LIMITED REPORT

Changing Fire Risk in a Changing Climate: A Literature Review and Assessment

by

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Environment Branch

SRC Publication No. 11341-2E01

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TABLE OF CONTENTS

page

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION AND OBJECTIVES

Role and Significance of Fires

Forest fires have a significant and natural role in the world's boreal forest (e.g. Stocks 1991). Disturbances, such as fires, are key to the health and growth of forests. Fire is the disturbance type with the greatest impact on boreal forest dynamics (Engelmark et al. 1993). These statements are especially representative of the study area as it has one of highest fire occurrences in Canada (Harrington 1982) and the ecosystem is adapted to fires. The study area is the boreal forest of the Canadian Prairie Provinces of Alberta, Saskatchewan, and Manitoba, termed "Prairies" here.

Fire is also important to people, including their governments, communities and businesses. It poses severe risk to property (including timber and fibre supplies) and health and lives, air quality factors such as gases, particles and visibility, and is problematic to recreation and tourism. Yet, the fire management business also presents business and job opportunities.

Climate- Fire Links

Characteristics of forest fires are very dependent on weather and climate (e.g. Flannigan and Harrington 1988). Hely et al. (2001) confirm that weather is the most important factor for fire occurrence in Western Canada. The characteristics of fire affected by weather and climate include frequency, size, intensity, seasonality, type and severity. The climate elements that affect fire include temperature, precipitation, humidity, and wind speed and direction (Flannigan et al. 1998). Weather and climate are closely linked in that climate is the prevailing pattern of weather conditions over a long time. Weather is the physical state of the atmosphere at a given place and time.

Climate and forest fires are directly and indirectly linked in several important ways. The main factors affecting area burned are weather, ignition, fuels, and fire control activity (Flannigan and Van Wagner 1991). Weather and climate also affect fire indirectly through their effect on ignition and fuel types. For example, weather conducive to thunderstorms can lead to lightning-caused fires. Climate is also a strong factor determining forest community types which in turn affect flammability.

Fires release considerable amounts of CO_2. CO_2 is one of the main "greenhouse" gases. The greenhouse gases are one of the strongest factors driving the present global warming (Albritton et al. 2001).

Drought conditions are a good example of the climate-fire links. The risk of fire increases with increasing drought duration and intensities. Torn et al. (1998) write that hot and dry spells promote drying of fuels and create the highest fire risks. A changing climate affects the temporal and spatial patterns of weather elements that in turn affect fire risk. Because fire behaviour can respond immediately to fuel moisture, fire activity is very sensitive to climate change. Climate factors involved are affected by precipitation, relative humidity, air temperature, and wind speed. (Weber and Flannigan 1997). Therefore, the effects of current and future climate change on fire are a major concern.

Alternatively, fires can affect climate. Greenhouse gases and aerosols are released into the atmosphere by fires. The greenhouse gases released by fires increase the "greenhouse effect" and add to the climate change. Fires also result in changed land cover that also has effects on climate.

Considerable climate change is occurring now, and the rate of change is expected to increase in the future (Albritton et al. 2001). It is important to increase our knowledge of the linkages of weather and climate with fire in order to be able to project possible changes in fire patterns.

Knowledge of the range of possible future fire conditions provides direction regarding the nature of adaptation to a changing fire regime. We need to develop much additional information regarding fire adaptation science and management, including adaptation measures, how to model them, and their moderating effect on fires. Adaptation characteristics include costs and benefits, their effectiveness, practicality, and side-effects. A knowledge of adaptation options, their characteristics, and modeling capabilities are some factors required for an improved projection of climate impacts on fires.

Fire is a Dominant Climate Impact

Fire is one of the most important current and future climate change impacts on the boreal forest because of its dominant role in interacting with other impacts. For example, drought or insect stressed trees tend to be more susceptible to fire. The role of fire is emphasized here because of the important role of fire in the synergistic interactions among the suite of climate change impacts on the forest ecosystem and dependent socioeconomic systems. Fire is a force of change for several important forest characteristics, including composition, structure, and successional development. Fire and other disturbances are very important in determining the regionally dominant vegetation (Suffling 1995). Fire also has important synergies with other disturbances such as insects, diseases, and wind-throw (i.e. damage to trees by wind).

Fire is also one of the most immediate and rapid of the suite of climate impacts. Fire management will be affected quickly and significantly by continued warming effects on fire behavior, especially in Western Canada (Stocks 1991). Fire has a fast response time to suitable weather events. It follows that fire and it's effects will be among the first climate change impacts to require early and rapid adaptive responses.

Several authors point out that the direct effects of climate change on forest composition could easily be overwhelmed by the more immediate and drastic effect of climate change on fire characteristics (e.g. Flannigan et al. 2000, Price and Rind 1993, Weber and Flannigan 1997).

Objectives

Primary objectives of this paper are to update the literature review done as part of the Canada Country Study [CCS] by Wheaton (1997) and Saporta et al. (1998) and to examine synergistic impacts related to fire. Emphasis is placed on peer-reviewed literature, where possible. Wheaton (1997) wrote the forest chapter for the Prairie and Northern Region of the CCS, and Saporta et al. (1998) wrote the national sectoral chapter. The main findings from the CCS, however, are briefly reviewed to set the context and to demonstrate changes from that assessment. The CCS provided a comprehensive assessment of the state of knowledge of climate change impacts in Canada. Even though disturbances were recognized as a critical climate impacts issue at that time, only a handful of references regarding climate change and disturbances were available for use in that assessment.

Synergies of fire with other subjects of this report are emphasized. These other issues include growth and productivity, zonation, moisture, insects and diseases. As the synergies are numerous and often complex, only selected examples are used within the scope of this report.

Other main objectives include identification and discussion of:

- impact and adaptation models and methodologies. The impact models examined are those that simulate the relationship between climate and fire.
- current and future fire management adaptive measures.
- impacts and adaptations knowledge gaps and research needed.

This framework is designed to help improve the understanding of the current and future fire risk as driven by climate change. The scope of the study permits an overview of each of these objectives only.

RECENT PAST CLIMATE AND FIRE TRENDS

Past climate and fire trends are described for the study area in order to provide the context for future changes in both variables. The recent past is one indicator of near future trends (e.g. five years or so), but the effect of climate change factors such as increasing greenhouse gases must also be considered.

Climate Trends

The study area corresponds fairly well with the climate region designated by Environment Canada (1995) as the Northwestern Forest. This region has already undergone significant regional climate changes including (Environment Canada 1995):

- a statistically significant increase in annual average temperature of 1.4°C over the 1895-1992 period. The only other Canadian climatic region with a greater increase is the Mackenzie District, at 1.7°C.
- statistically significant increases have occurred in spring (March, April, May) at 2.1°C, and summer (June, July, August) at 1.2°C during the 1895-1992 period.
- temperature increases have been predominantly in the daily minimum temperatures which show a statistically significant increase of 2.1°C for 1895-1991.
- precipitation is much more variable than temperature, and no discernible change was found for the 1948-1992 period for annual precipitation. In contrast, national annual precipitation amounts show an overall increase.
- annual average cloudiness appears to have increased slightly (1%) over the 1953-1991 period; however this change is not statistically significant.

More recent work by Zhang et al. (2000) using the best available adjusted data confirms the above findings, and is also consistent with even earlier work by Gullett and Skinner (1992) supporting the reality of these trends. Highlights from Zhang et al. (2000) for the study area for the 1900-1998 period are:

- mean daily maximum temperature exhibits the greatest warming (statistically significant) for Canada in the Prairie Provinces, with the highest warming focused on Saskatchewan at 1.5°C for the annual value. The season of greatest warming is the spring (March, April, May), with winter (December, January, February) a close second, but not significant. The warming in summer (June, July, August) is about 1.0°C and it is statistically significant.
- again, the greatest increase in the mean daily minimum temperature in Canada is in the Prairie Provinces, at 1.5°C for the annual values.
- significant decreases in the daily temperature range have occurred, with statistically significant decreases of around 0.5°C (annual average). This change is a result of the more rapid increases in the daily minimum temperatures.
- annual precipitation totals show a 5-10% increase (statistically significant) over the study area, with generally only the northern parts having statistically significant values. In contrast, national annual precipitation averages have more rapid increases at 5-30%.

Although the causes of these trends are a result of several factors, Zhang et al. (2000) point out the correspondence between observed trends and those projected by the Global Climate Models [GCMs] when forced with historical greenhouse gas increases.

Fire Trends

An important question is how have the changes in climate in the study area affected the number of fires started and the area burned? Firstly, what are the trends in fire number and area burned? The area burned in the boreal forest has increased dramatically in the 1980s, especially in Canada, and likely in the former USSR (Stocks 1991, Price and Rind 1993). The average burned area in Canada has increased more than 50% since 1970 (Van Wagner 1988). Western Canada accounts for a large portion of the nation's burned area (85% for the 1953 to 1980 period (Flannigan and Van Wagner 1991)).

The number of fires in Canada has increased by about 65% during the 1930-1990 period, with most of the increase occurring in the most recent 20 year portion of the record (Stocks 1991). Only a small number of fires, however, produces most of the area burned. Only two to three percent of forest fires in Canada grew larger than 200 ha, but these fires accounted for 87-98% of the total area burned (Curren 1991).

Fire statistics indicate that fire occurrence is increasing in the boreal forest (Weber and Stocks 1998). From 1980 to the mid-1990s, Canada has recorded five of the worst fire-years in history (Phillips 1995). The reasons for the trend of increasing number and area of fires over the recent decades include increased population leading to increased forest use and human-started fires, and expanded capability of detecting fires (Curren 1991). Since weather and climate are driving forces behind fire occurrence, part of this trend in fire statistics would seem to be related to the temperature increase, especially as the increase is largest in spring and summer in this region. However, the portion of the change related to weather and climate has not been determined to the author's knowledge (e.g. by trends in SSR) and no updated work on this trend has been found for the 1990s. It is likely that even greater temperature and related trends would be found because of the increasing temperature trends in the study area. Updated trend analyses of both fire weather and fire characteristics are needed for Canada, as well as for provinces and climatic regions.

More regional fire activity statistics are more relevant here, and annual fire numbers and area burned time series for 1970 to 1999 are depicted in Figures 1 and 2. Time series for each of the Prairie Provinces and for the total area are shown. The overall pattern of fire numbers appears to show a general weak increase over time, with considerable variation. Peaks occurred during 1976, 1980-81, 1984, 1987-90, 1994-95, and 1998-99. Each succeeding peak, except for 1994-95, is higher than or similar to the previous peak. Alberta's fire numbers appear to be higher in general than the numbers for either Saskatchewan or Manitoba. Saskatchewan seems to attain higher values more often than Alberta, after 1985.

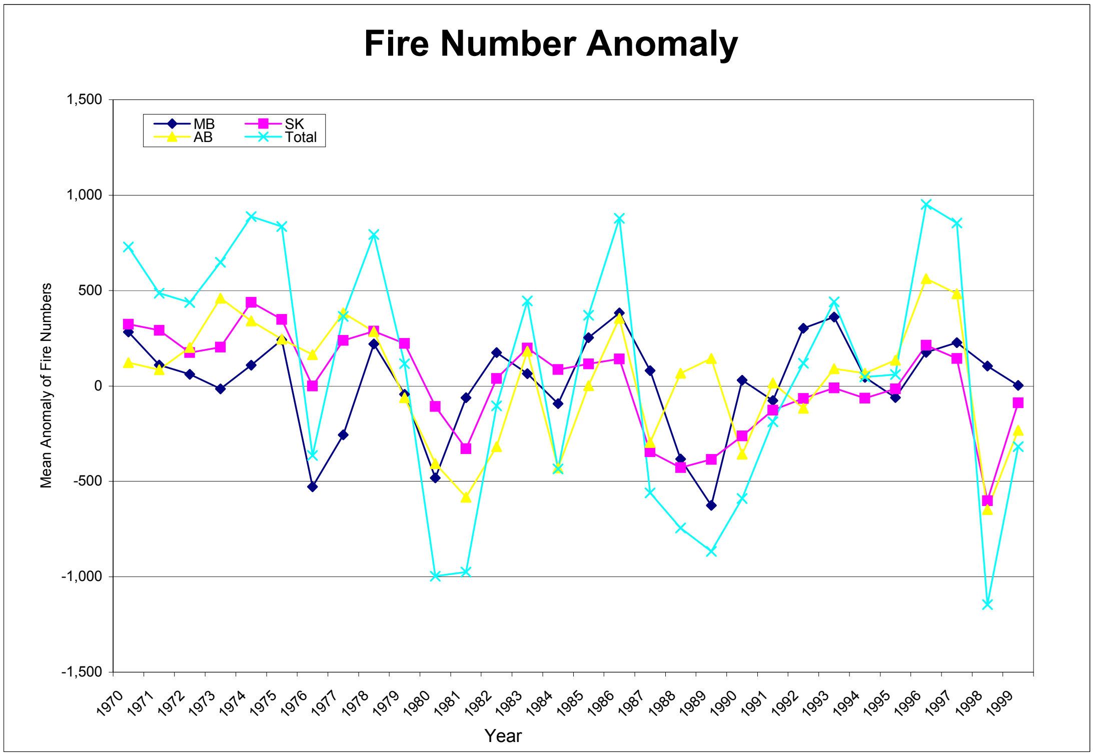


Figure 1: Time series of the numbers of fires in Alberta, Saskatchewan, and Manitoba and the total number (1970-99). (National Forestry Database Program 2001)

The time series of area burned for each province and the total area for the 1970-1999 period is shown in Figure 2. The overall pattern seems to have a base level that is punctuated by four distinct peaks. These maxima are recorded for 1980-82, 1988-89, 1994-5, and 1999. The province's time series pattern are much more similar for area burned than numbers of fires. An overall trend is not discernible, however, the 1970s' numbers were very low and stable compared to those of the 1980s and 1990s.

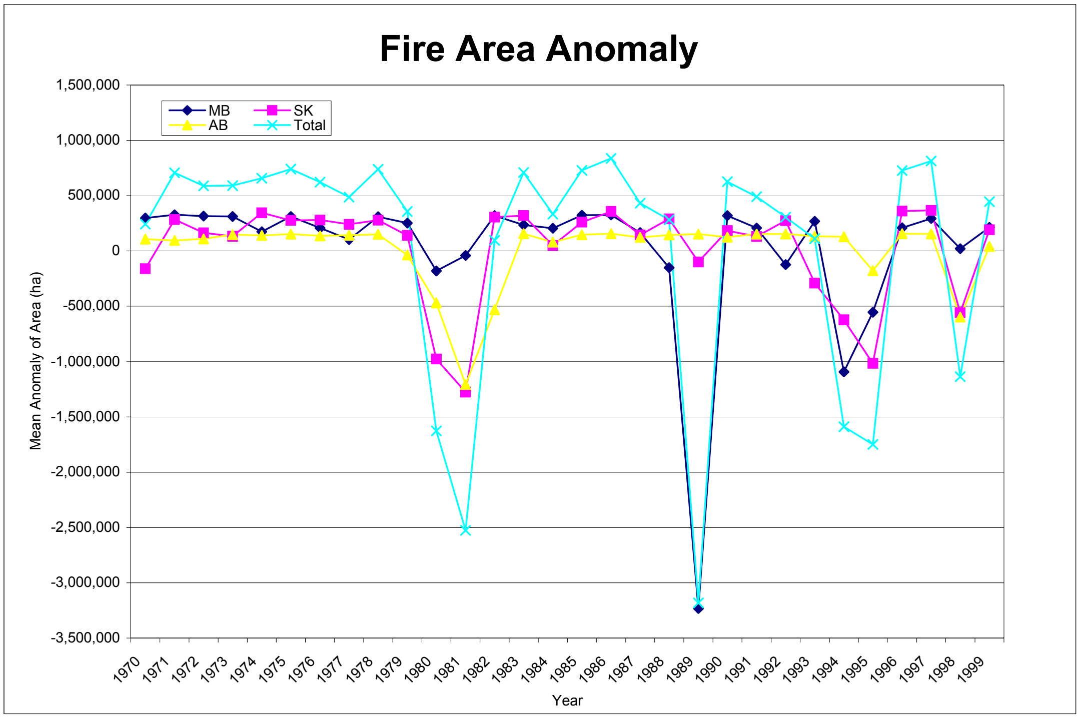


Figure 2: **Time series of the area burned by fire in Alberta, Saskatchewan, and Manitoba and the total number (1970-99)**. (National Forestry Database Program 2001)

The ripple effects of fire behaviour into socio-economics sectors should also be considered. Very few publications have presented such data as fire management costs and benefits. In fact, Dore and Burton (2000) note that although some progress has been made to identify adaptation options in general, very little information exists on the actual costs and benefits of adaptation, or the residual costs that occur, despite adaptation measures. Wittrock and Wheaton (1997) provide one of the few discussions on the time series of fire management budgets and they also link these costs with fire activity. They found a very high correlation (r=0.97) of area burned with annual expenditures. Given these relationships, they also suggest methods of estimating fire managements costs based on climate projections. They demonstrated that, as expected, very high fire activity years translate into years with high fire management costs.

In summary, it appears that the recent trends in forest fire activity are consistent with the warming trends in Western Canada in the past 20 years. Area burned, fire numbers and costs have exceeded expectations since about 1980. The study area is especially vulnerable to changes in the risk of fire.

FIRE IMPACT MODELS

Fire impact models include those methods used to mathematically link weather and climate variables with fire behaviour variables. Most of the studies reviewed use the Canadian Forest Fire Weather Index [FWI] System components of the Canadian Forest Fire Behaviour Prediction System [FBP] (Forestry Canada Fire Danger Group 1992) for their impact model to translate climate scenario results into fire characteristics. The FBP is an empirical model based on wildfire and prescribed burn data (Hely et al. 2001). The FWI system consists of daily cumulative moisture codes and indices which estimate moisture contents of three fuel layers, then integrates them into daily and seasonal estimates of general fire behaviour. The FWI represents the relative intensity of a spreading fire. The FWI is also reported to be a good indicator of fire growth conditions and is used universally across Canada, in parts of the US, and other nations (Wotton et al. 1998). Hely et al. (2001) also report that the FBP systems appears to be an efficient fire behaviour prediction system for the boreal forest.

Another fire behaviour model used in North America, especially the United States, is the BEHAVE system (e.g. Andrews 1986 in Hely et al. 2001). BEHAVE was developed in the United States and is a deterministic model based on the physical properties of fuels. It is used to estimate surface fire behaviour. Hely et al. (2001) have compared the two systems. An important difference is that the FBP model selected the weather factor as being the most important among all fire behaviour variables, while the BEHAVE model selects the vegetation factor. They report that the maximum explained variance is always attributed to the weather, emphasizing the importance of the weather driver, yet again.

The Seasonal Severity Rating [SSR] and the Monthly Severity Rating [MSR] are also used by these researchers. They are averages of the daily severity rating which is computed from the Fire Weather Index [FWI] (Wotton et al. 1998).

MAIN FINDINGS FROM THE CANADA COUNTRY STUDY

The relevant literature available for the Canada Country Study [CCS] assessment was very sparse, especially that with quantitative published information. Quantitative information was selected for the study area from each of the papers.

Climate scenarios used were Global Climate Model (GCM) based type forced by an equilibrium $2xCO_2$ atmosphere. Canadian and American climate models were used. It is very important to note which GCM and which run of the GCM was used for the study as the impact results for each GCM run may, and often are quite different. It is also useful to describe some basic aspects of the future climate scenario used because of this strong effect. A climate scenario is defined as coherent, internally consistent and plausible descriptions of a possible future state of the world (Parry and Carter 1988).

Main findings from the CCS, with specific results for the study area, include:

- a projected doubling of fire risk and area burned in southern parts of the study area, with decreases towards the northeast and north, indicating little change (Bergeron and Flannigan 1995). The FWI was used as the impact model linking weather and fire. The climate scenario used was based on the Canadian Climate Centre's second generation GCM results (CCC GCMII 1990).

- lengthening of the fire season by about 24 days (Wotton and Flannigan 1993). The GCM experiment used was the same as that of the Bergeron and Flannigan (1995) above. A modification of the Canadian Forest Fire Danger Rating System [CFFDRS] definition of season was used to define the start and end points of the fire season. The fire season start was defined as beginning after three days of maximum temperatures greater than 12°C. The season is defined to end after three consecutive days of maximum temperatures below 5°C.

C about 47% increase in the seasonal severity rating [SSR] for the only station available for the study area (Hudson Bay) (Flannigan and Van Wagner 1991). The SSR is an indicator of area burned. Three American GCM-based climate scenarios were used as impact drivers, and the increase in SSR is given as the average for all three climate scenarios.

- greater than 40% increase in lightning frequencies over the study area (Price and Rind 1993). The Goddard Institute for Space Studies GCM-based scenario for a doubled carbon dioxide atmosphere was used. Lightning is an important ignition source for fires. Risk of severe drought conditions was estimate to increase from 1% currently to almost 50% for about 2060. This would exacerbate the fire danger posed by increase lightning. Precipitation increases were projected, but the increased potential evapotranspiration was far greater, resulting in the increased drought.

Lightning can also damage forests even when a fire does not start, which can then lead to increased risk of insect and disease attack. Lightning-caused fires represent about 35% of fires in Canada. Yet lightning is an important ignition factor because lightning-caused fires account for 85% of the total area burned (Stocks 1991). Lightning fires often start in remote areas so they are more difficult to monitor and attack (Flannigan 2000).

These results are summarized in Table 1 in order to enable comparisons with more recent studies discussed in the next section. Table 1 describes the estimated change in various fire characteristics, and includes the climate scenarios and impacts models used as well as the relevant reference. It is very important to pay attention to the climate scenarios and models used, as each combination can result in different estimates of fire activity.

Table 1 Summary of possible climate change impacts on fire characteristics in the study area

Fire Characteristics Simulated	Impacts for the Prairie Provinces Boreal Forest	Global Climate Model Runs used for the Climate Scenarios	Impact Model	Uncertainties (examples)	Comments	Source
Fire risk and area burned	Doubling of risk and area burned in the south. Risk decreases to less than normal values towards the N in Alberta and NE in Sask.	Canadian General Circulation Model II (daily data for 9 years) for double carbon dioxide equivalent	Canadian Forest Fire Weather Index System	Drought, synoptics, species changes, season length	Demonstrates a large spatial variability. Climate change induced vegetation changes may alter the fire regime and vice versa.	Bergeron and Flannigan (1995)

Table 1 continued

Fire Characteristics Simulated	Impacts for the Prairie Provinces Boreal Forest	Global Climate Model Runs used for the Climate Scenarios	Impact Model	Uncertainties (examples)	Comments	Source
Season length	Season length increases by about 24 days	Canadian General Circulation Model II (daily values) for double carbon dioxide equivalent	Can. Forest Fire Danger Rating System (CFFDRS) start and end criteria (modified)	Frequency of rainfall and drought events	Balancing effect of shorter day length in spring and fall should be considered	Wotton and Flannigan (1993)
Area burned (1May to 31 August)	46% increase in annual area burned (as indicated by SSR) (climate scenario average)	GFDL1980 GISS1988 OSU 1989 GCMs for doubled carbon dioxide equivalent (monthly anomalies)	Seasonal Severity Rating of the CFFDRS	Relation between area burned and season severity rating	Likelihood of a longer fire weather season and windspeed changes were not considered. Only one station (Hudson Bay) used from the Prairie Provinces	Flannigan and Van Wagner (1991)
Lightning and drought	>40% increase in lightning frequencies over continental regions; 25% increase generally over the study area. Severe drought (1% occurrence now) increases to nearly 50% by 2060. Fuel buildup increases because of climate zonation migration and the resultant vegetation stress.	GISS GCM for double carbon dioxide	Lightning parameterization in the GCM (Similar results to observed were obtained)	Other factors influencing the fire regime	Possible changes in lightning and fire could act as positive feedbacks to climate change	Price and Rind (1993)
Fire season severity (fire activity indicator)	Mean Seasonal Severity Index increases about 30% for the Canadian GCM and by about 0-20%for the Hadley GCM for 2060. Maximum Seasonal Severity Index increases by about 20-30% for the Canadian GCM and 0-20% for the Hadley GCM for 2060.	Canadian and Hadley Centre transient GCMs	Seasonal and Monthly Severity Ratings of the FWI system	Other factors influencing the fire regime, e.g. ignition, vegetation types.	Improved knowledge of the climate-fire relationships and the interactions of fire with other disturbances is needed. A recent, warm period baseline of 1985-94 was used.	Flannigan et al. (2000)
Fire danger levels	All the GCMs show a significant increase in area under high to extreme fire danger in central Canada. Earlier start and later end to the fire season. Decreases in area of moderate fire danger levels, and increases in area under extreme fire danger. June shows the most significant increase with most of W. Can. under extreme fire danger levels.	Canadian Climate Centre, UK Hadley Centre, Max Planck Inst. and National Centre for Atmospheric Research GCMs used (current versions for doubled carbon dioxide)	FWI converted to Daily Severity Ratings and Seasonal Severity Ratings	Transient analyses to show the effects in a time series fashion Shifts in forest types were not considered	A short and warmer than average baseline period of 1980-89 was used. More severe and frequent fires, shorter fire return periods, younger stands and less carbon storage could result.	Stocks et al. (1998)
Area burned	Approximate doubling of the area in the severe FWI class in Alberta from 2010 to 2020 to almost all of northern Alberta by 2050.	GISS transient (decadal results)	Seasonal components of FWI	FWI approximation to area burned	Synergistic effects on mean age, productivity, species proportions, and volume are also estimated for decadal time slices to 2050	Hartley and Marshall (1997)

LITERATURE REVIEW UPDATE: POST CANADA COUNTRY STUDY

This section is focussed on CCS literature published after the CCS, i.e. about 1997. As in the previous section, this section focuses on quantitative results specific to the study area. Topics emphasized are synergies, impact and adaptation methodologies and models, and adaptive measures. The results from key papers are summarized in Table 1. Careful attention to methods are required, as different GCMs, climate scenarios, and impact models (e.g. for fire danger), and their assumptions can all lead to different results.

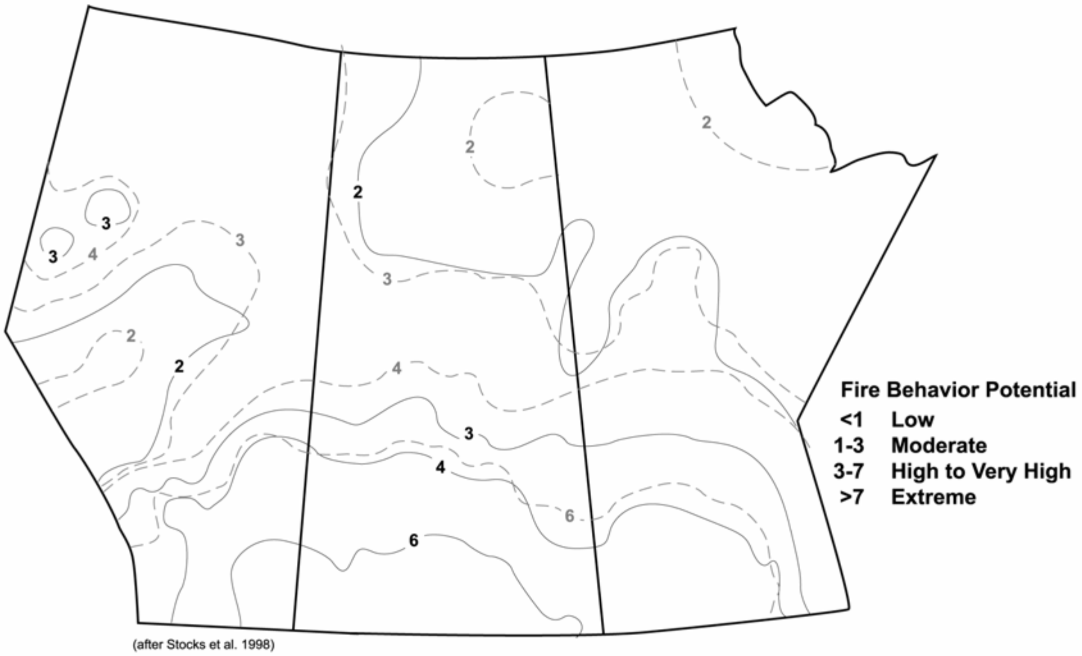
A number of the above-mentioned studies pointed out several synergies, although it appears that few, if any have explored integrated impacts. For instance Flannigan and Van Wagner (1991) mentioned that they did not include the effects of a longer fire season, or increase in lightning amounts in their assessment of the effects of climate change on FWI. In contrast, Wotton and Flannigan (1993) only examined season length (Table 1). Price and Rind (1993) only estimated climate change effects on lightning occurrences and drought, but not the other characteristics. An issue-by-issue approach is suitable at that preliminary stage, but more comprehensive and integrative approaches are required for the next stages of impact assessments.

For example, the lengthening of the fire season into the future has several implications for fire characteristics such as area burned and numbers of fires, as well as for the ecosystem, and fire management and policies. A longer fire prone season means a longer time for fires to start and to burn; a longer time for being prepared to deal with fires, greater costs, longer hiring season for employees, and longer monitoring. The balancing effect of the shorter daylength in the spring and fall is not known (Wotton and Flannigan 1993), and should be determined.

Main advancements in the newer literature represent more integrated and at times, dynamic approaches. Some of the most recent relevant climate change impacts work regarding forest fires has been done by Flannigan et al. (2000), Stocks et al (1998), Kadonaga (1997), and Hartley and Marshall (1997).

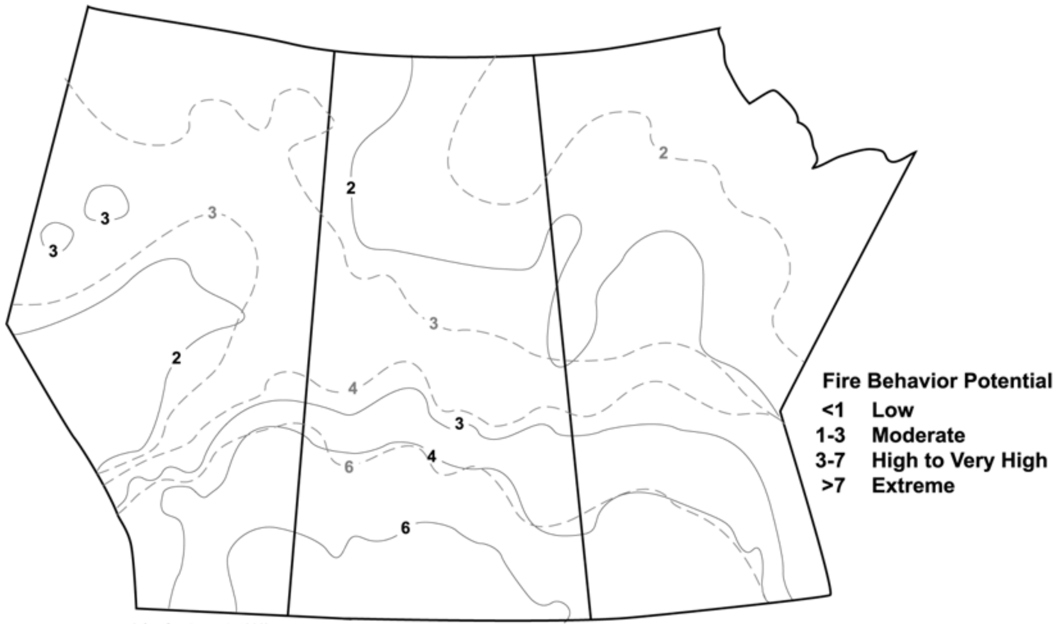
Stocks et al. (1998) examined more than one aspect of the fire season, including season length, fire danger intensities, and area burned. They also used several GCMs to develop their climate scenarios, instead of just one, as was often the case for work before 1997. The use of several scenarios is recommended by the IPCC so that a range of possible futures is examined (Carter et al. 1999). A similar impact model was used, the FWI, but in the forms of the Daily Severity Rating and the Seasonal Severity Rating. Windspeed and humidity anomalies from the GCM runs were also used, rather than assuming no change in these variables.

Results from Stocks et al. (1998) were difficult to regionalize for the study area, since they presented results for all of Canada and Russia at a coarse resolution. Therefore, we redrew their maps to focus on the study area and superimposed the baseline on the climate change impact results (Figures 3 to 6). Stocks et al. (1998) chose a baseline period or reference period to be 1980 to 1989. This mapping method is useful to show the patterns of the northward shift of the potential fire behavior classes. The highest SSR ratings for the baseline period for the study area are in the high fire danger category (Figure 3). The southern edge of the boreal forest has this high SSR rating. Fire danger generally decreases northwest-ward to a moderate rating in northwest Saskatchewan and northern Manitoba for the 1980s.



(after Stocks et al. 1998)

Figure 3: **Average fire seasonal severity ratings (SSR) for the Canadian Prairies showing the 1980-1989 baseline SSR data (____) and projected 2 x CO_2 SSR (----) using the Canadian GCM.** (adapted from Stocks et al. 1998)



(after Stocks et al. 1998)

Figure 4: **Average fire seasonal severity ratings (SSR) for the Canadian Prairies showing the 1980-1989 baseline SSR data (____) and projected 2 x CO_2 SSR (----) using the United Kingdom GCM**. (adapted from Stocks et al. 1998)

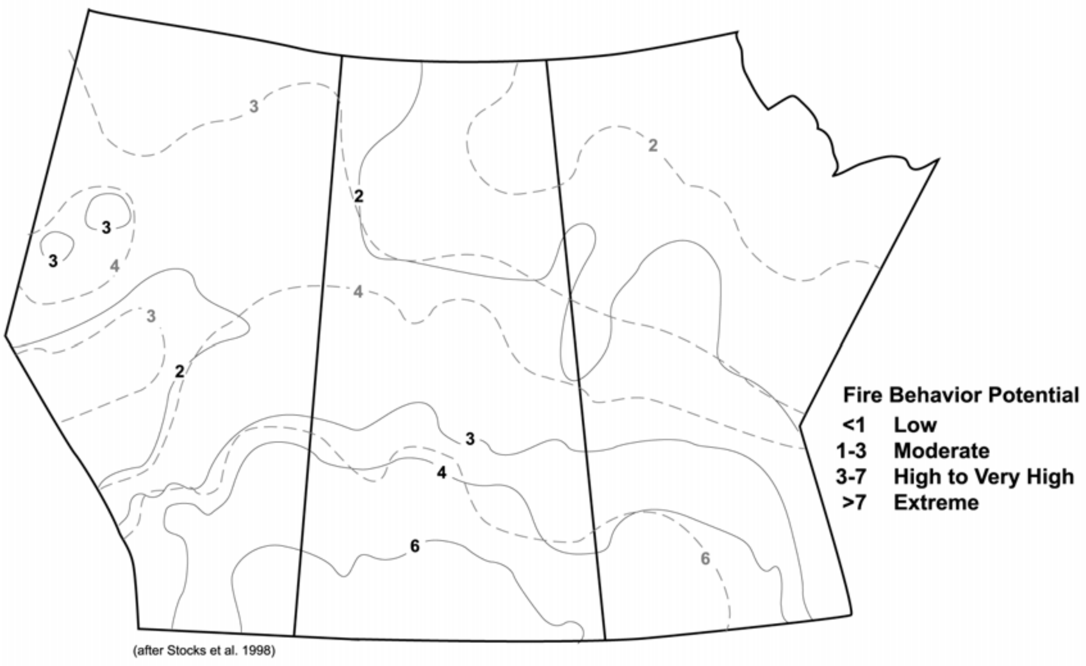


Figure 5: Average fire seasonal severity ratings (SSR) for the Canadian Prairies showing the 1980-1989 baseline SSR data (____) and projected 2 x CO_2 SSR (----) using the German GCM. (adapted from Stocks et al. 1998)

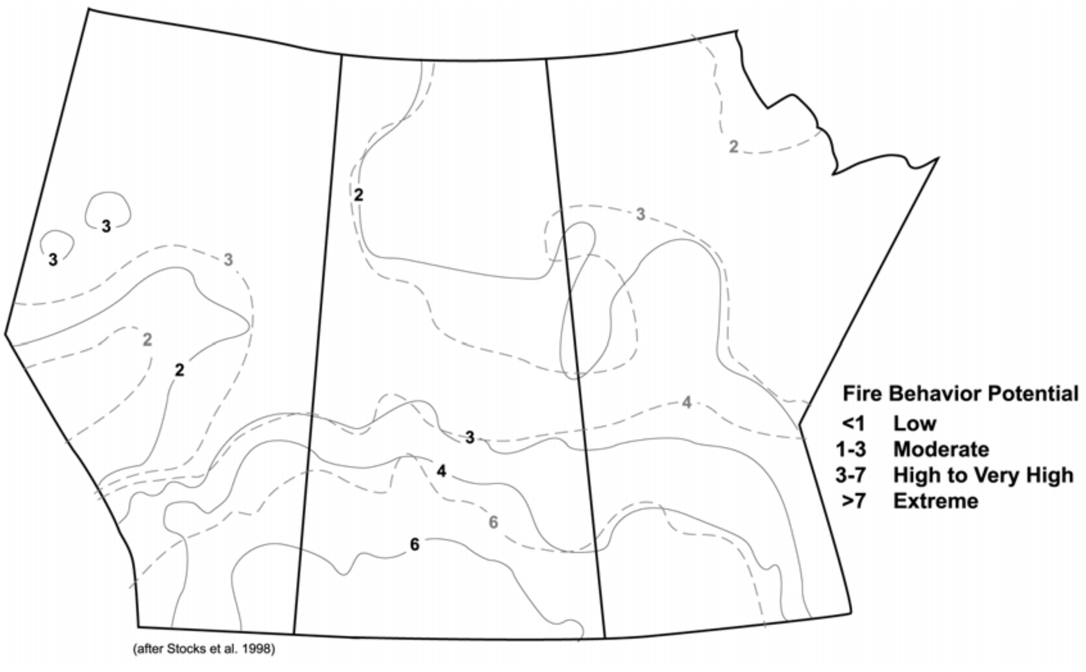


Figure 6: Average fire seasonal severity ratings (SSR) for the Canadian Prairies showing the 1980-1989 baseline SSR data (____) and projected 2 x CO_2 SSR (----) using the United States GCM. (adapted from Stocks et al. 1998)

Choice of baseline for comparison with climate change results has several implications. Stocks et al. (1998) chose the 1980 to 1989 period. First, it is a very short period, and usually longer periods are chosen for more stable statistics. Secondly, the warming trend has accelerated in the later portion of the record. The 1980s were among the warmest years of a long term record. Seven years of that decade were also drier than normal for the northwestern forest region (Environment Canada 1995 23,35). This means that the SSR baselines are likely higher than for earlier decades. Therefore future comparisons are being made with SSR baselines that are already fairly high as compared to the longer record. As a result, these SSR estimates for climate change are likely more conservative than if they would have been compared with longer baselines or baselines earlier in the record. The IPCC guidelines state that the 1961 to 1990 period should be used for a climate baseline (Carter et al. 1999).

Four GCMs were used for climate scenarios for a doubled CO_2 atmosphere by Stocks et al. (1998): from the Canadian Climate Centre, UK Hadley Centre, German Max Planck Institute, and the US National Centre for Atmospheric Research [NCAR]. The Canadian GCM climate scenario shows the southern boreal moving from high potential to very high fire behaviour potential. Northeast Saskatchewan and northern Manitoba increases from a medium-moderate potential class increases to high-moderate fire behaviour potential. This moderate fire behaviour (class 3) isoline displays a considerable northward shift of almost 300 km under this climate change scenario. The area under the class 2 behaviour shrinks northward, and almost disappears from Manitoba. The other climate scenarios produce fire scenarios that are in remarkable agreement with the Canadian GCM results, except that the German GCM shows even farther shifts northward of the greater fire risk zones in the southern and central regions (class 4).

Several advancements that can be made based on such work as by Stocks et al. (1998). For example, results showing the *changes* between the fire danger ratings for the baseline and the warmer climate would have been useful, and perhaps more robust than only the results for a changed climate. Showing baseline values on the same maps as the climate change impact results would also demonstrate the shifts in location of the SSR classes. The choice of baseline as 1980-89 should also include the IPCC recommended 1961-1990 period for stability and comparison with other impact studies.

Other limitations that Stocks et al. (1998) recognized were:

- use of double carbon dioxide equilibrium runs, instead of transient (i.e. time series) runs from the GCMs. This approach would allow exploration of the fire danger dynamics both before and after doubled carbon dioxide equivalent levels in the atmosphere. The newer GCM results have several improvements, including “warm starts” (i.e. using historical greenhouse gas forcing), instead of $1xCO_2$, and improved component models (e.g. ocean, sea-ice, and land-surface) (Hengeveld 2000).
- coarse spatial resolution. For many purposes, including impact assessment and regional management, changes of area in each category by province, or region would be more useful than the national aggregates. For adaptation purposes, for example, landscape level information may even be required.
- effects on fire of climate change-induced shifts in forest types and ages.

Flannigan et al. (2000) were one of the first (for fire impacts) to use transient GCM based scenarios, rather than just results for doubled carbon dioxide equilibrium runs. Unfortunately, the results are not provided as time series, but just shown for 2060. The Canadian and the Hadley GCMs were used to create the climate scenarios. The fire impact models were the commonly used components of the Canadian Forest Fire Weather Index mentioned earlier, the SSR and Monthly Severity Rating [MSR]. The Monthly Seasonal Severity Rating for the study area shows increases of about 30% for the Canadian GCM, and about 0-20%for the Hadley GCM for the 2060 time period (Figures 7 to 8). Maximum Seasonal Severity Rating increases by about 20 to 30% for the Canadian GCM and 0 to 20% for the Hadley GCM for 2060 (Figures 9 to 10). The authors note that these increases in SSR suggest similar increases in fire activity, especially area burned, assuming other factors remained equal.

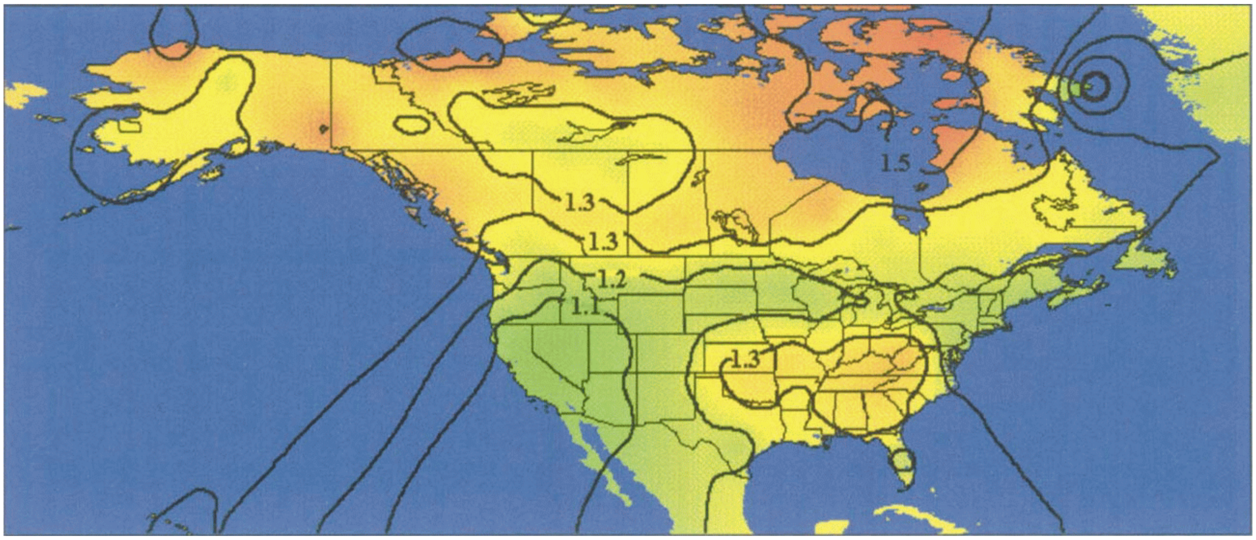


Figure 7: The ratio of the mean Seasonal Severity Rating (SSR) for 2060/present day (1984-94) using the Canadian GCM. (Flannigan et al. 2000)

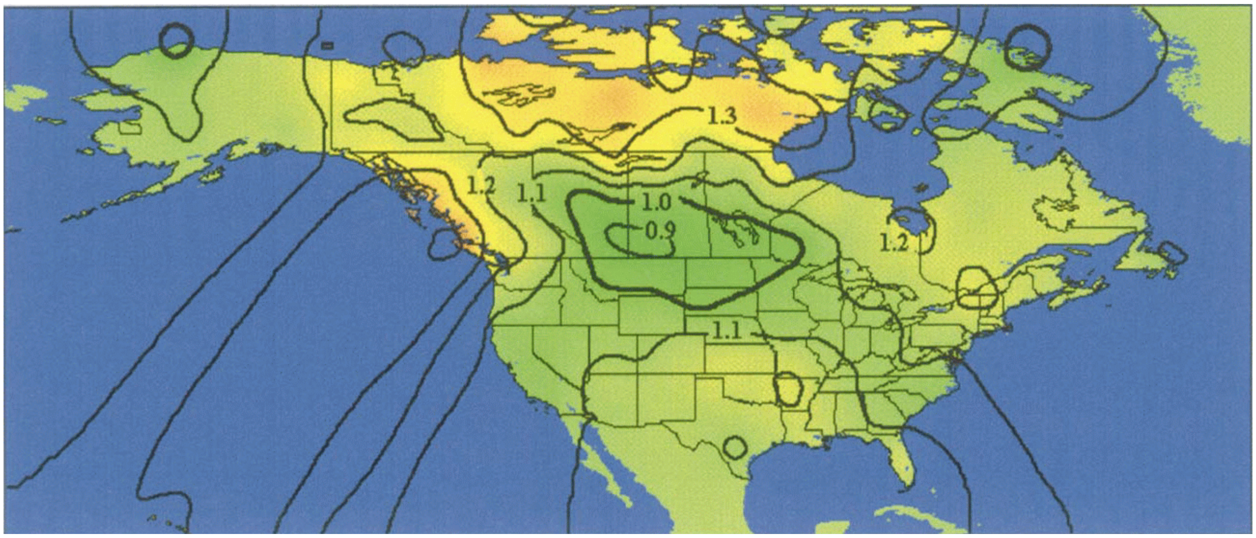


Figure 8: The ratio of the mean Seasonal Severity Rating (SSR) for 2060/present day (1985-94) using the Hadley GCM. (Flannigan et al. 2000)

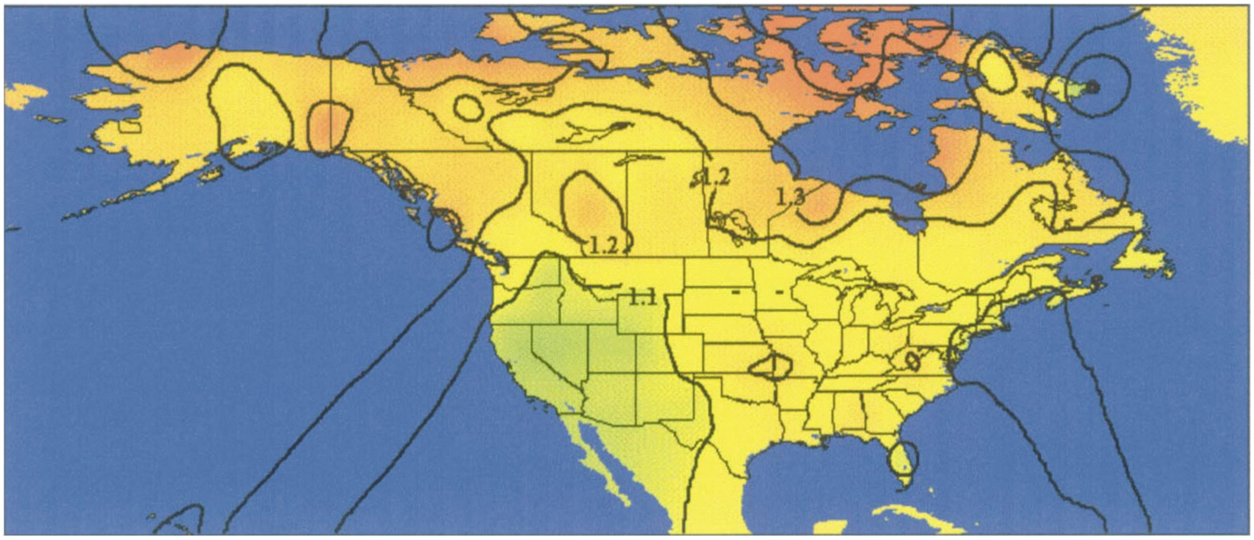


Figure 9: The ratio of the maximum Seasonal Severity Rating (SSR) for 2060/present day (1985-94) using the Canadian GCM. (Flannigan et al. 2000)

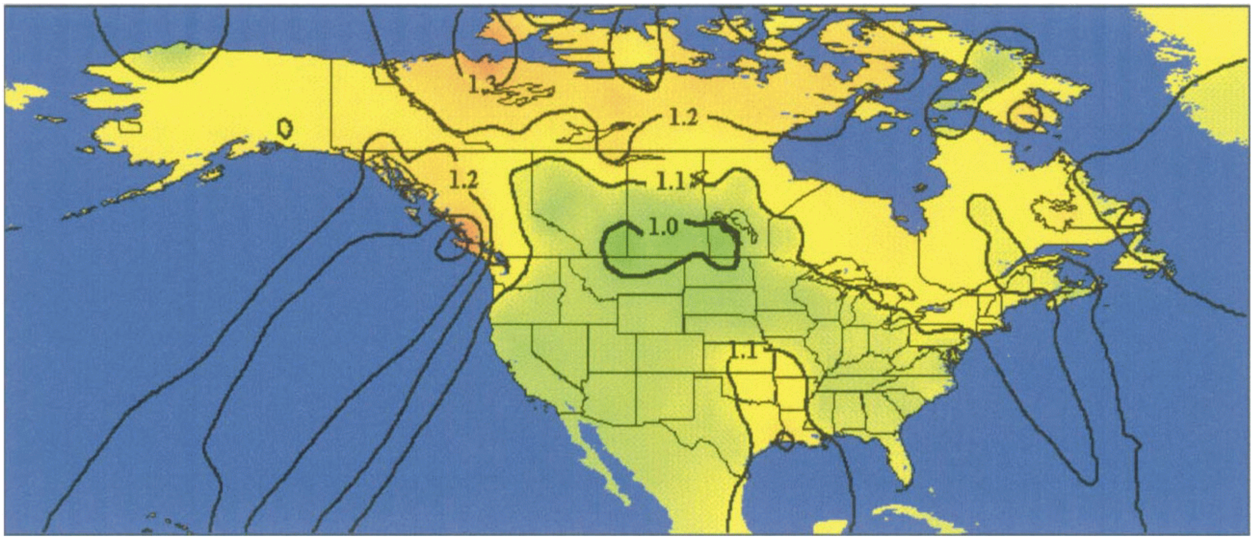


Figure 10: The ratio of the maximum Seasonal Severity Rating (SSR) for 2060/present day 1985-94) using the Hadley GCM. (Flannigan et al. 2000)

Hartley and Marshall (1997) examined fire potential, as indicated by seasonal FWI (June to August) on a decadal basis from 1990 to 2050. Although their study area was the Mackenzie basin, their region three coincides with our project area in Alberta. The GCM used for the climate scenarios was the transient Goddard Institute for Space Studies [GISS] results available at that time. They mapped the FWI seasonal classes for each decade, and provided time series results for mean area burned (in terms of inventory units), tree ages, and unit forest productivity from 1990 to 2050. The relationship between FWI and observed area burned based on work by Kadonaga (1997) was used to project future area burned.

Climate change resulted in a potential increase of area burned in all their regions (Hartley and Marshall 1997). For region three, the change in mean regional burns is relatively rapid, especially for 2020 to 2050 which shows a tripling in area burned (Figure 11). The FWI class maps for that region appear to show a decrease in the severe class to about 2010, then about a doubling from 2010 to 2020, with rapid increases to almost full coverage of northern Alberta by the severe category by 2050 (Figure 12). These results imply a relatively gradual change to some threshold, and rapid changes after that point. This possibility requires further examination, because decision-makers and stake-holders may be lulled into thinking that the response is slow and only moderate adaptation is required if they do not know that fire behaviour may accelerate later.

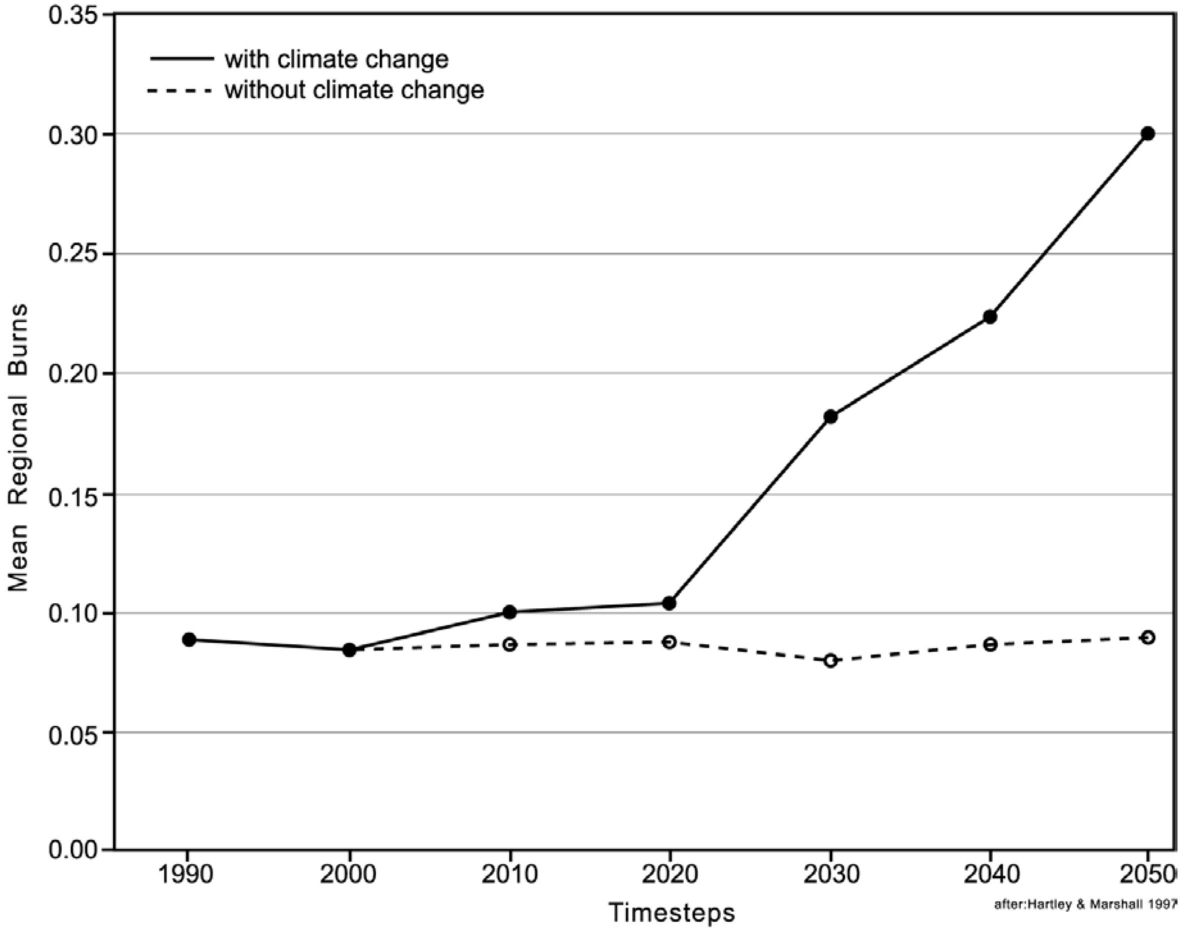


Figure 11: **Fire disturbance of inventory units (1990-2050)** (Hartley and Marshall 1977)

Many important research questions are still to be addressed regarding climate change impacts on fire. Updated emission scenarios and GCMs have recently been developed to produce new climate change scenarios for the Third Assessment Report [TAR] of the IPCC. Projected global temperature increases of the TAR are greater than those of the Second Assessment Report, and are now 1.4 to 5.8°C to 2100 (Albritton et al. 2001). New climate change scenarios are coming available now, and new climate-fire experiments should also be run to determine the effects of this new climate information. This is an ongoing cycle of improvement, especially when improved regional climate information is available.

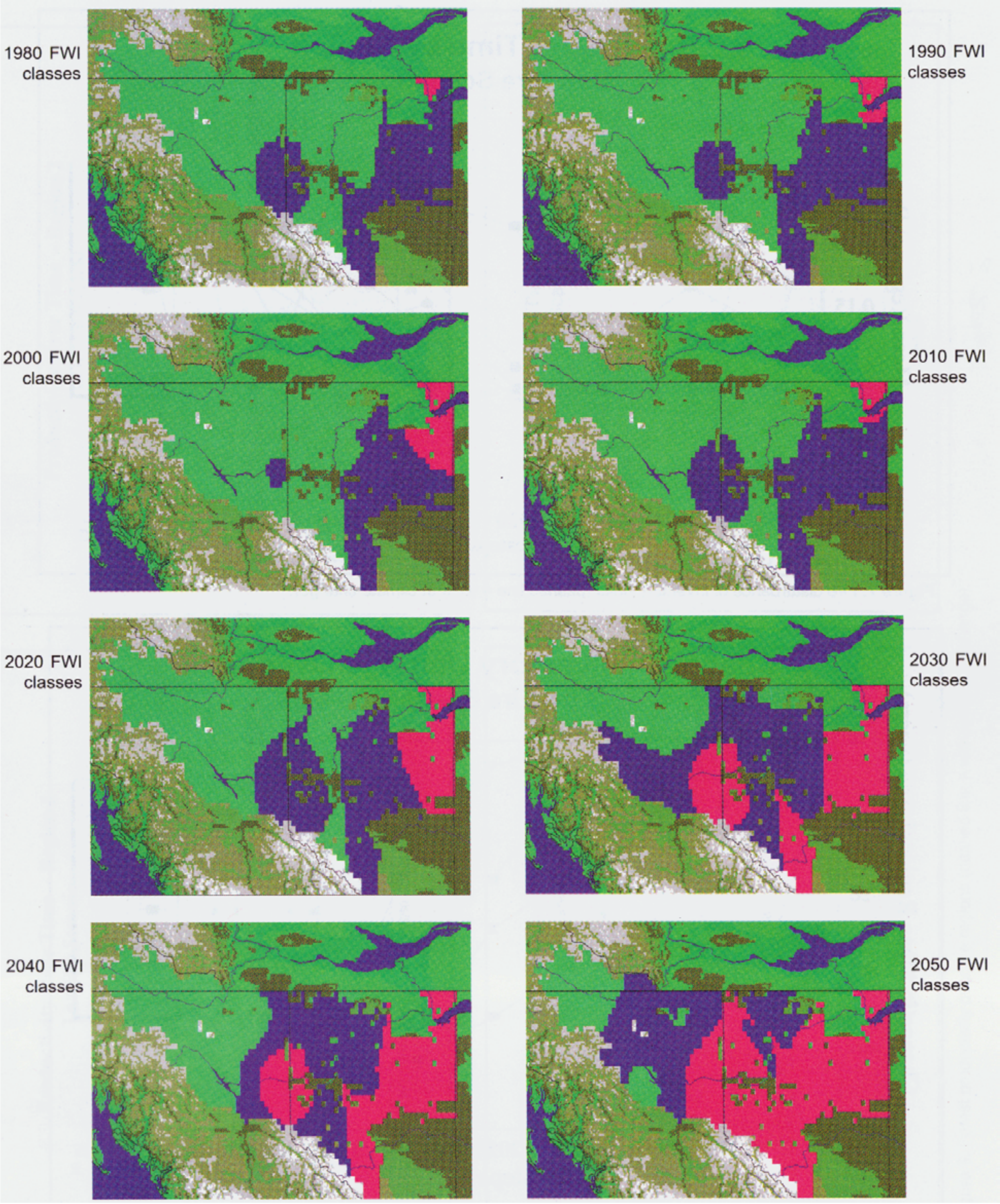


Figure 12: Changes in Inventory Unit age over time (1980-2050) (Hartley and Marshall 1977)

The knowledge of the relationship between weather and fire appears strong, but this does not seem to hold as well for the climate-fire relationship. The climate-fire relationship is most commonly modelled by the FWI System, especially in Canada. The relationship between FWI and its components and fire characteristics have been examined for parts of the study area by authors including Harrington et al. (1983), and Wittrock and Wheaton (1997). Kadonaga (1997) determined the relationship between median summer FWI and burned area in the Northwest Territories.

Harrington et al. (1983) found significant correlation coefficients (r) of 0.25 to 0.29 for mean and extreme monthly FWI and monthly area burned for four stations in Saskatchewan. Kadonaga (1997) found r values of 0.45 and 0.60 for Yellowknife and Fort Smith areas. Wittrock and Wheaton (1997) calculated the correlation coefficient for average monthly SSR (June, July and August) and area burned (northern Saskatchewan) to be 0.45. Surprisingly, they also found the relationship of the average maximum temperature and area burned to be almost as high, at 0.40. So temperature seems to be an important variable in the relationship.

Wittrock and Wheaton (1996) realized the importance of assessing other impact models for possible use and discussed the advantages and disadvantages of other models of possible use. Those models discussed in the findings included the Palmer Drought Severity Index [PDSI], weighted sequence of dry days, atmospheric circulation variables, and several aridity models. Wittrock and Wheaton (1997) calculated the correlation of the PDI and area burned for northern Saskatchewan to be -0.47, or slightly better than the SSR. The U.S. National Interagency Fire Center (NIFC) uses a combination of several indicators to monitor weather and climate conditions and to estimate the fire season outlook (NIFC 2001). These indicators include the PDSI, winter snow-cover, and the El Nino-Southern Oscillation.

Studies done for other regions outside of Canada have applied other impact models. For example, Gardner et al. (1996) discuss several of the models developed to simulate fires at landscape scales. They use EMBYR, an event-driven, grid-based simulation model. They also examine interactive effects by linking the fire simulations to a vegetation recovery model. This allows testing of the sensitivity of landscape pattern to climate change. Unfortunately, their study area was Yellowstone National Park, so the results are not directly applicable to this study area. However, they show that small changes in climate and the subsequent fire regime changes can produce rapid shifts in pattern and process at landscape scales.

In conclusion, the research work since the Canada Country Study [CCS] provides further evidence to support the CCS findings that an escalation in fire risk as driven by climate change is expected in the study area. These changes are likely occurring now, and will become more noticeable in the next few decades. The literature reviewed here, however, is still weak in the areas of synergies and adaptation and the next sections are a small start to remedy this gap.

EXPLORING SYNERGIES AND BUILDING INTEGRATED ASSESSMENTS

This section provides only a glimpse of the synergies that should be part of more complex impact and adaptation assessments. For more realistic assessment, synergies should be included in impact assessments, from the conceptual and mathematical modelling to the strategic planning. Both direct and indirect effects of climate change should be considered when estimating climatic change effects on fires. The direct effects include the fire weather effects on fuels. The indirect effects include categories such as climate change effects on 1) vegetation which then affects fuel types, 2) ignition occurrence through lightning or through human-causes, and 3) effects on other disturbances, such as insects, diseases, and wind-storms, which change fuel levels. Several of these factors interact and can act to increase or decrease overall fire activity, depending on the time and space scales being considered.

The interaction of fire with other disturbances is an important, but neglected research area. Disturbances such as drought is very important as they not only act directly as a stress on trees, but also may result in trees being more susceptible to insect and disease activity because of that stress. Drought not only sets up that chain reaction, but also increases the chance of fire because of the drying of the fuel load. Insect and disease damaged forests appear to be more prone to fires. Forest fire potential increases because crown breakage and wind-throw increase surface fuel loads (e.g. Stocks 1987). Then, after a fire passes, the forest is more susceptible to yet another disturbance, wind-throw (Flannigan et al. 2000), as the structure is weaker and may be more exposed to wind. Disturbances such as drought, insects and diseases are also projected to increase with climate warming, and would likely amplify fire activity. Researchers such as Swetnam and Betancourt (1998) state that the spatial and temporal linkages among these dynamic interactions appear to be a research gap.

Changes in vegetation growth and species as affected by climate may lead to changing fuel amounts and types. For example, if climate conditions favourable for growth occur over several years, then the fuel buildup would increase. Where soil moisture is not limiting, increasing temperatures may cause an increase in growth (e.g. Singh and Wheaton 1991) which would result in increasing fuel amounts. So more variable sequences of favourable growth interspersed with drought may be more important to fire potential than continued drought, for example. Climate changes may also encourage different species and their compositions, which are more or less susceptible to fire. For example, changes from coniferous to deciduous species would tend to decrease flammability. Boreal spruce is classified as being highly flammable, and aspen as very low flammability (Hirsch et al. 2000), especially after aspen has leafed out.

Li et al. (2000) have begun to advance the understanding and modelling of the linkages between fire disturbance patterns and vegetation dynamics. They also used different impact models than used previously namely, the fine fuel moisture code (of the Canadian FWI system) and a model for landscape dynamics [SEM-LAND]. The landscape changes investigated included fragmentation, diversity and wildlife habitat availability. The authors also added that fire management effects need to be considered in future work. This is another interesting level of interaction that would certainly add to the information required to explore climate change adaptation.

Possible effects of increased forest fire on the forest industry include increased loss of wood supply, increased salvage operations, increased fire preparedness and management, and increased risk to property and lives.

Water supply and demand is a critical area that is affected by climate, especially droughts and floods, both of which are expected to increase with climate change. Floods and their rainfall events would act to suppress fires, but droughts would increase fire risk. Droughts increase water demand and decrease supplies. For example, air tankers used in fire suppression require a lake that is a minimum of about 1.2 m deep and 3 km long to access water safely (Renaud p. comm. 2001). Droughts lead to decreasing lake levels and sizes, and could eventually result in fewer lakes for air tanker water supply. Estimations of this effect have yet to be made.

Synergies between changing human uses of the forest and climate change also exist. For example, increased recreation and lengthened summer recreation seasons are anticipated (Wheaton et al. 1992). This could lead to increased ignition risk due to this human activity. As more human activity and infrastructure is encouraged to move northward with warmer temperatures, more infrastructure and values would be at risk to forest fire. This means greater forest fire management challenges, including budget amounts, equipment, and personnel. Adaptation options, in terms of research, policies, and implementation, need to consider these synergies in order to be successful at projecting and coping with increasing fire risk.

ADAPTATION OPTIONS AND VULNERABILITIES

An important goal of improved knowledge about adaptation is to determine how adaptation will affect impacts, that is, will they reduce negative impacts and enhance positive impacts, as they are designed to do. Adaptation is often considered to be actions of humans, but ecosystem responses also need to be included for disturbance impact assessment. Ecosystem responses are briefly discussed in the synergy section, and human adaptation is considered here. Some of the questions to be addressed are: Who is adapting, that is, who has responsibility for fire management? The provincial governments have this role in the Prairie Provinces. Northern communities and industries are affected by fire, however, and are also adapting to changing fire conditions. Industries are affected by fire in their management areas, and also have adaptation roles. People outside of the study area are affected in terms of the changes in recreational potential of the landscape after a fire, in air quality problems, and in all the non-market values of the forest, for example.

Vulnerability to climate change is the degree to which a system is susceptible to damaging or adverse effects from climate change including climatic variability and extremes (McCarthy et al. 2001). Vulnerability is a function of the climate that a system is exposed to, the sensitivity of that system and the system's adaptative capacity. In this case of forest fires in the study area, the climate is very extreme and even at present has a high level of fire danger potential in southern parts. Although the boreal forest of the study area is adapted to fire, there are likely threshold levels that would push or exceed this adaptive capacity. The same is true of the human fire management systems. Therefore a discussion of adaptation options is very important to exploring vulnerability levels.

We found no literature regarding the effects of fire suppression and other fire management activities on the severity of the climate change impact on fire. The effects of suppression, for example, need to be considered to determine accuracy of the fire danger estimates. The costs of fire management are quite high in more severe fire years, and would increasingly become a barrier to adaptation. Some of the suite of climate change impacts can be avoided or lessened by applying adaptation options, but some may not. The more severe fire-weather situations and their fires appear to be in this category, and therefore may be among the most dangerous of the climate change impacts.

Burton et al. (1993) developed the classic framework of adaptation measures discussed earlier. The list, modified to include examples for fire adaptation, is:

- bear the losses (i.e. no adaptive action).
- share the loss (through insurance, disaster relief, for examples).
- modify the threat (e.g. using fire breaks).
- prevent effects (e.g. rapid initial attacks on fires).
- change use (e.g. from coniferous to deciduous trees).
- change location (to places less vulnerable to fire).
- increase research (new fire suppression technologies, improved fire models).
- and educate, inform, and encourage behavioural change.

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Additional adaptation measures more specific to fire management and mostly in the category of modify the threat, or prevent effects, or preparedness, and include:

- landscape management to change the fuel continuity and arrangement (Hirsch et al. 2000). Fuel breaks would consist of less flammable tree species, such as aspen and mixed wood. Traditional fuel breaks, topography, and lake patterns could also be considered. Harvesting in certain patterns, slash disposal, pruning and thinning would also act to mange vegetation patterns to decrease risk of fire spread. Prescribed burning would also decrease fuel loads to help the prevent spread of fire.
- strategic placement and amounts of infrastructure (e.g. roads as breaks, roads and bridges for access, power, water supplies, communication, climate stations, lookout towers).
- priority protection zonation (e.g. for communities, industrial sites, and other high value areas in terms of property and lives).
- rapid initial attack response capabilities.
- technology transfer, technology enhancements and innovations.
- fire-climate modelling research improvements.
- monitoring, and early warning systems using seasonal forecasts coupled with fire-climate-economic models to forecast future disturbance risks and costs/benefits, for example.
- strategic planning for longer term enhancement of adaptation capacity.
- emergency response system.

Other adaptation measures relevant to sustainable forest management would include enhancing forest recovery and regeneration after disturbances. Use of prescribed burning to help cope with insect and disease disturbances as well to fire management. The effect of increased fire and increased use of fire management activities of various types on sustainable forest management should be explored.

An anticipatory adaptation forest fire management system should be used. The objectives would be to reduce negative impacts and enhance positive impacts within a sustainable forest management framework. Such a system would include estimations of the areas of the forest and times that are most susceptible to fire and other disturbances given the expected changes in climate. Interagency cooperation would become even more essential as fire danger increases. There would be an increasing value for flexible use of human resources, equipment, technology and knowledge transfer.

Strategic planning for fire management, as well as the many market and non-market uses and values of the boreal forest in Western Canada, especially, need to take the possibility of increasing fire danger patterns into account. Fire management planning considerations include budget, staffing, technologies, equipment, and warning and monitoring systems. Policy implications of climate change must be seriously considered. More property, communities and many other values are at risk as climate changes. More resources of many kinds are required to even maintain current fire management levels. Resources may soon exceed the demands for dealing with fire, and adaptation for this contingency should be explored.

Research Needs

Specific knowledge gaps are presented in previous sections with the related findings. More general gaps and research needs are discussed here.

Climate-fire linkages:

The understanding of the relationship between day to day weather and fire danger is fairly well understood. However, the relationship between the temporal and spatial patterns of weather, i.e. climate, and fire risk requires much more understanding. Examples of research questions include:

- What changes in climate produce what changes in fire impact model results? This would be a sensitivity analyses. For example, what is the sensitivity of SSR to temperature and precipitation changes of certain amounts?
- What do changes in the variance of climate elements mean for fire levels?
- How well do fire impact models estimate past fire activity? Improved testing is required. More than one impact model should be used. Each has their advantages and disadvantages, and suitable, or inappropriate assumptions, depending on the objectives.
- What are the past trends in fire-climate indicators (e.g. SSR) over time?
- How can fire numbers and area burned and other indicators of fire activity be modelled using fire impact models?
- What are the effects of a changing climate on the forest's carbon cycle?

Estimation of climate change impacts:

- Use or develop climate change scenarios with improved time (e.g. daily and monthly for years to decades) and spatial scales (e.g. landscape).
- Use several climate change scenarios for an improved range of possible future climates.
- Improved understanding of changes in lightning activity and relations with fire activity.
- Determination of the costs and benefits of impacts, including nonmarket values. Increased use of economic modelling is required.
- What early effects of climate change are expected and can they be observed yet? Fire effects could be a suitable early indicator for climate change.

The modelling and prediction of future fire activity are very complex. Several characteristics of the fire regime are important, including season length, intensity, frequency, and severity. The three main fire drivers are ignitions, fuel and weather each have several components and are dynamic. Then other influences such as fire management and land use change should be considered (Flannigan, p. comm. 2001). Therefore long term research programs are required and several research groups must be involved in a comprehensive network to tackle such an important, but complex issue.

Estimation of fire management options, i.e. adaptation to climate impacts:

< Modelling of the effect of current adaptation or fire management effects on fire activity.
< Estimation of the costs and benefits of adaptation.
< Determination of future adaptation options required (adaptation scenarios) and how costly and beneficial they might be.
< What is the current adaptation capacity of people and institutions responsible for or affected by fire?
< Assessment of the implications for insurance of changing fire levels?

Interactions with other impacts:

< What are the joint effects of fire and other disturbances, such as insect and diseases, wind-throw, and harvesting?
< What are the interactions of fire and changes in weather suitable for different species, and for regeneration?
< How can these interactions be jointly explored and modelled?
< What changes in air pollution impacts would occur with changes in fire activities?
< What are the impacts of climate-driven fire changes on communities, including safety, jobs, ecological resources, and industry?

Policy relevance:

< What is the implication for policy of increasing risk of fire?

Climate-fire relations is an important and complex research area for many reasons. This is only a sample list of the many requirements to address these uncertainties.

CONCLUSIONS

Considerable evidence continues to confirm that forest fire activity will increase in the boreal forest of the Canadian Prairie Provinces with continuing climate change. The avenues of increasing risk are through increasing fire season length, increasing fire danger levels, and increasing ignition factors. Early evidence points to both times and regions of the study area that are sensitive to damage, that is, vulnerable to escalating fire danger. The most vulnerable portions of the Western Canadian Boreal Forest appear to be south and central Alberta and Saskatchewan. The season of increasing vulnerability to fire appears to be spring. Springs in the western boreal forest have already become warmer and are arriving earlier. The evidence continues to indicate that Western Canada would bear, and is bearing the brunt of the greatest risk of fire danger. Considerably more research and communication are required.

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ACRONYMS

CCC is the Canada Country Study: Climate Impacts and Adaptation available from Environment Canada, Toronto
GCM is Global Climate Model
GFDL is the Geophysical Fluid Dynamics Laboratory
FWI is the Fire Weather Index of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987). FWI represents the relative intensity of a spreading fire.
GISS is the Goddard Institute for Space Studies
IPCC is the Intergovernmental Panel on Climate Change
MSR is the Monthly Severity Rating Component of the FWI
OSU is the Oregon State University
SSR is seasonal severity rating of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987). The SSR is the average of the daily severity rating . It is computed from the Fire Weather Index (FWI). FWI represents the relative intensity of a spreading fire.
TAR is the IPCC Third Assessment Report (2001)