Predicted changes in fire weather suggest increases in lightning fire initiation and future area burned in the mixedwood boreal forest

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Abstract Forecasting future fire activity as a function of climate change is a step towards understanding the future state of the western mixedwood boreal ecosystem. We developed five annual weather indices based on the Daily Severity Rating (DSR) of the Canadian Forest Fire Weather Index System and estimated their relationship with annual, empirical counts of lightning fire initiation for 588 landscapes in the mixedwood boreal forest in central-eastern Alberta, Canada from data collected between 1983 and 2001 using zero-inflated negative binomial regression models. Two indices contributed to a parsimonious model of initiation; these were Seasonal Severity Rating (SSR), and DSR-sequence count. We used parameter estimates from this model to predict lightning fire initiation under weather conditions predicted in $1 \times CO_2$ (1975–1985), $2 \times CO_2$ (2040–2049) and $3 \times CO_2$ (2080–2089) conditions simulated by the Canadian Regional Climate Model (CRCM). We combined predicted initiation rates for these conditions with existing empirical estimates of the number of fire initiations that grow to be large fires (fire escapes) and the fire size distribution for the region, to predict the annual area burned by lightning-caused fires in each of the three climate conditions. We illustrated a 1.5-fold and 1.8-fold increase of lightning fire initiation by 2040–2049 and 2080–2089 relative to 1975–1985 conditions due to changes in fire weather predicted by the CRCM; these increases were calculated independent of changes in lightning activity. Our

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simulations suggested that weather-mediated increases in initiation frequency could correspond to a substantial increase in future area burned with 1.9-fold and 2.6-fold increases in area burned in 2040–2049 and 2080–2089 relative to 1975–1985 conditions, respectively. We did not include any biotic effects in these estimates, though future patterns of initiation and fire growth will be regulated not only by weather, but also by vegetation and fire management.

1 Introduction

Natural disturbances are regulated by the interplay of biotic and abiotic factors (Paine and Levin 1981; Pickett and White 1985). Forest fire is the dominant natural disturbance in Canada's western boreal forest (Stocks et al. 2002), where the fire regime of a given area reflects the integration of weather conditions, ignition agents, fuel variability, and fire suppression (Schoennagel et al. 2004). The ongoing interaction between fire, weather and vegetation contributes to the community of species that persist in the system (Greene and Johnson 1999; Johnson et al. 2001). Global climate change is predicted to alter weather patterns from those observed historically (IPCC 2001), and fire activity is expected to react immediately to these changes (Overpeck et al. 1990). Shifts in vegetation communities and species ranges resulting directly from successful migration of propagules in response to changing bioclimatic envelopes are expected, but at a relatively slow rate (Weber and Flannigan 1997; Clark 1998; Johnstone and Chapin 2003). As a result, changes in weather may influence community structure most rapidly through fire-mediated transformation of vegetation, whereby the post-disturbance establishment of species is influenced by weather conditions (e.g., Hogg and Wein 2005), and/or where changes in disturbance regime alters community structure (Paine et al. 1998; Jasinski and Payette 2005; McIntire et al. 2005; Johnstone and Chapin 2006). Forecasting changes in fire activity as a function of climate change is one step towards understanding the future state of this boreal ecosystem.

Many methods can be used to study the relationship between climate change and fire, but climate change simulation models provide choice weather data for studies looking forward in time. In Canada, fire weather conditions are evaluated using the Fire Weather Index (FWI) System developed by the Canadian Forest Service (Van Wagner 1987). The FWI system integrates daily precipitation, humidity, temperature and wind speed into a suite of indices such as the Fine Fuel Moisture Index or the Seasonal Severity Rating. There is some discrepancy in predicted future fire activity in eastern Canada from analyses using data from climate change models (Flannigan et al. 1998, 2005; Flannigan and Wagner 1991). However it is generally agreed that future weather conditions will contribute to more extreme calculated FWI indices in the western boreal forests of Canada (Flannigan et al. 1998; Parisien et al. 2005), along with an extended fire season (Wotton and Flannigan 1993) and an increase in area burned (Flannigan et al. 2005). These patterns have a host of contributing processes which may interact in non-linear ways. For example an increase in area burned could result from more fire initiations, larger fires, or more and larger fires. We suggest that by breaking fire activity into phases and assessing the influence of weather conditions on each phase individually, a more informative, hierarchical estimate of future fire activity can be derived.

Lightning fires produce the majority of area burned in Canada (Weber and Stocks 1998). However predictions of spatio-temporal patterns in lightning activity from Global Climate Model (GCM) or Regional Climate Model (RCM) data in Canada are not currently available, though this genre of research is underway (J-P Blanchet, Université de Québec à Montreal, personal communication). In previous work we illustrated a positive relationship between empirical patterns of historical (1983–2001) lightning fire initiation and two measures of fire weather over a large study region in the boreal mixedwood forest (Krawchuk et al. 2006; Krawchuk 2007). We used a joint fire weather-lightning index to quantify simultaneous instances of low fuel moisture and lightning activity, and the seasonal severity rating (SSR) to quantify annual variation in lightning fire risk independent of lightning activity. Though lightning is (obviously) a fundamental element of lightning fire initiation, the SSR index illustrated that we can infer patterns of lightning fire initiation based on weather characteristics independent of explicit information on lightning activity.

This study had three objectives. The first objective was to develop a predictive statistical model of lightning fire initiation using empirical data quantifying the relationship between initiation and a suite of weather indices, independent of lightning activity. We developed five annual indices based on the Daily Severity Rating (DSR) of the FWI System (Van Wagner 1987), then selected those indices resulting in the most parsimonious model of annual counts of lightning fire initiation. Data were assembled for 588 landscapes in the mixedwood boreal forest in central-eastern Alberta, Canada between 1983 and 2001. We refer to these as observed, current conditions. The second objective was to use this statistical model to predict future rates of lightning fire initiation based on weather data provided by a regional simulation of climate change. We used parameter estimates from objective one to predict lightning fire initiation under simulated $1 \times CO_2$ (referred to hereafter as 1975–1985), $2 \times CO_2$ (hereafter 2040–2049) and $3 \times CO_2$ (hereafter 2080–2089) conditions interpolated from the Canadian RCM (CRCM; Laprise et al. 1998). By necessity, these predictions assume the relationship between lightning activity and weather variables is time and space-invariant. The third objective was to estimate the magnitude of change in area burned that might result from this simple increase in initiation frequency. We generated estimates of the area burned in each year of simulated data by incorporating our predictions of future lightning fire initiation (objective two) with existing, regionally based empirical estimates of the number of fire initiations that grow to be large fires (fire escapes; Cumming 2005) and the fire size distribution (Cumming 2001a). These data provided an estimate of future changes in area burned due to changing fuel moisture conditions conducive to lightning fire initiation, independent of additional changes to other phases of fire activity.

2 Methods

The study region was a 58,000 km^2 area of boreal mixedwood forest in central-eastern Alberta, Canada (Fig. 1). The climate is continental with mean historical winter and summer temperatures of $-13.2°C$ and $+13.5°C$, respectively and total precipitation in summer and winter in the range of 240 and 64 mm, respectively (Strong and Leggat 1992). Topography is relatively uniform with elevation of approximately

Fig. 1 The study area is indicated by the *gray square*, within the province of Alberta, Canada

200 to 1,000 m. Glacial movement through the region has resulted in rolling morainic deposits on the uplands and smoother glacio-lacustrine deposits on the lowlands (Rowe 1972). Forest tree species are stratified by soil moisture regime (Strong and Leggat 1992). Upland mesic sites are dominated by mixtures of trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.) or white spruce [*Picea glauca* (Moench) Voss]. Paper birch (*Betula papyrifera* Marsh) is present but pure stands are rare. White spruce and balsam fir [*Abies balsamea* (L.) Mill] dominate older stands but pure stands are not currently abundant. Xeric sites are vegetated by jack pine (*Pinus banksiana* Lamb), sometimes in association with aspen. Moist, poorly drained sites are dominated by black spruce [*Picea mariana* (Mill.) B.S.P.]. There are extensive wetlands including open areas of muskeg bog,

fens, swamps and marshes. Tamarack [*Larix laricina* (Du Roi) Koch] is the dominant tree species in fens. Further information about this area can be found in Krawchuk et al. (2006).

The Province of Alberta is partitioned into townships using an administrative grid system, each township measuring approximately 9,600 ha, varying slightly due to geographic corrections. Each township in the study region was considered as a spatial sampling unit, hereafter referred to as a landscape. The study region was divided into three-dimensional space-time samples, called voxels, with the units landscape and year. All spatial analyses were done in ESRI ArcMap 9.1 (ESRI 2005) using the NAD27 UTM zone 12 projection. All statistical analyses were done in R (R Development Core Team 2005 version 2.2.0).

Our first objective was to develop a predictive statistical model of observed patterns in lightning fire initiation. Data for observed, current conditions were collected throughout the fire season (May 1 to September 30) between 1983 and 2001 and summarized for each year. Records of lightning fire initiation were acquired from Alberta Sustainable Resource Development (ASRD; Historical Wildfire Database 2005). The ASRD digital records describe the date, approximate location and cause of all fires detected in Alberta since 1961. We registered all lightning-caused fires detected during the fire season over the study interval to the appropriate voxel. Un-detected or un-recorded fires may have occurred in the region but fire detection efficiency appears to have been constant over the study interval (Cumming 2005). Multiple fires within the same landscape on the same day were a result of a single environmental condition and counted as a single event. If these fires were to spread, they would likely coalesce into a single, larger fire so the ecological implication of synthesizing these data is minimal. We refer to these counts as 'initiations'. The fire data ranged between zero and nine initiations per voxel, contained a large proportion of zeroes (87%), had a mean of 0.17 and standard deviation of 0.52. There was no evidence for consistent spatial or temporal autocorrelation in counts of initiations per voxel using Bonferroni-corrected local Moran's I coefficients or Mantel *r*-statistics (Krawchuk et al. 2006).

We quantified weather conditions conducive to initiation from empirical data for each voxel using five indices based on the DSR (daily severity rating) of the FWI System. The DSR was calculated from daily data collected from 65 provincial weather stations operated and calibrated by ASRD in and around the region, using recorded solar noon values of temperature, relative humidity, wind speed and 24 h accumulated rainfall (Van Wagner 1987). We interpolated the DSR across the study region to provide estimates of daily conditions for every landscape across the region using an inverse-distance weighting method with six nearest neighbours. This method was validated in the study region by Krawchuk et al. (2006).

We created five annual indices based on the (daily) DSR to represent different hypotheses of weather patterns that might explain the observed spatio-temporal variation in initiation among voxels. These indices were based on the premise that there would be a positive linear or quadratic relationship between a given index and either initiation occurrence or count per voxel. An increased value of each index would represent an increase in the number of days with fire weather appropriate for initiation given a lightning discharge. Indices were assumed to be conditional on lightning activity and can be thought of as providing an appropriate fuel moisture framework within which lightning activity might interact. The indices included

(1) DSR-days, (2) weighted DSR-days, (3) DSR-sequence, (4) DSR-sequence count, and (5) Seasonal Severity Rating (SSR):

1. DSR-days. We identified each day in the fire season where the interpolated DSR in a landscape was greater than three. The decision rule was binary, a day was scored as either zero (less than or equal to three) or one (greater than three). For each voxel, the DSR-days index was the sum of the scores. A critical value of three was selected based on work by Anderson and Englefield (2001) wherein they quantified the cumulative distribution of observed lightning fire initiations as a function of DSR and showed that 50% of initiations occurred at a DSR of 3.3 or higher. The study done by Anderson and Englefield (2001) was conducted in the mixedwood boreal forest of Saskatchewan, within roughly 500 km of our study region.

2. Weighted DSR-days. We identified each day in the fire season where the DSR in a landscape was greater than three, as in DSR-days, above. However each of these days was then given a score, weighted using the logistic transformation $\exp^{(DSR-4)}/1+\exp^{(DSR-4)}$. The weighting scheme was the based on the logistic function, bounded by zero and unity. This sigmoid functional form describes the hypothesis of a non-linear increase in initiation associated with increasing values of DSR. Higher levels of DSR approached unity asymptotically under the suggestion that for DSR of roughly nine or greater, the conditional probability of initiation would not increase substantially. For each voxel, the weighted DSR-days was the sum of these scores.

3. DSR-sequence. This variable was devised to give higher values to voxels with consecutive days, or sequences, of high DSR values. We hypothesized that voxels with longer sequences of days with a DSR greater than three would be increasingly more likely to incur an initiation due to increasing fire risk. We identified days where the DSR in a landscape was greater than three for more than 1 day in succession. For each of these instances of consecutive days (i), we calculated a value of $S_i = d(d + 1)/2$, where d is the number of consecutive days in instance i, when DSR was greater than three, for $i = 1$ to n. For each voxel, the DSR-sequence was the sum of S_i to S_n. The index was based on work by Flannigan and Harrington (1988) showing a strong relationship between long sequences of dry days and area burned.

4. DSR-sequence count. This was a count of the instances (i) per voxel identified by DSR-sequence (3). For example, if there were $i = 12$ instances of two or more days in succession with DSR greater than three, the DSR-sequence count was 12.

5. Seasonal Severity Rating (SSR). The SSR was the mean annual DSR for each voxel. We hypothesized that the SSR over the fire season would represent seasonal conditions, such as "a dry year".

Each of the five indices described the temporal pattern of fire weather in a slightly different way, however we expected these DSR-based indices to be correlated since they were derived from the same data. Pearson correlation coefficients between the indices ranged from 0.62 to 0.99. Our first goal was to select the index, or set of indices that parsimoniously described variation in lightning fire initiation.

Previous work with a subset of these data (Krawchuk 2007) suggested the selection of the zero-inflated negative binomial (ZINB) model [Simon Jackman's (pscl) package] for regression analysis. The distribution of raw data and residuals from

preliminary regression analyses supported this distribution over a zero-inflated Poisson, negative binomial, or Poisson model of errors. We selected the mixture distribution for the ZINB model over the conditional hurdle since all indices that contributed to the negative binomial component of the model should also be considered in describing the zero values. We used Simon Jackman's pscl package for the statistical modelling.

We could not include all candidate variables in a true global model since correlation among DSR indices resulted in convergence failure. Instead, we screened the five candidate variables independently in both the binomial and negative binomial component of the ZINB model using the Wald statistic and a critical $\alpha = 0.05$ to provide a sub-global set of variables that explained the most variation in initiation. We selected a best model from this sub-global model using backward stepwise selection. We used the Akaike's Information Criterion (AIC) for selection among candidate models, and also tested for statistical significance from the null hypothesis ($\beta = 0$) for each parameter estimate using the Wald statistic and a critical $\alpha = 0.05$ (Stephens et al. 2005). Residual analysis was used to assess distribution assumptions of the model (Lambert 1992; Cameron and Trivedi 1998). We used the differences between the estimated and empirical probabilities of initiation to assess how well the model described variation of initiation counts, based on Lambert (1992). Goodness of fit was assessed using a parametric bootstrap (Efron and Tibshirani 1998) on two metrics, the sums of squares and total regional count of initiations over the study period, using parameter estimates from the best model.

The second goal of the study was to use the statistical model to predict future rates of lightning fire initiation based on weather data provided by a regional simulation of climate change. We predicted initiation counts under future conditions using parameter estimates from the ZINB model of observed initiation (Table 1), and simulated DSR-sequence count and SSR for the years 1975–1985, 2040–2049, and 2080–2089. We generated 1,000 random deviates from the ZINB for each landscape in each year.

The simulated daily weather data used to calculate the annual DSR-sequence count and SSR indices were acquired from the second policy run of the Canadian Regional Climate Model (CRCM; Laprise et al. 1998) nested within the Canadian Global Climate Model (AGCM2). Data were prepared and calibrated by the Canadian Forest Service and these methods are described fully in Wotton (2001), we summarize key details below. The CRCM produces simulated weather data every 15 min, but are archived at 6-h intervals (0600 UTC, 1200 UTC, etc. . .) for 45-km^2 grid boxes across western Canada. Existing methods were used to convert grid box averages of the CRCM to point value estimates, and these point values

Table 1 Parameter estimates for the best ZINB model quantifying lightning fire initiation

Variable	Estimate	SE	p value	ΔAIC
β_0 (binomial)	+1.06	0.16	5.60×10^{-11}	
DSR-sequence count	−0.34	0.047	1.31×10^{-13}	113
β_0 (negative binomial)	−1.53	0.11	1.63×10^{-45}	
SSR	+0.13	0.038	2.14×10^{-3}	10

The Δ AIC was calculated as the change in value when the variable was removed from this model. The binomial component estimates the probability of zero events, so the negative estimate for DSR-sequence count corresponds to a positive relationship with fire occurrence

were used to calculate daily DSR values for solar noon weather data. Solar noon temperature was estimated using the simulated maximum daily temperature and subtracting 2°C. Relative humidity was estimated using a night time temperature proxy of dew point, since simulated specific humidity outputs from the CRCM did not correlate well with relative humidity in validation studies (Wotton 2001). Wind speed was calculated directly from the CRCM grid boxes. Simulated rainfall was adjusted for DSR calculations by subtracting 1.5 mm per day from daily rainfall.

We interpolated the point estimates of DSR across the study region using the inverse-distance methods described for objective one. Though data were available from the CRCM for the entire year, we restricted our calculations to the fire season of May 1 to September 30 for this study. We compared the distribution of SSR and DSR-sequence count representing simulated and observed, current conditions. We also compared the distribution of SSR and DSR-sequence count for the three time slices of simulated data (1975–1985, 2040–2049, 2080–2089).

The third objective of our study was to estimate the magnitude of change in area burned that might result from future changes in initiation frequency. Spatio-temporal patterns of initiation are one component of the lightning fire regime of a region. The initiation declares a location from which a fire has the potential to grow, but not all initiations grow to be large fires due to fire suppression activity (Cumming 2005; Arienti 2006a) or because environmental factors such as changes in vegetation or moisture extinguish the fire. We evaluated the potential effect of increased initiations expected in the future on area burned using existing, regionally derived empirical estimates of the number of initiations that escape to be large fires, and the size distribution of such fires. Here, we use the term 'escaped' to describe a fire that reaches a size greater than 9 ha. Cumming (2005) and Arienti (2006a) have estimated the probability of fire escape conditional on initiation for this study area. We selected the probability of escape, $p_{esc} = 0.084$, estimated from data observed between 1971 and 1993. Cumming (2001a) estimated the size distribution for fires in the study region greater than 9 ha from data observed between 1961 and 1998. Following Cumming (2001a), we used a truncated exponential distribution to simulate fire size:

$$PX_t (x) = \frac{\sigma^{-1} \exp(-x/\sigma)}{1 - \exp(-b/\sigma)}$$

where PX_t is a truncated probability distribution function of x, fire size, with shape parameter, $\sigma = 2.56$ and the truncation point, $b = 11.18$ corresponding to a maximum size of 643,000 ha (Cumming 2001a).

We used the estimates of escape probability (p_{esc}) and the fire size distribution with our predictions of initiation to calculate annual area burned by lightning fire under simulated 1975–1985, 2040–2049, and 2080–2089 conditions. In this study we assumed that escape probability and the fire size distribution were time- and space-invariant though data suggest that changes in fire operations implemented in 1983 may have reduced p_{esc} to 0.064 (Cumming 2005). The values selected for p_{esc} and the fire size distribution will influence the absolute results of area burned calculated below, but not the relative value (i.e., trend through time). Fire suppression effectiveness has also likely influenced the fire size distribution over time, but the distribution provided by data from as far back as 1961 captures important temporal variability and acknowledges the potential for fire policy to adapt in the future to allow fires

to burn more freely in some areas. Cumming (2001a) also showed that vegetation influences fire size however we did not include this information in the framework of this study.

The regional, annual number of initiations was calculated by taking the sum of all voxels, for each of the 1,000 deviates from the initiation model. For each of these 1,000 deviates, we multiplied the regional, annual sum of initiations by p_{esc} to produce the number of escaped fires (F_{esc}). We then generated F_{esc} random samples from the truncated exponential fire size distribution. The cumulative area of these samples was the regional area burned for each year of simulated climate data. We used the median of each year's distribution in a linear regression analysis to test for a slope significantly different from zero, indicating a trend in area burned through time. These data were time slices rather than transient values however the hypothesis of a positive trend through time is still valid. The standard error estimate of the slope parameter was corrected using a sandwich estimator to account for temporal autocorrelation in residuals. We calculated the mean of the annual medians for each time slice (e.g., mean of the annual medians for 1975–1985, 2040–2049, 2080–2089) to quantify the ratio in area burned resulting from expected changes in initiation frequency.

3 Results

The DSR-sequence count and SSR variables were selected in the best model of lightning fire initiation (Table 1), the former describing the binomial (excess zero) component, the latter describing the counts per voxel. The specification of the model was supported by the raw residuals. Parametric bootstrap indicated the model was a good fit for the data using both the sums of squares (SS = 3,961.6, p = 0.13, n = 1,000) and regional counts of initiation (RCI = 2,607, p = 0.51, n = 1,000) metrics. The difference between the estimated and empirical probabilities for initiation values was small, showing no systematic shortcomings in our predictions of initiation. The distribution of the DSR-sequence count and SSR variables over the 19 years of the study data are illustrated in Fig. 2 using box-and-whisker plots; both variables showed their highest values in 1998.

Simulated SSR and DSR-sequence count indices of 1975–1985 conditions had a broader variance than observed, current conditions (Fig. 3). However, the overall relationship suggested the 1975–1985 data were representative of current weather conditions, as was demonstrated by Wotton (2001). The median of the simulated indices for 2040–2049 and 2080–2089 scenarios showed the marked increase through time over indices for simulated 1975–1985 conditions and observed, current conditions for 1983–2001 (Fig. 3). The upper whiskers of DSR-sequence count were highest in the 2040–2049 conditions. The generated frequency distribution of initiation increased through time in association with increasing fire weather conditions (Fig. 4). The ratio of both the median and mean initiations per voxel for 2040–2049:1975–1985 and 2080–2089:1975–1985 were 1.5 and 1.8, respectively.

The distributions of simulated area burned illustrated an increase through time, with substantial variation within and among years (Fig. 5). There was a significant positive, linear trend in median area burned over time (β = + 1,854.6, SE = 271.0,
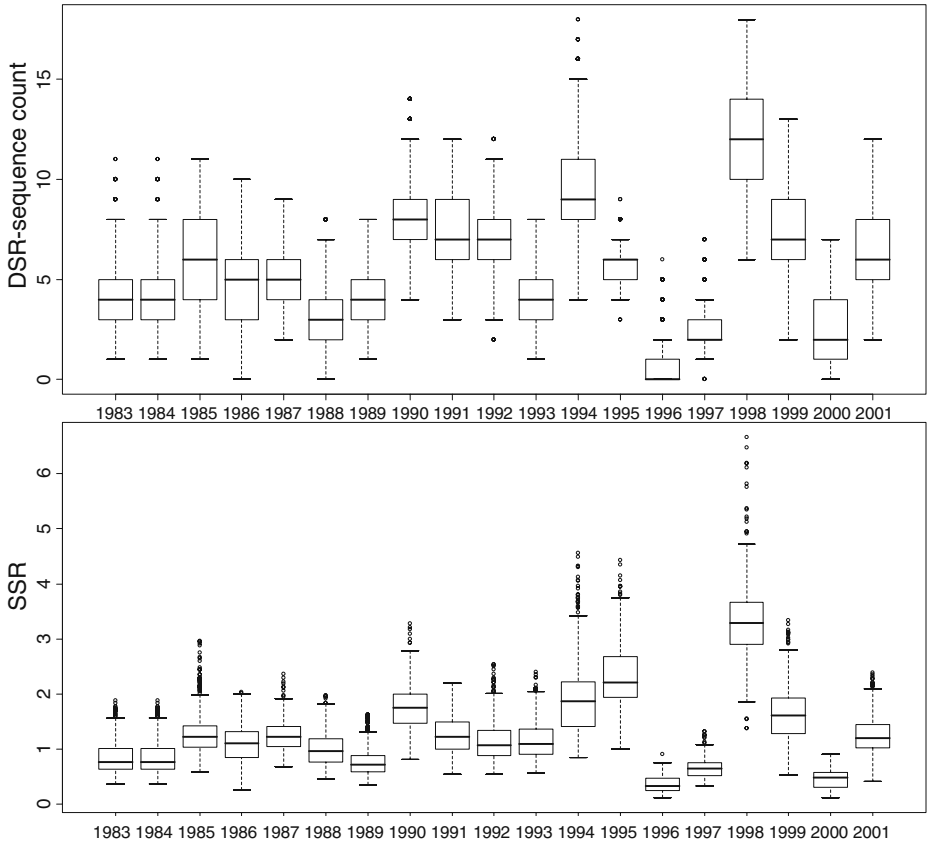
Fig. 2 The annual distribution of observed DSR-sequence count and SSR per voxel between 1983 and 2001

$n = 31$, $p = 7.7 \times 10^{-12}$). The ratio of the mean median area burned for 2040–2049/ 1975–1985 conditions was 1.9, and for 2080–2089/1975–1985 conditions was 2.6.

4 Discussion

The predicted future rate of lightning fire initiation increased in central-eastern Alberta due to changes in fire weather conditions simulated by the CRCM. Our simulations suggested that the 1.5-fold increase in initiation between 1975–1985 and 2040–2049 conditions, and 1.8-fold increase between 1975–1985 and 2080–2089 conditions correspond to 1.9-fold and 2.6-fold increases in annual area burned, respectively. However the increased frequency of fire weather conditions conducive to initiation provides a conservative estimate of future lightning fire activity. Calculations by Price and Rind (1994) based on climate simulations suggest an increase in lightning activity for the USA and the northern hemisphere. In California, Fried et al. (2004) suggest climate change will increase the intensity and spread rate of fires such that they are more likely to escape initial containment efforts and burn larger areas. Similarly,
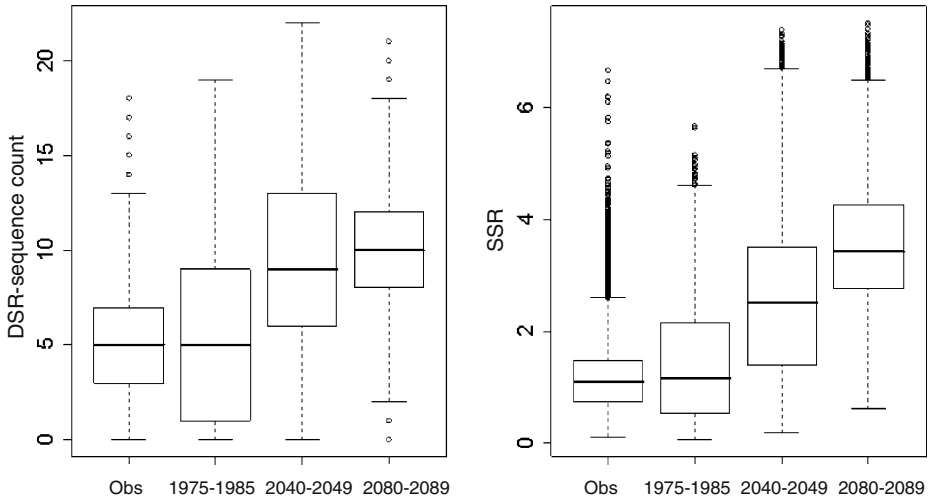
Fig. 3 The distribution of DSR-sequence count and SSR per voxel observed for 1983–2001, and simulated for 1975–1985, 2040–2049, and 2080–2089

Arienti (2006a) showed the probability of fire escape increased under more extreme observed fire weather conditions. Wotton and Flannigan (1993) suggest that the fire season might begin earlier in our study region under $2 \times CO_2$ relative to $1 \times CO_2$ conditions (May 16 versus May 30). Our time series of climate data was generated from fire weather projections from May 1 to September 30 such that the extension of the fire season into the spring was included in our simulations. Our data did not account for a 9-day projected extension of the fire season into the fall. An extended season would allow for more initiations, and for existing fires to burn longer, changing the fire size distribution under future climate conditions.

Fig. 4 The distribution of mean predicted initiations per voxel for 1975–1985, 2040–2049, and 2080–2089 generated from 1,000 random deviates from the zero-inflated negative binomial model. The *dashed horizontal line* illustrates the observed mean number of initiations per voxel for 1983–2001
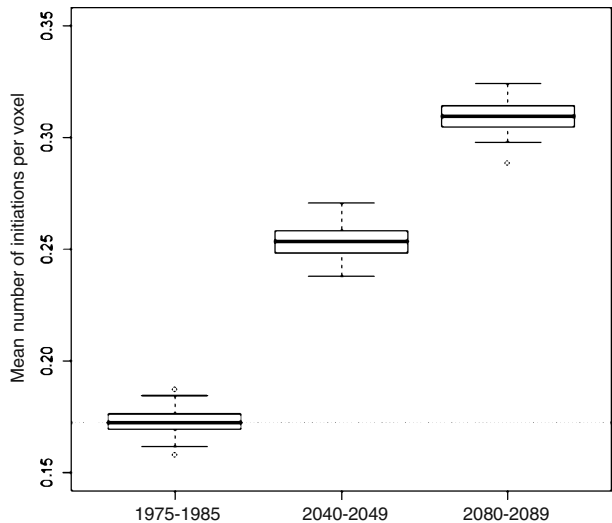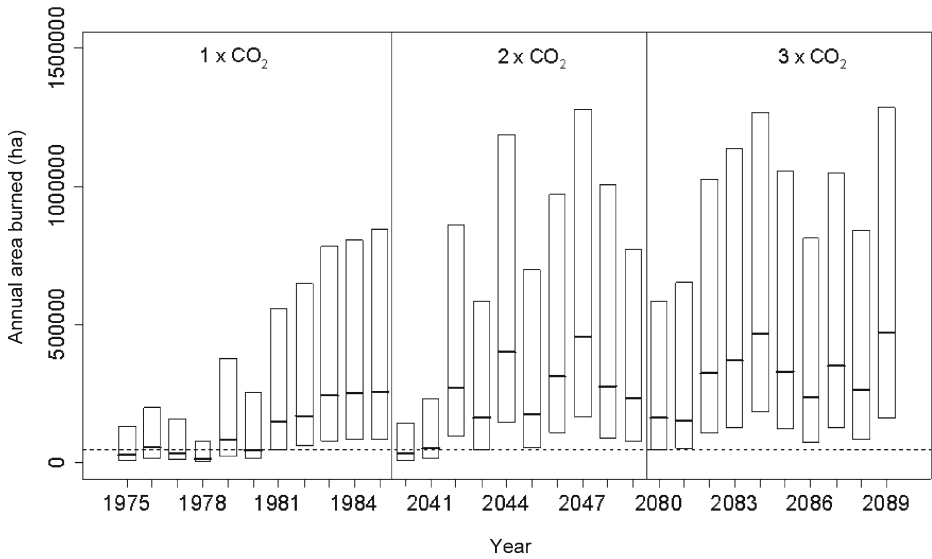
Fig. 5 The distribution of 1,000 iterations of annual area burned, omitting *whiskers* and *outliers* of the box-plots for presentation purposes. *Solid vertical lines* show the split for years representing 1975–1985, 2040–2049, and 2080–2089. The *dashed horizontal line* shows the area representing a 0.5% annual burn rate calculated from 54 years of regional fire history data by Cumming (1997)

The magnitude of our predictions for area burned correspond with those calculated by Flannigan et al. (2005), who estimated the relationship between historical measures of area burned (lightning and human-caused fires) and weather data, then predicted future area burned using these parameter estimates and weather data provided by the Hadley and Canadian GCMs. The Hadley and Canadian GCM simulations predict 3.4 and 1.1-fold (respectively) increases in area burned for this study region for a $3 \times CO_2: 1 \times CO_2$ scenario (Flannigan et al. 2005), respectively. Tymstra et al. (2007) showed a 1.2-fold increase in area burned between $2 \times CO_2$ and $1 \times CO_2$ conditions and a 1.4-fold increase between $3 \times CO_2$ and $1 \times CO_2$ conditions in a simulation study of fire behaviour under two climate scenarios in a study region adjacent to ours. The magnitude of these estimates (Flannigan et al. 2005; Tymstra et al. 2007) of future area burned are equivalent to those we generated purely from changes in the initiation phase of fire activity, independent of changes in escape, the length of fire season, cause, or fire size. This suggests that an integrated, hierarchical estimate of future fire activity might be very different from those predicted here, or by Flannigan et al. (2005) and Tymstra et al. (2007).

We demonstrated that an increase in initiation rate of less than twofold within the currently defined fire season can result in a substantial increase to area burned. Our results counter suggestions that changes in initiation rate may not be ecologically meaningful since a small number of initiations are typically responsible for the majority of area burned (Weber and Stocks 1998). Environmental conditions influence the likelihood of a fire initiation growing to be large (Arienti 2006a), but an increased number of initiations results in more chances to experience suitable conditions for large fires to occur.

Future patterns of initiation and behaviour will by regulated not only by changes in weather, but also by changes in vegetation. The annual probability of initiation in a landscape varies with disturbance history and the relative composition of coniferous and deciduous species (Krawchuk 2007). In the boreal mixedwood forest, initiation probability is low in recently burned and aspen-dominated areas and higher in black or white spruce-dominated (*Picea mariana* and *P. glauca*) and recently harvested areas, likely due to variation in fuel composition (Krawchuk et al. 2006; Krawchuk 2007). Arienti (2006b) have demonstrated increased lightning fire initiation along linear features such as roads, seismic lines or pipelines that are vegetated by native and non-native grasses. Fire behaviour, such as spread rate, is also influenced by vegetation and weather (Forestry Canada Fire Danger Group 1992; Cumming 2001b; Hély et al. 2001; Bergeron et al. 2004). As such, management decisions that direct vegetation composition via forest harvesting and wildfire suppression will also contribute to changes in fire activity in the future. Expected changes in fire activity due to weather conditions, such as those presented herein, need to be integrated with forest landscape models to further understand the complex outcome of these interacting factors.

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