FIRE BEHAVIOR POTENTIAL IN CENTRAL SASKATCHEWAN UNDER PREDICTED CLIMATE CHANGE

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SUMMARY DOCUMENT

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SYNOPSIS

The effect of climate change on fire behavior may become a critical issue for resource management in the Canadian boreal forest. This study applies a procedure to assess the effects of climate change on fire behavior potential in central Saskatchewan (135,000 km^2), an area that characterizes the transition from mixedwoods to pure coniferous forest types. Head fire intensity (HFI), a measure of the fire's energy output, was used to quantify fire behavior potential because it can be related to fire behavior characteristics, suppression effectiveness, and fire effects. Percentile HFI maps were created with fuels data and fire weather from three simulated climate scenarios produced by the Canadian Regional Climate Model (CRCM). These scenarios represent base (1×CO_2), double (2×CO_2), and triple (3×CO_2) levels of carbon dioxide in the atmosphere. Our results show a marked increase in fire behavior potential in a 2×CO_2 environment, whereas little change was observed from 2×CO_2 to 3×CO_2. According to our results, the number of days that could support extreme fire behavior potential may quadruple in a 2×CO_2 climate. Furthermore, fires are also expected to be more intense, on average. An increase in fire intensity would likely be translated into greater fire spread and more erratic fire behavior, leading to increased area burned. However, a changing climate does not necessarily entail a ubiquitous or uniform increase in fire potential throughout an area. Indeed, we found that there was significant spatial variation in the effects of climate change on HFI values, due to the interaction and spatial variation between fuel types and weather patterns.

Role of fire in the western boreal forest

The boreal forest covers 35% of Canada's landmass and stretches from coast to coast. Historically, fire has been a dominant disturbance in the boreal forest; and as such, several species have co-evolved with it. Fire is needed for maintenance of boreal forest ecosystems, but it also has negative socioeconomic consequences and safety implications. Sound fire management aims to minimize these negative impacts. To this end, a thorough understanding of the factors driving fire behavior – topography, forest fuels (i.e., vegetation), and weather – is crucial. Changing weather patterns can dramatically alter wildfire activity. In fact, climate models used to predict fire danger have shown that for future climate conditions Saskatchewan might exhibit one of the largest increases in fire danger in North America (Flannigan et al. 1998), as well as a potential lengthening of the fire season (Wotton and Flannigan 1993).

A changing climate could therefore have far-reaching implications on sustainable forest management policies and practices in regions that are already experiencing high recurrence of fire. In Saskatchewan, for example, fires consumed almost 800,000 ha of forest in the 2000 fire season alone – an area larger that Prince Edward Island – in spite of high fire suppression expenditures and some of the most advanced technology available. In fact, analysis has shown that regardless of the level of protection, a small percentage (i.e., 2-3%) of ignitions are likely to continue to escape initial attack (McAlpine and Hirsch 1999), due to multiple fire situations, remote ignitions, and weather conditions under which fires become uncontrollable. In Canada, such escaped fires generally account for over 95% of the total area burned by all wildfires (Weber and Stocks 1998). Given current and possible future increases in weather conditions conducive to fire, resource and fire managers need tools to assess fire potential on the landscape and to assist them in strategic planning and risk mitigation.

Linking climate models with fire behavior prediction

Recently, models predicting future climatic conditions have been combined to fire danger rating systems in order to understand how a changing climate may affect fire regimes. Tools such as the Canadian Global Climate Model (CGCM) are coarse-scale climate models that simulate the effects of changes in atmospheric CO_2 concentrations on future weather patterns at the continental scale. However, finer spatial resolution models are necessary in order to link weather patterns to fire danger, because features that influence fire behaviour, such as topography and vegetation, can vary substantially over short distances. The CRCM is such a model specific to Canadian landscapes. Wotton et al. (1998) used weather data generated from this model to calculate a weather-based fire danger index, the Canadian Forest Fire Weather Index (FWI) System, which provides relative measures of fire danger. This modeling exercise showed that the boreal forest of Alberta, Saskatchewan, and Manitoba could be subject to a 50% increase in seasonal fire severity under a doubling of the current CO_2 levels.

This study builds on the work of Wotton et al. (1998), as we also assessed fire danger in central Saskatchewan with CRCM, but we used more recent simulations, included the 3×CO_2 scenario in the analysis, and incorporated available forest fuels to derive an absolute measure of fire behaviour For each of these climate scenarios (described below), the CRCM-generated weather was used as input variables into the Canadian Forest Fire Behavior Prediction (FBP) System. Head Fire Intensity (HFI), a variable predicted by the FBP System, is a quantitative measurement of fire potential that has direct fire management relevance. The objectives of this report, which presents the key findings of Kafka et al. (2001), were to 1) analyze fire behavior potential changes in central Saskatchewan with changes in atmospheric CO_2 and 2) discuss their implications for fire and forest management.

The boreal mixedwood of central Saskatchewan

The study area (Fig. 1) covers 13,450,150 ha of central Saskatchewan and is predominantly situated in the boreal forest Mixedwood region, whereas the northern part lies in the Northern Coniferous and Upper Churchill regions (Rowe 1972). The climate is one of long cold winters and short cool summers. The mean summer temperature is 16.9°C for the month of July and annual average precipitation is 400 to 500 mm, peaking during the summer months. The study area receives approximately 2500 hours of sunshine per year, the highest in Canada.

Figure 1. *Study area (shaded area) in Saskatchewan, Canada.*

The study area is flat to gently rolling or undulating terrain, with an average elevation of 400 m, increasing from northeast to southwest. The topography within the Mixedwood region consists mainly of rolling morainic deposits on uplands and smoother glaciolacustrine deposits on lowlands. In contrast, the Northern Coniferous and Upper Churchill regions are within the Precambrian Shield and are an assemblage of rocky ridges, sandy plains, poorly drained depressions, and numerous lakes.

In the Mixedwood region, white spruce (*Picea glauca* (Moench) Voss) and balsam fir (*Abies balsamea* (L.) Mill.) are the most common upland coniferous species with black spruce (*Picea mariana* (Mill.) BSP) in the lowlands. Trembling aspen (*Populus tremuloides* Michx.) and balsam poplar (*Populus balsamifera* L.) are the dominant deciduous species. In the Northern Coniferous and Upper Churchill regions, black spruce is the dominant species with jack pine (*Pinus banksiana* Lamb.) on uplands and sandy plains, and tamarack (*Larix laricina* (Du Roi) K. Koch) on lowlands.

Saskatchewan has a very active fire environment. Between 1945 and 2000, the average area burned was 270,000 ha/yr. Large fires have occurred throughout the study area, but some areas have historically experienced more area burned than others, generally because of the distribution of more flammable fuels (Parisien et al. 2004). The study area is located in the full response zone, which means that most fires undergo aggressive initial attack, and there is maximum fire suppression effort. Towns and infrastructure are largely concentrated in the southern part of the study area, and this is therefore where most human-caused ignitions occur. Forestry is practiced throughout the sector, whereas agriculture is generally confined to the southern portion (aspen parkland) and in the more suitable sites to the north. Mining and tourism are also common in some areas.

The Canadian Forest Fire Danger Rating System

The Canadian Forest Fire Danger Rating System (CFFDRS) consists of two main subsystems: the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) and the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). The FWI System and the FBP System have been used extensively by operational fire management agencies since the 1970s and 1990s, respectively, to improve prediction of fire danger in Canada. The FWI System assigns a relative rating of fire danger using simple weather observations to produce three fuel moisture codes: Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC) and three fire behavior indices: Initial Spread Index (ISI), Buildup Index (BUI), Fire Weather Index (FWI). The Fire Weather Index is the index of the FWI System that encompasses the most information because it is derived from all the other FWI System components. The FBP System uses the three fuel moisture codes of the FWI System in addition to information on forest fuels, topography, wind speed, and wind direction to provide a quantitative measure of fire behavior. The FBP System uses 16 fuel types based on fire behavior characteristics under specific weather and fuel conditions (Table 1). The FBP System fuels of our study were mapped at a resolution of 100 m (Fig. 2 on page 7).

Table 1. *The Canadian FBP System fuel types found in the study area and their main characteristics.*

Fuel type name	Designation	Key characteristics
Boreal Spruce	C-2	• Moderately well stocked • Black spruce tree crowns extending to or near the ground • Labrador tea is a dominant ground cover • Deep organic layer
Mature Jack or Lodgepole Pine	C-3	• Fully stocked (1000 - 2000 stems/ha) mature trees • Live crown is well above the surface fuels • Herbs and shrubs are sparse
Immature Jack or Lodgepole Pine	C-4	• Pure, dense stands (10000 - 30000 stems/ha) of immature trees • Continuous vertical and horizontal fuel continuity • Large quantity of standing dead understorey • Heavy dead and down fuel loading
Leafless Aspen	D-1	• Pure, semi-mature moderately well stocked stands • Ladder fuels absent • Well developed shrub layer • Continuous leaf litter
Jack or Lodgepole Pine Slash	S-1	• Continuous slash from mature jack or lodgepole pine stands • Slash is usually 1 - 2 years old retaining up to 50% of its foliage
Boreal Mixedwood	M-1/2	• Moderately well stocked stands of boreal coniferous and deciduous species, leafless (M-1) or green (M-2) • Conifer crowns may extend to or near the ground • Moderate shrub and herb layer • Coniferous/deciduous composition influences fire behavior
Grass	O-1a/b	• Continuous grass: matted (O-1a) or standing (O-1b) • Fuel loading and percent cured influences fire behavior

Source: Forestry Canada Fire Danger Group (1992).

Although the FBP System requires more data than the FWI System for the user, it has the advantage of providing a direct, quantitative measure of fire behavior potential such as head fire intensity (HFI) (used in this study), rate of spread, and crown fraction burned. The HFI is defined as the rate of energy release per unit time per unit length of fire front (measured in kilowatts per meter) and is a good measure of fire behavior potential, as it is related to fire behavior characteristics, fire effects, and fire suppression effectiveness. In terms of fire suppression success, HFI values can be grouped into three general categories: at HFI values below 2000 kW/m (Photo 1), initial attack crews can generally contain fires, as they are slow-spreading surface fires, with only intermittent crowning of individual trees; at HFI values between 2000 and 10,000 kW/m (Photo 2) fires exhibit more crowning, making them difficult to control with machinery and aircrafts; and

Photo 1*: Fire with head fire intensity estimated at 1,500 kW/m.*

Photo 2*: Fire with head fire intensity estimated at 6,500 kW/m.*

***Photo 3**: Fire with head fire intensity estimated at greater than 10,000 kW/m.*

at HFI values greater than 10,000 kW/m (Photo 3), fire behavior becomes extreme with full-blown crown fires, and direct attack of the fire front is generally impossible (Hirsch et al. 1998).

In Canada, HFI varies substantially by fuel type under similar fire weather conditions. For example, the Leafless Aspen (D-1) fuel type (Photo 4) does not burn as readily as the coniferous fuel types and often act as effective fuel breaks. The Boreal Spruce (C-2) fuel type (Photo 5), which covers 37.7% of the study area (Fig. 2), is the most flammable fuel type because it represents well-stocked stands of conifers that have an abundance of ladder fuels, which increases the likelihood of a fire crowning. Another coniferous fuel type, Mature Jack or Lodgepole Pine (C-3) (Photo 6) is also highly flammable, but only burns into the tree crowns under extreme conditions, due to the absence of ladder fuels. In the study area, four regions with distinct fuel type compositions were arbitrarily delineated and were used to interpret the spatial variation in fire behavior potential (Fig. 2). The ***Northern Region***, an 80 to 100-km wide zone that follows the northern limit of the study area, is characterized mostly by the Boreal Spruce, Mature Jack Pine, and Mixedwood fuel types; the ***Central Region*** is mainly composed of large tracts of the Boreal Spruce fuel type; the ***Southwest Region*** has a significant Aspen fuel type component; and the ***Southeast Region***, which combines several fuel types, including a large area (the Cumberland Delta) covered by the Grass (O-1) fuel type.

***Photo 4**: Leafless Aspen (D-1) fuel type in the FBP System.*

***Photo 5**: Boreal Spruce (C-2) fuel type in the FBP System*

Climate Scenarios

The simulated fire weather used in this analysis consisted of second-run CRCM outputs generated by Laprise et al. (2003) for three climate scenarios representing base ($1{\times}CO_2$), double ($2{\times}CO_2$) and triple ($3{\times}CO_2$) atmospheric CO_2 concentrations. These scenarios represent past and future atmospheric conditions for the 1975 - 1985 ($1{\times}CO_2$), 2040 - 2049 ($2{\times}CO_2$), and 2080 - 2089 ($3{\times}CO_2$) decades. Weather for each climate scenario was simulated

***Photo 6**: Mature Jack or Lodgepole Pine (C-3) fuel type in the FBP System.*

daily over a period of 10 years; however, we only used the data from May 1st to August 31st, because this period is representative of a typical fire season in Saskatchewan. Spatially, the CRCM produced weather outputs for 169 points separated by a distance of 45 km arranged in a grid. The noon-hour local standard time weather variables (temperature, relative humidity, wind speed, and 24-hour precipitation) generated by the CRCM were used as inputs for the FWI System and FBP System. These were combined with fuel information to generate HFI percentile maps for all three climate scenarios.

Predicting Head Fire Intensity for Climatic Scenarios

Percentile HFI values were calculated using a raster grid representing FBP System fuel types, as well as the required fire weather outputs. A percentile is a measure of relative standing in which a certain proportion (i.e., percentage) of the data lies below the percentile value. Topography was not considered because it did not vary much throughout the study area. Because intense fire behavior does not occur under average conditions we built percentile HFI maps for the 80th and 95th percentiles. This corresponds to the minimum HFI value that can be expected on the landscape, throughout the fire season, 20% (80th percentile) and 5% (95th percentile) of the time.

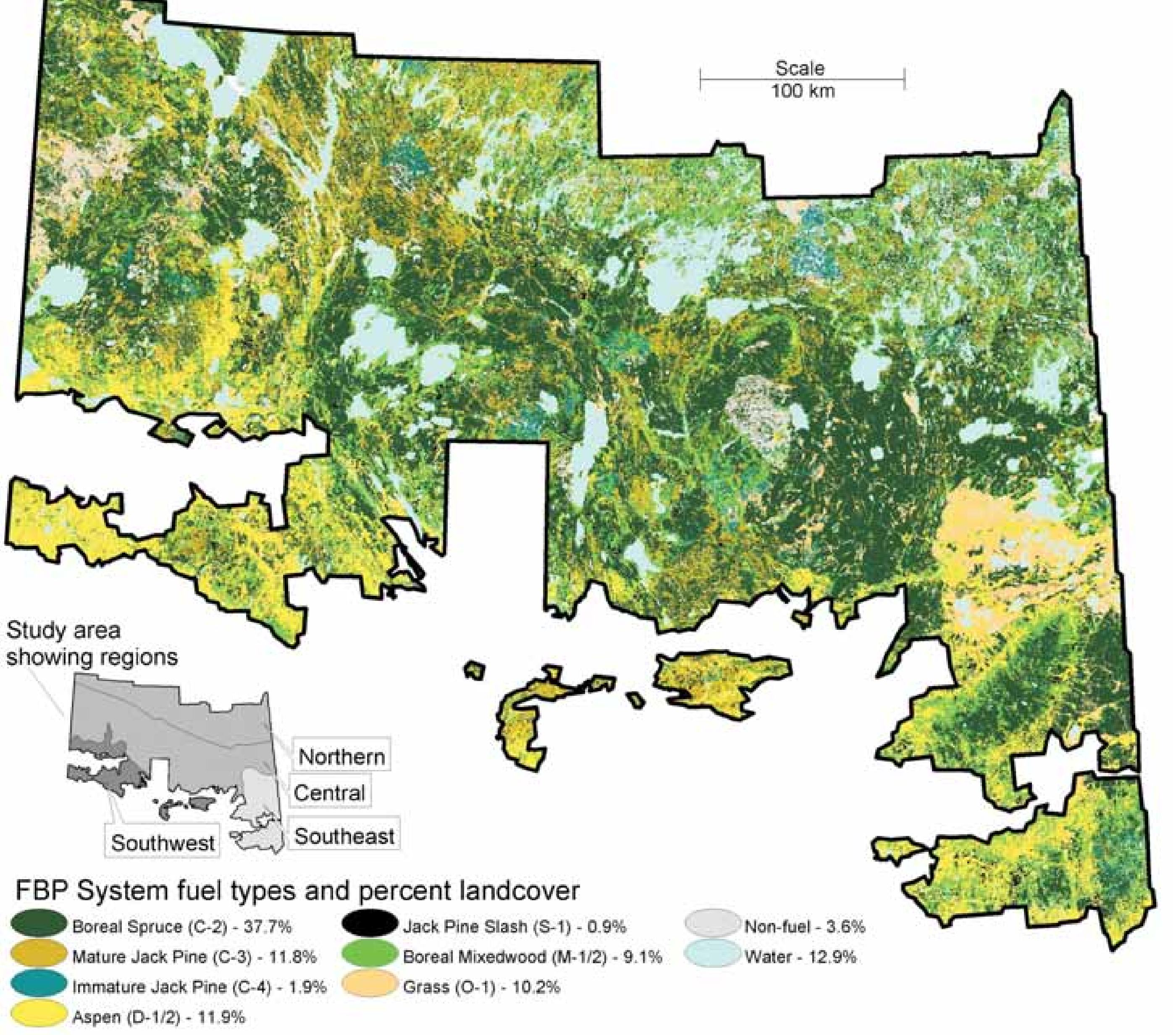

Figure 2. *Fire Behavior Prediction (FBP) System fuel types in the study area.*

For each climate scenario, an HFI map was created for the 80th and 95th percentiles. Even though outputs of both percentiles were considered for analysis, only the 80th percentile maps are presented. To build these maps the following steps were undertaken:

- At each CRCM point, the 80th and 95th percentile Fire Weather Index values were selected for each of the scenarios.
- The FFMC, BUI, and wind speed associated with the selected percentile Fire Weather Index values, along with dominant wind directions, were obtained and interpolated using an inverse distance weighted function between the CRCM points in the Spatial Fire Management System (sFMS).
- In sFMS, the interpolated fire weather grids were used with the fuel type coverage to calculate HFI at each pixel.

For each climate scenario at the 80th and 95th percentile, changes in the frequency distribution of HFI values were compared aspatially. For interpretation purposes, values of the percentile HFI maps were classified in three HFI classes based on relevance to fire suppression effectiveness: the < 2,000 kW/m class; the 2,000–9,999 kW/m class; and the ≥10,000 kW/m class. For the three climate scenarios at the 80th percentile, we examined the spatial distribution of mapped HFI classes as well as absolute and relative change of HFI values from $1{\times}CO_2$ to a $2{\times}CO_2$. In this study, we define absolute change in HFI as the difference in HFI between climate scenarios ($2{\times}CO_2 - 1{\times}CO_2$), whereas relative change in HFI as the ratio of HFI between the climate scenarios ($2{\times}CO_2 \div 1{\times}CO_2$).

Effect of Climate Change on Fire Behavior Potential

General and regional distribution of HFI

In the $1{\times}CO_2$ scenario, under 80th percentile conditions, most of the study area had HFI values below 10,000 kW/m. By contrast, there was a significant shift toward more extreme HFI values in the $2{\times}CO_2$ and $3{\times}CO_2$ scenarios (Fig. 3); however, these scenarios had comparable proportions of their area greater than 10,000 kW/m. From the $1{\times}CO_2$ to the $2{\times}CO_2$ scenario at the 80th HFI percentile, the proportion of HFI values in the ≥10,000 kW/m class increased by 21%, whereas in the < 2,000 and 2,000–9,999 kW/m classes, the proportion decreased by 11% and 9%, respectively. A similar trend existed at the 95th percentile but the proportion of change was smaller in magnitude; both <2,000 and 2,000–9,999 kW/m classes decreased by 3% and 6% while the ≥10,000 kW/m class the proportion increased by 9%. Interestingly, the $1{\times}CO_2$ scenario predicted that about half of the study area had HFI values greater than 10,000 kW/m on 5% (95th percentile) of fire season days, whereas in the $2{\times}CO_2$ scenario, half of the study area had HFI values greater than 10,000 kW/m on 20% (80th percentile) of the days (Fig. 3, text insets). Therefore, from a $1{\times}CO_2$ to a $2{\times}CO_2$ climate scenario, the number of days in which half or more of the study area could potentially exhibit extreme fire behavior (≥10,000 kW/m) could increase 4-fold. The weight of evidence in this study suggests that fire behavior potential

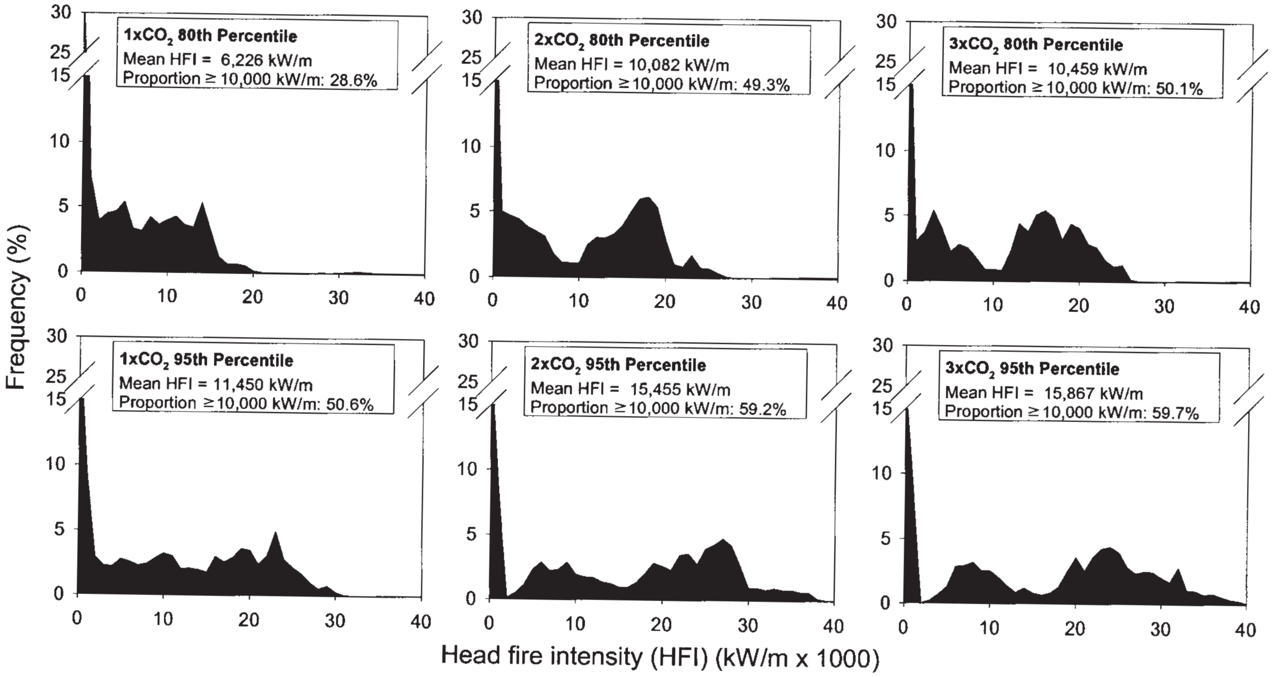

Figure 3. Frequency distribution of head fire intensity (HFI) values in a $1{\times}CO_2$, $2{\times}CO_2$, and $3{\times}CO_2$ scenario for the 80th and the 95th percentile and mean HFI and proportion of area covered by HFI ≥ 10,000 kW/m.

in a $2\times CO_2$ environment would yield conditions where direct fire suppression by crews and air tankers would be unsafe or unlikely to be effective.

Surprisingly, the proportion of the study area by HFI class from the $2\times CO_2$ to the $3\times CO_2$ scenario varied only slightly, suggesting little change in fire behavior potential from the middle to the end of this century. In fact, the proportion of area within each HFI class between these two scenarios did not vary by more than 2%. However, similar HFI values between these two scenarios does not imply that they have the same fire weather. A more in-depth examination of the simulated weather variables generated in the $1\times CO_2$, $2\times CO_2$, and $3\times CO_2$ climate scenarios provides a possible explanation for this plateau in fire behavior potential (Fig. 4). Although average temperature continues to rise from the $2\times CO_2$ to the $3\times CO_2$ scenario, which should translate into more extreme fire behavior potential, there is in the $3\times CO_2$ scenario a parallel increase in precipitation and relative humidity, as well as a decrease in wind speed, that counteracts the effect of increasing temperature on fire behavior potential.

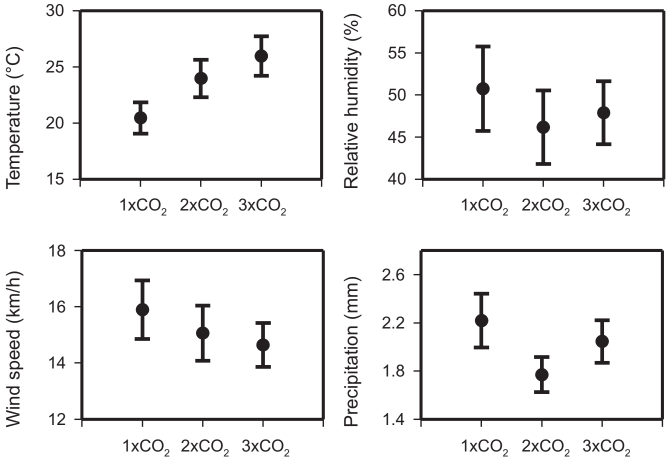

Figure 4. *Means (dots) and standard deviations (whiskers) for noon-hour temperature, relative humidity, wind speed and 24-hour precipitation for the three* CO_2 *climate change scenarios calculated from the 169 Canadian Regional Climate Model grid points.*

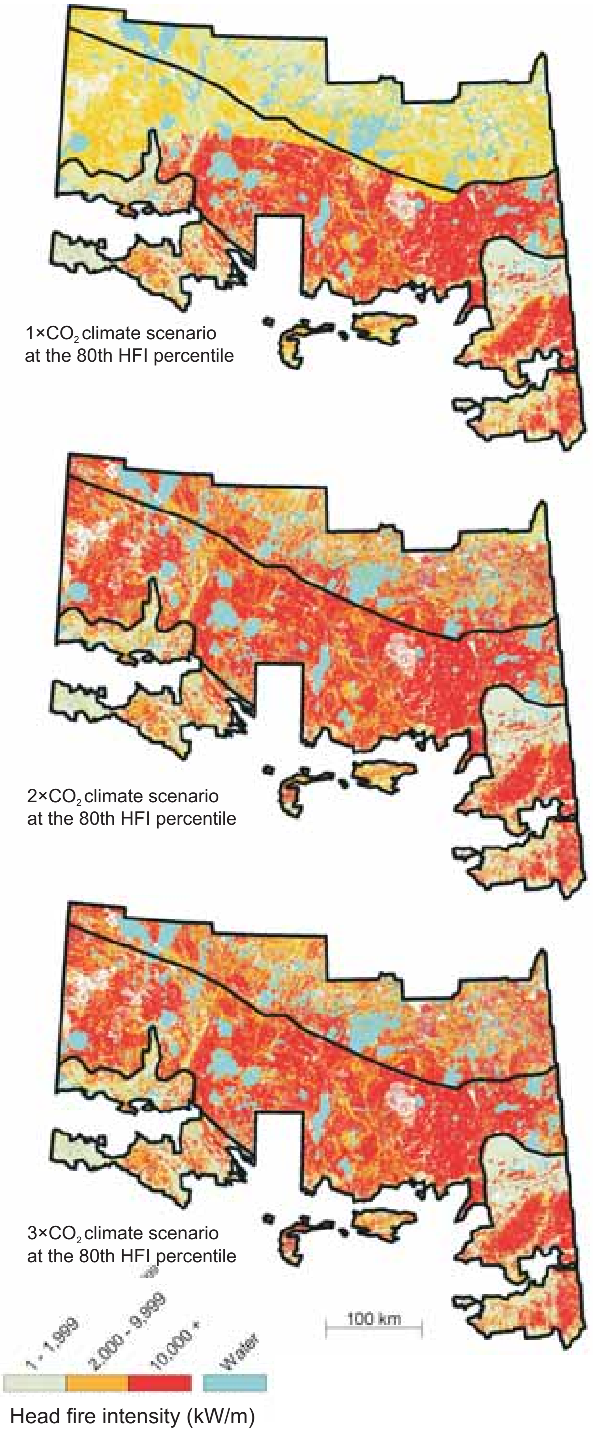

Figure 5*. Maps of* 80^{th} *percentile head fire intensity values for the* $1\times CO_2$*(top),* $2\times CO_2$*(middle), and* $3\times CO_2$ *(bottom) climate scenarios in central Saskatchewan.*

Although the regional distribution of HFI also shows that a general trend toward more extreme HFI values in the $2\times CO_2$ scenario as compared to the $1\times CO_2$ scenario (Fig. 5), there was marked spatial variation throughout the study area in terms of increases in fire behavior potential. The ***Northern Region*** and ***Central Region*** showed a substantial increase in fire behavior potential, whereas in most of the ***Southeast Region*** and part of the ***Southwest Region*** these changes were not as pronounced. These HFI maps are useful for direct interpretation of fire behavior potential; however, the extent and pattern of spatial changes in their percentile HFI values can be further assessed with maps of absolute change and maps of relative change.

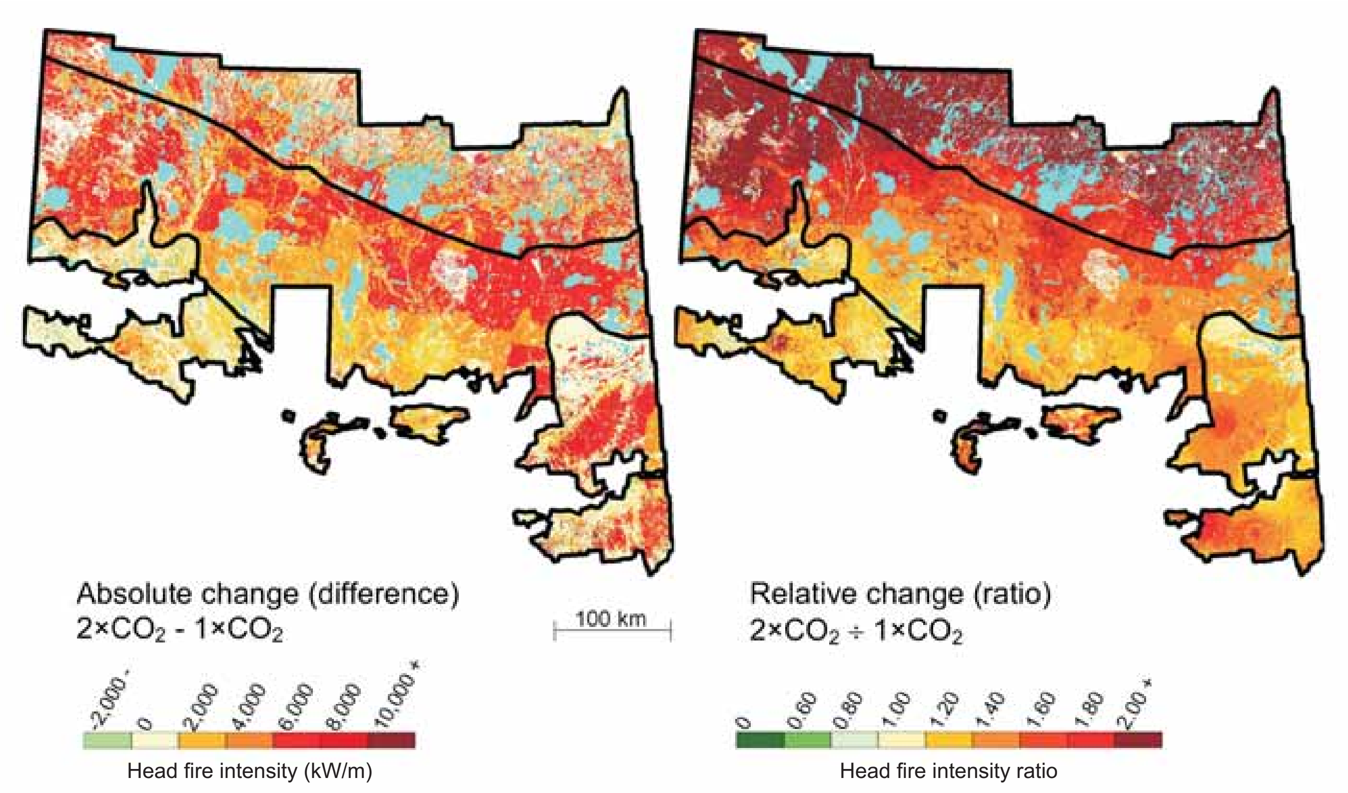

***Figure 6**. Map of absolute and relative change in head fire intensity from the $1\times CO_2$ to the $2\times CO_2$ climate scenario in central Saskatchewan.*

Absolute and relative change of HFI

The ***Central Region*** of the study area had, by far, the highest absolute increase in fire behavior potential (Fig. 6). This increase, which is substantial and likely translates into significantly more frequent high-intensity wildfires and persistent smoldering fires, was due in part to its abundance of the highly flammable Boreal Spruce fuel type, which is more sensitive to change in fire weather. Even though the average absolute increase in HFI in the ***Central Region*** was substantial at the 80th percentile, the relative change in HFI in this area was comparatively low in comparison with the ***Northern Region***. This said, results from the map of absolute change in HFI represent little significant change from a fire management perspective in the Central Region, as most of the region was already above 10,000 kW/m in the $1\times CO_2$ scenario (Fig. 4), and therefore, well beyond the ability to control fire using direct attack.

Overall, there was a significant south to north gradient towards increasingly higher relative change in fire behavior potential. The ***Northern Region*** had the highest relative change in fire behavior potential with practically the entire section experiencing at least a doubling in HFI. This was due not only to the possibility of a greater proportional increase in fire weather severity, as documented by Kafka et al. (2001), but also to the fact that the fire behavior potential of Mature Jack or Lodgepole Pine fuel type, which has a higher height to live crown base, increases sharply when intermittent crowning occurs (HFI values above 2,000 kW/m). This crowning threshold was likely overcome in the $2\times CO_2$ scenario, due to more extreme fire weather conditions. This makes the ***Northern Region*** of the study area particularly sensitive in terms of future increases of fire behavior potential, because there might be a general change from a fire regime of surface or intermittent fires to one that supports more continuous crown fires. This higher frequency of more extreme fire behavior, along with the remoteness of the ***Northern Region***, could result in more wildfires escaping initial attack and burning out of the control in a $2\times CO_2$ environment. Conversely, analyses revealed that deciduous stands had a significantly milder response to climate change than other fuel types, making the ***Southeast*** and ***Southwest Region*** less susceptible to increased fire threat in the upcoming century.

Implications for fire and forest management

In central Saskatchewan, fires that escape initial attack usually do so under weather conditions conducive to high fire behavior potential. Until there is a change to more

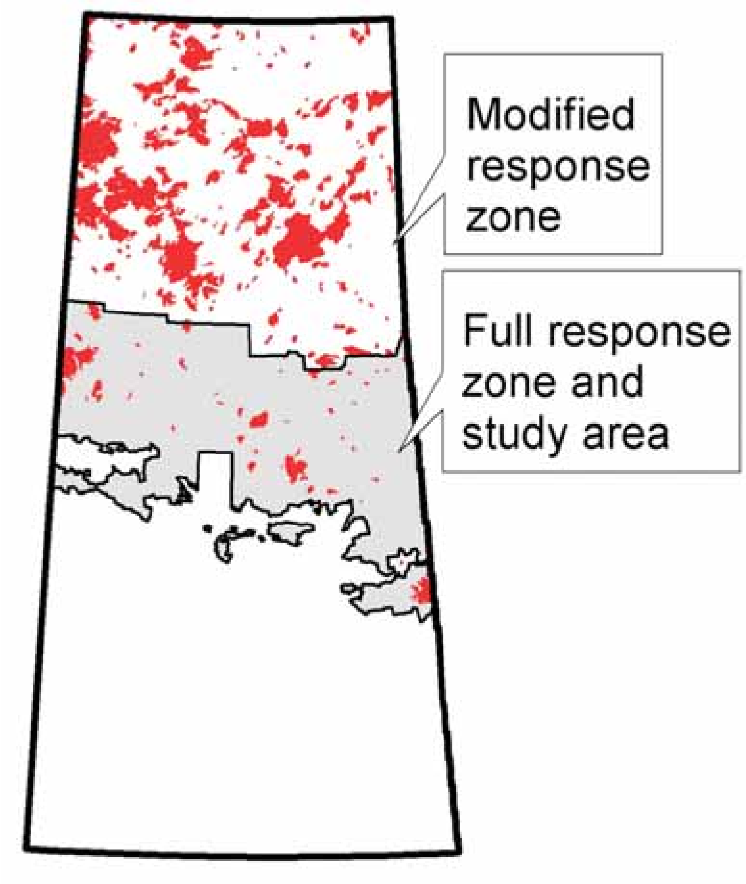

Figure 7. *Large fires (≥1000 ha) in Saskatchewan from 1975 to 1985. This period corresponds to the $1\times CO_2$ climate scenario in central Saskatchewan.*

moderate burning conditions, these fires cannot easily be contained using available fire suppression resources. Our research suggests that in this area, $2\times CO_2$ and $3\times CO_2$ environments will produce a higher frequency of days of high to extreme fire weather conditions, as well as more intense fires on average. An increase in fire intensity would likely be translated into greater fire spread and more erratic fire behavior, leading to increased area burned. However, a changing climate does not necessarily entail a ubiquitous or uniform increase in fire potential throughout an area. Indeed, we found that there was significant spatial variation in the effects of climate change on HFI values, due to the interaction and spatial variation between fuel types and weather patterns.

Due to the different adaptations of boreal species to fire, changes to the fire regime could possibly result in a change in species composition. For instance, there could be a northern shift in the limit between the grasslands and southern edge of the boreal forest in Saskatchewan. In any case, it is likely that climate-induced changes in the fire regime will have a greater impact on vegetation than the direct effects of climate itself (Weber and Flannigan 1997). Furthermore, larger, more intense fires will inevitably be translated into changes in ecological processes. For example, altered regeneration patterns of vegetation could affect stand level composition. In the face of such change to biological communities, and inevitably forest resources such as merchantable timber, the forestry industry will also have to adapt to climate change.

Preliminary results from CGCMs predict a significant increase in area burned in our study area by the end of the 21st century (Flannigan et al. 2004). Our results show that from the $1\times CO_2$ to the $2\times CO_2$ climate scenario, we could expect a 4-fold increase in the number of days in which high intensity fires (≥10,000 kW/m) can occur. Although we did not attempt to correlate this increase in fire weather to area burned in the $2\times CO_2$ climate scenario, it is possible to appreciate what such an increase may have on an area by looking at the large historical fires (≥1000 ha) that occurred during the period of the base scenario (Fig. 7). However, despite more frequent and more extreme fire behavior potential, it is possible that more area burned could result in less available fuels for fire spread in the future and thus act as a negative feedback that would eventually reduce the size of large fires.

In terms of fire management activities, applications for long-term predictions of fire behavior potential at an operational level are numerous: pre-positioning of resources, preparedness planning, prioritization of fire and forest management activities, wildland-urban interface concerns, and fire threat evaluation. Although many other factors will undoubtedly influence the interaction between wildfires and the forest, such as land-use patterns, number of ignitions, public attitudes and policies, an increase in fire behavior potential is expected if the fuels and fire suppression remains similar to present and atmospheric CO_2 concentrations continue to rise. Solutions created to respond to climate change will likely need to encompass more than just better and more fire suppression. Notwithstanding the possibility of reduced emissions, it seems evident that adaptation strategies such as fire-smart communities (Partners in Protection 2003) and fuels management to limit area burned, as described in Hirsch et al. (2001), will need to be not only considered, but acted upon to reduce the impact of increased fire behavior potential on values at risk.

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Photo credits

Both covers: W.J. de Groot, Coffee fire, Saskatchewan, 1980

Photo 3: International Crown Fire Modeling Experiment

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