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Climatic change and fire potential in South-Central British Columbia, Canada

CRAIG R. NITSCHKE and JOHN L. INNES
Department of Forest Resources Management, 2045-2424 Main Mall, Vancouver, BC, Canada V6T 1Z4

Abstract

The incidence and severity of forest fires are linked to the interaction between climate, fuel and topography. Increased warming and drying in the future is expected to have a significant impact on the risk of forest fire occurrence. An increase in fire risk is linked to the synchronous relationship between climate and fuel moisture conditions. A warmer, drier climate will lead to drier forest fuels that will in turn increase the chance of successful fire ignition and propagation. This interaction will increase the severity of fire weather, which, in turn, will increase the risk of extreme fire behaviour. A warmer climate will also extend fire season length, which will increase the likelihood of fires occurring over a greater proportion of the year. In this study of the North Okanagan area of British Columbia, Canada, the impacts of climate change of fire potential were evaluated using the Canadian Forest Fire Danger Rating System and multiple climate scenario analysis. Utilizing this approach, a 30% increase in fire season length was modelled to occur by 2070. In addition, statistically significant increases in fire severity and fire behaviour were also modelled. Fire weather severity was predicted to increase by 95% during the summer months by 2070 while fire behaviour was predicted to shift from surface fire-intermittent crown fire regimes to a predominantly intermittent-full crown fire regime by 2070 onwards. An increase in fire season length, fire weather severity and fire behaviour will increase the costs of fire suppression and the risk of property and resource loss while limiting human-use within vulnerable forest landscapes. An increase in fire weather severity and fire behaviour over a greater proportion of the season will increase the risks faced by ecosystems and biodiversity to climatic change and increase the costs and difficulty of achieving sustainable forest management.

Keywords: British Columbia, climate change, fire behaviour, fire severity, forest management, Okanagan, risk, uncertainty, vulnerability, wildfire

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Introduction

For forest managers, a major question is how climate change will affect the magnitude and frequency of both natural and anthropogenic disturbances. Local, regional and global changes in temperature and precipitation can influence the occurrence, timing, frequency, duration, extent and intensity of disturbances (Dale *et al*., 2001). Global circulation models (GCM) predict that a 1.4–5.8 °C increase in global temperatures, with 0 to $\pm$ 1 mm day^{-1} change in precipitation, will occur by 2070 in western Canada (Franklin *et al*., 1992; National Assessment Synthesis Team, 2000; Gitay *et al*., 2002; Taylor, 2003). Climate change impacts are expressed in ecosystems in part through alterations in disturbance regimes (Dale *et al*., 2001). Wildfire is recognized as a source of economic loss and as an ecological process that is susceptible to change with shifts in climate (Swetnam & Betancourt, 1990). The predicted increase in the frequency and severity of fires (Li *et al*., 2000; Flannigan *et al*., 2003; Wotton *et al*., 2003) is a change that could rapidly alter ecosystems and promote the creation of new communities (Overpeck *et al*., 1990; Swetnam & Betancourt, 1998; Hansell & Bass, 1998). Goldammer & Price (1998) suggest that fire may be a driving force in changing forest ecosystems under climatic change. The interaction between climate change and fire regime may eclipse the vulnerability that

Correspondence: Craig R. Nitschke, tel. +1 604 822 3450, fax +1 604 822 9106, e-mail: crnitschke@gmail.com

species and ecosystems face from the direct effects of climate change alone, as well as the direct socioeconomic impacts (Weber & Flannigan, 1997). It is, therefore, important to gain an understanding of the relationships between climate and fire behaviour at a scale that is meaningful to forest managers.

The occurrence and impacts of forest fires are closely connected to climate and weather (Carey *et al*., 2006). Weather is a combination of climatic parameters that reflect daily variability in climate within an area (i.e. observations) while climate is the average weather within that area over a period of time (i.e. trend). As a consequence, our need to understand how fire regimes and climatic change interact is critical for management decisions (Morgan *et al*., 2003). The occurrence of natural forest fires depends on a combination of three factors: weather conditions, ignition sources and availability of fuels (Goldammer & Price, 1998). Fire frequency, size, intensity, seasonality and type depend on climate, forest structure and composition (Dale *et al*., 2001). The initiation and spread of fire is driven in part by the interannual variability in climatic factors (defined as weather; Carey *et al*., 2006), particularly temperature, relative humidity (RH), precipitation and wind direction and velocity (Agee, 1993).

Weather is one side of the fire behaviour triangle (the fire behavior triangle is comprised of weather, topography and fuels; Agee, 1993) and is an important factor in predicting fire behaviour (Agee, 1993) and fire initiation and propagation (San-Migual-Ayanz *et al*., 2003). Fire initiation and propagation, and thus fire weather, are major components in the definition of fire risk, with Bachmann & Allgöwer (1998) defining fire risk as a function of the probability of a fire occurring and the consequences of the fire. Fire risk is, thus, directly related to the climate variables that influence occurrence (i.e. initiation) and consequence (i.e. propagation). Models that estimate fire risk based on the integration of influencing variables provide a means of quantifying the level of fire risk under current and future conditions. These models frequently use meteorological variables and/or vegetation indices to assess fire risk (see, e.g. Illera *et al*., 1996; Viegas *et al*., 2000; San-Migual-Ayanz *et al*., 2003). The use of weather variables provides a uniform method for rating fire and danger that is independent of topography, fuel types and ignition risks (San-Migual-Ayanz *et al*., 2003), enabling comparisons between regions and across time. This is supported by Carey *et al*. (2006) who found that climate and weather are more important than topography and fuel pattern for determining fire risk. The simplicity of a risk index that uses weather variables enables the comparison of current fire risk in relation to both past and future climatic conditions.

The Intergovernmental Panel on Climate Change (IPCC) (1998) and Lemmen & Warren (2004) recommend the use of a vulnerability approach for assessing climate change, where both current and future vulnerabilities are assessed. Vulnerability is defined as the degree that a system or a system component is susceptible to sustaining damage from a hazard (Turner *et al*., 2003). Vulnerability assessments need to be robust and consider the hazards (perturbations or stressors) that can affect the resilience of the system in question (Luers, 2005). Assessing the vulnerability of fire weather can aid forest managers in making informed decisions on management actions that can reduce the impacts associated with increased fire potential and severity. Thus, an assessment of fire weather vulnerability within a region can provide an understanding on how change in climatic variables will influence the potential for fire initiation and propagation, enabling fire management agencies and forest managers to base their strategic fire management plans on risk, rather than uncertainty. Currently, many fire management agencies base their tactical and strategic planning based on fire danger rating systems. These plans include the spatial and temporal deployment of fire suppression resources (Wotton *et al*., 2003). These fire danger rating systems provide an opportunity to assess the vulnerability of fire potential in a manner that is operationally applicable, which, in turn, can help managers develop adaptation and mitigation plans.

The causal link between weather and fire risk has long been recognized in Canada, with research and development of forest fire danger rating systems beginning in 1925 (Van Wagner, 1987). Most fire danger rating systems assess the potential fire danger in a region using meteorological variables to determine the probability of forest fire ignition and the capability of fire spread (San-Migual-Ayanz *et al*., 2003). Over the last 15 years, studies on the potential impacts of future climate change on fire potential have investigated large areas of Canada (see, e.g. Flannigan & Van Wagner, 1991; Wotton & Flannigan, 1993; Flannigan *et al*., 1998). These studies have generally focused on the effects of climate change on fire potential over large spatial areas and not on smaller, more local scales (Swetnam & Betancourt, 1998). Although these studies are very important, they generalize the potential response within regions, potentially leading to over- or underestimates of fire potential at smaller scales. Improving the spatial and temporal resolutions of current fire potential estimates will help forest and fire managers. Regions that are topographically diverse and contain a variety of ecosystems are of particular concern, but are precisely what forest managers have to contend with. To overcome these limitations, fire potential was evaluated at the landscape-level in order to provide results that are specific to the scale commonly utilized by forest managers.

Study area

Fire potential was evaluated under current climate and future climate change scenarios for a 145 000 ha landscape located in the North Okanagan region of British Columbia, Canada (latitude 49°52′6″ to 50°41′6″ North and longitude 119°14′6″ to 119°59′48″ West, see Fig. 1). The landscape comprises crown land and is tenured to Tolko Industries Ltd. as Tree Farm License (TFL) 49. The TFL contains five biogeoclimatic (BEC) zones (Meidinger & Pojar, 1991): Ponderosa Pine (PP), Interior Douglas Fir (IDF), Montane Spruce (MS), Engelmann Spruce and Subalpine Fir (ESSF) and Interior Cedar Hemlock (ICH) zones.

Five weather stations are located within or adjacent to the landscape (Fig. 1 and Table 1). They range from 430 to 1500 m in elevation and are managed by the Ministry of Forests and Range (SA, SPR and FIN) or Environment Canada (BM and KA). These stations were selected because they provided a wide representation of the study area and they contain the longest and most complete data records in the area (Table 1).

Methods

The effects of potential climate change on the fire potential and severity ratings were determined using three global climate models, five weather stations, the Forest Fire Weather Index (FWI) component (Van Wagner, 1987) and the Forest Fire Behaviour Prediction (FBP) System (see Hirsch, 1996) of the Canadian Forest Fire Danger Rating System (CFFDRS). In the first step of the analysis, weather scenarios with a daily time step were generated from the weather records of each of the five weather stations. Monthly outputs from global climate change models were then integrated with the daily weather records of the five weather stations. Once the GCM outputs were integrated into the local weather data, the impacts of climate change of fire potential were evaluated using the above components of the CFFDRS.

Climate change scenarios

Climate change outputs were obtained from the Canadian Institute for Climate Studies, Canadian Climate Impacts and Scenarios Project (2005). A regional climate model (RCM) was not available for the study area in question so three GCM/emission scenarios were used: CGCM1-gax, CGCM2-A2x and the HadCM3-A2x (Flato *et al.*, 2000; Johns *et al.*, 2003). For each GCM, the relevant grid point immediately above the study region was utilized (see Fig. 1) for the output periods 2025 (2010–2039), 2055 (2040–2069) and 2085 (2070–2100). The CGCM-gax scenario is an IS92a simulation that increases greenhouse gases 1% yr^{-1} until 2100 and includes sulphate forcing. The IS92a scenario is an older

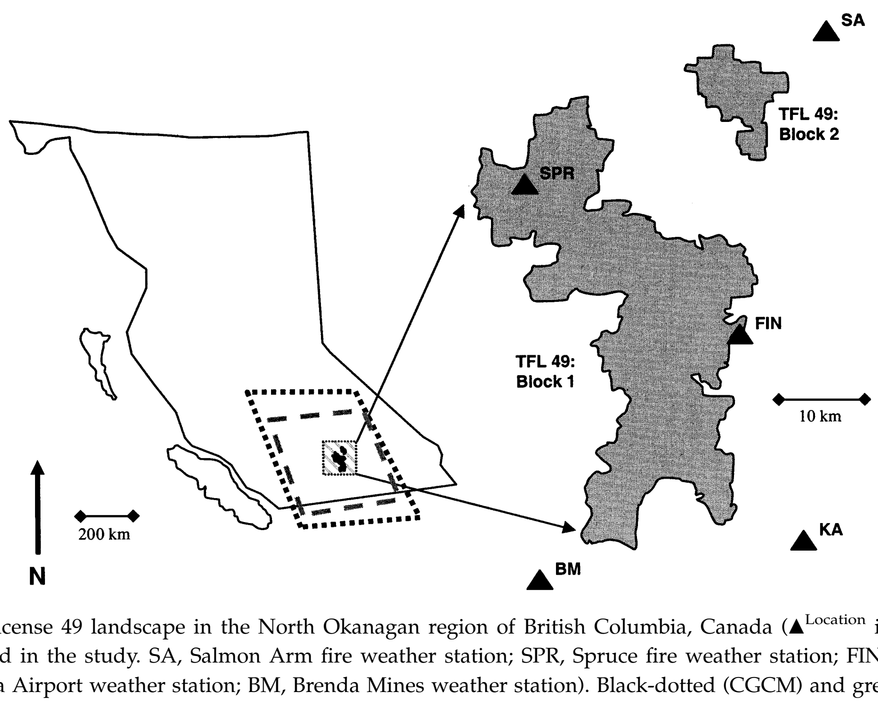

Fig. 1 Tree Farm License 49 landscape in the North Okanagan region of British Columbia, Canada (▲^{Location} indicates locations of weather stations used in the study. SA, Salmon Arm fire weather station; SPR, Spruce fire weather station; FIN, Fintry fire weather station; KA, Kelowna Airport weather station; BM, Brenda Mines weather station). Black-dotted (CGCM) and grey-dashed (HadCM3) lines indicate the general location of the GCM grid points used in study. GCM, global circulation models.

Table 1 Weather station characteristics

Variable	KA	SA	FIN	SPR	BM
Latitude (north)	49°53′60″	50°41′6″	50°12′24″	50°24′48″	49°52′6″
Longitude (west)	119°17′60″	119°14′6″	119°28′48″	119°59′48″	119°59′36″
Last data year	2003	2003	2003	1998	2003
Station operator	EC	MOFR	MOFR	MOFR	EC
Years of observations	34	24	11	15	26
Maximum # of observations	34	24	11	15	26
Minimum # of observations	6	9	2	1	4
Mean maximum temperature (°C)	12.3	10.8	11.1	7.5	6.1
Mean relative humidity (%)	53	67	65	67	68
Mean wind direction (Azimuth°)	247	219	183	209	198
Mean wind speed ($m\,s^{-1}$)	7.0	6.6	4.9	7.7	7.9
Mean precipitation (mm)	226	471	414	420	433
Elevation (m)	430	527	670	1463	1492
BEC zone	PP-IDF	IDF-ICH	IDF	MS	MS-ESSF

EC, Environment Canada; MOFR, Ministry of Forests and Range; BEC, biogeoclimatic.

Table 2 Average predicted annual climate change for the North Okanagan, BC, Canada

Climate period	Minimum temperature (°C)	Mean temperature (°C)	Maximum temperature (°C)	Precipitation (%)	Relative humidity (%)	Wind velocity (%)
2010–2039	1.1	1.1	1.2	2.9	−0.98	0.4
2040–2069	2.2	2.4	2.7	−1.8	−1.96	−1.4
2070–2100	3.8	4.0	4.3	1.7	−2.75	−3.6

Ensemble predictions from three GCM models.
GCM, global circulation models.

scenario that represents the middle of the range, a lesser degree of warming by 2100, due to an increased cooling effect by sulphur dioxide than the newer Special Report on Emission Scenarios (SRES) (Canadian Institute for Climate Studies, 2006). The HadCM3 and the CGCM2 models use the IPCC's SRES emission scenario, A2 (Nakicenovic *et al*., 2000). The A2 SRES emission scenario models climatic change under both increased economic and population growth at regional scales. This storyline was chosen because of its regional representation and because the region used in this study has shown continual population and economic growth over the last 10 years, a trend that is expected to continue. Multiple scenarios were used following Nakicenovic *et al*. (2000), who argued that due to the large amount of uncertainty regarding greenhouse gas and sulphate aerosol emissions, multiple scenarios that span a range of possible future climates should be adopted. Each of the three different GCMs and corresponding emission scenarios predicted a different future in terms of potential changes in temperature, precipitation, humidity and wind speed. The average annual predicted changes for the region, based on an ensemble of the GCM models, are provided in Table 2.

Generating local weather scenarios

The development of multiple climate change scenarios for the area required the generation of local weather scenarios to incorporate the recorded variation in daily weather patterns. Daily data were used following the protocols of Bürger (1996). Five weather stations were used to provide an integrated representation of regional climate with a microclimatic component. The microclimatic component was incorporated by generating multiple weather scenarios for each station. Local weather scenarios were created for each station, with error analysis being used to estimate the sampling distributions for minimum temperature, maximum temperature, RH, wind speed, wind direction and precipitation (Pacala *et al*., 1996) and Monte Carlo techniques to sample the probability distributions of parameters to select outcomes (Luo *et al*., 2005). For each day, 1 January to 31 December, the average and standard deviation of each variable was calculated. For days that had less than two observations, the sampling distribution of the daily observations from the preceding and following days were used to create the sampling distribution. The arithmetic average for each variable, for each day, was used to represent the average daily climate for each weather station and to form the average weather scenario for each weather station (Table 1 illustrates the annual average climate).

Monte Carlo techniques were used to sample the probability distributions of each daily variable to create ranges of change for each variable. Following Luo *et al*. (2005), the sampling distribution created by the error analysis was assumed to be a prior distribution for each variable. The sampling method also enabled the maintenance of the same level of independence between each variable. It was assumed that: (1) precipitation and wind speed are ≥ 0; (2) RH is $\geq 0\%$ and $\leq 100\%$; and (3) minimum temperature is less than or equal to maximum temperature. Six of the generated weather scenarios from each station were then randomly selected with three representing a combination of variables below the annual averages provided in Table 1 and three representing above-average conditions. The scenario combination was chosen to provide an equal representation of below- and above-average conditions, while maintaining high variability between scenarios. Combining the average weather scenario with the six scenarios generated through the use of error analysis and Monte Carlo sampling resulted in the creation of seven weather scenarios for each local weather station in the study. This permitted the incorporation of a more realistic level of variability for each local variable than would have been the case if a classic sensitivity analysis that looked at the average, lower and upper bounds for each variable, respectively, had been used (Pacala *et al*., 1996; Zorita & von Storch, 1999). Global circulation outputs were applied to each generated scenario.

Bürger (1996) and Zorita & von Storch (1999) have both argued that the inclusion of local variability is of great importance if climate change scenarios generated by GCMs are to be downscaled to the local-scale for use in ecosystem studies. The generation of multiple local weather scenarios can be used as the foundation for the development of more robust climate change scenarios specific to the area of interest and/or concern. Because an RCM was not available for the study area, statistical downscaling of climate change scenarios from a GCM to the local weather stations in the North Okanagan was attempted using multivariate statistical techniques. Statistical downscaling failed due a lack of a continuous and consistent weather record for the region, the topographic diversity within the region, and the presence of the 450 km^2 lake adjacent to the study area. GCMs do not produce realistic representations of surface climates in areas where local weather patterns are forced by topography and large lake systems (Brandsma & Buishand, 1997). These factors resulted in a low explanation of the variation, with R^2-values for all multivariate tests being below 30%, and a high degree of error. Based on the recommendations of Tabachnick & Fidell (2001), statistical downscaling was abandoned because of the poor statistical relationships identified.

A direct adjustment approach was therefore used to integrate climate change scenarios into the local weather scenarios generated for each station. This involved adjusting the weather station records using the predicted outputs from a GCM (Wilks, 1999; Wang *et al*., 2006). The predictions for changes in temperature, precipitation, wind speed and RH for each month from the three GCM scenarios were applied to the five local weather stations. Changes in temperature were increased by the predicted amount while changes in wind speed, precipitation and RH were multiplied by a factor that represents a percent change in that variable (e.g. 0.94 or 1.10). Wind direction was held constant. The changes were applied on a month-by-month basis to create a daily time series of weather that represents the local variation along with monthly variation of the GCM predictions. By applying three GCM scenarios, broken into 2025 (2010–2039), 2055 (2040–2069) and 2085 (2070–2100) outputs, to seven local weather scenarios, a total of 70 scenarios were generated for each station. Multiplied by the number of weather stations, a total of 350 individual scenarios were created that integrate local variation and climate change predictions for the region at five different locations and elevations within each grid point (see Fig. 1 and Table 1). These scenarios were used to evaluate the vulnerability of fire weather and, thus, fire potential under climatic change using components of the CFFDRS. Nitschke & Innes (2008) successfully used this same approach to model the vulnerability of tree species to climatic change within the same study area.

Canadian forest FWI

The Canadian Forest FWI System is an integral part of the national system for rating forest fire danger and has been in use across Canada for over 30 years (Stocks *et al*., 1989). The system uses daily weather observations to estimate the moisture content of three different fuel classes, then uses these to generate a set of relative indicators of potential rate of fire spread, fire intensity, and fuel consumption (see Fig. 2). Van Wagner (1987) and Amiro *et al*. (2004) give a detailed description of the fuel moisture codes and fire behaviour indices.

As a nonlinear relationship exists between the fire danger rating predicted by the FWI and the control effort required to suppress a fire (Van Wagner, 1987), the FWI was weighted by converting the FWI to a daily severity rating (DSR). By using the DSR instead of the FWI, it is possible to average severity ratings between

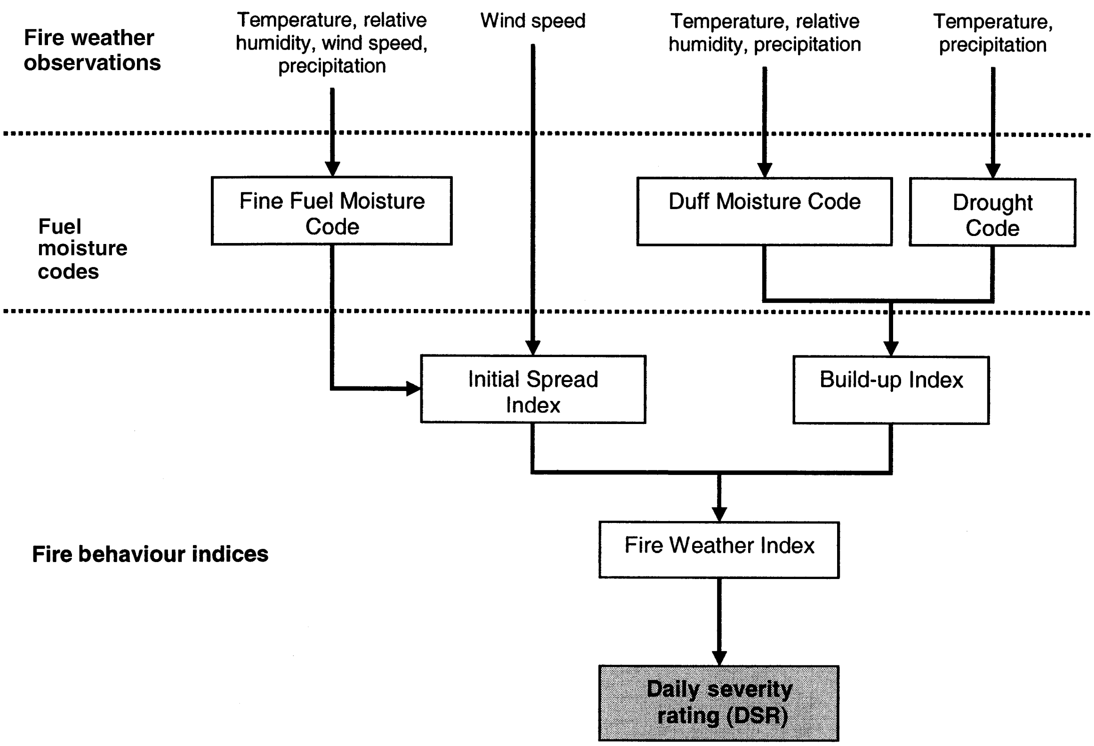

Fig. 2 Canadian Forest Fire Weather Index (adapted from Van Wagner, 1987) with added Daily Severity Rating calculation step.

stations in a given spatial location and between time periods. This is not possible with the FWI rating (Van Wagner & Pickett, 1985; Van Wagner, 1987). The DSR enables a comparison of the potential impact of climate change on fire severity on a landscape through the application of GCM outputs to the current climate record of adjacent weather stations.

For this study, the equations used to calculate the FWI, derived from Van Wagner & Pickett (1985), were programmed into MICROSOFT EXCEL (Microsoft, 2002, MICROSOFT EXCEL® 2002, Microsoft Corporation, USA). The weather scenarios generated from each weather station were then assessed to determine the potential impact of climatic change on fire weather within the study area. A two-sample Student's *t*-test was performed to test whether differences exist between the current mean fire severity and fire severity under climatic change.

Monthly severity ratings (MSR)

The MSR were calculated for each weather station to determine if any shifts in the monthly fire weather distribution would occur with climate change. The results of this analysis show the monthly contribution of fire weather potential over a year. This enables the determination of what each month and season contributes to fire weather potential over a fire season and more importantly which time of the year is most critical within each ecosystem.

Canadian forest FBP system

The Canadian Forest FBP System (Hirsch, 1996) was used to examine potential changes in fire behaviour. Fuel types, as defined in the FBP system, were identified using the British Columbian Ministry of Forests and Range (MOFR) (2006) fuel plot studies for the Kamloops Forest Region. The MOFR fuel classifications were combined with forest inventory data for the TFL 49 landscape using ARCGIS 9.0 [Environmental Systems Research Institute (ESRI), 2004] in order to classify the landscape into FBP system fuel types (Fig. 3, Table 3).

Fire behaviour was predicted by calculating the head fire intensity (HFI) for the described fuel types using the fire behaviour equations described by Hirsch (1996). HFI intensity was calculated using the following equation:

$$\begin{aligned}\text{HFI (KW m}^{-2}) = 300 &\\ &\times \text{Total Fuel Consumption (kg m}^{-2}) \quad . \\ &\times \text{Head Fire Rate of Spread (m min}^{-1})\end{aligned}$$

The fuel consumption parameters required to calculate the Total Fuel Consumption (kg m^{-2}) rate for each fuel type were provided by Hirsch (1996) and the

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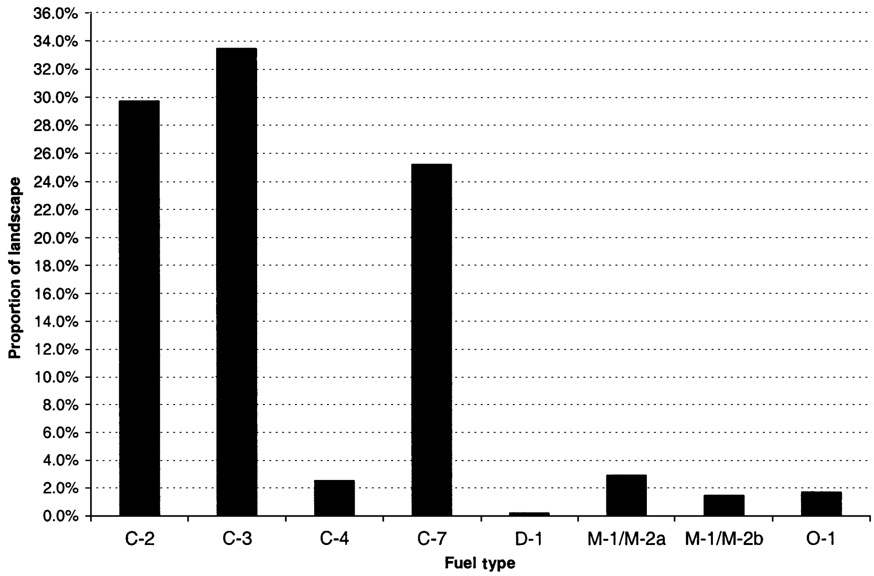

Fig. 3 Proportion of TFL 49 landscape occupied by FBP fuel types. FBP, Fire Behaviour Prediction.

Table 3 FBP fuel types classified on TFL 49

Fuel type	Fuel type characteristics
C2	Spruce (*Picea* sp.), subalpine fir (*Abies lasiocarpa*) and western red cedar (*Thuja plicata*) dominated stands
C3	Mature lodgepole pine (*Pinus contorta* var. *latifolia*) dominated stands
C4	Immature lodgepole pine dominated stands
C7	Ponderosa pine (*Pinus ponderosae*), Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) and western larch (*Larix occidentalis*) dominated stands
D1	Pure deciduous stands: trembling aspen (*Populus tremuloides*), paper birch (*Betula papyrifera*), black cottonwood (*Populus balsamifera* ssp. *Tichocarpa*)
M1/ M2a	Deciduous dominated mixed stands ($\geq$50% deciduous component)
M1/ M2b	Coniferous dominated mixed stands ($\geq$50% coniferous component)
O1	Grasslands (<10% tree cover)

FBP, Fire Behaviour Prediction; TFL, Tree Farm License.

predicted head fire rate of speed was calculated from the FWI for each climate scenario.

The six HFI categories described by Hirsch (1996) were reclassified to a more standard classification based on Agee (1993) and are shown in Table 4. Because this is an aspatial analysis, the percent slope was assumed to be 0. This assumption made the analysis aspect- and slope-neutral, providing uniform results (San-Migual-Ayanz *et al.*, 2003) from which to assess potential change under different climate conditions.

Table 4 Fire behaviour classification

Fire behaviour rating	Fire type	HFI range (KW m^{-1})
1	Surface fire	1–500
2	Surface fire with torching	500–2000
3	Intermittent crown fire	2000–4000
4	Crown fire	>4000

A two-sample Student's *t*-test was performed to test whether differences exist between the current mean fire behaviour and fire behaviour under climatic change.

Results

Fire weather

The analysis indicated that the average DSR distribution for a given year will increase until it has nearly doubled by 2100 (Fig. 4). Severity ratings above 7 represent the potential for extreme fire behaviour, between 3 and 7 reflect high to very high potential, from 1 to 3 represent moderate fire behaviour potential and <1 equals low fire potential (Stocks *et al.*, 1998). The shift in the annual DSR trend results in an increase in the mean fire season length by nearly 30%, with 90% of this increase occurring in the spring (MAM) by 2100 (Fig. 5). The spring fire season will increase in duration by 27% (25 fire season days). The summer gains 2 extra fire days and the fall only 1 extra fire day. Also, by 2100,

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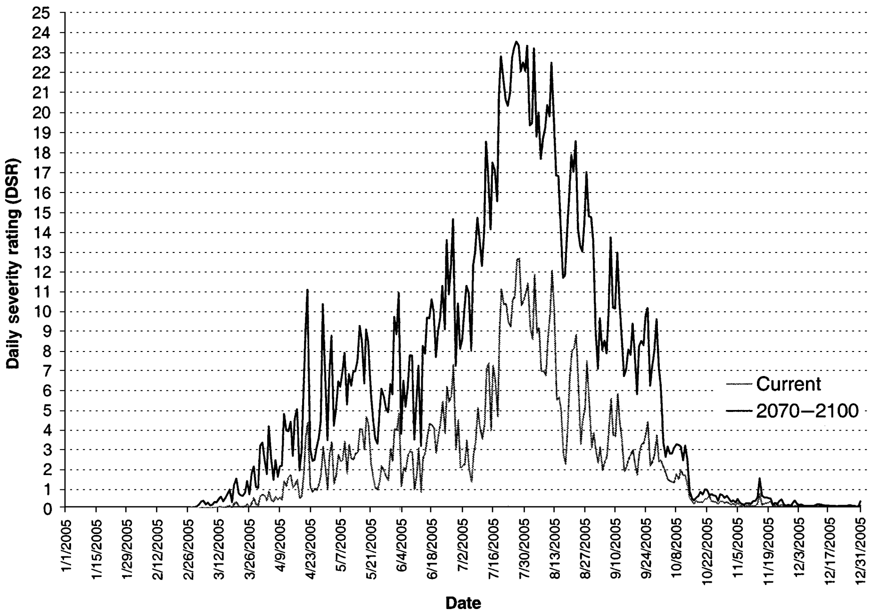

Fig. 4 Comparison of DSR distribution between current climatic conditions and future conditions (2070–2100). DSR, daily severity rating.

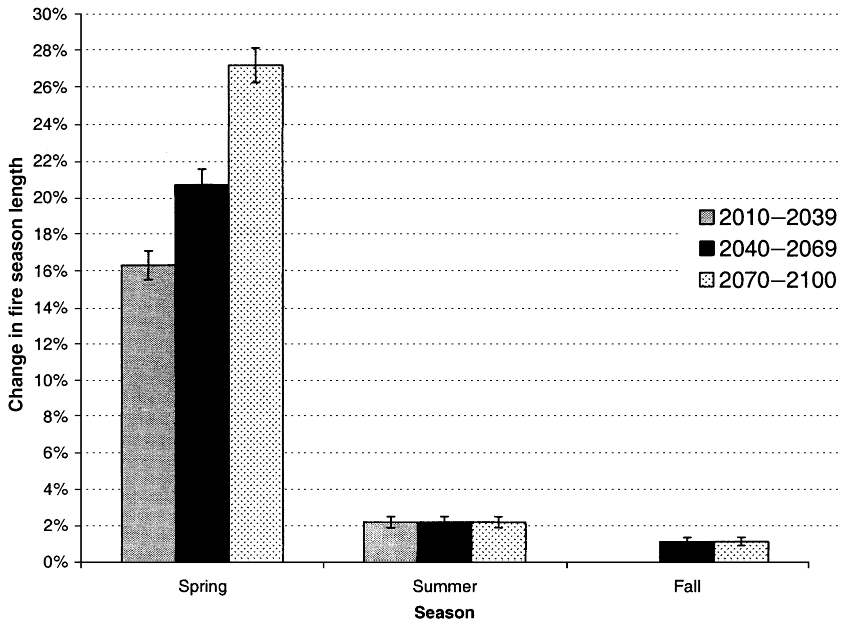

Fig. 5 Change in fire season length from current to 2010–2100.

the mean fire severity significantly increased by 42% in the spring, 95% in the summer (JJA) and 30% in the fall (SON) (Fig. 6 and Table 5). Comparison of Figs 5 and 6 reveals very little change for both the summer and autumn fire season lengths, although both seasons increased in severity, particularly the summer season. The spring season shows an increasing trend in fire season length over time, while the summer and autumn seasons show a linear increase. The spring season has the highest predicted increase in potential fire weather severity from 2010 to 2039, and dramatic increases are predicted for the summer season from 2040 to 2100. The spring and autumn seasons show consistent increases in fire weather potential over time while substantial change is predicted after 2040 for the summer season. Annual fire seasons will progressively lengthen from

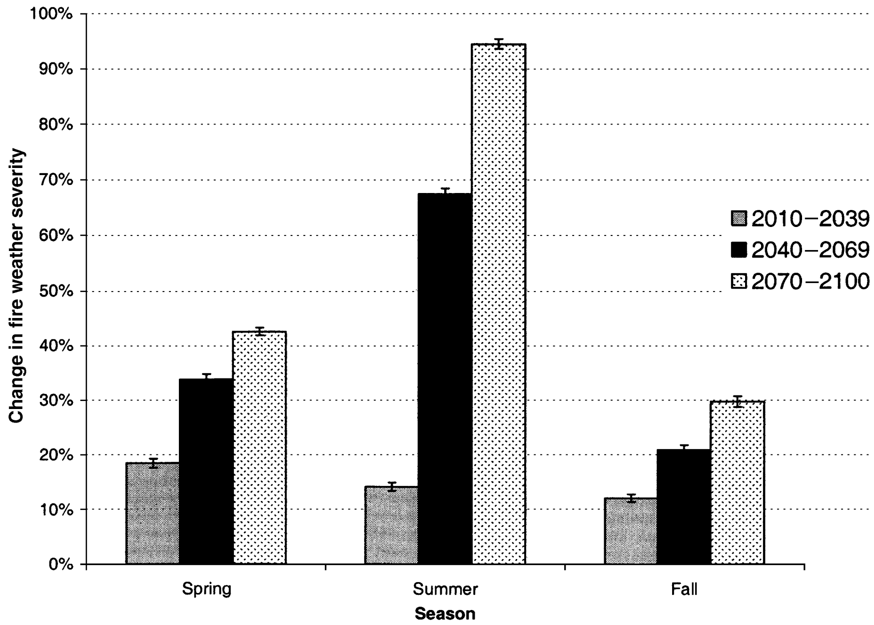

Fig. 6 Change in fire weather severity from current to 2010–2100.

Table 5 Summary of Student's *t*-test results on mean fire severity: *P*-values

Season	2010–2039	2040–2069	2070–2100
Spring	<0.001**	<0.001**	<0.001**
Summer	<0.001**	<0.001**	<0.001**
Fall	0.024*	<0.001**	<0.001**

*Statistically significant at $\alpha = 0.05$.
**Statistically significant at $\alpha < 0.001$.

now to 2100, predominantly in the spring (Figs 4–6), while fire season severity will increase significantly in all seasons, with particularly dramatic increases occurring in the summer season from 2040 to 2100.

Figure 7 illustrates the distribution of the MSR from spring to fall; winter had an MSR of zero and was, therefore, excluded.

In general, the summer season will still have the greatest proportion of fire severity ratings over the entire fire season. However, the contribution of the summer season differs between BEC zones. The summer season comprises 54–78% of the current fire weather potential and will constitute 57–74% of the fire weather potential by 2100. In every BEC zone except one (the MS zone), the summer contribution decreases at the expense of the spring and/or fall seasons. Fire seasons and fire weather potential will differ only slightly from ecosystem to ecosystem within a local study area (Fig. 7). Increases in fire season length can be expected to occur because of increases in fire weather potential in both the spring and fall seasons in every ecosystem except the MS where the fall season will not likely contribute to fire season length. In the ICH zone, the fall season is when the increase to fire season length may occur, while in the IDF and PP, the spring time will contribute the greatest to this increase. The ESSF zone will likely see a synchronous increase in fire season from both the spring and fall seasons. There may be small asynchronous shifts in the distribution of fire weather potential between ecosystems. The distribution of fire weather potential needs to be considered in conjunction with an increase in fire weather severity. When this is done, every ecosystem examined will show increases in fire season length (Fig. 5) and increases in fire weather severity (Fig. 6). Consequently, increasingly longer and more severe fire seasons can be expected between now and 2100.

Fire behaviour

The impacts of climatic change on fire behaviour are summarized by BEC zone in Figs 8 and 9. Figure 8 shows the mean fire behaviour for all fuel types within each BEC zone while Fig. 9 illustrates the mean percentage of change within each BEC zone and for each time period. Ninety-five percent confidence intervals are provided to illustrate the sensitivity of fire behaviour response to climatic change. Table 6 summarizes the results of the *t*-tests, which were used to determine if a statistically significant difference in fire behaviour could be detected.

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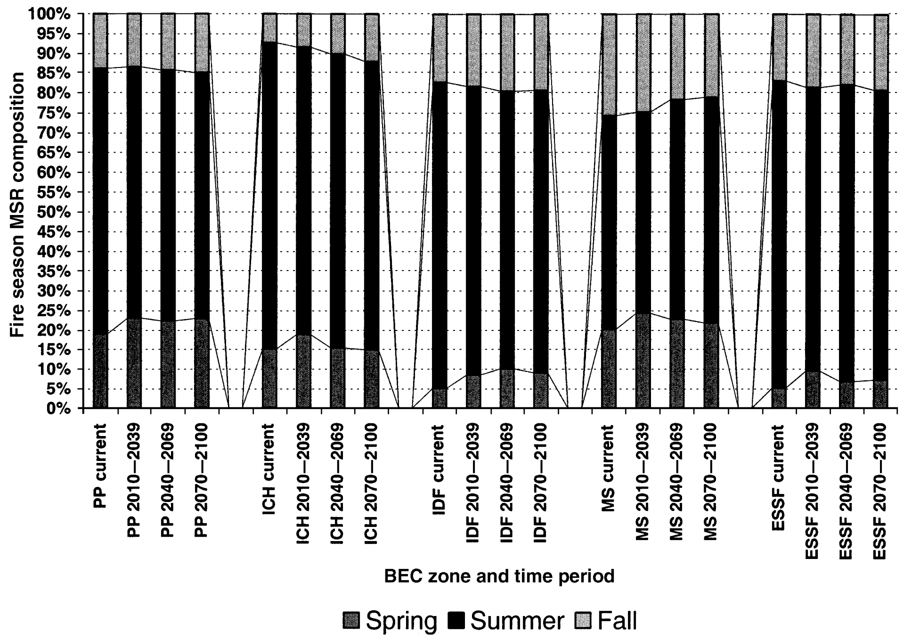

Fig. 7 Monthly contribution to fire weather potential by BEC zone by time period. BEC, biogeoclimatic.

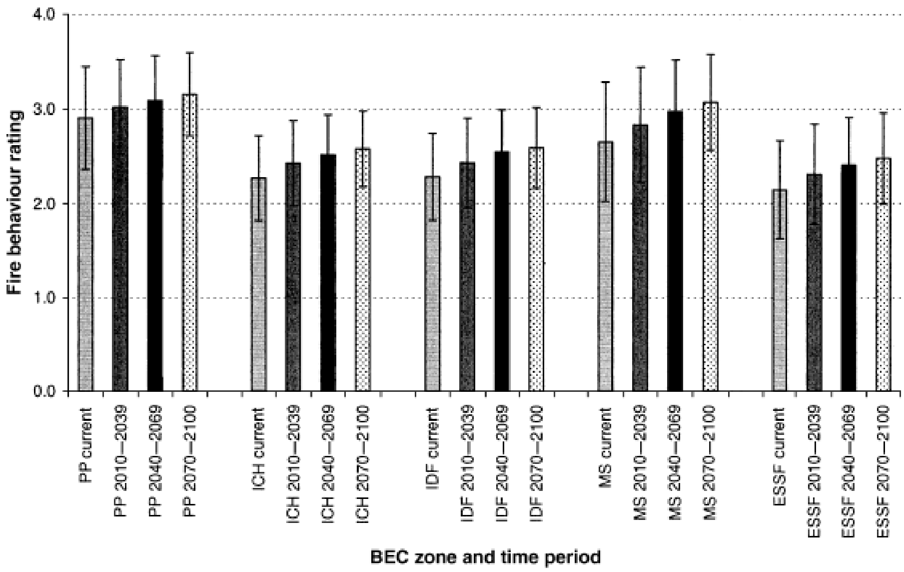

Fig. 8 Mean fire behaviour by BEC zone and time period (Table 5 provides definitions for the fire behaviour rating on the *Y*-axis). BEC, biogeoclimatic.

Statistically significant ($P = 0.1$) increases in fire behaviour will occur in all BEC zones by 2100 (see Table 6). A *P*-value of 0.10 was used to infer a significant response because the costs associated with making a Type II error (i.e. no significant change in fire behaviour is falsely predicted) were determined to outweigh the costs associated with making a Type I error (i.e. significant change in fire behaviour is falsely predicted) (McCoy, 1996). The detrimental influence of volatile and unpredictable disturbances, such as wildfire, in ecological systems makes Type II errors more costly than Type I errors (Johnson, 1999). To provide support to the *t*-test results, confidence intervals were calculated to provide both an estimate of the effect and a measure of uncertainty (see Figs 8 and 9).

The mean and variance in fire behaviour for the ICH, IDF and ESSF zones under the current climatic conditions were observed to have a fire behaviour rating (see Fig. 8) between 2 and 3. Under climatic change, the mean rating increases and the confidence intervals

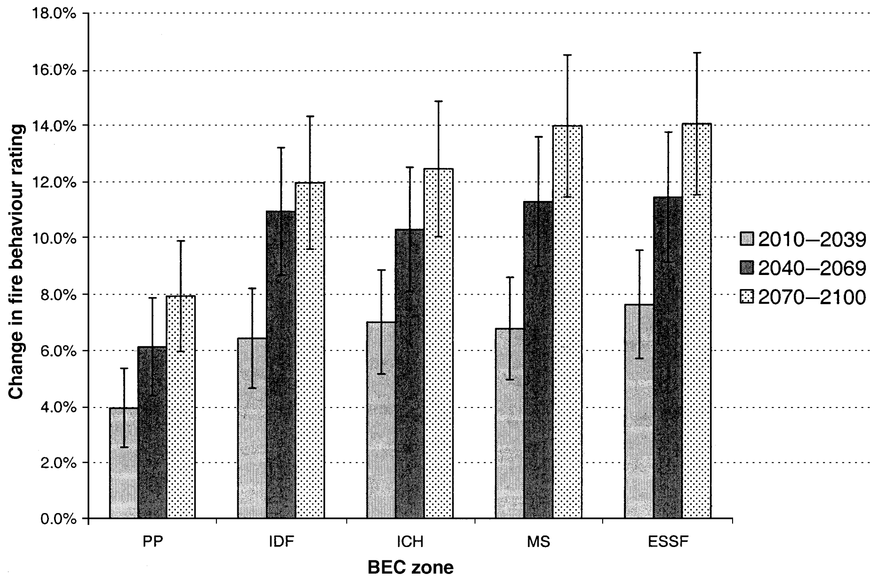

Fig. 9 Percentage of change in mean fire behaviour by BEC zone and time period and 95% confidence intervals. BEC, biogeoclimatic.

Table 6 Summary of Student's *t*-test results on mean fire behaviour: *P* values

BEC zone	2010–2039	2040–2069	2070–2100
PP	0.28	0.16	0.08*
ICH	0.18	0.07*	0.03**
IDF	0.14	0.07*	0.09*
MS	0.17	0.14	0.02**
ESSF	0.13	0.11	0.06*

*Statistically significant at $\alpha = 0.10$.
**Statistically significant at $\alpha = 0.05$.
PP, Ponderosa Pine; IDF, Interior Douglas Fir; MS, Montane Spruce; ESSF, Engelmann Spruce and Subalpine Fir; ICH, Interior Cedar Hemlock; BEC, biogeoclimatic.

approach 3. This suggests that the average fire behaviour regime will shift from predominantly surface fires with torching regime to an intermittent crown fire regime. The PP and MS zones were also observed to have a mean fire behaviour rating between 2 and 3, although the variance in behaviour exceeded class 3. Under climatic change both the mean rating and confidence intervals exceeded 3. This suggests that the average fire behaviour regime will shift from mixed surface fires with torching – intermittent crown fire regime to mixed intermittent crown fires – full crown fire regime.

Discussion

The results presented here suggest that climate change will have an influence on fire weather severity and fire season length in the North Okanagan. The increase in fire weather severity will also lead to a significant increase in mean fire behaviour in all the major ecosystems located within the study area. Mean fire season length is predicted to increase by 17 days by 2039 and by 28 days by 2070. The increase in fire season length will be driven by warmer and drier spring months, with 25 of the 28 extra fire days predicted to occur from March to May. The results are consistent with larger scale studies that have investigated the impact of climatic change on fire season length. Wotton & Flannigan (1993) predicted that fire season length would increase by 30 days across Canada, while Li *et al.* (2000) predicted a 28–29-day increase in west-central Alberta. Stocks *et al.* (1998) predicted that fire seasons will have an earlier annual start and later end date across Canada and Russia.

The increasing trend in fire severity agrees with other studies but the magnitude differs, which is probably an artefact of the scale used in previous studies. Li *et al.* (2000) predicted a 46% increase fire weather severity in west-central Alberta, consistent with the 40% increase projected by Flannigan & Van Wagner (1991) for Canada. Stocks *et al.* (1998) predicted that fire weather severity could double in the boreal regions of both Canada and Russia by 2100. Stocks *et al.* suggested that the summer season would show the greatest increase in fire weather severity, with every season, except winter, showing modest increases.

In this study, fire season severity was also found to increase in each season, except winter, although the changes in each season differed. By 2085, fire weather severity is expected to increase by 42% in the spring, 95% in the summer and 30% in the fall. The results are consistent with the studies described above if only the spring season is considered. When we compare all the studies together, there is broad parity between results, especially when it is considered that four different scales, different GCMs scenarios and different weather station data were used. The use of the FWI system strengthens the agreement as it provides a uniform measure of fire weather rating (San-Migual-Ayanz *et al*., 2003). The results confirm that a change in climate will increase fire season length and fire weather severity and that this change can be expected to be broadly applicable across a range of scales, from local to international levels.

The parity that exists between studies identifies that climate change will increase the risk and impact of forest fires in the future. However, there are important differences that exist between this study and previous ones. Previous studies have generalized their findings across large areas and reported the annual increase in fire severity and fire season length. The findings for the North Okanagan study area suggest that changes in climate will lead to an increase in fire season length, starting much earlier in the spring than at present, but that the fire season will not necessarily extend longer in the autumn. Similar studies simply report an increase in fire season length but do not discuss the impact climate change will have on the distribution of the fire season across the calendar year. Knowledge of the seasonal response to climate change provides a greater understanding of when and where change will occur in the fire season. This knowledge can have a significant impact on the timing of management actions that are associated with an increased risk of a forest fire being ignited; such as prescribed burning.

The seasonal response of fire severity to climate change is also important to understand. Past studies have also generalized changes in fire severity over large areas and an annual time step. This can result in an incorrect or vague estimate in the seasonal fire severity response to climate change. For example, Stocks *et al*. (1998) predicted that across Russia and Canada's Boreal forest fire severity could double in the summer with 'modest increases' in spring and fall fire severity. What does a 'modest increase' constitute and what aid is this rating to forest managers? In this study the change in fire severity was found to differ substantially across seasons. The 95% increase in summer fire weather is in agreement with the findings of Stocks *et al*. (1998) but the spring and fall increases differ from what could be considered as a 'modest increase'. The predicted increase in the spring fire severity alone is consistent with the annual increase predicted by the previous studies described above. These studies do not consider this increase as modest. The local and seasonal level response of fire severity and fire season length to climate change suggests that the North Okanagan will experience an increase in fire season length along with an increase in fire weather severity. The risk of successful fire ignition and propagation will expand earlier into the spring and will reach its highest probability during the summer season. The increased length and severity of the fire season will have significant impacts on fire behaviour and fire prevention and suppression costs. For forest managers this may result in a reduction in summer operations; for the public, increased restrictions on forest-based recreational activities may be implemented, and for fire managers increased planning and resources may be required to mitigate the increased fire risk. Despite these actions, the chance of a forest fire occurring will continue to increase due the climate change-driven increase in fire season length and fire weather severity. This will decrease our ability to successfully suppress fires while increasing the economic and ecological costs of future fires. The relationship between fire weather severity and burned area is linear (Flannigan & Van Wagner, 1991). If this relationship holds for the North Okanagan, by the 2085 (2070–2100) climatic period a 42% increase in the area burned during spring fires, a 95% increase during summer fires and a 30% increase during fall fires are predicted.

The results of the fire behaviour analysis identified that statistically significant changes are expected in mean fire behaviour within each main ecosystem type. Although much variation exists and the significance of some of the responses is lost at a smaller significance level, a general increase in fire behaviour is predicted. The interaction between fire weather and fuel types suggests that fires will potentially be more volatile and difficult to control as they shift from a mean behavioural regime of surface fires with torching to crown fires. The increase in fire behaviour correlates well with the increase in fire weather severity. Increased fire weather severity is supposed to reflect increased severity in fire behaviour and difficulty in fire suppression (Van Wagner, 1987). The shift from surface fires to crown fires supports this assumption, and also the assumption that the area burned is linearly related to fire weather severity. As mentioned above, the interaction of topography was not considered here, but it is the focus of subsequent research (see Nitschke, 2006). The absence of topography likely does not confound the assumption to a great degree as climate and weather were found by Carey *et al*. (2006) to be generally more important than topography for determining area burned. Changes in fuel flammability and ignition sources due to climatic change also need to be considered since these may influence area burned along with changes in fire weather.

The predicted increase in fire season length, fire weather severity and the resultant shift in fire behaviour regime will likely result in larger, more intense and more frequent fires that may influence the ability of forest managers to maintain a sustainable timber supply and conserve biodiversity. Increased fire frequency could facilitate the migration of vegetation by creating opportunities for fire-tolerant species and limiting the regeneration of fire-intolerant species (Noss, 2001). Understanding the potential threat of climate change on fire severity can provide an incentive for managers to design 'fire-smart' forest landscapes (see Hirsch *et al*., 2001) and to incorporate the impacts of climate change into sustainable forest management planning. Fire-smart management uses forest management practices to reduce the risk of fire on a landscape. The fire-smart management approach alters fuel composition and structure to decrease fire behaviour potential and increase the ability to successfully suppress fires (Hirsch *et al*., 2001).

In the light of the results identified in this study and their broad agreement with other studies, it seems logical that forest managers in the North Okanagan should begin to incorporate proactive fire management on their management areas, rather than relying only on reactive approaches (fire suppression). Miller & Urban (1999) identified that fire suppression has disrupted many historic fire regimes by allowing dead fuel to accumulate and understorey tree density to increase in many forests. As a consequence, fires have become less frequent but larger and more severe (Ryan, 2000). The 2003 fire season in British Columbia suggested strongly that a similar trend may be present in southern half of the province.

Integrated fire management needs to link fuel management with fire suppression to help reduce the risks posed by fire under future climatic conditions. The alteration of fuel structure and composition will help adapt landscapes to longer and more severe fire seasons. Such changes will also help in the mitigation of forest fires once they are initiated. Ancillary to the identification of when and how much fire potential will change is an understanding of where on a landscape fire risks will be the greatest. However, the interactions between fuels, topography and weather will not provide the detail required for managers to use at the operational level. The same holds true for investigations into fire weather. Although broad agreement exists at multiple levels, it is at the local level that results will be meaningful to forest managers and stakeholders.

Conclusion

This assessment of the vulnerability of fire weather and fire behaviour potential to climatic change has shown that significant changes can be expected on the TFL 49 landscape in the North Okanagan region of British Columbia, Canada. The study predicted that an increase in fire season length should be expected, with the majority of the increase occurring in the spring. Significant increases in fire weather severity for all seasons were predicted. The summer season could potentially experience a doubling in fire weather severity by 2070 if climate change occurs as modelled. The increase in fire weather severity is acknowledged by many as being an indicator for increases in fire size (Flannigan & Van Wagner, 1991; Flannigan *et al*., 2003).

A significant increase in fire behaviour was also predicted. Fire behaviour is predicted to shift from predominantly surface fire with torching regimes to an intermittent crown fire regime in three of the ecosystems on the landscape, while in the other two ecosystems shift from a mixed surface fire with torching – intermittent crown fire regime to a mixed intermittent crown fire – full crown fire regime could be expected. The consensus is that the escalation in fire behaviour due to increased severity in fire weather will make fires more volatile and difficult to suppress (Amiro *et al*., 2004) in the future.

If climate changes as predicted, forest managers and stakeholders that use the TFL 49 landscape can expect longer fire seasons and increased fire weather severity which will increase the risk of successful fire ignition. In addition, once a fire is ignited more severe fire behaviour can be expected that will increase the risk and danger faced by fire fighters and the general public living in the surrounding areas. To help reduce the future risk of increase fire severity and behaviour, there is a need for forest managers and stakeholders to consider incorporating proactive fire management practices to help adapt forested landscapes to more severe fire regimes in the future. The achievement of sustainable forest management requires that adaptation strategies take precedent over mitigation strategies if the risk associated with forest fires is to be reduced under future climates.

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