results were gathered from data on annual area burned in Ontario from 1976-2006 by Podur et al. (2010). They reveal that lightning-caused fires comprised 46% of the total number of fires reported, but about 83% of the area burned.

In more recent statistics, our analysis from datasets gathered from the Canadian National Fire Database (CNFDB) show that an annual average of 1273 forest fires occurred for the period between 1990 and 2013 in Ontario (Fig. 2, Appendix A). These forest fires burned an annual average of 169 404 ha (Fig. 2). Three percent of these fires (827 of 30 552) were ‘large’ (greater than 200 ha in size) and lightning-caused (Fig. 3, Appendix B). These 3% of fires were responsible for 87% of the total area burned. Lightning-caused forest fires lead to a disproportionate amount of area burned because: (1) they are more likely to occur in remote locations where they take longer to detect; and 2) because they often arrive in temporal clusters, which can overwhelm fire organizations (Wotton et al. 2010). The combination of these factors can lead to lightning-caused forest fires to burn for a long period of time, before they are fully extinguished. As a result of their significant contribution to the total number of fires and area burned, research into large lightning-caused forest fires has become essential.

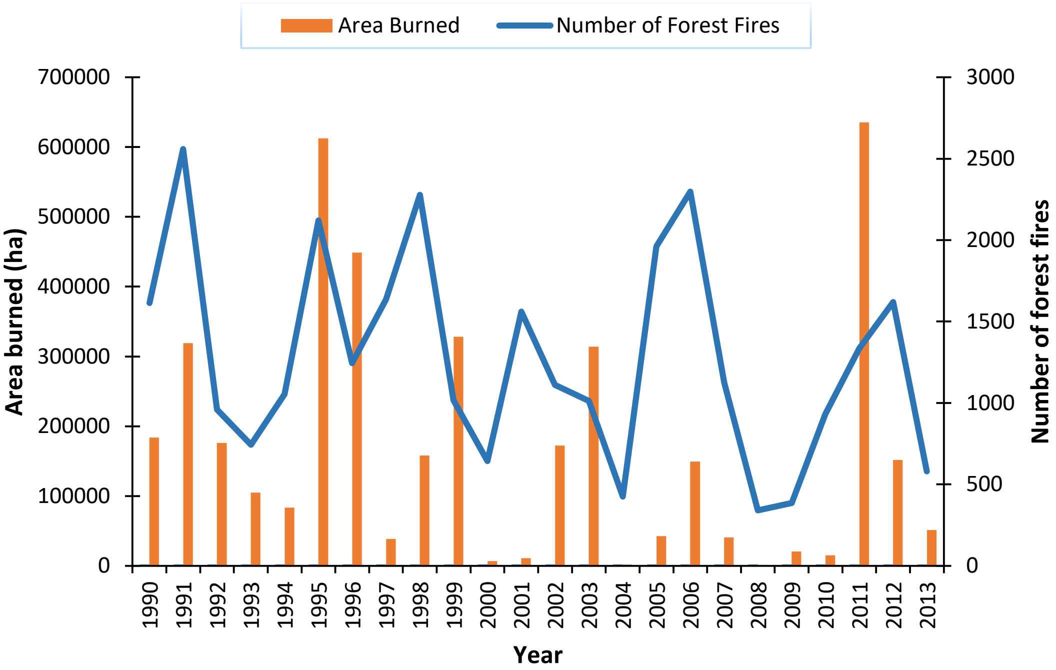


Fig. 2. Area burned and number of forest fires in Ontario from 1990-2013

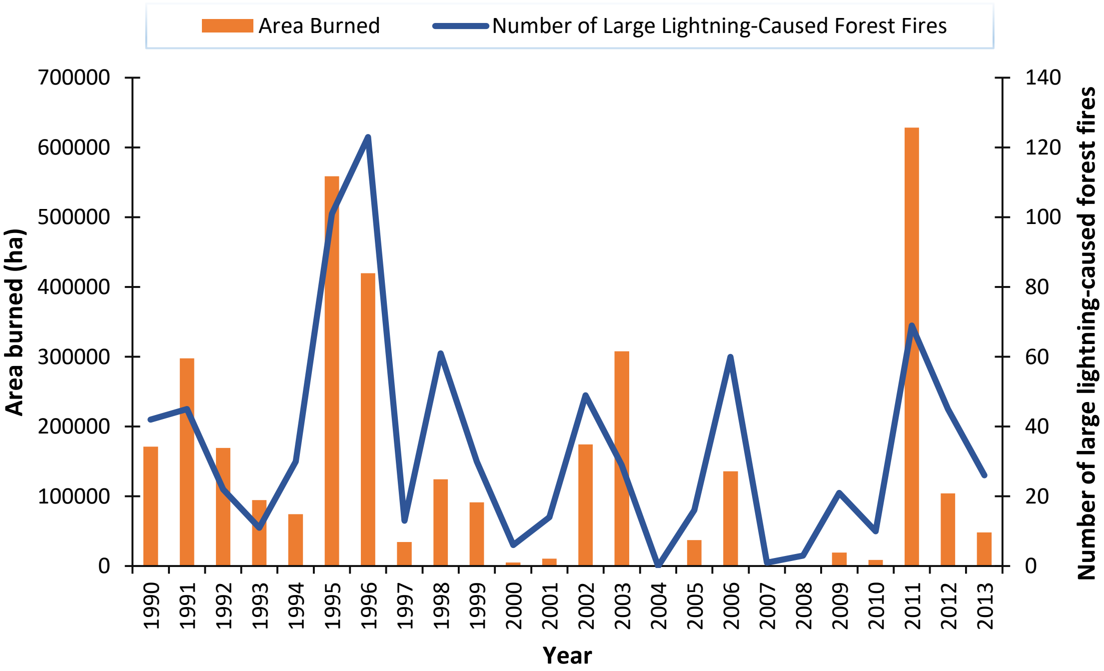


Fig. 3. Area burned and number of large lightning-caused forest fires in Ontario from 1990-2013

1.1 Objective

Most projections of future area burned are based on projecting fire danger indices, and there is a lack of studies (Tymstra et al. 2007; Podur and Wotton, 2010; Podur et al. 2010) that quantify the potential changes in area burned due to climate change in Canada. This study will provide a more quantitative methodology, by incorporating the use of fire growth simulations. The Natural Resources Canada (NRCan) strategic fire management decision-support tool, called *Prometheus*, is a spatially explicit, deterministic fire growth simulation model based on the Canadian Forest Fire Behaviour Prediction System (FBP) and wave propagation equations (Tymstra et al. 2010). The objective of this study is to predict the impact of climate change on area burned by large, lightning-caused forest fires in northwestern Ontario by combining this spatially explicit fire growth simulation model, with predictions of future fire weather, fuel moisture, and fire danger indices under climate change from a general circulation model. Integrating fire growth simulations allows for a better comparison of outcomes for different scenarios. Although fire growth simulation is an immature field of fire research and there is much room for improvement, this model has proven to be effective for long-term projections and decision-support for the management of 'large' fires (Tymstra et al. 2010). This study hopes to provide some insight into the complex relationships between weather, large forest fires, and area burned.

2. Methods and Data

2.1. Study Area

In Canada, the boreal forest is the largest forest region, occupying approximately 315 mill. ha (Weber and Stocks, 1998). Our study area focused on the boreal forest – the Ontario

Shield Ecozone - of the Northwest Region of Ontario, as shown in Fig. 4. The Ministry of Natural Resources and Forestry (MNFR) in Ontario divided the province into three administrative regions: Northwest Region, Northeast Region, and Southern Region. Each region comprises of a number of district offices for the purpose of managing Ministry programs and resources at a regional level (see MNRF, 2016). Our study was limited to the Northwest Region.

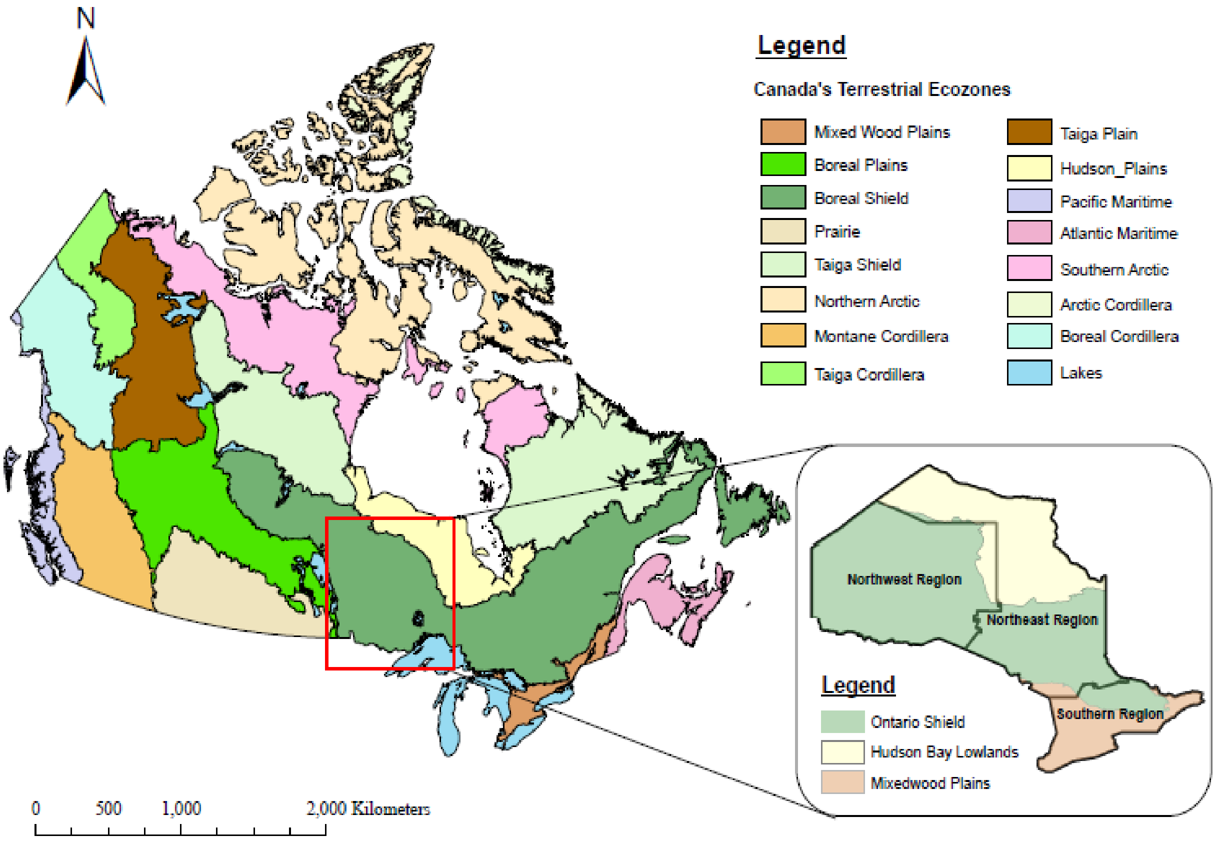


Fig. 4. The study area is located in the boreal forest – specifically the Ontario Shield Ecozone – of the Northwest Region of Ontario

The Ontario Ministry of Natural Resources (OMNR) has partitioned the province of Ontario into three ecozones (highest level of ecosystem classification in Ontario) based on ecology, topography, and climate: Hudson Bay Lowlands; Ontario Shield; and Mixedwood Plains. The Ontario Shield Ecozone consists of Ontario's portion of the national Boreal Shield Ecozone. This ecozone is the main vegetation domain in Ontario, covering more than 65 336 847 ha, or more than half of the province's area (66.2%). The northern portion of the ecozone comprises coniferous forests composed of spruce species, balsam fir, jack pine, tamarack, and hardwoods including white birch and poplars. In the south, mixed and deciduous forests of tolerant hardwoods (i.e. sugar maple) are more common (Crins et al. 2009). According to Thompson (2000), in the conifer-dominated boreal forests in the northern and central parts of the ecozone, as well as in the oak and pine forests in the southern part, fire is the dominant disturbance agent influencing the composition and structure of Ontario's boreal forest. The OMNR has also partitioned the province of Ontario into three fire management zones: Intensive Zone, Measured Zone, and Extensive Zone (Fig. 1). This study focused on the extensive zone (303 371 km^2) that encompasses the northern portion of the fire region. In this zone, only fires that threaten human safety or property values are aggressively attacked. All other fires are monitored, but not actively suppressed (Martell and Sun, 2008). We focused on this protection zone because the average annual area burned is much higher, than in the intensive and measured zones (Bridge et al. 2005).

2.1. Forest fire data

Data on the ignition, spread and extinguishment of all fires detected has been stored in digital form by each fire management agency. For every fire that occurs, this data takes place in the form of individual point records. Fires are spatially referenced with the latitude and longitude of the known or estimated ignition point. Other characteristics about the fires are based on observations by the fire management agency (Wotton et al. 2010). Our forest fires were chosen from The Canadian National Fire Database (CNFDB), which is a collection of forest fire data – fire locations (point data) and fire perimeters (polygon data) – provided by Canadian fire management agencies including provinces, territories, and Parks Canada (Natural Resources Canada, 2016*a*). For this analysis, we obtained only a subset of these agency fire records: Fire ID, location (latitude, longitude), start date (month, day, and year), general cause type (lightning-caused and/or human-caused), and final area burned (ha).

For the purposes of fire management, fires are classified into two types: initial attack fires, and large fires. Forest fires that 'escape' initial attack and grow larger than 200 ha, are classified as large fires. Stocks et al. (2002) found that for the period from 1959 to 1997 fires over 200 ha in size were only 3% of fires occurring in Canada, but 97% of the total area burned. For the purpose of our study, we limited our analysis to large forest fires. Analysis from datasets gathered from the Ontario Ministry of Natural Resources (OMNR) for the period of 1976 to 2001 show that roughly 43% of the forest fires that occur are caused by lightning. The remaining 57% are caused by people, yet lightning-caused fires produced 81% of the area burned (Wotton and Martell, 2005). People-caused fire occurrence processes are difficult to document and quantify because they are influenced by human behaviour, fire prevention measures, and land-use patterns. We therefore limited our analysis to large, lightning-caused forest fires and leave people-caused forest fires for future study.

2.2. Fire weather data

Fire occurrence and spread is influenced by fuel moisture, which is in turn strongly influenced by fire weather. For our baseline scenario we used fire weather observations from the OMNR's network of fire weather stations for the period from 2002 to 2013. This year corresponds to the most recent forest fire data available for the province of Ontario at the time of analysis. Thirteen weather stations were selected to complete the fire weather analysis (Table 1; Fig. 5). ArcGIS 10.3.1 was the primary software used to determine which weather stations were to be selected. ArcGIS provides users with a variety of different geoprocessing tools to perform countless geoprocessing tasks. We used Near (Analysis) – a Proximity Tool - which measured the distance between the centroid of the chosen forest fire (the input feature) to the nearest weather station (the closest feature in another layer) from OMNR's network of fire weather stations. In proximity tools, the distance between any two features is calculated as the shortest separation between them. The results were then recorded in the input features attribute table, where the fields for distance and feature ID of the closest feature were added. For further information on how proximity tools calculate distance, see ESRI, 2016.

Table 1. Representative weather stations in the Ontario Shield selected for the weather analysis

Weather Station Number	Weather Station Name	Code
10100	Red Lake	RED
10103	Deer Lake	DEE
10207	Big Trout Lake	BTL
10215	Weagamow Lake	WEA
10218	Bearskin Lake	BKN
10220	Opapimiskan Lake	PAP
21004	Fort Hope	FTH
21012	Summer Beaver	SUM
21014	Kasabonika	KAS
21016	Webequie	WEB
99005	Lansdowne House	WLF
99049	Job Lake	JOB
99051	Anaconda	ANA

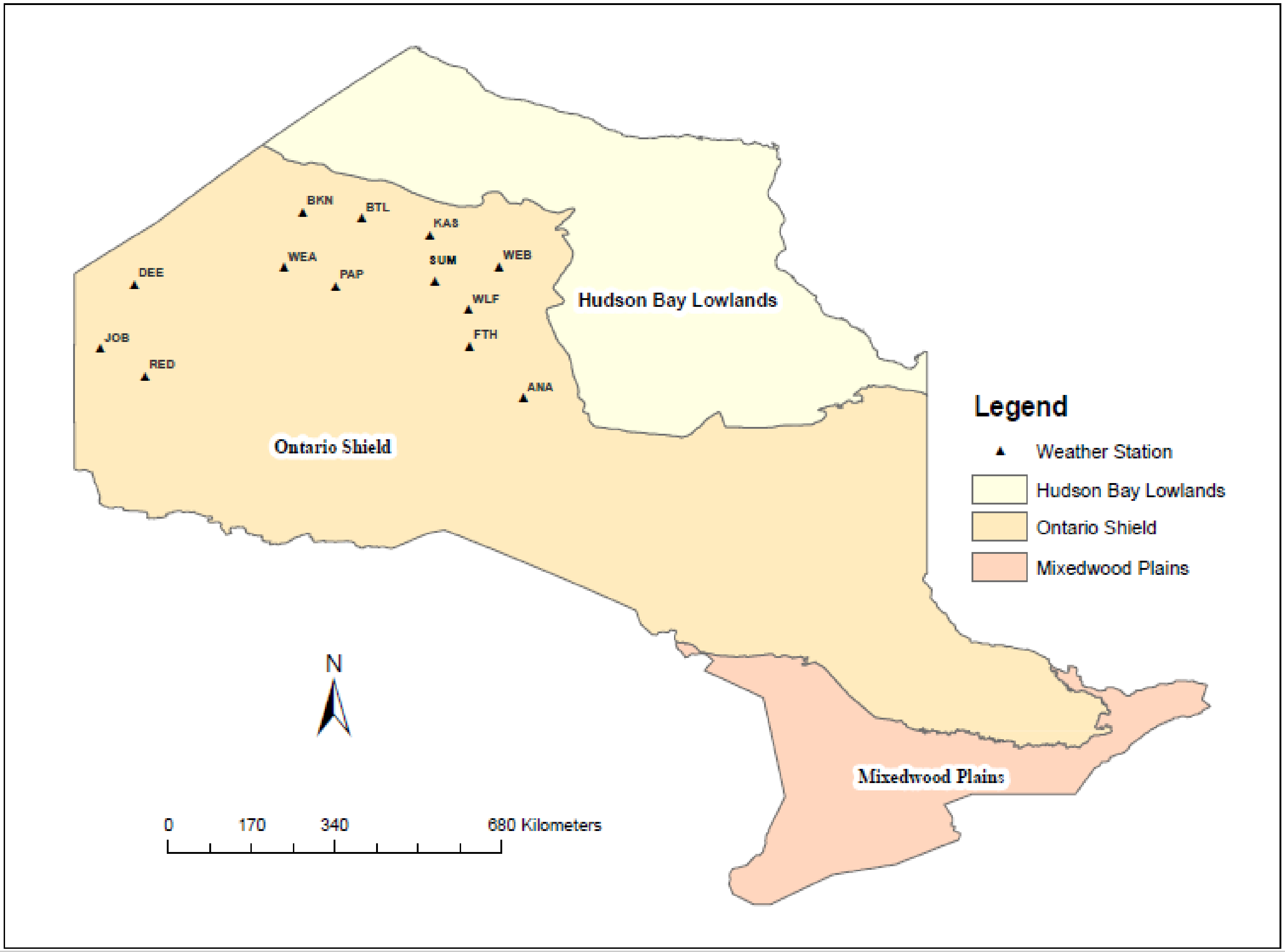


Fig. 5. Ecozones of Ontario and the locations of the selected thirteen weather stations

Fire weather observations were used to estimate a daily series of fuel moisture codes and fire behaviour indices using the Canadian Forest Fire Danger Rating System (CFFDRS). The CFFDRS has two major components: The Fire Weather Index (FWI) System (Van Wagner, 1987), and the Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group, 1992). The FWI system is used by fire management agencies across Canada to assess potential fire intensity. The FWI system requires as input, daily ambient temperatures (˚C) collected at 12:00 local standard time (LST), relative humidity (RH) (%) measured at 1.4m above the ground in a radiation shielded screen, mean wind speed (km/h), and daily rainfall (mm). For this study, the fire season was established as starting on 1 May and ending on 31 October.

The outputs of the FWI system are three fuel moisture codes that track moisture in different levels of the forest floor. The Fine Fuel Moisture Code (FFMC) is a numeric rating of the moisture content of the surface litter layer on top of a decaying organic layer, with a depth of 1.2cm. FFMC is an indicator of the ease of ignition and the flammability of fine fuel. The Duff Moisture Code (DMC) provides a measure of the moisture content of loosely compacted upper organic layers of the forest floor, with a depth of 7cm. The DMC is used as an indicator of receptivity of the forest floor to lightning fire ignition and forest floor consumption. The Drought Code (DC) is a numeric rating of the moisture content in deep, compact organic layers or heavy downed woody material, with a depth of 18cm. The DC is used as an indicator of long-term effects of drought and amount of smouldering in deep duff layers and large logs. The FBP System relies on outputs from the FWI System to provide quantitative assessments of fire behaviour in various major fuel types. This system outputs three relative fire behaviour indices, which roughly follow the elements of Byram's classic fireline intensity formula (Byram, 1959). The Initial Spread Index (ISI) combines the effects of wind speed and FFMC to create a unitless index of potential rate of spread (ROS). The Buildup Index (BUI) combines the DMC and DC to determine the total amount of fuel available for combustion. The final fire danger index, the Fire Weather Index (FWI), combines the ISI and BUI to indicate the potential intensity of a fire. It is a unitless value, used as a general index of fire danger across Canada (Van Wagner, 1987).

2.3. Future fire weather scenarios

Following the methods used by Podur and Wotton (2010), we created a series of climate scenarios for future decades by applying monthly temperature and rainfall anomalies from future climate scenarios to the daily weather streams. We used GCM output from emission scenario runs using the Canadian Climate Centre GCMs, specifically CGCM3 and using their T63 grid (Flato et al. 2000). In the GCM3 T63, each grid cell covers approximately 2.8 by 2.8 degrees of longitude and latitude; approximately an area 300 km by 200 km in northern Ontario. A cubic spline interpolation technique (Flannigan and Wotton, 1989) was used to interpolate anomalies to each weather station before applying them to the weather station data, in order to associate a temperature and precipitation anomaly with each of the weather stations.

In the Intergovernmental Panel on Climate Change (IPCC) 4th assessment report on climate change, three core future scenarios were used: A2, A1b, and B1 scenarios (IPCC, 2007). For our study, we chose the A2 emission scenario - sometimes referred to as the business-as-usual scenario - which describes a very heterogeneous world. Briefly, A2 represents a world of independently operating nations, a continuously increasing global population, and slow per capita economic growth and technological change (IPCC, 2007).

From the A2 emission scenario, time series of surface air temperature and precipitation were obtained. Temperature and precipitation anomalies were calculated using the GCM decade 2010-2019 as a baseline period, which is a more current baseline period than the one used by

Podur and Wotton (2010), which was a decade earlier (2000-2009). Our 2010-2019 baseline period generally corresponds to the 2002-2013 period in the weather station records that we were using. These time periods do not need to be exactly the same because we are using the GCM period solely as an indication of baseline periods at the end of the 20th century and beginning of the 21st century. In terms of precipitation, monthly precipitation anomalies were applied as ratios to the daily precipitation amount in the OMNR daily fire weather streams. This means that in order to estimate the monthly precipitation anomalies, the mean monthly total amount of precipitation in each future decade was divided by the corresponding mean monthly rainfall in the baseline period. In terms of temperature, to estimate the monthly temperature anomaly, the mean monthly temperature from the baseline period was subtracted from the corresponding monthly temperature from each future decade. This created a simple temperature difference that was added to the daily temperature stream for the corresponding daily fire weather stream. Two decades of future fire climate were used to create the anomalies that were applied to the weather station data: the decade of 2040 (2040-2049), which will be referred to as the 2 x CO_2 scenario and the decade of 2090 (2090-2099), which will be referred to as the 3 x CO_2 scenario.

As a result, when the monthly precipitation and temperature anomalies from the GCM were applied to the OMNR weather records for 2002-2013, future daily fire weather scenarios were created. Following the same methods as Podur and Wotton (2010) again, these future daily fire weather scenarios were used to generate future fuel moisture and fire danger scenarios. Using this method, the 2002-2013 fire weather dataset becomes the baseline scenario.

2.4. Prometheus Fire Growth Simulations

In a previous study, Tymstra et al. (2007) investigate the impact of climate change on area burned in Alberta's boreal forest for low, moderate, high, very high and extreme Fire

Weather Index (FWI) conditions by integrating the use of fire growth simulations using *Prometheus.* Using similar methods, we extend this study into Ontario and use *Prometheu*s, together with predictions of future fire weather, fuel moisture, and fire danger indices under climate change from a GCM, to assess the impact of climate change on area burned.

As mentioned earlier, *Prometheus*: The Canadian Wildland Fire Growth Simulation Model has been developed as a spatially explicit, deterministic fire growth simulation model designed to run in Canadian fuel complexes. The foundation of this model is the Fire Behaviour Prediction System (FBP) subsystem of the CFFDRS (Van Wagner, 1987), and wave propagation algorithms developed by Richards (1990). The FBP system predicts the physical characteristics of a forest fire at various points around the fire perimeter, such as predicting the rate of spread for the spatial simulation of fire front propagation. Wave propagation equations use a mathematical approach to simulate the complex geometry of a growing fire perimeter over a long period of time in a heterogeneous environment. The model is then implemented at high spatial and temporal resolutions through computer programming and simulation modelling (For more information about the development and structure of *Prometheus*, see Tymstra et al. 2010).

Prometheus uses spatial input data on topography (slope, aspect, and elevation), fuel types, and weather to simulate fire growth. The *Prometheus* daily weather stream requires maximum and minimum temperatures, minimum RH, maximum and minimum wind speed, wind direction and precipitation. The fire weather observations were collected at 12:00 local standard time (LST). For all scenario runs, which include the baseline, 2 x CO_2, and 3 x CO_2 scenarios, we assumed that the maximum and minimum temperature and maximum and minimum wind speeds are the same (an example of the weather streams used as input into *Prometheus* for a single fire for each of the three scenarios, is shown in Tables 2, 3, and 4).

Table 2. Baseline Fire weather conditions for Forest Fire SLK25 used in *Prometheus* simulations

Temp, temperature; RH, relative humidity; WS, wind speed; WD, predominant wind direction; FFMC, Fine Fuel Moisture Code; DMC, Duff Moisture Code; DC, Drought Code; ISI, Initial Spread Index; BUI, Buildup Index; FWI, Fire Weather Index

Month	Day	Temp (˚C)	RH (%)	WS (km h $^{-1}$)	WD	Rain (cm)	FFMC	DMC	DC	ISI	BUI	FWI
June	8	25.8	32	1.9	65	0.0	93.5	56.0	106.6	7.8	55.8	19.6
June	9	27.6	26	1.6	60	0.0	93.5	61.5	115.0	7.7	61.3	20.4
June	10	20.5	44	2.3	177	0.0	91.2	64.7	122.0	5.7	64.5	17.0
June	11	15.4	81	2.3	70	7.1	41.3	37.9	116.1	0.0	41.7	0.1
June	12	12.9	69	1.1	19	0.5	56.0	39.1	121.8	0.3	43.4	0.5

Table 3. 2 x CO2 Fire weather conditions for Forest Fire SLK25 used in *Prometheus* simulations

Abbreviations for weather elements and codes the same as Table 2

Month	Day	Temp (˚C)	RH (%)	WS (km h $^{-1}$)	WD	Rain (cm)	FFMC	DMC	DC	ISI	BUI	FWI
June	8	27.5	32	1.9	65	0	93.8	67.2	102.1	8.1	66.8	22.2
June	9	29.3	26	1.6	60	0	93.8	73.1	110.8	8	72.7	22.9
June	10	22.2	44	2.3	177	0	91.4	76.5	118.2	5.9	76.1	19
June	11	17.1	81	2.3	70	6.4	43.9	46.7	114.1	0.1	46.7	0.1
June	12	14.6	69	1.1	19	0.4	58.8	48	120.1	0.4	48	0.7

Table 4. 3 x CO2 Fire weather conditions for Forest Fire SLK25 used in *Prometheus* simulations

Abbreviations for weather elements and codes the same as Table

Month	Day	Temp (˚C)	RH (%)	WS (km h $^{-1}$)	WD	Rain (cm)	FFMC	DMC	DC	ISI	BUI	FWI
June	8	31.6	32	1.9	65	0	94.5	75.3	110.8	8.8	74.8	25.1
June	9	33.4	26	1.6	60	0	94.5	82	120.2	8.7	81.5	25.9
June	10	26.3	44	2.3	177	0	91.9	86	128.3	6.3	85.5	21.3
June	11	21.2	81	2.3	70	7	45.1	50.9	123.4	0.1	50.8	0.2
June	12	18.7	69	1.1	19	0.5	61.8	52.5	130.2	0.5	52.5	0.8

Since forecasted hourly values were unavailable in our weather records, *Prometheus* used a dual sine-exponential function (Beck and Trevitt, 1989) to convert the daily weather streams into hourly weather streams. Specifically, this function interpolates diurnal variations in weather conditions over a 24-h period. As well, Hourly Fine Fuel Moisture Code (HFFMC) values were calculated using the Lawson method of diurnal FFMC calculation (Lawson et al. 1996). These are essential components in completing the fire growth simulations.

Table 5. Forest fires used as input into the *Prometheus* simulation model

Fire ID	Year	Month	Day	Cause Type	Area Burned (ha)	Longitude	Latitude
NIP19	2013	6	7	Lightning-caused	2968	-87.9676	52.6492
NIP23	2013	6	7	Lightning-caused	259	-88.0448	51.8852
NIP25	2013	6	7	Lightning-caused	523	-88.4437	51.8627
NIP43	2013	7	1	Lightning-caused	2490	-87.9799	51.9253
NIP44	2013	7	3	Lightning-caused	315	-87.0954	51.173
NIP45	2013	6	19	Lightning-caused	800	-86.9544	51.7571
NIP48	2013	7	4	Lightning-caused	356	-86.7452	52.9289
NIP51	2013	7	4	Lightning-caused	680	-87.7645	53.9397
RED24	2013	7	2	Lightning-caused	304	-94.0772	51.3815
RED31	2013	7	2	Lightning-caused	16302	-94.3249	51.503
RED32	2013	7	2	Lightning-caused	2308	-86.9544	51.7571
RED41	2013	7	1	Lightning-caused	401	-89.7857	54.1071
SLK16	2013	6	7	Lightning-caused	474	-90.3474	52.8983
SLK21	2013	6	7	Lightning-caused	1649	-91.5383	53.16
SLK23	2013	6	8	Lightning-caused	666	-89.9286	54.0473
SLK24	2013	6	4	Lightning-caused	490	-89.6911	53.9119
SLK25	2013	6	8	Lightning-caused	1182	-89.1363	53.392
SLK31	2013	6	10	Lightning-caused	4842	-90.5736	53.9331
SLK35	2013	7	3	Lightning-caused	314	-90.055	52.4228
SLK37	2013	7	4	Lightning-caused	201	-90.9483	52.9624
SLK41	2013	6	26	Lightning-caused	566	-94.0745	52.9898

For the forest fire growth simulations and area burned calculations, forest fires were chosen solely from the year 2013 from the extensive protection zone of the Ontario Shield in northwestern Ontario. During this year, 41 forest fire starts occurred that were either human-caused and/or lightning-caused. For the purpose of our study, we strictly stuck to lightning-caused forest fires, which brought our number down to 37 fires. 21 of the 37 lightning-caused forest fire starts that occurred that year escaped initial attack (greater than 200 ha). These 21 ‘large’ lightning-caused forest fires were then used as input into the *Prometheus* model **(**Table 5). The growth of these 21 forest fires were simulated for each of the three scenarios (baseline, 2 x CO_2, and 3 x CO_2 scenarios), using a standard burn period of 1000-2200 h. No fire growth was simulated outside of this time period. The fuel map that is the basis of the *Prometheus* runs, allows for the forest fires to burn and capture the full fuel variability within the landscape. Each of the forest fires were allowed to burn for five consecutive days.

3. Results

To examine and compare the average increase in area burned of the 2 x CO_2 and 3 x CO_2 scenarios from the reference baseline scenario, the weighted area burned (ha) of individual forest fires for the three climate scenarios were tabulated and graphed (Table 6, Fig. 6). The projected increases in the average area burned in the extensive zone of the Ontario Shield of northwestern Ontario using the *Prometheus* wildland fire growth simulation model, were striking. Overall, for our CGCM3-A2 scenario, in which there is no decrease in CO_2 emissions in the long-term (referred to as business-as-usual), the 2 x and 3 x CO_2 scenarios resulted in an average increase in area burned of 64.75% and 174.45%, respectively, from the reference baseline scenario. This represents almost a tripling of area burned by the end of the 21st century. The difference in area burned between the baseline and 2 x CO_2 and 3 x CO_2 scenarios varies from fire to fire. However, there is a general overall warming and increased area burned trend, as a result of future temperature, precipitation, and key fire danger indices changing considerably between scenarios.

Table 6. **Weighted area burned (ha) by forest fire and climate scenario**

Forest Fire ID	Baseline	2 x CO_2	3 x CO_2
NIP19	3022	3677	7887
NIP23	4725	5990	9169
NIP25	29947	39112	56975
NIP43	91007	118514	141971
NIP44	58110	66724	77282
NIP45	19464	23427	33356
NIP48	161	310	484
NIP51	94	192	301
RED24	33	150	399
RED31	997	2754	3391
RED32	5584	10799	12165
RED41	10471	12531	17859
SLK16	28508	35902	56179
SLK21	85528	96802	137355
SLK23	15	24	74
SLK24	34008	40310	55225
SLK25	8140	9643	17193
SLK31	18594	22543	36902
SLK35	11985	17813	22018
SLK37	2227	4691	5774
SLK41	8596	13691	19399
Total	421215	525599	946814

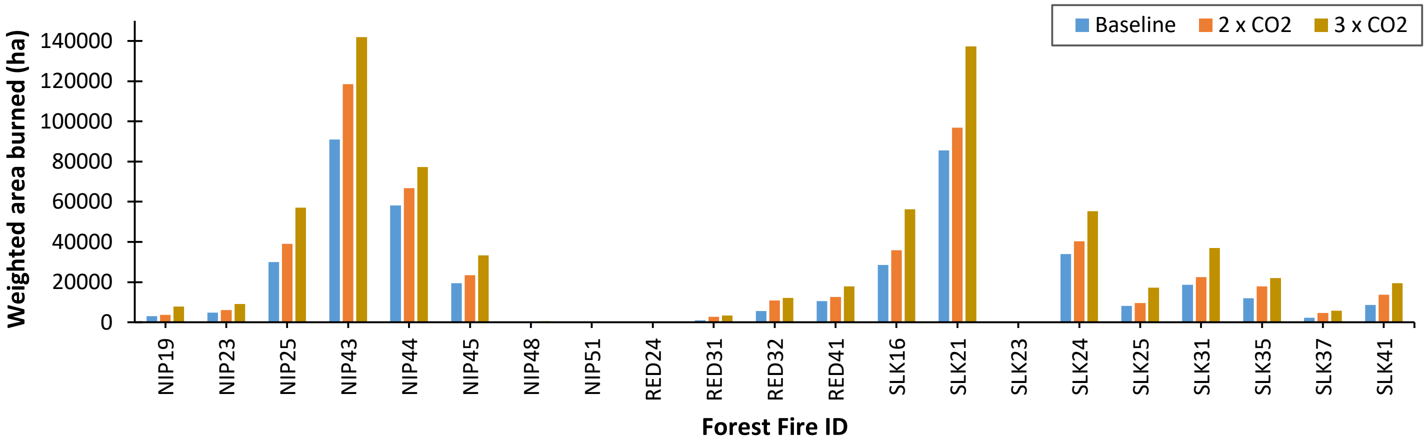


Fig. 6. Graphed weighted area burned (ha) by forest fire and climate scenario

Area burned is determined by a complex set of variables including the size of the sample area, the period under consideration, the extent of flammable forest, topography, the presence of lakes or roads on the landscape, fuel characteristics, season, latitude, fire control policies and priorities, fire control, organizational size and efficiency, fire site accessibility, simultaneous fires, and weather (Flannigan et al. 2005*b*). Various studies, however (Flannigan and Harrington, 1988; Flannigan et al. 2005*b*; Duffy et al. 2005) suggest that temperature is the most important predictor of area burned, with warmer temperatures associated with increased area burned. In particular, Flannigan and Harrington (1988) suggest that the significance of temperature could be attributed to its association with blocking ridges, or it could reflect the fact that forest fire area expands exponentially on only a few days of high temperature and strong winds. Fig 7. illustrates the effect of the length of the simulation on the area burned and temperature of three forest fires (RED31; SLK31; and SLK37), and shows the correlation between area burned and temperature. The overall general trend shows that the difference in area burned between each climate scenario increases, as the length of the simulation, as well as the temperature increases.

Take forest fire SLK31 (Fig.7*b*) as an example. This example shows that the difference in area burned between each climate scenario increases (from approx. 1500 ha in the baseline scenario, to approx. 2000 ha in the 2 x CO_2 scenario, to approx. 3500 ha in the 3 x CO_2 scenario) at 81 h into the simulation, and as the temperature increases (from approx. 18˚C in the baseline scenario, to approx. 20˚C in the 2 x CO_2 scenario, to approx. 24˚C in the 3 x CO_2 scenario). This difference in area burned between each climate scenario continues to increase as the simulation proceeds, and with warmer temperatures. In addition, this example may simply just imply that the forest fire area expanded significantly on only a few days of high temperature – which in this case is representative of the third, fourth, and coming to fifth day of high temperatures.

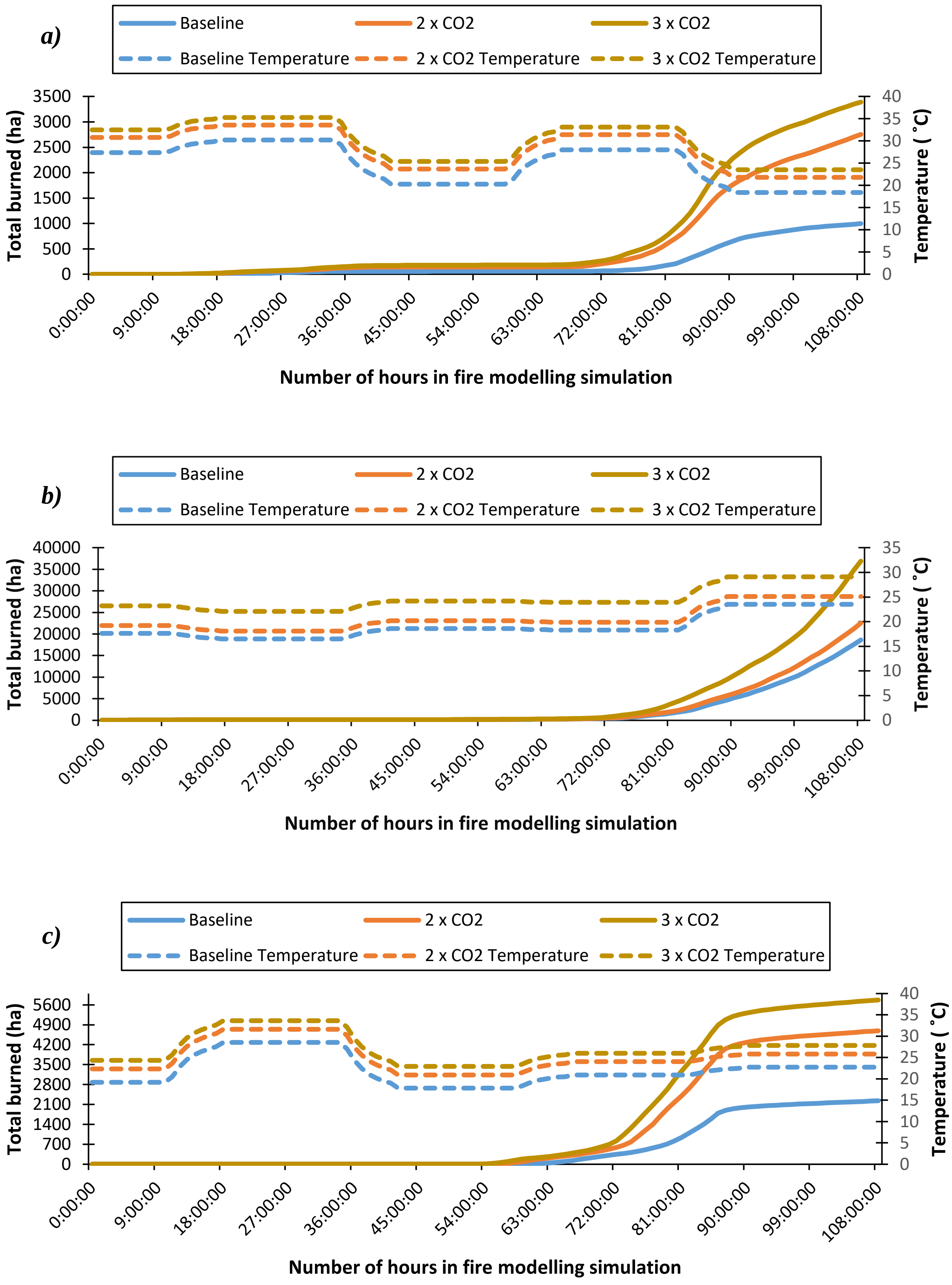
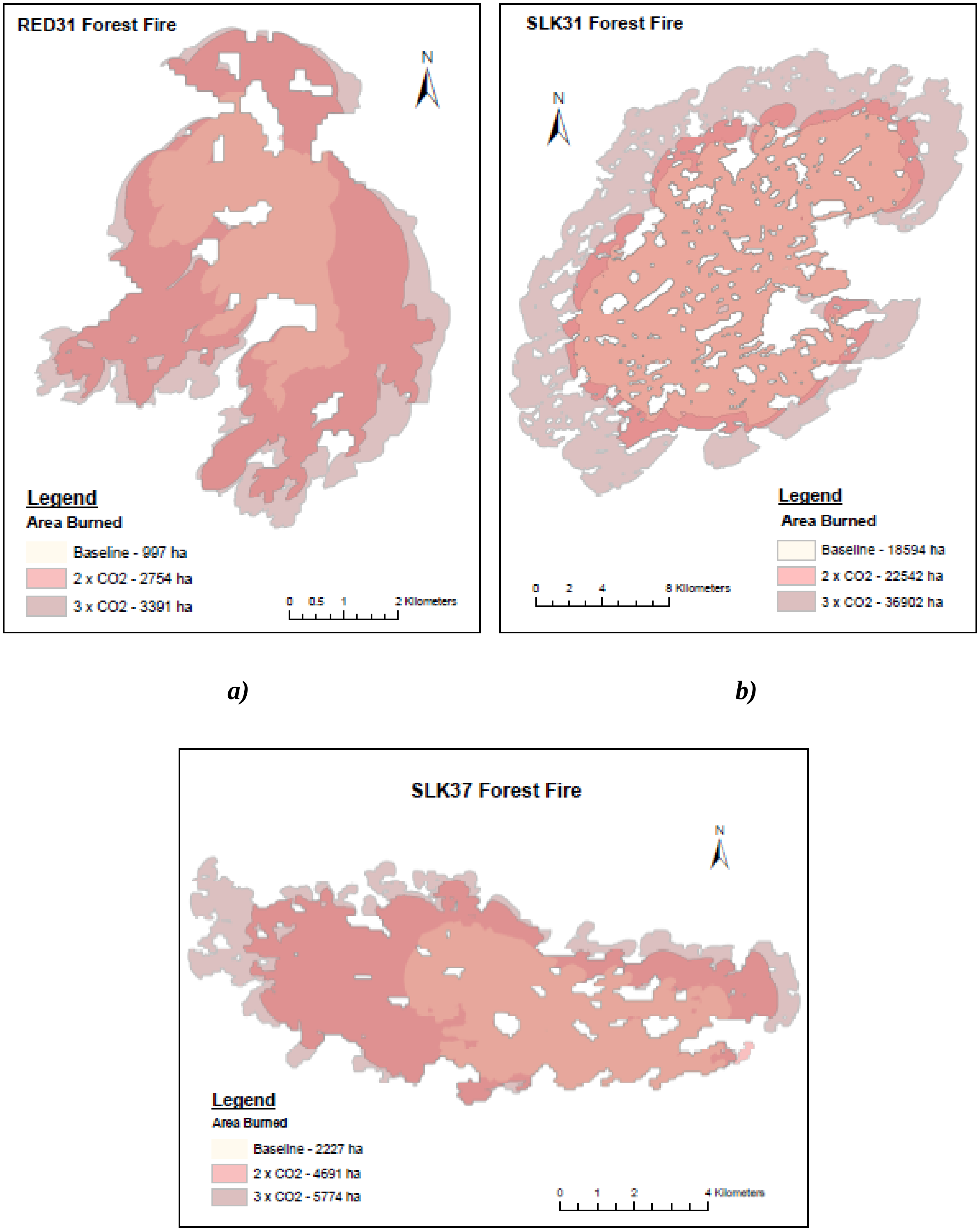


Fig 7. The effect of the length of the simulation on the area burned and temperature of three forest fires *a*) RED31; *b*) SLK31; and *c*) SLK37



a)

b)

c)

Fig 8. ArcGIS Map Overlays of the difference in the area burned between the three climate scenarios for forest fire: *a*) RED31; *b*) SLK31; and *c*) SLK37

ArcGIS 10.3.1 was used to visually display the difference in the area burned between the baseline, 2 x CO_2, and 3 x CO_2 climate scenarios of individual forest fires. ArcGIS provides users with the Overlay Toolset, which contains tools to overlay multiple feature classes to combine, erase, modify, or update spatial features, resulting in a new feature class. Fig. 8 visually displays the difference in the area burned between the three climate scenarios for forest fire *a*) RED31; *b*) SLK31; and *c*) SLK37. The light brown colour represents the reference baseline scenario, the burgundy colour represents the 2 x CO_2 (2040) scenario, and the purple colour represents the 3 x CO_2 (2090) scenario. All scenarios state the total area burned (ha). These maps are visual representations, implying that the greatest difference in area burned is between the 1 x CO_2 and 3 x CO_2 scenarios, as projected in this study.

4. Discussion

Our model predicted the impact of climate change on the area burned by large, lightning-caused forest fires. For the purposes of fire management, fires are classified into two types: initial attack fires and large fires. In this study, we have classified forest fires that 'escape' initial attack and grow larger than 200 ha, as large fires. In Ontario, specifically, we gathered data from The Canadian National Fire Database (CNFDB) that suggests for the period from 1990 to 2013, lightning-caused forest fires over 200 ha were only 3% of fires occurring in Ontario, but responsible for 87% of the total area burned. Lightning-caused forest fires have a tendency to burn larger areas because they occur in remote locations, where both the detection and arrival of suppression resources can be delayed. This study places an emphasis on large, lightning-caused forest fires because of their significant importance and contribution to the total number of fires and area burned in Ontario. Numerous studies (Strauss et al. 1989; Flannigan and Wotton, 1991;

Podur et al. 2010) have also generally accepted that the dominant contribution to the area burned by forest fires in Canada is from large, lightning-caused fires.

Fire management agencies across Ontario strive to better their suppression capability in order to prevent the loss of human life/injury and to reduce and mitigate the loss of values at-risk. The OMNR spends roughly $85 million each year on fire management activities (Martell, 2001). Large fire management is a significant component of this expense. Escaped fires result in substantial fire agency expenditures on suppression activities because they are difficult to supress due to the high intensities at which they grow. A permanent staff of 220, collaborates with 640 fire fighters that are hired each fire season. OMNR operates an aircraft fleet that includes 9 large CL-415 air tankers and 5 smaller Twin Otters that can serve as air tankers. In addition, 14 helicopters, 15 detection aircraft, and 7 bird-dog aircrafts are hired each season, though these numbers vary from year to year (Martell, 2001). Improved geomatics (i.e. Geographic Information Systems (GIS); Remote Sensing), decision-support systems, and educational campaigns are also contributing to minimize the impact of forest fires. However, in a continually changing climate, quantifying the impact of all these initiatives becomes very challenging.

Debates about the effectiveness of suppression and whether it has an impact on the average annual area burned are on-going. To-date, the impact of initial attack systems on area burned have been studied in far greater detail, than studies on large forest fire suppression systems. The relationship between suppression, weather, and area burned is believed to be different for large fires, compared with initial attack fires. Numerous studies (Cumming, 2005; Martell and Sun, 2008; Ward et al. 2001) suggest that fire suppression, by means of initial attack, contains many fires at small sizes, that would have otherwise grown to larger sizes, and reduced the overall average annual area burned. However, large fires and large-area burned years are associated with the development of persistent blocking high pressure systems, resulting in conditions of long periods of hot and dry weather, leading to significant drying of fuels (Stocks and Street, 1983). As a result, studies (Bridge et al. 2005; Martell, 2001) suggest that in large-area burned years, the conditions are such that the numerous fire starts and their quick rate of spread can be dangerous to fire fighters, can overwhelm fire management agencies where suppression activities become ineffective and thus, unlikely that suppression could influence the total area burned. Similarly, Podur and Martell's (2007) model of an extended attack system, which extends the work by previous modellers of initial attack systems (Martell et al. 1984), suggests that despite the impact of suppression, very severe weather will lead to high area burned regardless of fire suppression efforts in Ontario. Despite the continual deliberations, the effect of suppression capability and forest fire management policies and procedures are factors that need to be considered. However, projecting future forest fire suppression effectiveness of both the initial attack and large forest fire suppression systems in a changing climate remains a challenge. As a result, future changes in suppression effectiveness and capabilities were not directly included in the analysis of this study.

The results of our CGCM3-A2 scenario suggest that the 2 x CO_2 and 3 x CO_2 climate scenarios will result in an average increase in area burned of 64.75% and 174.45%, respectively, from the reference baseline scenario. This represents almost a tripling of area burned by the end of the 21st century. These increases are higher than most results from previous studies that have examined the equivalent of this A2 scenario. Flannigan et al. (2005*b*) used historical relationships between weather, the FWI System components, and area burned for ecozones on a monthly basis, together with two GCM's, to project future area burned in Canada. In their analysis, which also used the Canadian Climate Centre GCM, ecozones in Ontario show expected increases of approximately 60%-70% in area burned for the 3 x CO_2 time period. Tymstra et al. (2007) investigated the impact of climate change on area burned in Alberta's boreal forest for low, moderate, high, very high and extreme Fire Weather Index (FWI) conditions by using fire growth simulations, coupled with output from the Canadian Regional Climate Model. Their analysis, which also used the *Prometheus* fire growth simulation model, projected that the 2 x CO_2 and 3 x CO_2 scenarios will result in a relative increase in area burned of 12.9% and 29.4%, from the reference 1 x CO_2 scenario.

Our projections for the increase in area burned for the 2 x CO_2 time period from the reference baseline scenario, are much more similar to those suggested in other studies. For example, Flannigan and Van Wagner (1991) suggested that the area burned in Canada would increase by 44% for a 2 x CO_2 scenario due to an increase in Seasonal Severity Rating (SSR) – which is derived from the Canadian Fire Weather Index. Price and Rind (1994) used two empirical fire models, together with the Goddard Institute for Space Studies GCM to investigate the possible changes in area burned in a 2 x CO_2 climate. In their analysis, which also placed emphasis on lightning-caused forest fires, suggested that the area burned would increase by 78% for a 2 x CO_2 scenario, based on a 44% increase in lightning fire ignitions.

Nevertheless, our increases in area burned are lower than projected results from other previous studies (Balshi et al. 2005; Podur and Martell, 2007). In particular, Podur and Wotton (2010) used GCM predictions, coupled with a large fire growth and suppression model to examine probable changes in future area burned in Ontario. Their analysis, which also used large fires (>200 ha), suggested that the area burned in Ontario would increase by 190% by 2040, and an eightfold increase in area burned by the end of the 21st century. They support the belief that these increases are due to a large number of rapidly spreading fires that are difficult to control, overwhelm fire management agencies, and cause significant increases in area burned. Their analysis took into account the increase of fire occurrence (both human and lightning), large forest fire suppression system modelling, suppression capacity in the fire management organization in terms of extended attack, and suppression effectiveness. Their study also used a simplified elliptical fire growth model, as opposed to a spatially explicit, deterministic fire growth model as used in our study. The inclusion of these factors may be attributed to the significant differences in results between their study, and ours.

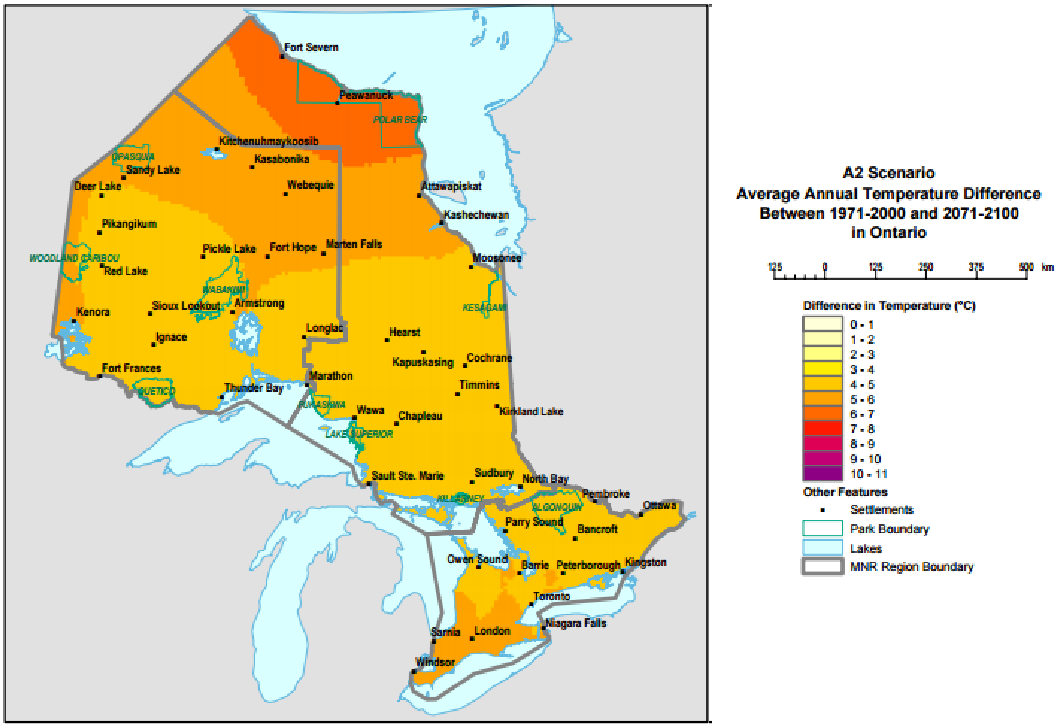


Fig 9. Projected change in average annual temperature in Ontario in 2071 to 2100 compared to 1971 – 2000 using the A2 scenario (Source: Colombo et al. 2007)

There is scientific consensus that the global climate has been warming, partly owing to anthropogenic activities (IPCC, 2014). Fire activity is strongly linked to weather, and increased average area burned due to climate change is anticipated. Our study focused on the extensive protection zone, which encompasses the northern portion of the Northwest Fire Region. In this zone, fires are not attacked unless they posed significant threats to public safety and/or property. Fig. 9 (Colombo et al. 2007) presents the changes in average annual temperatures across Ontario in 2071-2100, based on the A2 scenario. Within the province, there are regional variations in changes in temperature, though the entire province will see significant warming. In the Northwest Region and particularly within the extensive zone, increases in annual average temperatures of 5 to 6˚C is expected. Our study suggests that warmer temperatures are associated with increased area burned. Hence, the extensive zone of the Northwest Region of Ontario is likely to see larger area burns in the future, than the majority of the province.

An expanding wildland-urban interface is another emerging pressure that is expected to greatly influence future fire activity, area burned, and fire management practices in the extensive zone of the Northwest Region. According to Service Canada (2014), the Northwest economic region is expected to see an expansion of major industrial developments in the mining, forestry, construction, and energy sectors in areas that to-date, have seen relatively little industrial activity. For example, the construction sector has implemented numerous infrastructure projects along highways and bridges that have created hundreds of jobs. Large, lightning-caused forest fires that create large area burns are dominant in the Northwest region. This expansion of a wildland-urban interface is likely to increase the number of human-caused fires that require action to reduce the threat to people and property values, and to prevent large area burns. In order for fire management agencies to be able to respond to changes due to climate change and other emerging pressures, significant changes will have to occur in the way fire is managed.

Across Canada, large fast-spreading fires have resulted in evacuations of communities to become common in recent years. Numerous evacuations have occurred in the boreal region and involve Aboriginal communities where the population densities are low, but area burned is substantial (ICLR, 2012). This is particularly evident in the Boreal Shield of Ontario's Northwest Region, where the majority of area burned is located close to communities with >50% Aboriginal population (Fig. 10) (NRCan, 2016*b*). In the near future, we will likely see an increase in the number of evacuations, where many Aboriginal communities may become displaced as a result of increased fire activity due to climate change. These issues remain a challenge, and require further investigation.

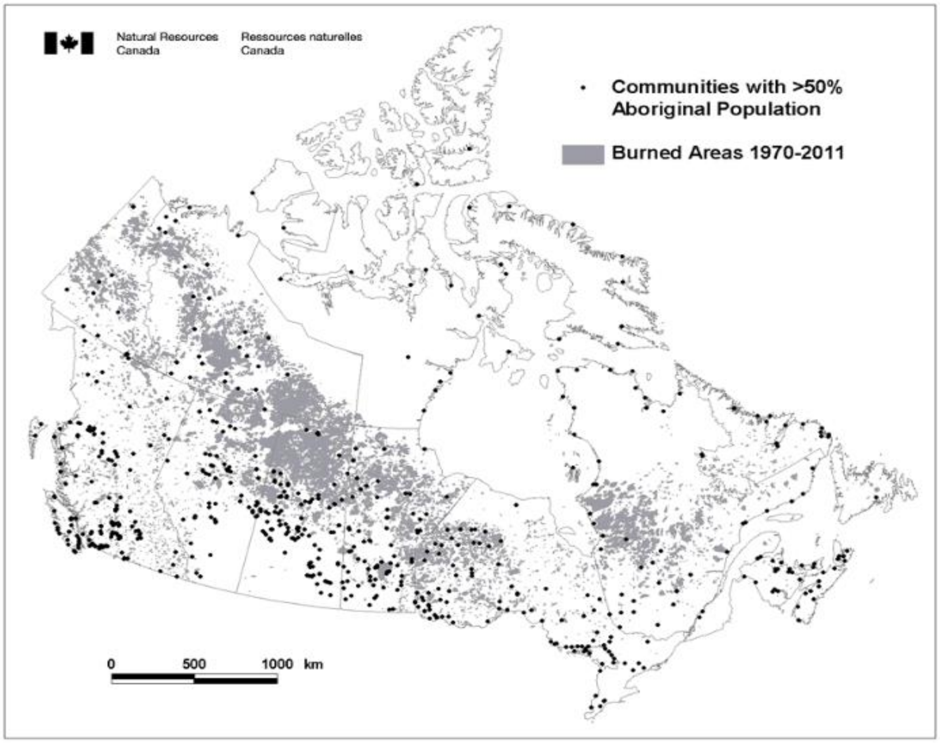


Fig 10. Map of Canada overlaying communities with greater than 50% Aboriginal population and burned areas from 1970 to 2011 (Source: NRCan, 2016*b*)

Forest fire management agencies across Canada use various interpolation techniques or none at all, in estimating fire danger between weather stations. Flannigan and Wotton (1989) investigated numerous interpolation techniques in the North Central Region of Ontario to determine which gave the most accurate description of fire danger between stations. Their results revealed that the use of three methods, the least squares second-order polynomial, smoothed thin-plate cubic spline, and the weighted interpolations, to estimate FWI values between observing stations would more realistically represent fire weather. Although interpolation techniques are now commonly used in fire studies (Wotton et al. 2003; Wotton and Martell, 2005; Flannigan et al. 2005*b*; Podur and Martell, 2007; Podur and Wotton, 2010), our study used a GIS-based approach - Near (Analysis): A Proximity Tool in ArcGIS 10.3.1 – to determine the nearest weather station to the centroid of the selected large fires. We assumed that results would not be adversely affected by the use of the nearest station weather data, as opposed to interpolated weather. This is because the way interpolation works, the nearest weather station would be the most heavily weighed upon anyway.

The *Prometheus* daily weather stream requires maximum and minimum temperatures, minimum RH, maximum and minimum wind speed, wind direction, and precipitation. Our study used daily weather streams consisting of temperature, RH, wind speed, and precipitation collected at 12:00 LST as input into *Prometheus*. These daily weather streams were not adjusted to minimum and maximum temperatures, minimum RH, and minimum and maximum wind speeds. We also used a default wind direction. Our study assumed that results would not be adversely affected by either the lack of min/max temperature and wind speeds, minimum RH, or the default wind direction. Coincidently, Tymstra et al. (2007) used south-west and south-east wind directions as input into *Prometheus*, only to find out that there was no real difference in the final area burned analysis using a south-west *v.* a south-east wind direction.

Our study used a standard 1000-2200 h burning period, which is indicative of the active period of fire spread that typically occurs from 1000 h to sunset. Climate change is likely to have a corresponding impact on the length of the burning period. However, no attempt was made to model and incorporate the impact of climate change on the length of the burning period. Changes in fire season length that are anticipated with climate change are also not included in this present study. In addition, climate change may result in changes to the vegetation types, and hence the fuel types. Despite this, fuel types in this study were assumed to be constant between our climate scenarios. The impact of climate change on the fuel component of fire environments warrants further investigation.

5. Conclusion

This study builds on similar studies conducted in Alberta (Tymstra et al. 2007) and less complex studies done for Ontario (Podur and Wotton, 2010). Our study used a spatially explicit, deterministic fire growth simulation model (*Prometheus*), and projected fire weather, fuel moisture, and fire danger indices under climate change from a general circulation model, to investigate the relationship between climate change and area burned by large, lightning-caused forest fires in northwestern Ontario. *Prometheus* is a wave propagation fire growth model that provided deterministic outputs of area burned by integrating the influences of fuel, weather, and topography. A total of 63 individual simulations were completed (21 fires x 3 climate change scenarios). Fire suppression was not directly used in this study, nor was any fire spread allowed outside the standard burn period of 1000-2200 h. The study estimates also did not explicitly take into account any changes in fuel types, ignitions, and fire season length that may influence area burned. Despite the study assumptions and limitations, we predict a 64.75% average increase in area burned by 2040 (2 x CO_2) and a 174.45% average increase in area burned by 2090 (3 x CO_2), from the reference baseline scenario. This represents almost a tripling of area burned by the end of the 21st century. Our predictions are in broad agreement with studies of boreal forest fire activity under climate change (Flannigan et al. 2005*b*; Tymstra et al. 2007; Podur and Wotton, 2010), that demonstrate a pronounced upward trend in area burned by forest fires in future decades.

Our findings provide some insight into the complex relationships between weather, large forest fires, and area burned. There is a scientific consensus that the global climate is warming due to increases of radiatively active gasses in the atmosphere, as a result of human activities (IPCC, 2014), and evidence of significant increase in area burned in Canada and in Ontario. Because of the relationship between temperature and area burned, and the coincidence of increases in area burned with climate change in recent years, a relationship can be inferred between the two. Such a relationship was reported by Flannigan and Harrington, (1988) and Flannigan et al. (2005*b*), who provide evidence suggesting that temperature is the most important predictor of area burned, with warmer temperatures associated with increased area burned.

Large fires and large area burned years are strongly associated with the development of persistent blocking high pressure systems, conditions that usually consist of long periods of hot, dry weather, leading to severe drying of fuels (Stocks and Street, 1983). When forest fires start in such conditions, they become too intense to control and overwhelm the fire management system. It is these fires that account for almost all of the average annual area burned in Canada (Stocks et al. 2003). Our study placed an emphasis on large fires because we believe that large fires are more complex, and that the relationship between weather and area burned are different for large fires, compared with initial attack fires.

There are numerous avenues for further research. In our study, we assumed that the future vegetation mosaic will have similar fuel characteristics to the present situation. Future studies should include changes to fuel types in a changing climate, with particular emphasis on the feedbacks caused by a changing fire regime. Fire suppression was not directly incorporated into our study. However, there is much more that needs to be learned and researched about how fire suppression takes place on large fires, how large fires actually grow and develop, and how weather and suppression interact during a large fire event. Future field studies of fire suppression on large fires have the potential to yield these kinds of insights. Fire growth simulation is also a relatively immature field of fire research. *Prometheus*, in particular, is a deterministic fire prediction model that incorporates physical mechanisms for fire spread. There are many opportunities for improvement within this model, such as the incorporation of stochasticity. One important such random phenomenon is fire spotting, in which an airborne (i.e. surface wind) burning firebrand falls beyond the main fire perimeter, and results in a fresh fire start. A stochastic model would have the possibility of taking this into account.

Nonetheless, the estimated increases in area burned will have significant ecological, economic, and social impacts for the province of Ontario. Fire management agencies should subsequently consider preparing and implementing effective mitigative and adaptive strategies to better prepare themselves, and their resources to the resulting future scenarios.

Appendix A: Historical Forest Fire Data – Lightning and Human-Caused Fires

Area burned and number of forest fires in Ontario from 1990-2013

Year	Area Burned	Number of Forest Fires
1990	183693	1614
1991	318811	2560
1992	175994	960
1993	104704	743
1994	83472	1053
1995	612436	2122
1996	448812	1245
1997	38524	1636
1998	158275	2278
1999	328261	1016
2000	6737	644
2001	10731	1561
2002	172075	1111
2003	314217	1012
2004	1611	424
2005	42339	1961
2006	149533	2298
2007	40652	1124
2008	1318	341
2009	20658	385
2010	14823	931
2011	635375	1334
2012	151569	1619
2013	51085	580

Appendix B: Historical Forest Fire Data – Large Lightning-Caused Fires

Area burned and number of large lightning-caused forest fires in Ontario from 1990-2013

Year	Area Burned	Number of Large Forest Fires
1990	171188	42
1991	297580	45
1992	169293	22
1993	94757	11
1994	74235	30
1995	558526	101
1996	419959	123
1997	34500	13
1998	124476	61
1999	91528	30
2000	5304	6
2001	10604	14
2002	174243	49
2003	308108	29
2004	0	0
2005	37370	16
2006	135759	60
2007	1400	1
2008	990	3
2009	19445	21
2010	8922	10
2011	628653	69
2012	104285	45
2013	48462	26

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