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Effects of climate on occurrence and size of large fires in a northern hardwood landscape: historical trends, forecasts, and implications for climate change in Témiscamingue, Québec

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Abstract

Questions: What climate variables best explain fire occurrence and area burned in the Great Lakes-St Lawrence forest of Canada? How will climate change influence these climate variables and thereby affect the occurrence of fire and area burned in a deciduous forest landscape in Témiscamingue, Québec, Canada?

Location: West central Québec and the Great Lakes-St Lawrence forest of Canada.

Methods: We first used an information-theoretic framework to evaluate the relative role of different weather variables in explaining occurrence and area burned of large fires (>200 ha, 1959-1999) across the Great Lakes-St Lawrence forest region. Second, we examined how these weather variables varied historically in Témiscamingue and, third, how they may change between the present and 2100 according to different scenarios of climate change based on two Global Circulation Models.

Results: Mean monthly temperature maxima during the fire season (Apr-Oct) and weighted sequences of dry spells best explained fire occurrence and area burned. Between 1910 and 2004, mean monthly temperature maxima in Témiscamingue showed no apparent temporal trend, while dry spell sequences decreased in frequency and length. All future scenarios show an increase in mean monthly temperature maxima, and one model scenario forecasts an increase in dry spell sequences, resulting in a slight increase in forecasted annual area burned.

Conclusion: Despite the forecasted increase in fire activity, effects of climate change on fire will not likely affect forest structure and composition as much as natural succession or harvesting and other disturbances, principally because of the large relative difference in area affected by these processes.

Keywords: Area burned; Deciduous; Dry spells; Fire occurrence; Global Circulation Model; Information-theoretic framework; Mixed-distribution; Mixed-effects modeling; Temperature.

Introduction

Although infrequent, fire is an important influence on the structure and composition of northern hardwood forests in eastern North America (Whitney 1986; Drever et al. 2006). Yet, outside some general observations, the possible consequences of climate change on fire have been little studied in this biome. While climate change across Canada is poised to increase the frequency of severe fire weather, area burned, ignitions and fire season length (Flannigan et al. 2005), these increases will likely occur mostly in the north and west, with some southern and eastern regions experiencing a decrease in these variables (Flannigan et al. 2001, 2005).

Across the northern hardwoods of the Great Lakes-St Lawrence forest region (Rowe 1972), climatic conditions amenable to fire ("fire weather") have been shown to exert a stronger influence on fire occurrence and area burned than topographical or biophysical variables (Drever et al. 2008). The principal focus in this study was therefore fire weather variables. More specifically, our study objectives were to: (1) simultaneously test three different hypotheses that relate weather variables to the occurrence probability of fire and area burned in the northern hardwoods of the Great Lakes-St. Lawrence forest region; (2) characterize past trends in the weather variable(s) that best predicted fire occurrence and area burned for a northern hardwood landscape in Témiscamingue, Québec, Canada; and (3) evaluate how various scenarios of climate change will potentially affect fire occurrence and area burned in this particular landscape. We focus on Témiscamingue because the northern hardwoods of western Quebec are transitional between the regions where a decrease and an increase in fire frequency is forecasted (Flannigan et al. 2001). Moreover, there exists an equivocal balance of evidence regarding climate change effects in this area. Contrary to the slight increase forecasted by Flannigan et al. (2001), Bergeron et al. (2006) forecasted a decrease in fire frequency with climate change, even with a tripling of atmospheric CO_2 concentrations. A more in-depth analysis for this particular landscape may resolve these differences.

Previous work on climatic conditions and their effects on fire occurrence and extent suggests three related hypotheses. These hypotheses and accompanying predictions were:

(1) *Water balance* – occurrence of fire and area burned are functions of precipitation surplus or deficit, the difference between total precipitation during the fire season and potential evapotranspiration. More and larger fires are predicted to occur with precipitation deficits than with surpluses (Drever et al. 2008).

(2) *Temperature and dry spells* – occurrence of fire and area burned are functions of the mean of monthly temperature maxima and weighted dry spell sequences. The higher the mean temperature and weighted dry spell sequences, the greater the number of fires and the greater the area burned (Flannigan & Harrington 1988).

(3) *Fire weather severity* – occurrence of fire and area burned vary as functions of fire weather severity, as estimated by the maximum value of the Canadian Drought Code (DC; Turner 1972) during a given fire season. Higher Drought Code values are associated with more fires and increased area burned (Girardin et al. 2004).

In this study, the weight of evidence for each of these hypotheses was compared under an information-theoretic framework that allowed us to identify the fire weather variables most strongly associated with fire occurrence and area burned.

Methods

Study areas: Great Lakes-St Lawrence forest region and Témiscamingue, Québec

The Great Lakes-St Lawrence forest region of Canada (Fig. 1, modified from Rowe 1972) extends from south-eastern Manitoba to the Saguenay valley north of the St Lawrence River in Québec. Also termed the Mixedwood Shield (CEC 1997), this region has low relief with rolling and forested hills, many lakes, wetlands, outwash plains and other glacial features. Mean elevation is approximately 360 m, ranging from zero to 1120 m a.s.l.. This 405 964 km^2 region has forest cover over 98% of its land area.

The study landscape in Témiscamingue (approx. 46°40′N; 78°45′W) occurs near the northern limit of Great Lakes-St Lawrence forest region (Fig. 1). This forest is classified as the western Sugar maple-Yellow birch bioclimatic domain (Robitaille & Saucier 1998). Sugar maple (*Acer saccharum* Marsh.) and yellow birch (*Betula alleghaniensis* Britt.) dominate mesic, mid-slope sites. Other characteristic tree species of this region are red pine (*Pinus resinosa* Ait.) and white pine (*P. strobus* L.).

Covering 179 300 ha, the Témiscamigue landscape is delineated on the west by the Ottawa River and its remaining boundaries correspond to "ecological districts" (i.e., relatively homogeneous units based on topography, elevation, surficial deposits, parent materials and hydrology; Robitaille & Saucier 1998). The area has a subpolar, continental climate with cold winters and warm summers. Mean annual temperature is 4.4°C, based on the nearest meteorological station (Barrage Témiscamingue: 46°42′N, 79°6′W, 181 m a.s.l.). Mean annual precipitation is 963 mm, with 23% (226 mm) falling as snow. The landscape's gentle to moderately steep hills with rounded and often rocky summits are formed from undifferentiated or rocky glacial tills of metamorphic or sedimentary origin. Soils are principally humo-ferric podzols (Brown 1981). Mean elevation is 311 m a.s.l. and slopes average approximately 9%. Forests extend across almost all the land, while lakes and other large water bodies cover about 20% of the total area. While several large fires

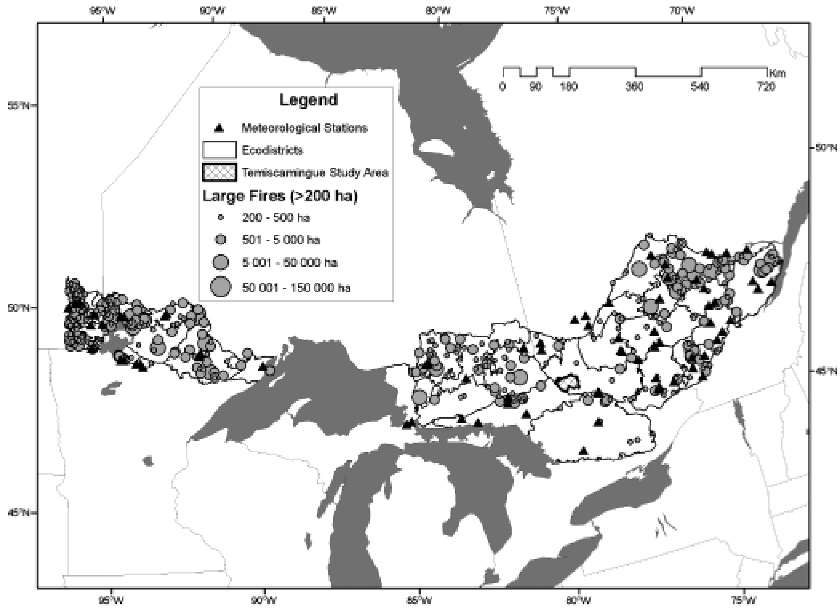

Fig. 1. Great Lakes-St Lawrence forest region, location of meteorological stations used, distribution of large fires analysed, and location of the Témiscamingue landscape.

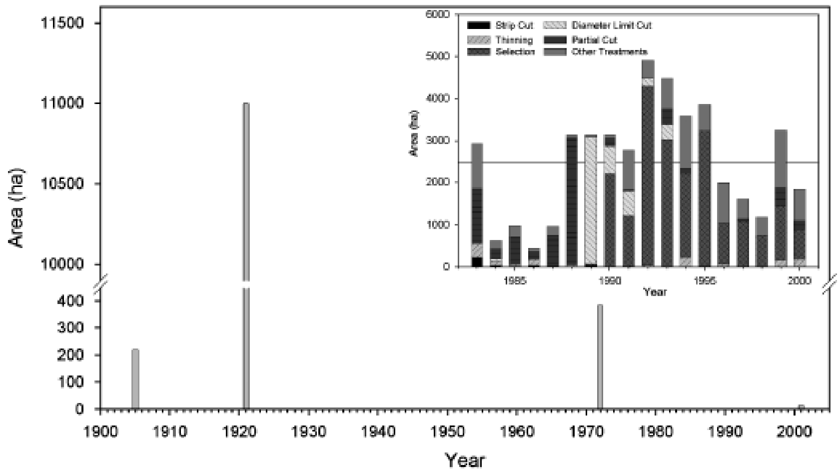

Fig. 2. Recent history of fire and forest harvesting (inset) in Témiscamingue, Québec. Fire data are derived from Drever et al. (2006). Harvesting data (line across figure indicates the mean) are derived from the forest inventory database of the Ministère des Ressources Naturelles du Québec.

burned in Témiscamingue at the end of the nineteenth century (Drever et al. 2006), fires have been infrequent during the twentieth century (Fig. 2). Industrial harvesting began in earnest about 1870 and today represents the dominant disturbance type, affecting on average about 2500 ha (1.4% of the total area) per year (Fig. 2).

Fire variables

The observational unit for analysing the relationship between the occurrence of fire, area burned and weather variables was ecodistrict-year, namely, a given year in a given ecodistrict. Ecodistricts are areas delineated by distinct assemblages of relief, geology, landforms, soils, vegetation, faunal use, water bodies and land use types (Ecological Stratification Working Group 1996).

The occurrence of fire and annual area burned for each ecodistrict were determined from the Canadian Large Fire Database of the Canadian Forest Service (http://fire.cfs.nrcan.gc.ca/research/climate_change/lfdb_e.htm). This 41-year database documents all fires >200 ha across Canada that occurred between 1959 and 1999, accounting for 97% of the total area burned in Canada (Stocks et al. 2002). All fires ($n = 392$) irrespective of cause were analysed to examine the overall fire regime rather than its anthropogenic or natural components. In our analyses, we modeled proportion of total forested area burned each year (PAAB) in each ecodistrict as the dependent variable to account for differences in ecodistrict size. Using only large fires reduced the confounding effects arising from small or localized fires that did not respond to environmental conditions (Lefort et al. 2004) as well as the influence of increasing efficiency in fire detection and suppression during the period of record.

The fire data were non-normal and exhibited a large clump of values at zero and skewed non-zero values. This data structure precipitated the use of a mixed-distribution, mixed-effects model for repeated measures data with clumping at zero and correlated random effects (Tooze et al. 2002; Martin et al. 2005). This approach involved combining a logistic regression using all ecodistrict-years to model the probability of the occurrence of fire ("fire occurrence model") with a lognormal regression to model the probability distribution of non-zero values using ecodistrict-years when PAAB$>$0 (the "area burned" model). The analysis involved the MIXCORR macro (Tooze et al. 2002) in SAS 8.2 (SAS Institute Inc. 2001). This method uses maximum likelihood methods for fitting the models, estimating explanatory variable effects on the occurrence probability and mean of non-zero values, and parameter estimation for both model components. We used a lognormal probability model to characterize the error structure of the area burned model. The two models were combined by calculating the overall likelihood for the mixed-distribution model, which is a product of the likelihoods of each model component.

The model forms were:

$$\text{Occurrence : logit(Probability of Fire)} = a_1 + b_1X_1 + c_1X_2 + u_1 \quad (1)$$

$$\text{Area burned : log(PAAB)} = a_2 + b_2X_1 + c_2X_2 + u_2 + \sigma_2^2 \quad (2)$$

where a_1 and a_2 are intercept parameters; b_1 and b_2 are slope parameters for explanatory variable X_1; c_1 and c_2 are slope parameters for explanatory variable X_2; u_1 is the random unit effect for the occurrence of fire (i.e. the variance in probability of fire attributable to different ecodistricts); u_2 is the random unit effect for area burned (i.e. the variance in area burned attributable to different ecodistricts); and σ_2^2 is the variance of the residuals. The MIXCORR macro also determines a covariance parameter, ρ, of the random effects between the occurrence and area burned model components. Explanatory variables with slope estimates for which the 95% CI excluded 0 were considered as exhibiting strong support from the data for an effect on our dependent variables.

Explanatory weather variables

The weather variables were computed by first compiling daily total precipitation and maximum temperature data (Apr-Oct, 1959-1999) from meteorological stations across the Great Lakes-St Lawrence region (Fig. 1) from Environment Canada. These daily data were attributed to a particular ecodistrict by first selecting stations within 50 km of the ecodistrict centroid, as determined with ARCVIEW 3.2a (ESRI 1996), and then filling in missing data with the nearest stations. The temperature and precipitation data sets were screened and corrected for missing daily values. A missing daily temperature datum was replaced with the corresponding value from the closest nearby ($<$50 km) meteorological station. In cases when such a station was not present or also missing data for the day in question, the mean monthly temperature for that month was used. We replaced missing precipitation data with the value for the same day from nearby stations or mean monthly values in the same manner as the temperature data.

Since we sought to forecast weather-fire relationships, we limited our analyses to temperature- or precipitation-based variables. Other variables such as wind speed and relative humidity are known to influence fire weather severity from day to day; however, these variables typically do not relate well to fire activity when averaged over time and space (Flannigan & Harrington 1988; Flannigan et al. 2005). While wind and humidity variables are available as output from Global Circulation Models (GCMs), modeling efforts that provide good predictive performance based solely on temperature or precipitation could potentially be a more robust tool for climate change forecasting because of relatively higher uncertainty or lack of confidence in wind speed and humidity estimates.

Four weather variables were evaluated: precipitation surplus/deficit (PptSurpDef); mean monthly temperature maxima (MonthlyMeanTx), the sum across the fire season of weighted dry-spell sequences (WeightedDrySpell) and the maximum value of the Canadian DC for each fire season.

While these explanatory variables are interrelated, correlations among them were below levels high enough to cause colinearity problems within our models (Burnham & Anderson 2002). Precipitation surplus/deficit is the difference between total precipitation accumulated during a fire season (Apr-Oct) and potential evapotranspiration (PET). The PET values (mm) for the fire season were obtained from the Canadian Ecodistrict 1961-1990 Climate Normals database of the National Ecological Framework for Canada (Marshall et al. 1999; http://sis.agr.gc.ca/cansis/nsdb/ecostrat/data_files.html). To estimate precipitation surplus/deficit, ecodistrict PET values were subtracted from total fire season precipitation. Mean monthly temperature maxima is the average of the maximum daily temperature values for each month of the fire season. The sum of weighted dry spell sequences, SEQQ (Flannigan & Harrington 1988), for each fire season was calculated as follows:

$$SEQQ = \sum_{j=1}^{m} w_j,$$

where

$$w_j = n_j(n_j + 1)/2$$

where n_j is the number of days in the jth sequence in a fire season, $j = 1, 2 \ldots m$, and m is the total number of dry-spell sequences over a given fire season.

The Canadian Drought Code (DC) estimates fire weather severity by providing a daily numerical index of the weather conditions conducive to fire involving deep organic layers of forest duff or heavy forest fuels (Turner 1972). It is calculated on a cumulative day-to-day basis and maintains a ledger of stored moisture by accounting for daily losses through evapotranspiration and gains from precipitation. See Turner (1972), Van Wagner (1987) and Girardin et al. (2004) for computational details. The DC is a significant predictor of fire frequency and area burned in the southern boreal forest of Canada (Girardin et al. 2004). Our analyses used yearly maximum DC, based on daily calculations, because occurrence and size of large fires are more intimately related to extremes of fire weather rather than to central tendency measures (Moritz 1997). Typically, DC estimates exhibit a seasonal trend – a slow increase to an apex in mid- to late August with a subsequent decline or rough constancy to October (McAlpine 1990); therefore, only years for which data were available for all of the fire season were used. Moreover, since the DC is especially responsive to precipitation (i.e. the index calculation may be affected for several days by one rainfall event; Girardin et al. 2004), any ecodistrict-years with more than 5 days of missing precipitation data ($n = 159$) were excluded from the analysis, leaving a final sample of 907 ecodistrict-years.

Model selection

We evaluated our fire-fire weather hypotheses using an information-theoretic framework (Burnham & Anderson 2002) to assess which hypothesis (model) provided the most parsimonious fit to the data and to determine which explanatory variables were responsible for this fit. Model averaging was used to account for model selection uncertainty (Burnham & Anderson 2002).

Trend characterization

To characterize the historical trends of weather variables related to fire in our study landscape, we compiled daily maximum and total precipitation data from the Barrage Témiscamingue meteorological station. The variables with most explanatory capacity for fire occurrence and area burned, as determined from the model selection analysis above, were derived from these data. Trends were modeled using a local regression method (PROC LOESS in SAS 8.2; SAS Institute Inc. 2000), which allowed us to fit complex curves to the time series data. The smoothing parameter (the data fraction used in each local regression) was chosen automatically by minimizing a bias-corrected Akaike's Information Criterion (Cohen 1999). In addition, a simple linear model (PROC REG in SAS 8.2) was used to evaluate overall trends (significant at $\alpha = 0.05$).

Special Report on Emissions Scenarios (SRES) and global circulation models

We evaluated four scenarios of future global change (A1B, A2, B1 and B2) based on the Intergovernmental Panel of Climate Change's Special Report on Emissions Scenarios (Nakicenovic & Swart 2000; Table 1). Temperature and precipitation data were obtained from two global circulation models: the Third Generation Coupled Global Climate Model (CGCM3) and Hadley Centre Coupled Model, version 3 (HadCM3; Gordon et al. 2000).

To characterize the future regional climate of Témiscamingue, a reference area was established centered on the study landscape that intersected three or six GCM grid cells, depending on the

Table 1. Summaries of SRES scenarios of future global change. See Nakicenovic & Swart (2000) for further details.

Scenario	Technological changes and socio-economic development	Global CO_2 emissions
A1B	Rapid introduction of more efficient technologies, balanced between fossil fuel-intensive and non-fossil fuel energy sources; very rapid economic growth	↑ to 2× 1990 level by 2050, then ↓ to 1.5× 1990 level by 2100
A2	Development primarily regional; self-reliance and preservation of local identities shape global development; per capita economic growth more fragmented and slower than in A1B	↑ to 3× 1990 level by 2100
B1	Reductions in material intensity; introduction of clean and resource-efficient technologies; rapid changes in economic structures toward a service and information economy	↑ to 1.5× 1990 level by 2050, then ↓ to 0.5× 1990 level by 2100
B2	Economic growth intermediate to B1 and A1 scenarios	↑ to 2× 1990 level by 2100

model. Area-weighted averages of simulated temperature and precipitation were calculated based on the proportions of each cell within the reference area. We used a downscaling technique, local intensity scaling (Schmidli et al. 2006), to correct intensity and frequency biases in modeled precipitation data relative to historical data. Trends were determined using the local and linear regression procedures described above. In several cases, an inverse or natural log transformation was necessary to normalize the residuals; predicted data were back-transformed to ease interpretation.

Future fire in Témiscamingue

To forecast the fire effects of climate change in Témiscamingue, we used a Monte Carlo approach that relied on the regressions that best explained fire occurrence and area burned. For each forecasted year, beginning in 2005, the occurrence probability of fire based on regressions using the projected climate variables was determined. In each iteration ($n = 1000$), we first generated a probability from a random number generator drawing from a uniform distribution between 0 and 1. If this random probability was less than the occurrence probability of fire given the forecasted climatic conditions for that year, fire was deemed to occur. The proportion of area burned was then determined according to the forecasted climatic conditions using the regression for PAAB. If no fire was forecasted to occur, PAAB for that year was set to zero. The forecasting for both the occurrence and area burned regressions incorporated the random effects specific to Témiscamingue and residual variation. Proportion burned per year was finally averaged across all iterations; these means were then multiplied by Témiscamingue's total area to forecast annual area burned. Trends were characterized with the local regression procedure outlined above. Computations were programmed in R v. 2.3.1 (R Development Core Team 2006) and SAS 8.2.

Results

Model selection and weather variables

The model denoting the temperature-dry spell hypothesis had an Akaike weight of 0.999, indicating that this model overwhelmingly received the highest level of relative support from the data (Table 2). The other two models had Akaike weights <0.001, and thus had relatively much lower data support. The high level of support for the temperature-dry-spell model may be attributed to its predicted effects on area burned rather than occurrence of fire because we found strong evidence of an effect on fire occurrence from all four explanatory variables (Table 3). Drought Code maxima (DC_max), mean of monthly temperature maxima (MonthlyMeanTx) and weighted dry-spell sequences (WeightedDrySpell) showed a positive effect while precipitation surplus/deficit (PptSurpDef) had a negative effect on fire occurrence. Only weighted dry spell sequences and precipitation surplus/deficit showed strong evidence of an effect on proportion of area burned, with the former having a positive effect and the latter a negative effect (Table 3).

Trends in weather variables and future annual area burned

For the mean of historical monthly temperature maxima, local regression analysis indicated the most parsimonious fit was provided with a LOESS smoothing parameter of 1.0, analogous to a straight linear fit ($AIC_{c1} = 134.85$; Fig. 3a), although no overall trend was detected ($P = 0.955$). With the exception of CGCM3-A2, all the model scenario combinations forecasted mean monthly temperature

Table 2. Results of model selection comparing three models characterizing the occurrence of fire and area burned as a function of climate variables in the Great Lakes-St Lawrence forest region, 1959-1999. Neg2LL indicates the negative 2log likelihood; K = number of parameters; AIC_c = Akaike Information criterion corrected for small sample sizes; ΔAIC_c = AIC_c difference between a given model and the one for which the strength of evidence is highest; w = Akaike weight, the probability a model provides the most parsimonious fit to the data; r = Pearson's correlation coefficient between observed and predicted values for the occurrence and area burned model components.

Model	Neg2LL	n	K	AIC_c	ΔAIC_c	w	r(Occur)	r(Area burned)
Temperature and dry spell	– 921.1	907	10	– 900.9	0	0.999	0.34	0.55
Water balance	– 902.9	907	8	– 886.7	14.1	< 0.001	0.29	0.54
Fire weather severity	– 900.7	907	8	– 884.5	16.3	< 0.001	0.30	0.54

Table 3. Parameter estimates and standard errors (SE) for explanatory variables as averaged over three models characterizing the occurrence of fire and area burned in the Great Lakes-St Lawrence forest region. A t-value > |1.96| (in bold type) indicates a parameter has 95% confidence intervals that do not include zero. "Occurrence" = the parameter estimate for the logistic model component while "Area burned" = estimate for the lognormal model component. Random effects are standard deviation estimates related to ecodistricts.

Model	Variable	Variable description	Occurrence				Area burned			
			Parameter estimate	SE	n	t	Parameter estimate	SE	n	t
	Explanatory									
Water balance	PptSurpDef	Precipitation surplus/deficit	– 0.002	0.001	1	**– 3.16**	– 0.002	0.001	1	**– 2.68**
Temperature and dry spell	MonthlyMeanTx	Mean maximum temperature for fire season months	0.174	0.072	1	**2.41**	0.003	0.064	1	0.04
Temperature and dry spell	WeightedDrySpell	Sum of weighted dry spell sequences across fire season	0.001	0.001	1	**2.78**	0.001	0.000	1	**3.18**
Fire weather severity	DC_Max	Maximum value of Drought Code for fire season	0.003	0.001	1	**3.37**	0.002	0.001	1	1.67
	Regression									
All	Intercept		– 7.053	1.853	3	**– 3.81**	– 7.780	1.676	3	**– 4.64**
All	Covariance		0.159	0.156	3	1.02				
All	Residual						1.584	0.186	3	**8.54**
All	Random effects		0.456	0.221	3	**2.07**	0.234	0.156	3	1.50

maxima that were best fitted with a smoothing parameter of 1.0 and that had a significant upwards trend overall (Table 4; Fig. 3a).

Historically, the seasonal sum of weighted dry-spell sequences fluctuated over time, with peaks in 1922, 1947 and 1997 (AIC_{c1} = 813.98, smoothing parameter = 0.116; Fig. 3b). An overall decrease was detected between 1910 and 2004 (slope parameter = -1.77 ± 0.73 (SE); $P = 0.02$), indicating a reduction in the length and frequency of dry spells. The CGCM3-A1B and CGCM3-A2 model scenarios forecasted trends in the seasonal sum of dry spell sequences that were best fitted with a smoothing parameter of 1.0, while the trend forecasted by CGCM3-B1 model scenario was best fitted with a smoothing parameter of 0.73 (Table 4; Fig. 3b). All three CGCM3 scenarios and the HADCM3-B2 model scenario showed non-significant trends. In contrast, the HADCM3-A2 scenarios showed a weak but significant increasing trend overall.

Based on the Monte Carlo simulations, all model scenarios forecasted an increasing trend in annual area burned (Fig. 3c). All trends from the CGCM3 scenarios were best fitted with a smoothing parameter of 1.0 while the HADCM3-A2 and HADCM3-B2 scenario trends were best fitted with smoothing parameters of 0.63 and 0.69, respectively (Table 4). With the exception of CGCM3-B1, all of the increasing trends forecasted by the model scenarios were significant.

Discussion

Model selection and weather variables

A combination of mean monthly maximum temperature and seasonal sums of weighted sequences of dry spells best explained variation in the occurrence of fire and area burned across the Great

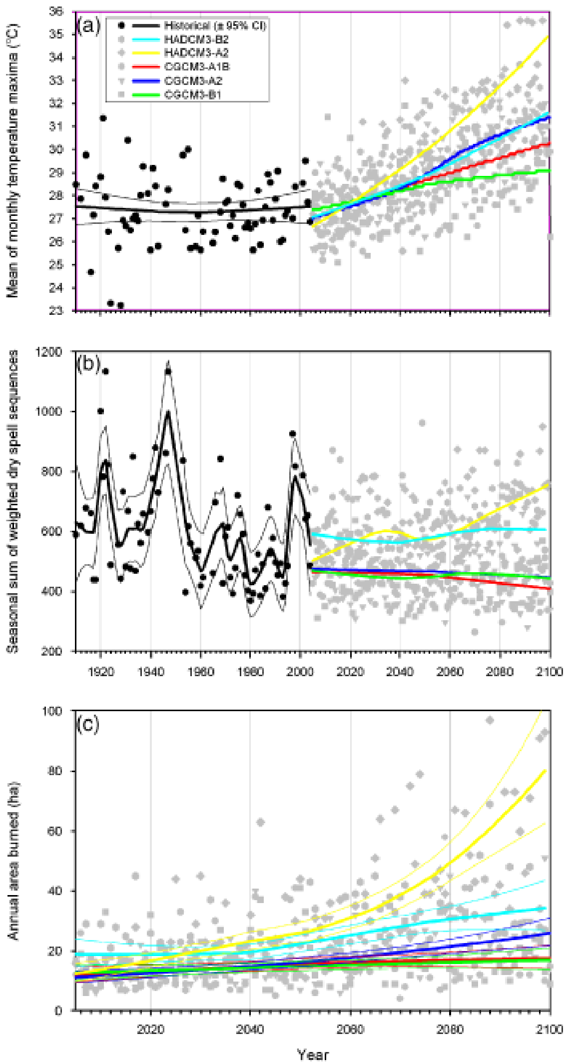

Fig. 3. Trends for Témiscamingue, Québec, for (a) historical and forecasted mean of monthly temperature maxima, (b) historical and forecasted seasonal sum of weighted dry spell sequences, and (c) forecasted annual area burned (with 5% and 95% confidence intervals).

Lakes-St Lawrence region. Weighted dry spell sequences as well as precipitation surplus/deficit – both precipitation-based variables – explained both fire occurrence and area burned, while the mean monthly maximum temperature explained only the occurrence of fire. Several ecodistricts may have similar temperatures but quite different precipitation patterns during a given fire season; therefore, at the ecodistrict scale, temperature may not correlate as well as precipitation with fuel conditions that influence final fire size. Several authors have reported that prolonged sequences of dry, hot days, particularly before and after emergence of broad-leafed canopies, significantly predict the occurrence of fire and area burned (Flannigan & Harrington 1988; Nash & Johnson 1996; Carcaillet et al. 2001). The significant effect of DC maxima on fire occurrence was unsurprising; the DC is a good predictor of the frequency of fire in the southern boreal forest of central Canada (Girardin et al. 2004).

Our finding of a significant effect of precipitation surplus/deficit on the occurrence of fire and area burned was more surprising; seasonally or monthly cumulated estimates of rainfall typically do not predict the frequency of fire or area burned, as it is the timing and frequency of rainfall that are paramount in influencing the fuel conditions related to ignition and the spread of fire (Flannigan & Harrington 1988). However, by including potential evapotranspiration in its calculation, precipitation surplus/deficit may reflect both the weather conditions necessary for fire to occur as well as a landscape-specific moisture balance that indicates the amount of precipitation available for storage in forest fuels.

Trends in fire weather and area burned

In terms of historical trends, the observed decrease in dry-spell sequences corroborates reported reductions in drought frequency for Québec's southern boreal zone since the end of the Little Ice Age (Bergeron & Archambault 1993; Lefort et al. 2003) as well as increases in the amount and frequency of summer precipitation between 1900 and 1998 (Zhang et al. 2000). Similar to our results, Zhang et al. (2000) did not detect a significant twentieth century trend in maximum temperatures in the Témiscamingue area. This apparent reduction in fire weather severity could be partly responsible for the decreasing trend in the frequency of fire observed in Témiscamingue during the twentieth century (Grenier et al. 2005; Drever et al. 2006).

For forecasted trends, the GCM output indicated an overall increase in mean monthly temperature maxima (Fig. 3a) and an increase in annual area burned for Témiscamingue (Fig. 3c). These findings corroborate other studies examining future fire weather severity and area burned in Canada in general, and west central Québec in particular. In terms of fire weather severity, Flannigan et al. (2000, 2001) showed a roughly 20% increase in severity in west central Québec by 2060 relative to reference periods (1985-1994 or 1960-1980, respectively for the two studies), as estimated using the mean seasonal severity rating or Fire Weather Index of the Canadian Fire Weather Index System (Van

Table 4. Results for LOESS (Cohen 1999) and linear regressions of the mean of monthly temperature maxima, weighted dry-spell sequences and area burned as a function of year, as forecasted by different Global Circulation Models (GCMs) for various scenarios. CGCM3 = Third Generation Coupled Global Climate Model; HadCM3 = Hadley Centre Coupled Model, version 3 (Gordon et al. 2000). AIC_c = Akaike Information criterion corrected for small sample sizes.

Model scenario	LOESS smoothing parameter	AIC_{c1}	Linear regression slope parameter (± SE)	*P*-value
Response variable: mean of monthly temperature maxima				
CGCM3-A1B	1.0	143.56	0.03 ± 0.005	<0.0001
CGCM3-A2	0.62	115.40	0.05 ± 0.004	<0.0001
CGCM3-B1	1.0	161.97	0.02 ± 0.005	<0.0001
HADCM3-A2	1.0	– 1111.95	0.09 ± 0.01	<0.0001
HADCM3-B2	1.0	– 1088.09	0.05 ± 0.01	<0.0001
Response variable: weighted dry-spell sequences				
CGCM3-A1B	1.0	– 1372.90	– 0.73 ± 0.45	0.1131
CGCM3-A2	1.0	– 190.55	– 0.26 ± 0.38	0.4973
CGCM3-B1	0.73	– 198.26	– 0.00005 ± 0.0008	0.9456
HADCM3-A2	0.5	– 233.73	0.003 ± 0.0007	<0.0001
HADCM3-B2	0.71	– 210.31	0.0009 ± 0.0007	0.2295
Response variable: area burned				
CGCM3-A1B	1.0	– 40.74	0.07 ± 0.03	0.0437
CGCM3-A2	1.0	– 82.58	0.17 ± 0.03	0.0001
CGCM3-B1	1.0	– 50.74	0.04 ± 0.03	0.1291
HADCM3-A2	0.64	– 61.53	0.67 ± 0.07	<0.0001
HADCM3-B2	0.69	– 57.80	0.18 ± 0.06	0.0048

Wagner 1987). Similarly, McAlpine (1998) described an increase from low to moderate seasonal fire weather severity in the parts of Ontario adjacent to Témiscamingue under a $2\times CO_2$ scenario relative to a 1980-89 reference period. Conversely, other studies indicated little to no change for west central Québec under a $2\times CO_2$ scenario (Flannigan et al. 1998; Stocks et al. 1998). In terms of proportion burned, our finding corroborates Flannigan et al. (2005) who showed a 50% increase in area burned for the region by 2080-2100, a period roughly corresponding to the tripling of atmospheric CO_2 concentrations. Our forecast contradicts Bergeron et al. (2006) who suggested that climate change will result in a continuation of the historical lengthening of fire cycles in southern Témiscamingue, even at $3\times CO_2$ concentrations. There may be several reasons for this contradiction: (1) their regressions relied on wind speed and relative humidity, rather than temperature or precipitation; (2) whereas Bergeron et al. (2006) used the fire and weather data for only the deciduous forests of western Quebec, our study examined a much broader spatial extent to build the regressions on which the forecasts were based; (3) we used many scenarios and two GCMs, whereas Bergeron et al. (2006) used only one GCM. In any case, both studies forecast only small changes in fire activity.

In summary, it appears that future fire activity in Témiscamingue will depend on the extent that temperature increases overwhelm the effect of any continuation of reduced dry spell sequences during the fire season. As temperature increases, the ability of the atmosphere to hold water increases non-linearly, meaning that unless precipitation increases significantly, warmer temperatures will mean increasingly dry fuels and soils (Wallace & Hobbs 1977). Last, future fire activity will depend on how forecasted increases in fire season length (Stocks et al. 1998; Flannigan et al. 2000) extend into the leafless periods during spring and autumn, which is the time during which deciduous forests are most susceptible to burning (Lafon et al. 2005; Drever et al. 2008).

Several methodological details are worth mentioning. Because our forecasts of annual area burned relied on regressions based on measures of central tendency, we precluded exclusion of extreme fire events. Therefore, our forecasts of fire activity should be evaluated as general potential trends rather than precise representations of future area burned. Moreover, the period that forms the basis of our weather-fire regressions is characterized by low fire activity relative to historical rates (i.e. nineteenth century and previously) (Weir et al. 2000; Bergeron et al. 2006). However, this paucity of fire is perhaps not necessarily a shortcoming in terms of forecasting because at least one of the likely causes behind this relative low fire activity – fire suppression – is poised to continue into the foreseeable future. Last, while our study focused on Témiscamingue, our results may apply, to some extent, to the broader climatic region in which our Témiscamingue landscape is found (i.e. to a mild sub-polar climatic region that extends from the Ontario-Quebec border to west of the Saguenay region; Gerardin & McKenney 2001).

Management implications

Despite the forecasted increase in area burned, our evidence suggests climate change may not dramatically increase the occurrence of fire in Témiscamingue. Compared with succession or harvesting (Fig. 2), wind and other disturbances, climate-related alterations in the occurrence of fire is unlikely to have major effects on forest structure and composition, especially if fire-fighting efforts continue. This situation implies a decrease in the resilience of pine-leading stands by a continuation of the historically low frequency of fire, a disturbance on which these stands depend for competitive advantage, vis-à-vis shade-tolerant hardwoods on well-drained mesic sites. This issue is especially pertinent for red pine, as the persistence of this species depends on a combination of infrequent, high-severity fires and moderately frequent surface fires of low to moderate intensity (Bergeron & Brisson 1990; Carey 1993). Without such disturbances, red pine, and to some extent white pine, will likely continue to experience further range reduction (Radeloff et al. 1999; Zhang et al. 1999; Thompson et al. 2006). Therefore, if maintaining the historical diversity of various stand types is a landscape-level objective, managers should implement and monitor silvicultural treatments that create adequate conditions for the regeneration of pine, even on mesic sites (e.g. partial cuts that open up the canopy followed by prescribed surface burns to expose mineral soil and liberate nutrients sequestered in the humus) (Van Wagner & Methven 1978).

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