Potential changes in monthly fire risk in the eastern Canadian boreal forest under future climate change

Héloïse Le Goff, Mike D. Flannigan, and Yves Bergeron

Abstract: The main objective of this paper is to evaluate whether future climate change would trigger an increase in the fire activity of the Waswanipi area, central Quebec. First, we used regression analyses to model the historical (1973–2002) link between weather conditions and fire activity. Then, we calculated Fire Weather Index system components using 1961–2100 daily weather variables from the Canadian Regional Climate Model for the A2 climate change scenario. We tested linear trends in 1961–2100 fire activity and calculated rates of change in fire activity between 1975–2005, 2030–2060, and 2070–2100. Our results suggest that the August fire risk would double (+110%) for 2100, while the May fire risk would slightly decrease (–20%), moving the fire season peak later in the season. Future climate change would trigger weather conditions more favourable to forest fires and a slight increase in regional fire activity (+7%). While considering this long-term increase, interannual variations of fire activity remain a major challenge for the development of sustainable forest management.

Résumé : Le principal objectif de cet article est d'évaluer si les changements climatiques futurs vont conduire à une augmentation de l'activité des feux dans la région de Waswanipi, dans le centre du Québec. Tout d'abord, nous avons utilisé des régressions linéaires pour modéliser la relation historique (1973–2002) entre les conditions météorologiques et l'activité des feux. Ensuite, nous avons calculé les composantes du système de l'Indice Forê-Météo à partir des simulations quotidiennes des conditions météorologiques du Modèle Régional Canadien du Climat pour le scénario A2 de changements climatiques (1961–2100). Nous avons testé les tendances linéaires de l'activité des feux sur la période 1961–2100, et calculé les taux de changement entre 1975–2005, 2030–2060, et 2070–2100. Nos résultats suggèrent que le risque de feu du mois d'août pourrait doubler (+110 %) d'ici 2100 alors que celui du mois de mai pourrait diminuer (–20 %). Ainsi, le pic saisonnier de l'activité des feux pourrait survenir plus tard dans la saison. Les changements climatiques futurs pourraient également créer des conditions plus favorables aux incendies forestiers, et donc à une légère augmentation de l'activité régionale des feux (+7 %). Bien que nos résultats suggèrent une augmentation à long terme de l'activité des feux, la variabilité interannuelle des feux demeure un défi important pour le développement d'un aménagement forestier durable.

Introduction

In boreal forests, fire is one of the main ecological processes shaping the forest mosaic. In return, regional fire regimes are influenced by forest structure and composition, topography, human activity (land use and ignition), and climate and weather (mainly drought, lightning, and wind). In Canada, climate and weather are the dominant controls of fire activity in boreal forests (Bessie and Johnson 1995; Carcaillet et al. 2001; Le Goff et al. 2007, 2008; Drever et al. 2008, 2009; Balshi et al. 2009). Climate change has direct and indirect effects on forest ecosystems. Direct effects include the alteration of species growth, reproduction, and migration. Indirect effects correspond to modifications of disturbance regimes such as forest fires, insect outbreaks, and diseases (Dale et al. 2001). Indirect effects, such as changes in fire regimes, may in fact have more dramatic impacts than direct effects (Weber and Flannigan 1997). While the impacts of climate change on forest ecosystems are extensively documented, climate change issues are generally not taken into account in the forest management planning process, because they are considered by forest managers to be too complex and uncertain to be included in deterministic timber calculations (Brumelle et al. 1990; Borchers 2005; Hoogstra and Schanz 2008). In fact, scientists have often failed to give information at time and spatial scales relevant and compatible with forest management planning (Burton 1998; Johnston et al. 2006; Le Goff et al. 2009).

Because of their connection with climate, forest fires may be viewed as a major vulnerability of forest management to climate change (Le Goff et al. 2005, 2007, 2008, 2009). This study contributes to the research effort made to provide information about potential impacts of climate change at a

Received 14 January 2009. Accepted 14 September 2009. Published on the NRC Research Press Web site at cjfr.nrc.ca on 9 December 2009.

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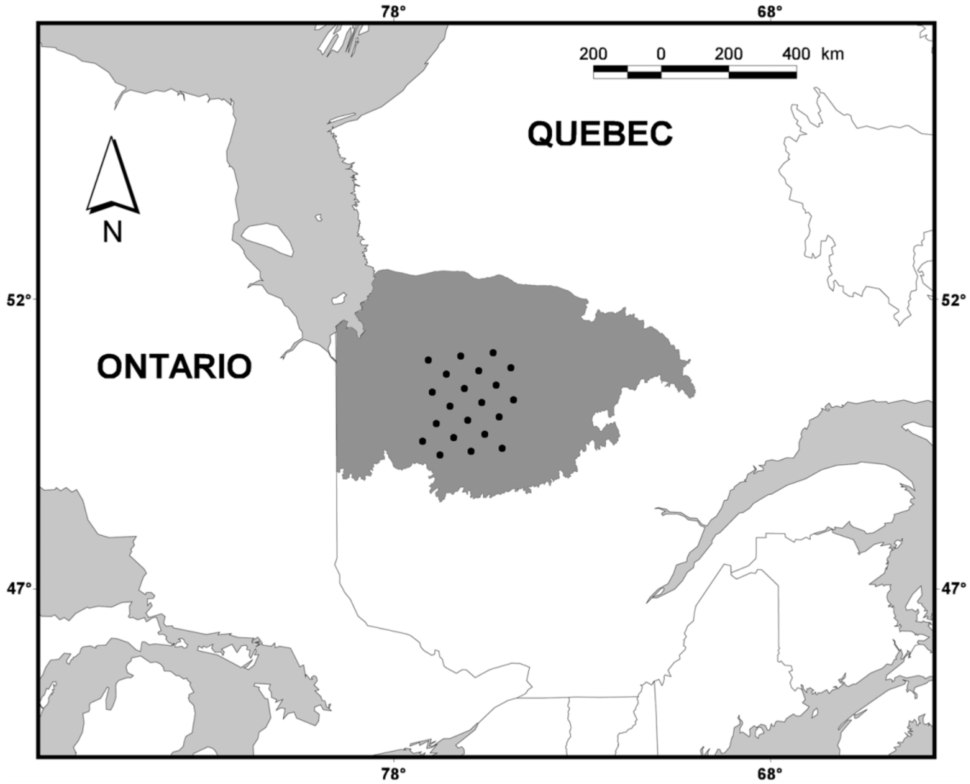
 doi:10.1139/X09-153

Fig. 1. Location of the study area. The grey area corresponds to the western black spruce – feather moss bioclimatic subdomain. The points indicate the Canadian Regional Climate Model cells covering the Waswanipi area.



spatial scale closer to the management scale, by using a study area covering few management units. Although available only for the A2 climate change scenario, the Canadian Regional Climate Model (CRCM) provides continuous daily climate outputs from 1961 to 2100 to examine future climate conditions with a resolution of tens of kilometres, while preceding research used General Circulation Model (GCM) outputs with a spatial resolution of hundreds of kilometres (Flannigan et al. 2005; Nitschke and Innes 2008*a*; Drever et al. 2009). We used CRCM daily weather outputs to calculate future fire conditions and future fire activity using regression modelling.

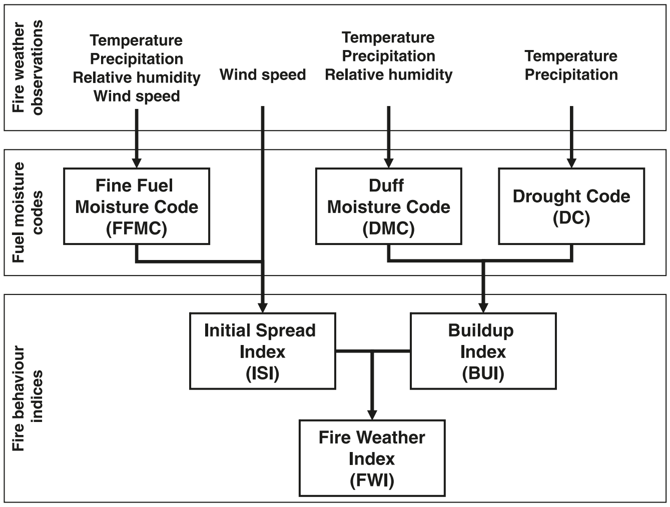
The aim of this paper is to evaluate whether future climate change would trigger an increase in the fire activity for the Waswanipi area, central Quebec. The specific objectives are (*i*) to model 1961–2100 fire activity (area burned and annual number of fires) using CRCM-predicted Fire Weather Index (FWI) system components for the western black spruce – feather moss subdomain and for the Waswanipi area using a regression approach; and (*ii*) to evaluate whether temporal trend can be detected in the predicted regional fire activity. First, we used multiple linear regressions to estimate the 1973–2002 fire activity (annual area burned and annual number of fires) using weather variables and fire weather indices. We also used logistic regression to estimate the monthly fire risk, defined here as the monthly probability of having a large (>500 ha) or very large (>2000 ha) burned area. Then we used daily 1961–2100 outputs from the CRCM to estimate future fire activity using previously calculated models. We tested linear trends in estimated fire activity for the 1961–2100 period and calculated rates of change in fire activity parameters between three reference periods: 1975–2005, corresponding to the current level in atmospheric CO_2 ($1 \times CO_2$), 2030–2060 ($2 \times CO_2$), and 2070–2100 ($3 \times CO_2$). Finally, we examined future changes in monthly fire risk distribution across the fire season for the three reference periods.

Data and methods

Study area

We examined the fire–climate relationship in the Waswanipi area, central Quebec. This territory is about 15 000 km^2 and is situated in the western black spruce – feather moss bioclimatic subdomain (Robitaille and Saucier 1998) (Fig. 1). It is composed of continuous boreal forest, where stands are dominated by black spruce (*Picea mariana* (Mill.) BSP) growing on thick glaciolacustrine tills originating from the Ojibway proglacial lake (Robitaille and Saucier 1998). Jack pine (*Pinus banksiana* Lamb.) is abundant on coarse-textured soils, while mixed stands of aspen (*Populus tremuloides* Michx), white birch (*Betula papyrifera* Marsh.), white spruce (*Picea glauca* (Moench) Voss), and balsam fir (*Abies balsamea* (L.) Mill.) can be found on upland till soils (Rowe 1972). To model the fire–climate relationship we calculated regression analyses for two territories: the Waswanipi area (15 000 km^2) and the western black spruce – feather moss bioclimatic subdomain (which encloses the Waswanipi area). We used two different territories, as the regression approach used to establish the historical fire–climate

Fig. 2. Structure of the Fire Weather Index System (adapted from Van Wagner 1987).



relation usually generates better results for larger territories owing to a smaller number of years with no fire activity.

According to the 1971–2000 climate normals from the Chapais weather station (49°47′N, 74°51′W, altitude 396.20 m), the area has 1235 degree-days per year above 5 °C and around 961 mm of precipitation, with one-third falling as snow. February is the coldest month and July the warmest, with a daily mean temperature of –16.6 and 16.3 °C, respectively (Environment Canada 2004).

Fire data

We used the provincial fire data provided by the ministère des Ressources naturelles et de la Faune du Québec for 1973–2007. This database reports all fires from all origins (from lightning as well as from human activities). We selected all fires >10 ha for our analyses to eliminate very small fires that were not contributing to the area burned. These data encompass the period during which systematic fire detection in the restricted fire management zone was made by detection planes, which only began in the late 1960s (Blanchet 2003).

We summarized the total area burned and the total number of fires for each day of the fire season considered. For the fire–climate analyses, we set the fire season from 1 May to 31 August, since this period accounted for more than 99% of the 1973–2007 annual area burned in the Waswanipi area.

No transformation allowed normality to be achieved at the monthly step because of the high frequency of months with no fire. Because of these numerous nonfire months, the monthly area burned variable behaves rather like a binomial variable. This property oriented our analyses to logistic regressions to model the monthly fire risk rather than to linear multiple regressions to model the total area burned in a month (see Flannigan et al. 2005). The fire risk is defined here as the monthly probability of having a large (>500 ha) or very large (>2000 ha) burned area.

Historical meteorological data

The FWI system (Van Wagner 1987) is used across Canada to evaluate the daily fire risk based on local daily weather data. It consists of moisture codes and fire behaviour indices calculated from the daily temperature, 24 h accumulated precipitation, relative humidity, and wind speed (Fig. 2; Van Wagner 1987; Wotton 2008). The three moistures codes track moisture in different levels of the forest floor. The Fine Fuel Moisture Code (FFMC) evaluates the moisture content in small, readily consumed fuels on the surface of the forest floor. The FFMC indicates the ease of ignition and flammability of fine fuels. The Duff Moisture Code (DMC) measures the moisture content of the moderate organic layers of the forest floor, where litter begins to decay. It provides an estimate of consumption of these duff layers and of medium-size woody debris. The Drought Code (DC) is an indicator of the moisture content of deep layers of the forest floor and of large down and dead woody debris on the forest floor. The Buildup Index (BUI) is a combination of the DMC and DC. It evaluates the potential fuel available for surface fuel consumption by the passing fire front. The Initial Spread Index (ISI) is a combination of FFMC and wind speed; it evaluates the potential rate of spread of a fire. Finally, the FWI is a combination of the BUI and the ISI, and the Daily Severity Rating (DSR) is essentially a logarithmic transformation of the FWI. Here, we evaluated whether one or several of these FWI components could provide good estimates of the regional fire activity in central Quebec, Canada.

Daily temperature, precipitation, wind speed, and relative humidity from 1 May to 31 August for 1960–2007 were extracted using BioSim 9 for the centre of the Waswanipi area (Régnière and Saint-Amant 2008). For each weather variable, BioSim 9 provided the mean daily value from the three nearest weather stations based on an inverse weighted spatial interpolation. Depending on the year considered, the selected weather stations were situated between 26 km (1979, weight 75.5%) and 408 km (1993, weight 17.6%) with a mean distance of 134 ± 64 km to the center of the study area. Values were adjusted for distance and elevation. We calculated annual and monthly mean, minimum and maximum values for each weather variable and FWI components from the daily 1960–2007 data set. We used these potential predictors (Table 1) in the linear regression analysis to model the log-transformed annual area burned and the log-transformed annual number of fires, and in the logistic regression analysis to model the monthly fire risk.

Historical fire–weather relation: annual step

The historical link between annual fire activity (log-transformed area burned and log-transformed number of fires), weather variables, and FWI components was calculated using multiple linear regressions (Flannigan et al. 2005; Bergeron et al. 2006) using SAS version 9.1 (SAS Institute Inc. 2000). The structure of the linear models is

$$[1] \quad Y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i + \varepsilon_j$$

where Y is the log-transformed annual area burned (or the log-transformed annual number of fires) in the territory investigated (Waswanipi area or western black spruce – feather moss subdomain), α is a constant, β_i is the regression coefficient estimate of the variable x_i selected among

Table 1. Description of the candidate explanatory variables for the linear (annual) and logistic (monthly) regression analyses.

Name	Description
TEMPme	Mean temperature
TEMPma	Maximum temperature
RAINme	Mean precipitation
RAINma	Maximum precipitation
RAINtot	Total precipitation
RHme	Mean relative humidity
RHma	Maximum relative humidity
RHmi	Minimum relative humidity
WSme	Mean wind speed
WSma	Maximum wind speed
FFMCme	Mean fine fuel moisture code
FFMCma	Maximum fine fuel moisture code
DMCme	Mean duff moisture code
DMCma	Maximum duff moisture code
DCme	Mean drought code
DCPma	Maximum drought code
ISIme	Mean initial spread index
ISIma	Maximum initial spread index
BUIme	Mean buildup index
BUIma	Maximum buildup index
FWIme	Mean fire weather index
FWIma	Maximum fire weather index
DSRme	Mean daily severity index
DSRma	Maximum daily severity index

the candidate explanatory variables (Table 1), and ε_j is the standard error associated with the model.

Multiple regression models were compared and evaluated using different statistics in addition to the adjusted coefficient of determination and the standard error of the estimates. The *F* ratio was used to evaluate the predictive capability of the model, considering the number of variables selected. The *F* ratio is obtained by dividing the explained variance by the unexplained variance. We used the Akaike information criterion corrected for small sample sizes (AICc; see Mazerolle 2006) to select the best model among three sets of candidate explanatory variables: weather variables only, FWI components only, and weather variables and FWI components taken together. We also reported the Bayesian information criterion (BIC). The BIC is another information criterion for model selection that we used to compare with the result obtained using the AICc. As underlined by Girardin et al. (2008), the empirical modelling provides evidence of statistical association between forest fire activity and climate, but only suggests possible biological relations (Arbaugh and Peterson 1989). Using a threshold of $p < 0.05$, there is typically a 5% chance that some of the 24 potential predictor variables may be retained in spite of weak biological justification or because of spurious relationships. Selected variables that had illogical ecological relationships to the model (e.g., positive influence of relative humidity or negative influence of FWI on fire activity) were thus manually removed from the candidate explanatory variables, and models were recalculated until all variables taken by the model were ecologically sound.

The stability of the regression model was tested using a split-sample calibration–verification scheme. Regressions were calculated for the entire time period of 1973–2007. Variables selected were then entered in a complete regression over two subperiods: 1973–1990 and 1991–2007. The regression coefficients estimated for one subperiod (calibration period) were then applied to the selected variables over the other subperiod (verification period) (see Girardin 2007). The strength of the relationship between the regression models and observations was measured using Pearson's correlation coefficients.

Historical fire–weather relation: monthly step

When examined at the monthly time step, the area burned produced many months without fire, so this variable was treated as a binomial variable. We used logistic regression analyses to model the monthly fire risk, using monthly weather variables and FWI components as potential explanatory variables. Monthly fire risk is defined here as the probability to have a month with area burned over 500 or 2000 ha. The structure of the logistic model is

$$[2] \qquad P_{\mathrm{FIRE}} = \frac{1}{1 - \exp(\alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i)}$$

where P_{FIRE} is the monthly fire risk, α is a constant, β_i is the regression coefficient, and x_i is the variable selected among the candidate explanatory variables (Table 1). We reported the same information criteria as for the previous regression analyses. Logistic regressions were calculated using the SAS version 9.1 (SAS Institute Inc. 2000) with a stepwise forward selection procedure. As for the linear regressions, we manually deleted aberrant variables.

To verify the stability of the regression coefficients, we calculated the logistic regression with the variables selected for the 1973–2007 period for two subperiods: from May 1973 to June 1990, and from July 1990 to August 2007. We evaluated submodels using the percentage of concordance (i.e., the proportion of events and nonevents correctly predicted by the submodels).

CRCM data

To anticipate climate conditions under climate change, we used daily 1961–2100 outputs from the CRCM. The CRCM contains a numerical description of the physical processes within the climate system. It is a limited-area regional climate model that uses boundary conditions provided by the Canadian GCM 2 (CGCM2) simulation (Plummer et al. 2006; Laprise 2008). While the Intergovernmental Panel on Climate Change (IPCC) recommends using a multimodel and multiscenario approach to determine an envelope of possible future impacts resulting from climate change (Bernstein et al. 2007), only one regional climate model and one climate change scenario (A2) with two realizations (simulations with different boundary conditions) were available for this study. The A2 scenario corresponds to a status quo situation (Nakicenovic et al. 2007): greenhouse gas emissions are continuing to rise at the current rate in a very heterogeneous world with a rapid population growth and regional-oriented economic development. It is generally considered the most pessimistic climate change scenario

Table 2. Multiple linear regression models for log-transformed annual area burned (AREA) and log-transformed number of fires (NB) for the western black spruce – feather moss bioclimatic subdomain (b) and the Waswanipi area (w) during the 1973–2002 period.

Model	Type	Coefficient	Variable	R_a^2	SE	F	p	AICc	BIC
AREAb	Weather	–0.674	RAINme	0.27	0.84	5	0.005	–7	–5
		–0.057	RHmi	—	—	—	—	—	—
		0.096	WSma	—	—		—	—	—
	FWI	0.160	BUIme	0.25	0.85	**12**	0.001	–9	–6
	All	0.103	WSma	**0.36**	**0.78**	10	0.000	**–13**	**–11**
		0.200	BUIme	—	—	—	—	—	—
NBb	Weather	–0.106	RAINma	0.40	0.22	12	0.000	–103	–100
		–0.01	RAINtot	—	—	—	—	—	—
	FWI	0.005	DCme	0.37	0.22	**20**	0.000	–102	–100
	All	–0.011	RAINma	**0.45**	**0.21**	14	0.000	**–105**	**–103**
		0.004	DCme	—	—	—	—	—	—
AREAw	Weather	–0.009	RAINtot	0.28	1.08	7	0.002	8	10
		0.137	WSma	—	—	—	—	—	—
	FWI	0.172	FFMCme	0.20	1.14	**9**	0.004	11	13
	All	–0.033	RAINma	**0.38**	**1.00**	8	0.000	**4**	**6**
		0.153	WSma	—	—	—	—	—	—
		0.198	BUIme	—	—	—	—	—	—
NBw	Weather	–0.014	RAINma	0.39	0.25	11	0.000	–93	–91
		–0.001	RAINtot						
	FWI	0.005	DCme	0.34	0.26	**18**	0.000	–91	–89
	All	–0.014	RAINma	**0.45**	**0.24**	14	0.000	**–96**	**–94**
		0.004	DCme						

Note: The model type corresponds to the set of potential explanatory variables used. "Weather" corresponds to the weather variables only (temperature, precipitation, wind speed and relative humidity), "FWI" corresponds to the FWI components only, and "All" corresponds to weather variables and FWI components taken together. Candidate explanatory variables are presented in Table 1. R_a^2, adjusted coefficient of determination; SE, standard error of the estimate; F, ratio of the model mean square to the error mean square; AICc, Akaike information criterion corrected for small sample sizes; BIC, Schwartz criterion. For each model type, the model with the lower AICc is presented. Among the model types, the model with the lowest AICc wa selected for the analyses. The best values for R_a^2, standard error, F ratio, AICc, and BIC are indicated in bold.

Table 3. Split-sample calibration–verification results for linear regression models of log-transformed annual area burned (AREA) and number of fires (NB) for the western black spruce – feather moss subdomain (b) and the Waswanipi area (w).

Model	Calibration period	p	Verification period	r
AREAb	1973–1990	0.049	1991–2007	0.57
	1991–2007	0.019	1973–1990	0.58
NBb	1973–1990	0.034	1991–2007	0.67
	1991–2007	0.001	1973–1990	0.43
AREAw	1973–1990	0.038	1991–2007	0.62
	1991–2007	0.012	1973–1990	0.51
NBw	1973–1990	0.151	1991–2007	0.75
	1991–2007	0.001	1973–1990	0.41

Note: p, significance of the regression in the calibration period; r, Pearson's correlation coefficient for the verification period between the modeled and observed data series (all coefficients are significant at $p < 0.05$). See Table 2 for a description of the regression models.

(Bernstein et al. 2007). Moreover, the examination of recent climate observations suggested that the A2 scenario used by the IPCC tends to underestimate changes in atmospheric CO_2 concentration and temperature (Rahmstorf et al. 2007), so the A2 scenario may actually provide conservative estimates of future climate conditions. We have chosen to use the CRCM rather than several GCMs with several scenarios (see Drever et al. 2009), as we were interested in a relatively small territory and wanted more accurate estimates of future climate conditions at the regional scale, which are more appropriate for forest management.

Continuous 1961–2100 daily weather data were obtained for the two available A2 realizations for the 21 CRCM cells covering the Waswanipi area (Fig. 1). Daily minimum and maximum temperatures were also extracted to calculate daily relative humidity at noon using the Goff–Gratch equation (Goff and Gratch 1946). We calculated the mean value of each meteorological variable for the 21 CRCM cells of each realization. Then we calculated the mean value of these two realizations. Monthly and annual mean and maximum were calculated using these mean daily values. The 1961–2007 median of temperature, wind speed, and relative humidity were adjusted according to the median of the corresponding historical series (by subtracting the difference between both medians). The rain series did not necessitate adjustments (the medians were close to each other). Then we used the adjusted daily meteorological variables to calculate the daily values of FWI components.

When compared to other months of the fire season, June accounted for the highest proportion of the annual area burned between 1973 and 2002 (42% for the Waswanipi

Table 4. Logistic stepwise regressions of monthly fire probability for the western black spruce – feather moss subdomain (b) and the Waswanipi area (w).

Model	Type	Coefficient	Variable	% concord.	AICc	BIC
P_{500b}	Weather	0.349	TEMPme	76	163	172
		–0.117	RHmi			
	FWI	0.186	BUIme	73	166	172
	All	0.193	TEMPma	**79**	**161**	**169**
		0.148	FFMCma			
P_{2000b}	Weather	0.393	TEMPme	79	145	153
		–0.139	RHmi			
	FWI	0.253	BUIme	80	137	**142**
	All	0.197	TEMPma	**82**	**134**	**142**
		0.221	BUIme			
P_{500w}	Weather	0.327	TEMPma	**83**	123	134
		–0.165	RHme			
	FWI	0.245	BUIme	**83**	**121**	**117**
	All	0.245	BUIme	**83**	**121**	**117**
P_{2000w}	Weather	0.416	TEMPme	**82**	113	121
		–0.161	RHmi			
	FWI	0.218	BUIme	**82**	**112**	**118**
	All	0.218	BUIme	**82**	**112**	**118**

Note: Candidate explanatory variables are presented in Table 1. % concord., proportion of events and nonevents correctly predicted by the model when compared to observed data; AICc, Akaike information criterion corrected for small sample size; BIC, Schwartz criterion. Best values for percentage of concordance, AICc, and BIC are indicated in bold.

area and 55% for the western black spruce – feather moss bioclimatic subdomain). For this reason, we examined the CRCM meteorological variables and FWI components for this month in particular. Annual area burned and annual number of fires were log-transformed to achieve normality according to a one-sample Kolmogorov–Smirnov test. Potential temporal trends were tested using a linear regression with time as predictor. To examine future trends in weather variables and FWI components, we extracted the mean and maximum June values, as this month accounted for the largest part of the annual area burned. We tested linear temporal trends in meteorological variables and FWI components using a simple linear regression with time as a predictor in Sigmaplot 11 (Systat Software, Inc. 2006). Normality of mean and maximum series was tested using a one-sample Kolmogorov–Smirnov test. Maximum rain and mean DSR failed this normality test.

Future fire activity and risk

We substituted historical weather variables and FWI components with those from CRCM in the best regression models previously identified to estimate 1961–2100 fire activity. We tested linear temporal trends in 1961–2100 log-transformed annual area burned and annual number of fires using linear regression with time as a predictor. Then we calculated mean values for 1975–2005 ($1 \times CO_2$), 2030–2060 ($2 \times CO_2$), and 2070–2100 ($3 \times CO_2$) to calculate the rates of change in fire activity ($2 \times CO_2$ / $1 \times CO_2$ and $3 \times CO_2$ / $1 \times CO_2$). We calculated rates of change in the monthly fire risk between the three reference periods for all months taken together, as well as for each month taken separately to verify whether future monthly distribution of fire risk will change under climate change.

Results

Historical fire–climate relation

Linear regression models of log-transformed annual area burned and log-transformed number of fires had adjusted R^2 from 0.20 to 0.45. The adjusted R^2 values were generally higher for the number of fires than for the area burned (Table 2). They were equivalent for the two territories considered. According to the lowest AICc, the best models always corresponded to the combination of weather variables and FWI components (Table 2). Verification analyses indicated good correlations between observed data and submodels (Pearson correlation coefficients >0.5, Table 3).

Monthly fire risk for the western black spruce – feather moss subdomain was best predicted by a combination of temperature and a FWI component (BUI or FFMC) (Table 4). Conversely, the Waswanipi fire risk was best explained by BUI only. For all models, concordance between modeled and observed data was around 80%. The verification displayed percentages of concordance >71% for all submodels, with percentages being more stable for the Waswanipi area (Table 5).

Climate change and future fire conditions

A positive linear trend was identified for the maximum and mean temperature ($p < 0.001$) and for maximum and mean relative humidity ($p < 0.001$, both) (Fig. 3). These trends were, however, less evident in the FWI components, as only maximum FWI and maximum DSR displayed a positive linear trend with time ($p = 0.030$ and $p = 0.017$, respectively) (Fig. 4).

Future fire activity in the Waswanipi area

A linear trend was detected for the 1961–2100 log-

Fig. 3. Mean (black) and maximum (gray) values for temperature (*a*), precipitation (*b*), relative humidity (*c*), and wind speed (*d*) as calculated for June 1961–2100 from the Canadian Regional Climate Model outputs for the A2 climate change scenario. Variables were adjusted according to the median of the historical data (1961–2007), except for the precipitation variable.

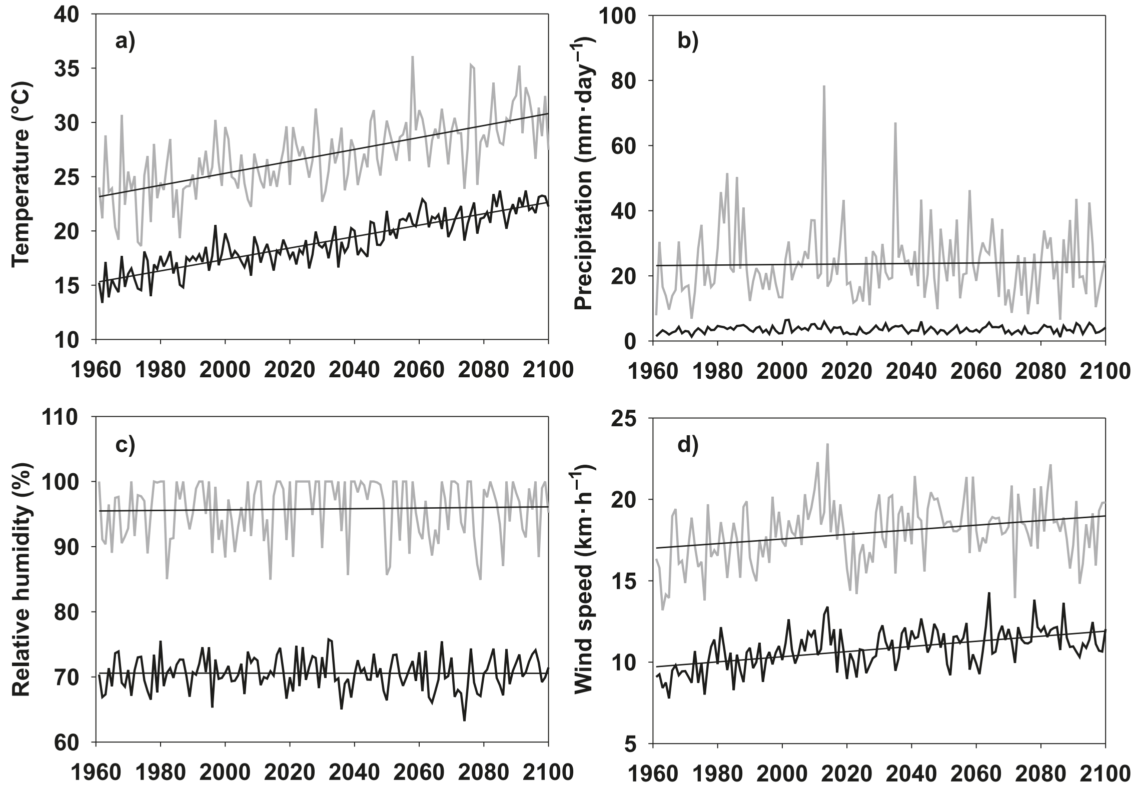


Table 5. Verification results for logistic regression models of the monthly fire probability for the western black spruce – feather moss subdomain (b) and the Waswanipi area (w).

Model	Calibration period	% concord.
P_{500b}	A	71.6
	B	86.5
P_{2000b}	A	78.3
	B	87.5
P_{500w}	A	82.7
	B	83.9
P_{2000w}	A	83.7
	B	81.8

Note: The monthly fire probability is defined as the probability to have a month with area burned over 500 ha (P_{500}) or 2000 ha (P_{2000}).We calculated the complete regression with variables selected for the 1973–2007 period for two subperiods: period A corresponds to the period from May 1973 to June 1990, and period B corresponds to the period from July 1990 to August 2007. The percentage of concordance (% concord.) indicates the proportion of events and nonevents correctly predicted by the model when compared to observed data.

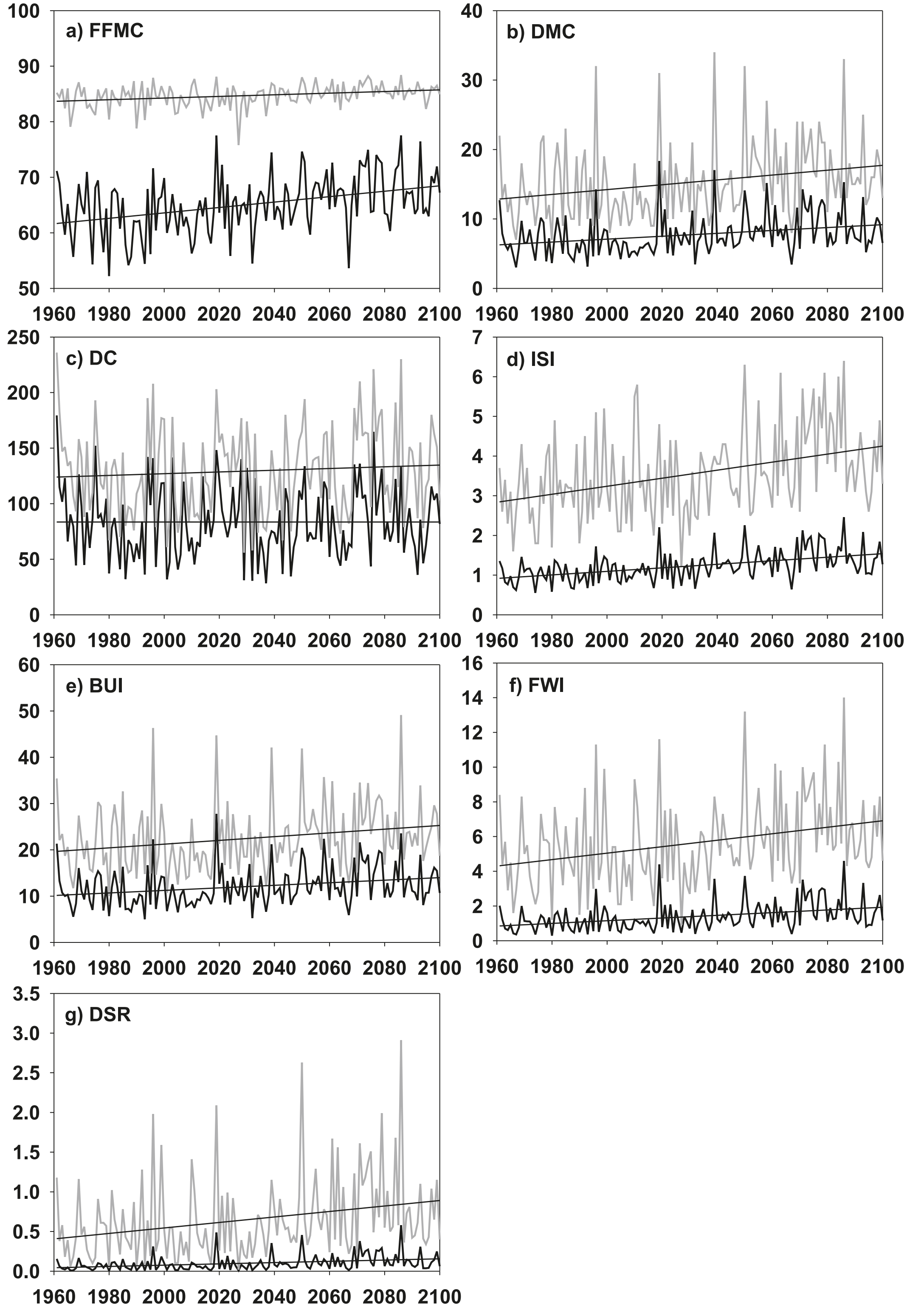
transformed annual area burned (R^2 = 0.13, p < 0.001), while no trend was detected for the annual number of fires (p = 0.47) (Fig. 5). The increasing trend in 1961–2100 log-transformed annual area burned was observable on the 10 year moving average, but the standard error associated with the model indicated a high interannual variation. When examining the rates of change between future and current periods, we observed a general increase in Waswanipi fire activity. This increase is more pronounced for the 3 × CO_2 period (2070–2100) than for the 2 × CO_2 period (2030–2060). By 2100, the annual area burned could increase by 7%, and the monthly fire risk could increase by 30%, with the highest increases observed in July (70%) and August (100%) (Table 6, Fig. 6). However, the annual number of fires did not exhibit changes, and the May fire risk displayed a decrease (–20%) (Table 6).

Discussion

Change in the fire season and fire management in Quebec

The monthly fire risk increased for June, July, and August, while the May fire risk slightly decreased between current and future time periods. These results suggest that spring fires may be less frequent in the future, while the fire risk would increase considerably in July and August in the future. This contrasts with the study of Wotton and Flannigan (1993), who suggested an earlier start of the fire season under climate change. Our study did not consider April, September, and October, because the area burned and

Fig. 4. Mean (black) and maximum (grey) values for the Fire Weather Index components as calculated for June 1961–2100 from the Canadian Regional Climate Model outputs for the A2 climate change scenario. FFMC, Fine Fuel Moisture Code; DMC, Duff Moisture Code; DC, Drought Code; ISI, Initial Spread Index; BUI, Buildup Index; FWI, Fire Weather Index; DSR, Daily Severity Rating. See Fig. 2 for the description of the FWI system.



the number of fire events during these months were too low to allow statistical analysis. However, these months may play an important role in the future fire season (Wotton and Flannigan 1993; Nitschke and Innes 2008*b*). The change in the fire risk distribution across the fire season represents a major challenge for the fire management strategy in Quebec.

Fig. 5. Log-transformed annual area burned (*a*) and log-transformed annual number of fires (*b*) for 1961–2100 in the Waswanipi area. The gray area indicates the 95% lower and upper limits of the error of the estimates. The thick, dark grey line indicates the moving mean (10 years) of the interannual estimates. Dotted lines indicate the 1961–2100 mean values of the estimates. See Table 2 for the description of regression models and Table 6 for the rates of change between reference periods.

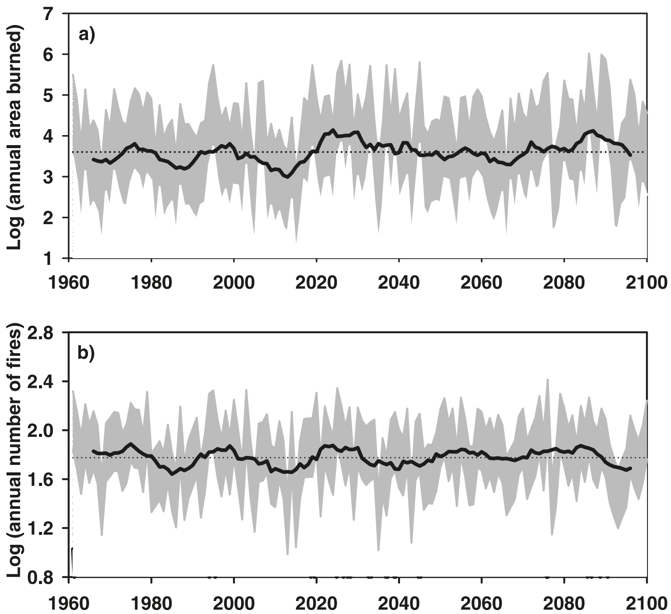
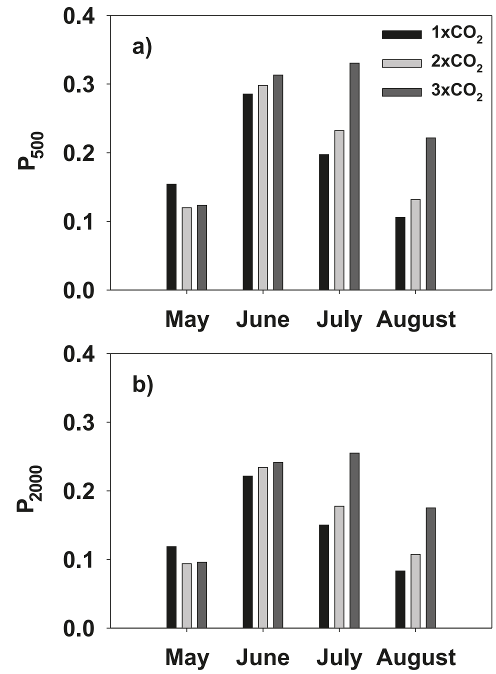


Table 6. Rates of change (%) in fire activity (annual area burned (AREA) and annual number of fires (NB)) in the Waswanipi area between future (2 × CO_2 or 3 × CO_2) and current (1 × CO_2, corresponding to the 1975–2005 period) mean values.

	Rate of change (%)	
Variable	2 × CO_2 (2030–2060)	3 × CO_2 (2070–2100)
LOG-AREA	4	7
LOG-NB	0	2
P500	5	33
P500 May	–22	–20
P500 June	4	10
P500 July	18	68
P500 August	25	109
P2000	7	34
P2000 May	–21	–19
P2000 June	6	9
P2000 July	18	70
P2000 August	29	110

While June is currently the main fire month, the future fire season would present a prolonged high fire risk from June to August. This suggests a prolonged effort of fire management, implying an increasing investment in fire control efforts. The fire management agency may more often face situations where its fire suppression capacity may be overwhelmed. The decrease observed in May could be linked to the increase in winter precipitation associated with climate change (Christensen et al. 2007), as the longer snow melt could delay the drying of forest fuels in spring.

Fig. 6. Anticipated changes in monthly fire risk under climate change in the Waswanipi area. The fire risk is defined here as the probability of having (*a*) large fire months (burned area >500 ha, P_{500}) or (*b*) very large fire months (burned area >2000 ha, P_{2000}). Changes in the fire risk were evaluated between three reference periods corresponding to an increasing atmospheric concentration of CO_2: 1975–2005 (1 × CO_2), 2030–2060 (2 × CO_2), 2070–2100 (3 × CO_2). Logistic regression models used to calculate fire risk are described in Table 4. See Table 6 for global rates of change.



Future fire activity under climate change

According to our results, the increase in fire-weather conditions (maximum FWI) as well as in fire activity (area burned) is relatively modest when compared to the results of other studies that used GCM data over the same territory (Flannigan et al. 2005; Bergeron et al. 2006). Future climate change would trigger fire-weather conditions more favourable to forest fires, and annual area burned will continue to increase when compared to the 1975–2005 reference period. Using the same linear regression approach, Flannigan et al. (2005) anticipated an increase of about 50%–100% in the area burned observed in the reference period 1975–1995 for the 2080–2100 period in the eastern part of the Boreal Shield ecozone. Bergeron et al. (2006) estimated that fire rate (annual proportion of area burned) would increase by 30% for 2080–2100 when compared to the rate for 1940–2003 in the Waswanipi area. The standard error associated with the fire activity estimates along with the use of a single climate change scenario (A2) constitute the main limitations of the interpretation of an increase in fire activity under climate change in the Waswanipi area. The main challenge in developing an ecosystem-based forest management plan is less this slight increase in fire activity and more the interannual variation in fire activity estimates. Yet our results suggest that fire will remain an important constraint for forest management in the context of climate change.

Wind is a key variable controlling fire activity, notably area burned and fire behaviour. This is confirmed by the selection of the maximum wind speed in the annual area burned models for the western black spruce – feather moss subdomain and for the Waswanipi area. However, no linear trend was detected in the 1961–2100 CRCM wind speed. Interestingly, the clear increase observed in temperature data over the 1961–2100 period is less perceptible in the FWI components, as only maximum FWI displayed a positive linear trend with time. Maximal DSR also displayed the same positive linear trend, as this index is essentially a log-transformed FWI. As speculated in previous work (Bergeron and Flannigan 1995), our results suggest that the increase in temperature alone is not a sufficient condition to lead to weather conditions favourable to forest fires. We postulate that in a certain measure, the increase in temperature would be compensated by the increase in relative humidity. While this might appear contradictory to the increasing linear trend observed in maximum FWI, this could be reconciled by considering the seasonality aspect. The variance explained by our linear models (R^2 from 0.36 to 0.48, using one to three predictors) is comparable to that of Flannigan et al. (2005; R^2 from 0.36 to 0.64, using one to four predictors).

Conclusions

To face current and future fire activity, several strategies might be developed. First, a diversified pool of management practices should be developed to enhance ecosystem resilience and resistance to environmental change in some cases, and to assist forest ecosystems to adapt to ongoing environmental change in other cases (Millar et al. 2007). This avenue consists in improving our fire management system by mapping intervention priorities and planning salvage logging modalities that satisfy sustainable forest management principles (Le Goff et al. 2005).

Second, as forest fires will remain a continuous constraint to forest operations and annual allowable cut calculations, current fire risk should be better integrated in annual harvesting calculations. As these calculations are implemented over time horizons where climate change impacts are expected, anticipated change in future fire risk should also be taken into account. Few studies identified approaches to take into account the potential timber losses linked to fire activity in the annual allowable cut calculations (Boychuk and Martell 1996; Armstrong 2004; Didion et al. 2007). Efforts should now be devoted to develop further these tools and to implement them in forest management.

Third, scientific tools to anticipate future fire regimes at time and spatial scales relevant for forest management should be continuously developed. Here, the 21 CRCM cells available for this study were insufficient to produce spatial analyses of future fire conditions and activity. Next steps should include the spatial mapping of these parameters across the province of Quebec, to plainly beneficiate the spatial resolution provided by the CRCM. We used a single model – single scenario approach as a first step in the use of the best available data, as our study is one of few using CRCM data (Flannigan et al. 2001; Amiro et al. 2001; Tymstra et al. 2007). However, future work will include other scenarios and other models to determine an envelope of possible future conditions under climate change. Statistical tools used to model fire activity using weather conditions are also being developed with, for example, the advent of the multivariate adaptive regression spline approach (Balshi et al. 2009). Here, we favoured a simple regression model including a small number of predictors to encourage potential applications as predictive tools for forest and fire management planning. Finally, a study combining climate parameters with lightning data and vegetation inputs would provide a more complete picture of fire regime controls (Krawchuck et al. 2006) and better reflect our current comprehension of regional fire regime dynamics.

Acknowledgements

Julie Fortin (Ministère des Ressources naturelles et de la Faune du Québec) provided the provincial fire data. Rémi Saint-Amant extracted the historical meteorological data from BioSim. We gratefully thank Travis Logan (Consortium Ouranos) for providing the data from the Canadian Regional Climate Model. We thank Alan Cantin and Lynn Gowman (Canadian Forest Service) for their help in computing FWI components. We also thank Lynn Gowman for editing the manuscript. Financial support was provided by the Sustainable Forest Management Network. Finally, we thank the two anonymous reviewers and the associate editor for providing comments that improved the quality of this paper.

References

Amiro, B.D., Stocks, B.J., Alexander, M.E., Flannigan, M.D., and Wotton, B.M. 2001. Fire, climate change, carbon and fuel management in the Canadian boreal forest. Int. J. Wildland Fire, **10**(4): 405–413. doi:10.1071/WF01038.

Arbaugh, M.J., and Peterson, D.L. 1989. Variable selection in dendroclimatology: an example using simulated tree-ring series. For. Sci. **35**: 294–302.

Armstrong, G.W. 2004. Sustainability of timber supply considering the risk of wildfire. For. Sci. **50**(5): 626–639.

Balshi, M.S., McGuire, A.D., Duffy, P., Flannigan, M., Walsh, J., and Melillo, J. 2009. Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. Glob. Change Biol. **15**(3): 578–600. doi:10.1111/j.1365-2486.2008.01679.x.

Bergeron, Y., and Flannigan, M.D. 1995. Predicting the effects of climate change on fire frequency in the southeastern Canadian boreal forest. Water Air Soil Pollut. **82**(1-2): 437–444. doi:10.1007/BF01182853.

Bergeron, Y., Cyr, D., Drever, C.R., Flannigan, M., Gauthier, S., Kneeshaw, D., Lauzon, È., Leduc, A., Le Goff, H., Lesieur, D., and Logan, K. 2006. Past, current, and future fire frequencies in Quebec's commercial forests: implications for the cumulative effects of harvesting and fire on age-class structure and natural disturbance-based management. Can. J. For. Res. **36**(11): 2737–2744. doi:10.1139/X06-177.

Bernstein, L., Bosch, P., Canziani, O., Chen, Z., Christ, R., Davidson, O., Hare, W., and Huq, S. Karoly, D., Kattsov, V., Kundzewicz, Z., Liu, J., Lohmann, U., Manning, M., Matsuno, T., Menne, B., Metz, B., Mirza, M., Nicholls, N., Nurse, L., Pachauri, R., Palutikof, J., Parry, M., Qin, D., Ravindranath, N., Reisinger, A., Ren, J., Riahi, K., Rosenzweig, C., Rusticucci, M., Schneider, S., Sokona, Y., Solomon, S., Stott, P., Stouffer, R., Sugiyama, T., Swart, R., Tirpak, D., Vogel, C., and Yohe, G. 2007. Climate change 2007: synthesis report. Intergovernmental Panel on Climate Change. Available online at http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf (last accessed on August 2008).

Bessie, W.C., and Johnson, E.A. 1995. The relative importance of fuels and weather on fire behaviour in subalpine forests. Ecology, **76**(3): 747–762. doi:10.2307/1939341.

Blanchet, P. 2003. Forest fires: the story of a war. Cantos International Publishing, Montreal, Que., Canada.

Borchers, J.G. 2005. Accepting uncertainty, assessing risk: decision quality in managing wildfire, forest resource values, and new technology. For. Ecol. Manage. **211**(1-2): 36–46. doi:10.1016/j.foreco.2005.01.025.

Boychuk, D., and Martell, D.L. 1996. A multistage stochastic programming model for sustainable forest-level timber supply under risk of fire. For. Sci. **42**(1): 10–29.

Brumelle, S., Stanbury, W.T., Thompson, W.A., Vertinsky, I., and Wehrung, G. 1990. Framework for the analysis of risks in forest management and silvicultural investments. For. Ecol. Manage. **36**(2-4): 279–299. doi:10.1016/0378-1127(90)90031-6.

Burton, I. 1998. Climate adaptation policies for Canada? Options politiques. **May**: 6–10.

Carcaillet, C., Bergeron, Y., Richard, P.J.H., Fréchette, B., Gauthier, S., and Prairie, Y.T. 2001. Change of fire frequency in the eastern Canadian boreal forests during the Holocene: Does vegetation composition or climate trigger the fire regime? J. Ecol. **89**(6): 930–946. doi:10.1111/j.1365-2745.2001.00614.x.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A., and Whetton, P. 2007. Regional climate projections. *In* Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *Edited by* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. Cambridge University Press, Cambridge, UK.

Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J., and Wotton, B.M. 2001. Climate change and forest disturbance. BioScience, **51**(9): 723–734. doi:10.1641/0006-3568(2001)051[0723:CCAFD]2.0.CO;2.

Didion, M., Fortin, M.-J., and Fall, A. 2007. Forest age structure as indicator of boreal forest sustainability under alternative management and fire regimes: a landscape level sensitivity analysis. Ecol. Model. **200**(1-2): 45–58. doi:10.1016/j.ecolmodel.2006.07.011.

Drever, R.C., Drever, M.C., Messier, C., Bergeron, Y., and Flannigan, M. 2008. Fire and the relative role of weather, climate and landscape characrteristics in the Great Lakes – St. Lawrence forest of Canada. J. Veg. Sci. **19**(1): 57–66. doi:10.3170/2007-8-18313.

Drever, C.R., Bergeron, Y., Drever, M.C., Flannigan, M., Logan, T., and Messier, C. 2009. Effects of climate on occurrence and size of large fires in a northern hardwood landscape: historical trends, future predictions, and implications for climate change in Témiscamingue, Québec. Appl. Veg. Sci. **12**(3): 261–272. doi:10.1111/j.1654-109X.2009.01035.x.

Environment Canada. 2004. Canadian climate normals [online]. Available from climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html?& [last accessed on August 2008].

Flannigan, M., Campbell, I., Wotton, M., Carcaillet, C., Richard, P., and Bergeron, Y. 2001. Future fire in Canada's boreal forest: paleoecology results and general circulation model – regional climate model simulations. Can. J. For. Res. **31**(5): 854–864. doi:10.1139/cjfr-31-5-854.

Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R., and Stocks, B.J. 2005. Future area burned in Canada. Clim. Change, **72**(1-2): 1–16. doi:10.1007/s10584-005-5935-y.

Girardin, M.P. 2007. Interannual to decadal changes in area burned in Canada from 1781 to 1982 and the relationship to Northern Hemisphere land temperatures. Glob. Ecol. Biogeogr. **16**(5): 557–566. doi:10.1111/j.1466-8238.2007.00321.x.

Girardin, M.P., Raulier, F., Bernier, P.Y., and Tardif, J.C. 2008. Response of tree growth to a changing climate in boreal central Canada: a comparison of empirical, process-based, and hybrid modelling approaches. Ecol. Model. **213**(2): 209–228. doi:10.1016/j.ecolmodel.2007.12.010.

Goff, J.A., and Gratch, S. 1946. Low-pressure properties of water from –160 to 212 °F. *In* Transactions of the American Society of Heating and Ventilating Engineers. Presented at the 52nd Annual Meeting of the American Society of Heating and Ventilating Engineers, New York. pp. 95–122.

Hoogstra, M.A., and Schanz, H. 2008. How (un)certain is the future in forestry? A Comparative assessment of uncertainty in the forest and agricultural sector. For. Sci. **54**: 316–327.

Johnston, M., Williamson, T., Price, D., Spittlehouse, D., Wellstead, A., Gray, P., Scott, D., Askew, S., and Webber, S. 2006. Adapting forest management to the impacts of climate change in Canada. BIOCAP synthesis paper [online]. Available from www.biocap.ca/ [last accessed on August 2008].

Krawchuk, M.A., Cumming, S.G., Flannigan, M.D., and Wein, R.W. 2006. Biotic and abiotic regulation of lightning fire initiation in the mixedwood boreal forest. Ecology, **87**(2): 458–468. doi:10.1890/05-1021. PMID:16637370.

Laprise, R. 2008. Regional climate modelling. J. Comput. Phys. **227**(7): 3641–3666. doi:10.1016/j.jcp.2006.10.024.

Le Goff, H., Leduc, A., Bergeron, Y., and Flannigan, M.D. 2005. The adaptive capacity of forest management to changing fire regimes in the boreal forest of Quebec. For. Chron. **81**: 582–592.

Le Goff, H., Flannigan, M.D., Bergeron, Y., and Girardin, M.P. 2007. Historical fire regime shifts related to climate teleconnections in the Waswanipi area, central Quebec, Canada. Int. J. Wildland Fire, **16**(5): 607–618. doi:10.1071/WF06151.

Le Goff, H., Girardin, M.P., Flannigan, M.D., and Bergeron, Y. 2008. Dendroclimatic inference of wildfire activity in Quebec over the 20th century and implications for natural disturbance-based forest management at the northern limit of the commercial forest. Int. J. Wildland Fire, **17**(3): 348–362. doi:10.1071/WF07080.

Le Goff, H., Flannigan, M., Bergeron, Y., Leduc, A., Gauthier, S., and Logan, K. 2009. Management solution to face climate change, the example of forest fires. *In* Ecosystem management in the boreal forest. *Edited by* S. Gauthier, M.-A. Vaillancourt, A. Leduc, L. De Grandpré, D. Kneeshaw, H. Morin, P. Drapeau, and Y. Bergeron. Presses de l'Université du Québec, Québec, Que., Canada.

Mazerolle, M.J. 2006. Improving data analysis in herpetology: using Akaike's information criterion (AIC) to assess the strength of biological hypotheses. Amphib.-Reptilia, **27**(2): 169–180. doi:10.1163/156853806777239922.

Millar, C.I., Stephenson, N.L., and Stephens, S.L. 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecol. Appl. **17**(8): 2145–2151. doi:10.1890/06-1715.1. PMID:18213958.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Tae Yong Jung, A., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., and Zhou, D. 2007. Emission scenarios [online]. Intergovernmental Panel on Climate Change. Available from http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0 [last accessed on August 2008].

Nitschke, C.R., and Innes, J.L. 2008*a*. Integrating climate change into forest management in South-Central British Columbia: an assessment of landscape vulnerability and development of a climate-smart framework. For. Ecol. Manage. **256**(3): 313–327. doi:10.1016/j.foreco.2008.04.026.

Nitschke, C.R., and Innes, J.L. 2008*b*. Climatic change and fire potential in South-Central British Columbia, Canada. Glob. Change Biol. **14**(4): 841–855. doi:10.1111/j.1365-2486.2007.01517.x.

Plummer, D.A., Caya, D., Frigon, A., Côté, H., Giguère, M., Paquin, D., Biner, S., Harvey, R., and De Elia, R. 2006. Climate and climate change over North America as simulated by the Canadian RCM. J. Clim. **19**(13): 3112–3132. doi:10.1175/JCLI3769.1.

Rahmstorf, S., Cazenave, A., Church, J.A., Hansen, J.E., Keeling, R.F., Parker, D.E., and Somerville, R.C.J. 2007. Recent climate observations compared to projections. Science, **316**(5825): 709. doi:10.1126/science.1136843. PMID:17272686.

Régnière, J., and Saint-Amant, R. 2008. BioSIM 9 – User's Manual. 2008. Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, Quebec, Que. Inf. Rep. LAU-X-134E.

Robitaille, A., and Saucier, J.P. 1998. Paysages régionaux du Québec méridional. Les Publications du Québec, Sainte-Foy, Canada.

Rowe, J.S. 1972. Forest regions of Canada. Environment Canada, Ottawa, Ont.

SAS Institute Inc. 2000. SAS OnlineDoc, version 8. SAS Institute Inc., Cary, N.C.

Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D., Hirsch, K.G., Logan, K.A., Martell, D.L., and Skinner, W.R. 2003. Large forest fires in Canada, 1959–1997. J. Geophys. Res. **108**(D1): 8149. doi:10.1029/2001JD000484.

Systat Software, Inc. 2006. SIGMAPLOT 10. San Jose, Calif., USA.

Tymstra, C., Flannigan, M.D., Armitage, O.B., and Logan, K. 2007. Impact of climate change on area burned in Alberta's boreal forest. Int. J. Wildland Fire, **16**(2): 153–160. doi:10.1071/WF06084.

Van Wagner, C.E. 1987. The development and structure of the Canadian forest fire weather index system. For. Tech. Rep. 35, Can. For. Serv., Ottawa, Ont., Canada.

Weber, M.G., and Flannigan, M.D. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. Environ. Rev. **5**(3-4): 145–166. doi:10.1139/er-5-3-4-145.

Wotton, B.M. 2008. Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research. Environ. Ecol. Stat.. doi:10.1007/s10651-007-0084-2.

Wotton, B.M., and Flannigan, M.D. 1993. Length of the fire season in a changing climate. For. Chron. **69**: 187–192.