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Dynamics of moisture content in spruce–feather moss and spruce–*Sphagnum* organic layers during an extreme fire season and implications for future depths of burn in Clay Belt black spruce forests

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Abstract. High moisture levels and low frequency of wildfires have contributed to the accumulation of the organic layer in open black spruce (*Picea mariana*)–*Sphagnum* dominated stands of eastern boreal North America. The anticipated increase in drought frequency with climate change could lead to moisture losses and a transfer of the stored carbon back into the atmosphere due to increased fire disturbance and decomposition. Here we studied the dynamics of soil moisture content and weather conditions in spruce–feather moss and spruce–*Sphagnum* dominated stands of the boreal Clay Belt of eastern Canada during particularly dry conditions. A linear mixed model was developed to predict the moisture content of the organic material according to weather, depth and site conditions. This model was then used to calculate potential depth of burn and applied to climate model projections to determine the sensitivity of depth of burn to future fire hazards. Our results suggest that depth of burn varies only slightly in response to changes in weather conditions in spruce–*Sphagnum* stands. The reverse holds true in spruce–feather moss stands. In conclusion, our results suggest that spruce–*Sphagnum* stands in the boreal Clay Belt may be resistant to an increase in the depth of burn risk under climate change.

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Introduction

In the context of growing global populations and global warming (IPCC 2007), managers are confronted with the challenges generated by increasing human needs and the environmental impacts of a rapidly changing climate. Adaptive strategies should be developed to minimise natural resource degradation induced by climate change and to provide continuity of forest socio-economic benefits (Fulé 2008). In Canada, the boreal forest represents ~60% of economic resources for the forest sector (Burton *et al.* 2003). There, the response of the boreal forest to future warming is a major concern because high-latitude boreal regions are likely to be among the most affected (IPCC 2007), and the size of their carbon pools is particularly important (Dixon *et al.* 1994; Prentice *et al.* 2001). Notably, projected increases in drought frequency and severity with climate change imply moisture loss and subsequent transfer of stored carbon into the atmosphere by increased fire disturbance and decomposition (e.g. Harden *et al.* 2000). Increasing the resistance of forests to fire and drought could slow carbon emissions and maintain the sustainability of forest resources (Millar *et al.* 2007; Girardin *et al.* 2013*a*).

In the boreal forests of eastern Canada, at the border of the provinces of Quebec and Ontario, a long fire cycle (time to burn all the land area, or mean fire return interval), a flat topography and a cold climate facilitate the accumulation of thick layers of organic soil, a process often described as paludification (Fenton *et al.* 2005; Lavoie *et al.* 2005*a*). High organic layer depth allows the establishment and expansion of *Sphagnum* species (Lavoie *et al.* 2005*b*; Fenton *et al.* 2007; Lafleur *et al.* 2010; Fenton and Bergeron 2011). These forests differ from other forested peatlands created in low-lying areas and from the discontinuous permafrost by the fact that peat mosses accumulate on well drained mesic soils independently from local topography or drainage and are primarily related to forest succession (Simard *et al.* 2007). Once *Sphagnum* species increase on the forest floor, fluctuations in water saturation of the organic layer decrease (Bergeron and Fenton 2012). The water table moves from the mineral soil into the organic forest floor, and organic layer depth becomes the dominant factor explaining the water table position (Fenton *et al.* 2006). Tree roots are unable to reach the mineral soil, inducing moister, colder and less nutrient rich environments, resulting in a drop in tree productivity (Payette and Rochefort 2001; Simard *et al.* 2007). Consequently, in the prolonged absence of fire, productive mature black spruce (*Picea mariana* (Mill.) BSP) stands dominated by feather moss develop into open and less productive forested peatlands dominated by *Sphagnum* species (Harper *et al.* 2003; Lecomte *et al.* 2006*a*, Fenton *et al.* 2007; Lafleur *et al.* 2010).

Depth of burn, considered here as the depth of the soil organic layer consumed during a forest fire, is crucial for the return of these forests to productivity (Lavoie *et al.* 2005*b*; Lecomte *et al.* 2006*a*; Simard *et al.* 2009). High depth of burn that consumes all of the organic layer on the ground leads to the establishment of dense pure black spruce stands on mesic sites with a dense structure (Lecomte *et al.* 2006*a*, 2006*b*). In contrast, low depth of burn leaves the untouched soil organic layer to accelerate the process of paludification (Lecomte *et al.* 2006*b*; Simard *et al.* 2009), which consequently tends to favour the establishment of open, less productive stands on mesic sites (Lecomte *et al.* 2006*a*; Simard *et al.* 2007).

The decrease in productivity associated with paludification is an important issue for the forest industry as it reduces the amount of harvestable timber. In spruce–*Sphagnum* stands, mixing of the organic layer (e.g. Lafleur *et al.* 2010) or prescribed burning (e.g. Renard *et al.* 2009) are practices that have been proposed to reduce *Sphagnum* establishment and favour the development of more productive spruce–feather moss stands. But there could be an unwanted feedback effect arising from such practices; high organic layer depths in peatlands promote high moisture content, which helps to protect against burning (Benscoter and Wieder 2003; Harden *et al.* 2006; Shetler *et al.* 2008; Kasischke *et al.* 2010; Benscoter *et al.* 2011; Turetsky *et al.* 2011*a*). A return to more productive forests could increase the overall stand vulnerability to fire and high depth of burn with climatic warming, and accelerate carbon emissions. It is therefore necessary to understand the trade-off between the increase in forest productivity and the loss of resistance to fire. Currently, the strength of the offsetting potential of organic layer thickness on potential depth of burn in a climate change context is unknown.

Here we assessed the moisture dynamics in spruce–feather moss and spruce–*Sphagnum* organic soil layers during an extreme fire season and used moisture information to project the effects of climate change on potential depth of burn in these stands for the period 2071–2100. We used *in situ* measurements of soil moisture content in deep layers (5–25 cm) of the forest floor and weather data for the parameterisation of a soil moisture content model. This model was then used to calculate potential depth of burn and was applied to climate model projections to determine the sensitivity of depth of burn in stands to future fire hazards. We tested three hypotheses related to soil moisture content dynamics and depth of burn responses to climate change: (i) soil moisture dynamics in spruce–*Sphagnum* (hereafter SpSp) stands are less sensitive to drought severity than spruce–feather moss (SpMo) stands; (ii) as a consequence of hypothesis (i), drier weather conditions are required in SpSp stands to increase depth of burn in comparison with SpMo stands and (iii) there will be less increase in depth of burn in SpSp stands in comparison with SpMo stands, within the predicted 2071–2100 climate change scenarios.

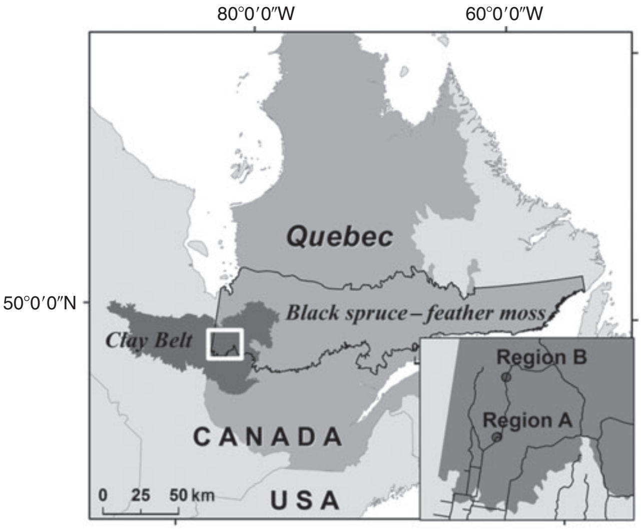

Fig. 1. Geographic location of the Clay Belt, eastern Canada and the regions (A, B) within which stands were selected.

Materials and methods

Study area and sampling design

The study area is located in the boreal forest of north-western Quebec, Canada (49°00′–51°30′N, 78°30′–79°31′W) (Fig. 1). A former proglacial lake (Lake Barlow–Ojibway) left a thick deposit of clay, forming the physiographic unit known today as the Clay Belt, which stretches across the Quebec–Ontario border and covers an area of ~145 470 km^2 (Vincent and Hardy 1977). The topography is flat; however, small rocky hills are present. Landscapes are dominated by black spruce stands with some jack pine (*Pinus banksiana* Lamb.) and aspen (*Populus tremuloïdes* Michx.) stands. Approximately 60% of the landscape consists of black spruce dominated stands, of which ~80% are open forests (Pelletier *et al.* 1996). The current level of fire activity is low, with a fire cycle estimated at 398 years from 1959 to 1999 (Bergeron *et al.* 2004). The climate is subpolar and subhumid continental, characterised by long, harsh and dry winters and short, hot and humid summers (Environment Canada 2012). The average annual temperature from 1970 to 2009 was 0.3°C, ranging from a minimum of −22.2°C in winter to a maximum of 17.4°C in summer, and the mean total annual precipitation was 862 mm (Environment Canada 2012).

Black spruce stands with either a feather moss or *Sphagnum* dominated understorey were selected to represent (i) spruce–feather moss (SpMo) stands and (ii) spruce–*Sphagnum* (SpSp) stands. One SpMo and one SpSp were selected in each of two regions (region A and region B) to obtain four stands in total (Fig. 1). Two separate regions were on clay substrate and were

Table 1. Characteristics of sampling sites

Stand age (time since the last fire) was extracted from a fire history map of the study area (Bergeron *et al.* 2004). Organic layer depth and bulk density are mean (± standard error) of *n* replicates per site. The number of trees and mean diameter at breast height (DBH mean) were sampled in a 100-m^2 plot encompassing the centre of the CS616 probes. *SpMo*, spruce–feather moss stands; *SpSp*, spruce–*Sphagnum* stands

Stand type	Region	Stand age	Latitude	Longitude	Organic layer depth (cm) $n = 15$	Bulk density (g cm^{-3}) $n = 4$	Number of trees per 100 m^2 (stem DBH > 9 cm)	DBH mean (cm)
SpMo	A	1914	49°22′44″N	−79°2′45″W	15 (4)	0.0989 (0.013)	45	12.40
	B	1886	49°44′42″N	−79°2′9″W	26 (7)	0.1038 (0.05)	36	12.10
SpSp	A	1775	49°22′59″N	−79°2′13″W	48 (15)	0.0766 (0.011)	42	4.53
	B	1725	49°44′42″N	−79°2′24″W	46 (16)	0.1098 (0.04)	30	7.43

selected to ensure that the sites originated from different fires. The distance between stands in the same region was less than 2 km. The thickness of the organic layer, the stand density and the *Sphagnum* dominance defined the type of site. Organic layer depth in the SpMo and SpSp stands were respectively <30 or >40 cm, as defined by Lafleur *et al.* (2010). SpMo stands had larger mean stem diameters and densities than SpSp stands (Table 1). Black spruce was the dominant species in each stand, but some white cedar (*Thuja occidentalis* L.) was present in SpSp stands and one balsam fir was recorded in one SpMo stand. The understorey of SpMo stands was dominated by feather moss species, except in region B where a few patches of *Sphagnum* spp. were also present. SpSp stands were dominated by *Sphagnum* spp.

Daily weather data and drought code

Two meteorological stations, one in each region and within a 1-km radius of the selected forest stands, were installed during spring 2010 to measure precipitation, air temperature and relative humidity. These variables were recorded at 60-min intervals using Campbell Scientific data loggers (CR10X) (Campbell Scientific Inc., Logan, UT, USA) from spring 2010 to autumn 2010 (technical system failures prevented 2011 data analysis). Precipitation was measured with TE525M sensors (Campbell Scientific Inc.), and air temperature and relative humidity were measured with L9598 probes (Campbell Scientific Inc.). There were no missing data for the 2010 fire season. The 2010 fire season ranked high in terms of fire danger, with extremely dry conditions from mid-May to late June stretching across a territory of 1000 km in the province of Quebec. Area burned during that season totalled 314 884 ha (10th largest year since 1971 in Quebec; Canadian Council of Forest Ministers 2012). The 2010 season was, therefore, an interesting opportunity for conducting our analysis.

Air temperature and 24-h accumulated rainfall data at noon local standard time measured with the micrometeorological stations were used to calculate the Drought Code (DC). The DC is a component the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) used in Canada to evaluate the severity of fire weather conditions by providing indices of fuel moisture and fire behaviour (Wotton 2009). DC is a relative indicator of the moisture content of deep, compact organic layers (~10 to 25 cm from the surface) weighing ~25 kg m^{-2} when dry. It reflects the long-term drying and consumption of deep forest floor layers and the effort required to extinguish a fire. For a temperature of 25°C and relative humidity of 30%, the response time of DC fuels to lose 2/3 of the free moisture is ~50 days (Van Wagner 1987; Wotton 2009). In the DC calculation, the layer absorbs moisture through precipitation and exponentially dries with increasing temperature (Wotton 2009). DC is unitless, with zero indicating low fire risk and 400 indicating high fire risk.

Additionally, daily precipitation, air temperature and relative humidity time-series for the 1971–2010 period were created by interpolation of Environment Canada's historical climate database using the BioSIM software (Environment Canada 2012). As part of the procedure, daily data from the four closest weather stations were adjusted for differences in latitude, longitude and elevation between the data sources and stand location, and averaged using a $1/d^2$ weight, where d is distance. Next, FWI System components were computed on this second weather dataset (Régnière and Bolstad 1994). Winter precipitation was included in the algorithms of the DC so fire behaviour indices also depended on snow accumulation (Girardin and Wotton 2009).

The DC is not a physical water budget in that it does not measure the fluxes of water into and out of fuel, nor does it incorporate process equations responsible for these fluxes (Anderson and Otway 2003; Otway *et al.* 2007; Waddington *et al.* 2012; Johnson *et al.* 2013). Therefore, the DC requires significant calibration to suit local moisture processes (input and output flows, internal mechanisms of water movements, etc.) and improve accuracy for the particular fuel conditions such as those encountered in this study. Below we describe our approach to calibrating the DC to *in situ* measurements of SpSp and SpMo stands' moisture content.

Volumetric and gravimetric moisture contents

Volumetric moisture content (%) was measured once per hour in each stand using Campbell Scientific CS616 moisture probes (Campbell Scientific Inc., Logan, Utah). In each stand, three holes were dug to obtain three replicates, in each of which probes with a length of 30 cm were installed horizontally at depths of 5, 15 and 25 cm in SpSp organic layers, and depths of 5 and 15 cm in SpMo stands (in these stand types, maximum organic soil depth was often <25 cm, so only two probes were installed). For data verification, soil samples centred on every 5-cm depth were also collected from the organic soil layer, with three replicates, seven times during the 2010 fire season (31 May, 29 June, 11 July, 26 July, 9 August, 23 August and

9 September). Gravimetric moisture content (GMC) (%) was assessed by weighing the moist samples, oven drying them at 60°C for 48 h, and reweighing when samples were dry (constant weight). GMC was calculated as follows:

$$\mathrm{GMC} = ((\text{wet mass} - \text{dry mass}) \div \text{dry mass}) \times 100 \quad (1)$$

Bulk density ($\mathrm{g\,cm^{-3}}$) was measured to convert volumetric moisture content to GMC (%) for analyses. Four times at each location, soil samples with a core of 403.89-cm^3 volume ($(7.75)^2 \times \pi \times 17$-cm depth), were collected especially for bulk density analysis along the vertical organic soil profile. Bulk density was calculated using the equation:

$$\text{Bulk density} = \text{dry sample} \div \text{sample volume} \quad (2)$$

And finally, the probe volumetric moisture content was transformed into GMC as:

$$\mathrm{GMC} = \text{volumetric moisture content} \div \text{bulk density} \quad (3)$$

The CS616 probes were calibrated for each stand type (SpMo and SpSp) by comparing CS616 values with moisture content measured by direct soil sampling similar to Lee *et al.* (2010) and Ferguson *et al.* (2002). We collected probe values on the same day as soil sampling occured. We then calculated replicate means by depth and soil moisture content of each replicate by 5-cm depths above the probe depth (example: soil sampling moisture content of 0–5 cm for probes at 5 cm). Linear regressions were used to obtain the best fit between probe moisture means and soil sampling moisture means.

Soil moisture content calibration

Development of a predictive model for daily GMC was carried out using a linear mixed-effects model (lme) (Pinheiro and Bates 2000). Mixed-effects models are flexible and powerful tools to describe relationships between response variables and covariates that are grouped according to classification factors. These models include fixed variables (as predictive variables in classical linear regression) and random variables, which describe the variability of some groups of observations and individual observations themselves. In our case, the mixed-effects model was an appropriate method to first consider the autocorrelation between our repeated daily observations. Second, organic layer depths in SpSp stands varied considerably (from 20 to >75 cm) inducing soil moisture content variations. Mixed-effects models allowed for inclusion of this variability.

Herein the GMC was formulated as:

$$\log(GMC_{jkdr}) = \beta_0 + \beta_1 D + \beta_2 DC_{jkdr} + \beta_3 ST + \beta_4 DC_{jkdr} ST + b_r + b_{dr} + b_{kdr} + e_{jkdr} \quad (4)$$

where GMC_{jkdr} (%) corresponds to the gravimetric moisture content registered at day *j* in the *k*th replicate of depth *d* in region *r*, D_{jkdr} to the depth in the organic layer and DC_{jkdr} to the daily DC registered in each region. A logarithmic (log) transformation is herein applied to GMC to linearise the relationship. ST was the stand type with a categorical value of 0 in SpMo stands and 1 in SpSp stands. Coefficients β_0, β_1, β_2, β_3 and β_4 are respectively the parameter estimates of the intercept, D_{jkr}, DC_{jkr}, ST and the DC × ST interaction. Terms b_r, b_{dr} and b_{kdr} respectively denote the random coefficients associated with the region, the depth and the replicates. Here, these random coefficients follow a normal distribution with mean of 0 and variance equal to σ_r^2, σ_{dr}^2 and σ_{kdr}^2. Finally, e_{jkdr} is the error. The model also accounted for the correlated errors through a first-order autoregressive structure. Stand random parameter level was not included in the model because variability between stands of the same ST was low. Categorical variable ST was multiplied with DC to include a different response of GMC to DC according to stand type (SpMo or SpSp). Other fixed variables were tested for model calibration (the season, DC corrected with length of the day), but the results were not significant (not shown). Models were calibrated using the lme (Pinheiro and Bates 2000) procedures included in the R freeware (R Development Core Team 2010). The 'corCAR1' class was selected to describe daily GMC correlation structure. This class implements an autoregressive correlation of order 1. Values vary from 0 to 1, with higher correlation attributed to observations closest in time. Serial correlation was evaluated with the correlation parameter p_x.

Model evaluation was done by analysing residual dispersion and normality. Additionally, to ensure that our model did not result from a seasonal cycle effect (Vecchi *et al.* 2012), we calculated Pearson's correlations between linearly detrended log(GMC) and DC. The 95% non-parametric bootstrap confidence corrected for temporally correlated data was computed to test the significance of the correlations (Mudelsee 2003). Finally, the predictive skills of the model were verified by correlating observed values and predicted values with the model-building dataset, as well as with the independent soil sampling data (GMC extracted from soil sampling).

Although in this paper we focussed on the DC as a predictor for GMC, similar analyses were also conducted using the Duff Moisture Content (DMC) of the FWI System as a predictor. The results of this second calibration led to the same conclusions. Appendix 1 presents the results obtained from the parameterisation of GMC with DMC.

Depth of burn calculations and projections

Our analysis aimed at presenting a simple method for directly linking fire weather conditions to depth of burn for future fire behaviour projections. Critical cumulative heat load for ignition depends on GMC and fuels can sustain combustion under gravimetric moisture conditions ranging from 140 to 500% (Zoltai *et al.* 1998; Benscoter *et al.* 2011). We thus defined potential depth of burn as the depth where moisture content is favourable for fire to be sustained. Next, we calculated mathematically daily depths at which limits of GMC were archived by fixing GMC_{jkdr} at either 140 or 500% and by solving Eqn 4. The use of two GMC thresholds was intended to capture the inherent variability in burning potential attributed to heterogeneity in the organic bulk density (Benscoter *et al.* 2011).

Our final objective was to project the potential daily response of depth of burn to climate change. We chose the 1971–2000 and 2071–2100 time horizons for model testing to underscore the heterogeneity of community responses in a context of highly contrasting fire hazards (Girardin *et al.* 2013*b*). We used 1971–2000 interpolated data from Environment Canada's historical climate database described earlier to calculate daily 30-year means of DC for the whole study area by averaging values of our four studied sites. Monthly temperature and precipitation data were collected from six global climate models (GCMs) and used in the calculation of the monthly DC. The monthly DC is an adaptation to the daily DC calculation designed for modelling purposes in the absence of daily weather data (Girardin and Wotton 2009, Girardin *et al.* 2013*b*). The GCM simulations are those of the IPCC (2007) and include the Bjerknes Centre for Climate (BCM2.0), Canadian Centre for Climate Modelling and Analysis (CGCM3T63 (T63 resolution)), Australia's Commonwealth Scientific and Industrial Research Organisation (CSIROMk3.5), GISS (GISSAOM), Institute for Numerical Mathematics (INMCM3.0) and National Institute for Environmental Studies (MIROC3.2 medres) models. Simulations were performed using the IPCC A2, A1 and B1 Special Report on Emission Scenarios (Nakićenović *et al.* 2000). The A2 and A1 storylines (intense forcing) projected an increase in annual temperatures of 5 or 4°C and an increase in precipitation of 13 or 11%. An increase in temperature of 3°C and in precipitation of 8% was projected under the B1 storyline (intermediate forcing) (Appendix 2, Table A2). Non-downscaled-GCM data were collected and averaged over the area encompassing 49.5°–51.5°N and 84°–78.0°W (four to six grid cells depending on model resolution) and debiased (i.e. corrected for systematic differences between simulated and observed current-climatic conditions; Bergeron *et al.* 2010; Girardin *et al.* 2013*b*). Differences in monthly DC between the future period (2071–2100) and the baseline period (1971–2000) were then computed and applied to the 30-year means of the daily DC computed from Environment

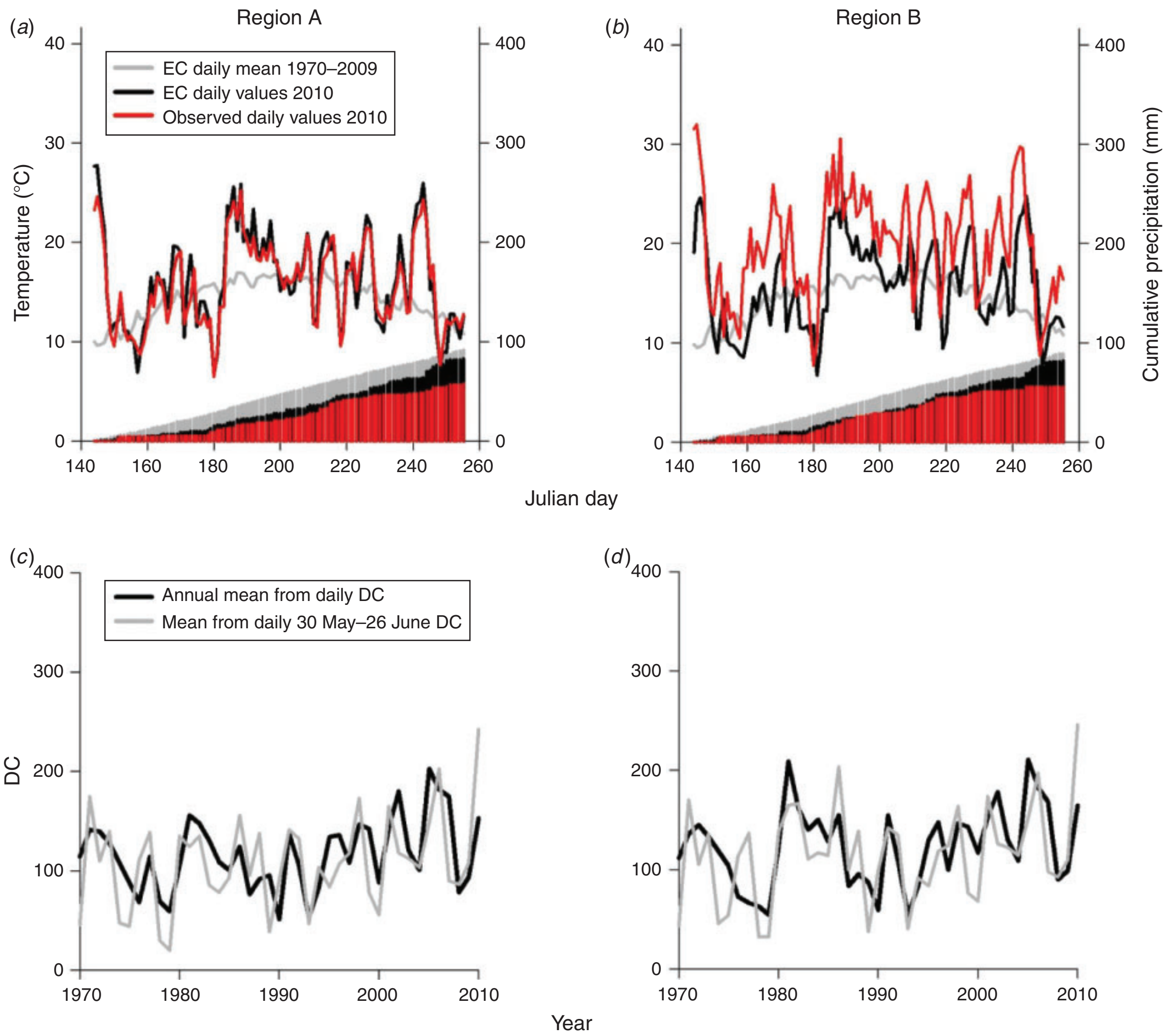

Fig. 2. Daily means of temperature (curves) and cumulative daily precipitation (bars) during the 2010 fire season recorded by *in situ* meteorological stations for (*a*) region A and (*b*) region B. Also plotted are the daily means and 1970–2009 averages interpolated from Environment Canada (2012) weather station data. Annual and early fire season means of the Drought Code (DC) from 1970–2010 computed from Environment Canada (2012) interpolated weather stations are plotted for (*c*) region A and (*d*) region B.

Canada's historical climate database. Data on the baseline period were not detrended as we assumed that a parallel trend would characterise conditions 100 years later. The resulting DC means were used to calculate future depth of burn as described previously.

Significant differences between future projections and current values of DC were tested using Student's *t*-test at the 5% significance level.

Results

Spruce–feather moss stand and spruce–Sphagnum stand moisture content dynamics

With mean temperatures of 15.5 and 15.9°C and total precipitation of 231.8 and 225 mm during the sampling period for region A and region B, 2010 was a particularly warm and dry fire season in comparison with the 1971–2009 mean (Fig. 2*a*, *b*). Meteorological values computed from interpolated Environment Canada data by BioSIM were slightly underestimated when compared with values computed from *in situ* weather data. Nevertheless, the unusual nature of the 2010 water deficit was well captured by the interpolation routine, with cumulative daily precipitation during the year 2010 being well below the 30-year averages (Fig. 2*a*, *b*).

Spring weather conditions during 2010 were particularly warm and dry, with air temperature values of ~30°C and almost no rain falling from 30 May to 26 June. In response to these spring conditions, DC showed a rapid increase of almost 200 units from May to June (Fig. 3). The rise in DC persisted, with intermittent ups and downs, until September when it reached values of 317 and 338 in regions A and B. Overall, the 2010 drought season was exceptional as it ranked 1st in terms of mean May–July DC magnitude since 1971 (Fig. 2*c*, 2*d*).

GMC values varied generally from ~50 to 330% at 5 and 15 cm for SpMo, whereas SpSp showed higher values for each depth (from ~440 to 900%) (Fig. 3). GMC in SpSp stands at 25 cm was high ranging from an average of 700 up to 900% for region A. Rapid variations in GMC of region A in SpSp stands were indicative of the changing water table's level in the organic layer induced by rainfall events.

In general, DC was much more responsive to drying and wetting by steeper increases and decreases compared with GMC. Nonetheless, GMC in SpMo stands responded to weather conditions in a similar manner to the DC, with a decrease in

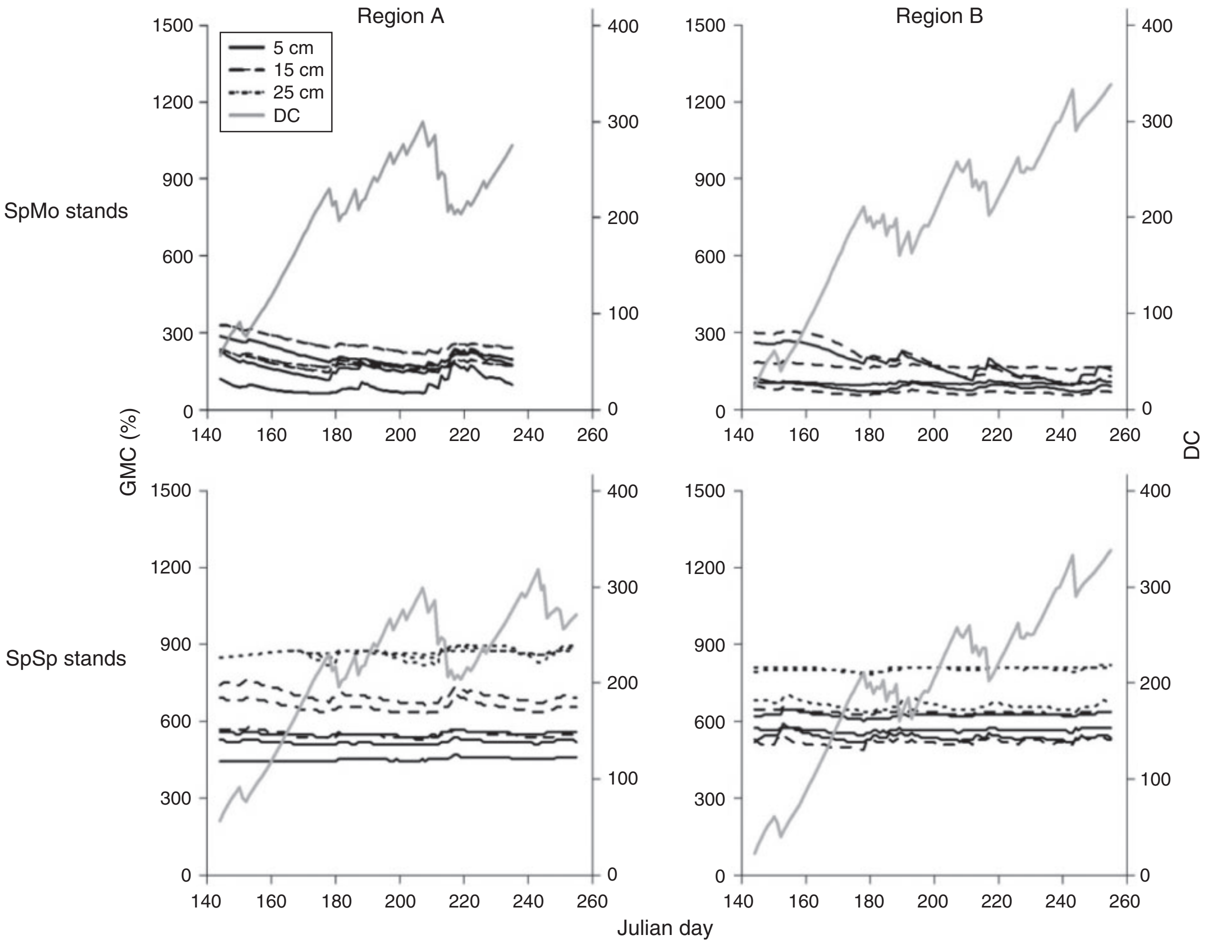

Fig. 3. Daily gravimetric moisture content (%) recorded in spruce–feather moss (SpMo) stands at 5 and 15 cm, and in spruce–*Sphagnum* (SpSp) stands at 5, 15 and 25 cm for each of three replicates. Also plotted are the daily Drought Code (DC) values computed from *in situ* meteorological data.

moisture as the season progressed and some variations during precipitation events. Moisture content response in SpSp stands showed little variation in GMC (Fig. 3). Additionally, a gradual decrease in soil moisture content during the season was not observed in SpSp stands. Replicates of SpMo stands in region B showed a decrease in GMC with DC, whereas other replicates showed little variation. Linearly detrended daily GMC and DC values were significantly correlated and this was true for the entire vertical profile (Table 2).

GMC calibration

A model relating GMC to DC and depth was parameterised using linear mixed-effects. Our model expressed well the variability of GMC in SpMo and SpSp stands (Fig. 4*a*). It should be noted that moisture content derived from soil sampling reflected a specific temporal value in the day (one sample at different times in the day), whereas moisture content sampled with probes expressed a daily average of moisture content. These differences contributed to explaining the high variability seen between the observed and predicted values (Fig. 4*a*). However, Pearson's correlation between observed and predicted values confirmed the good predictive skill of the model (SpMo: $r_{\text{pearsonT}} = 0.597$ (0.491; 0.674); SpSp: $r_{\text{pearsonT}} = 0.88$ (0.179; 0.622)).

All fixed variables included in the mixed model were significant ($P < 0.001$) with high temporal correlation in our data (correlation parameter $p_x = 0.99$). GMC was negatively correlated with the DC and positively correlated with the depth (Table 3). The coefficient associated with the SpSp stand type

Table 2. Pearson's correlation coefficients (*r*), and associated 95% bootstrap confidence intervals (95% CI) corrected for autocorrelation, computed between linearly detrended daily 2010 logarithmic-scaled Gravimetric Moisture Content (GMC) and daily *in situ* 2010 Drought Code (DC)

SpMo, spruce–feather moss stands; *SpSp*, spruce–*Sphagnum* stands

Stand type	Region	Depth (cm)	*r*	95% CI
SpMo	A	5	−0.927	−0.946; −0.896
		15	−0.881	−0.908; −0.845
	B	5	−0.747	−0.829; −0.634
		15	−0.724	−0.808; −0.613
SpSp	A	5	−0.829	−0.873; −0.773
		15	−0.918	−0.938; −0.890
		25	−0.697	−0.825; −0.359
	B	5	−0.766	−0.834; −0.651
		15	−0.811	−0.860; −0.743
		25	−0.768	−0.833; −0.671

Table 3. Coefficients and fit statistics for model of gravimetric moisture content (GMC)

GMC_{jkdr} corresponds to the gravimetric moisture, D_{jkdr} to the depth in the organic layer layer and DC_{jkdr} to the daily Drought Code. Coefficients β_0, β_1, β_2, β_3 and β_4 are the parameter estimates, and b_r, b_{dr} and b_{kdr} are the random coefficients

$$\log(GMC_{jkdr}) = \beta_0 + \beta_1 D + \beta_2 DC_{jkdr} + \beta_3 ST + \beta_4 DC_{jkdr} ST + b_r + b_{dr} + b_{kdr} + e_{jkdr}$$

	Value	Standard error	*P*
Fixed effects			
β_0 (Intercept)	5.06	0.12	≤0.001
β_1	0.02	0.006	≤0.05
β_2	−0.0011	0.00007	≤0.001
β_3	1.143	0.01	≤0.001
β_4	0.00096	0.00009	≤0.001
Random effects			
Region	0.096		
Depth in region	0.00004		
Replicates in depth in region	0.223		

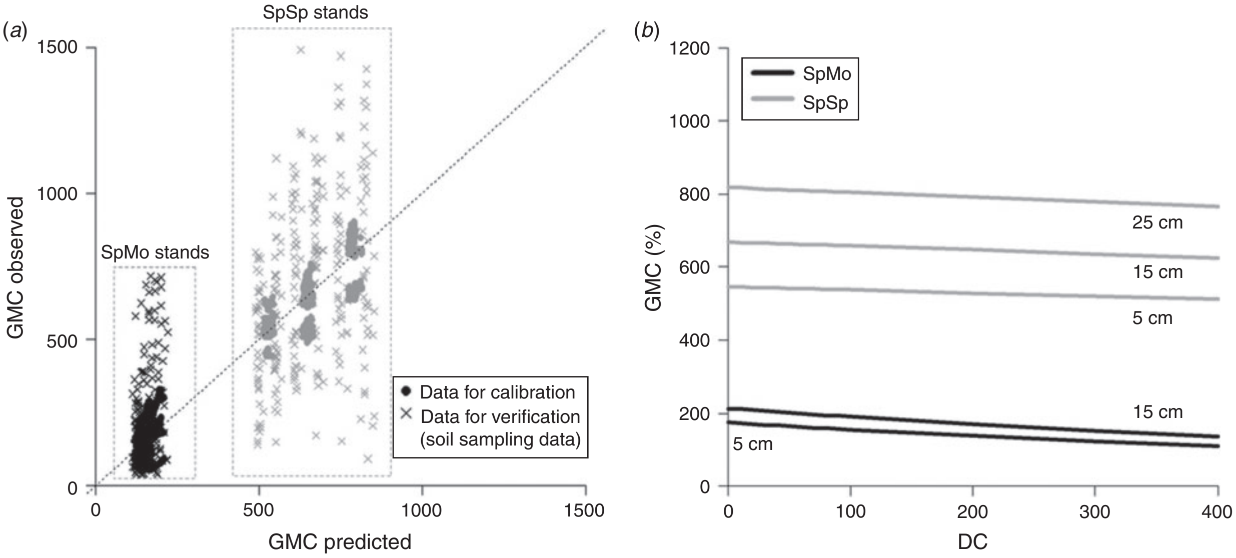

Fig. 4. (*a*) Verification of gravimetric moisture content (GMC) model predictive skills on independent soil sample measurements (crosses) in spruce–feather moss (SpMo) (black) and spruce–*Sphagnum* (SpSp) (grey) stands. A logarithmic (log) transformation was applied to all data. Also shown are the predicted *v.* observed GMC values from the calibration dataset (circles); (*b*) Curves of the gravimetric moisture content variation with the Drought Code (DC) per stand type and sampling depth.

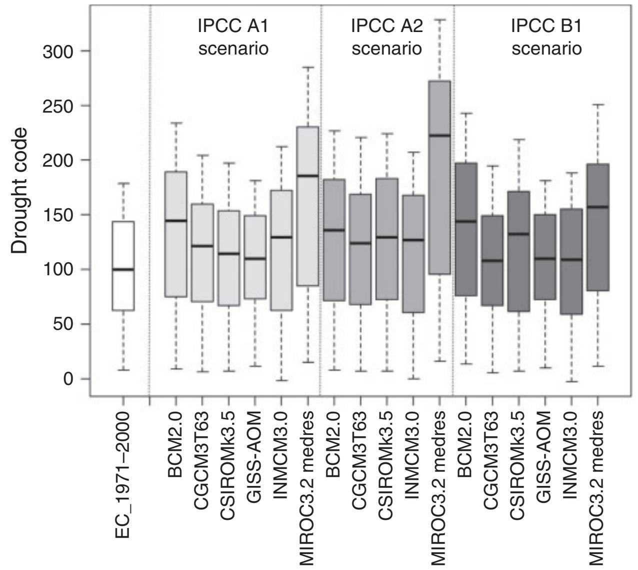

Fig. 5. Current (1971–2000) and projected (2071–2100) daily Drought Code (DC). Projected values are those simulated using the Bjerknes Centre for Climate (BCM2.0), Canadian Centre for Climate Modelling and Analysis (CGCM3T63 (T63 resolution)), Australia's Commonwealth Scientific and Industrial Research Organisation (CSIROMk3.5), GISS (GISSAOM), Institute for Numerical Mathematics (INMCM3.0), and National Institute for Environmental Studies (MIROC3.2 medres) models under the IPCC A2, A1 and B1 emissions scenarios.

(ST = 1 in Eqn 4) tended to increase with GMC. Calibration curves in Fig. 4*b* showed a GMC decrease of 63 and 78% in SpMo stands at 5 and 15 cm depth in response to varying DC of 400 units. GMC decrease is slightly lower for SpSp stands with differences of 3, 43 and 52% for 5-, 15- and 25-cm depths (Fig. 4*b*).

Depth of burn calculation and 2071–2100 projections

The 30-year daily means of DC for the period 1971–2000 varied from DC = 8 in April to DC = 179 in October with a mean of DC = 100 (plot EC1971–2000 in Fig. 5). In response to these DC variations, potential depth of burn in SpMo increased up to 4 or 10 cm under burning limit scenarios of GMC = 140% or GMC = 500%. GMC = 140% was never reached in SpSp stands and potential depth of burn increased only up to 2 cm under 500% burning conditions (Fig. 6).

Climate change projections indicate that DC values should increase over the 21st century by an average of 26 units, using all models and scenarios. DC could decrease slightly during spring (DC decreases with a maximum of 10 units with the INMCM3.0 model under the B1 scenario) and increase greatly during summer and autumn (DC increases by up to 153 units with the MIROC3.2 medres under scenario A2) (Fig. 5). Changes in DC are projected to be significant only during summer according to Student's *t*-test (Fig. 6, in grey). In response to changes in the DC, depth of burn in SpMo should follow the same trends as DC (decrease in spring, increase in summer); changes in depth of

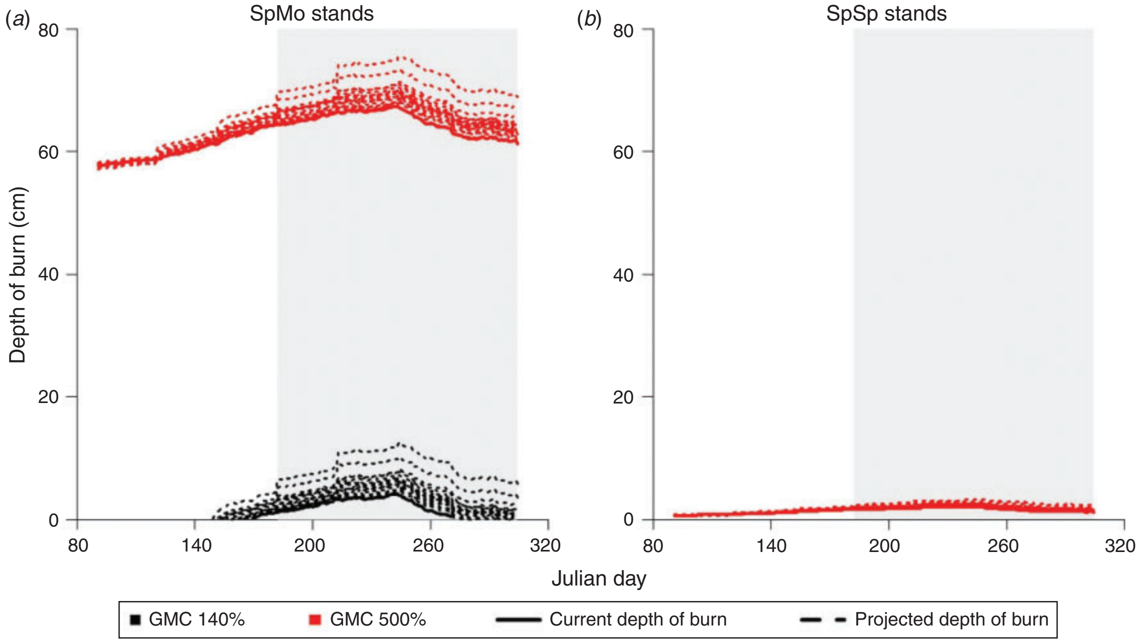

Fig. 6. Current (1971–2000) and projected (2071–2100) daily depth of burn (cm) in (*a*) spruce–feather moss (SpMo) and (*b*) spruce–*Sphagnum* (SpSp) stands under gravimetric moisture content (GMC) 140% (black) and GMC 500% (red) scenarios (GMC = 140% was never reached in SpSp stands). The deviations (dotted lines) computed from the 2071–2100 minus the 1971–2010 projections are plotted. Vertical grey bar corresponds to days of months that showed significant differences between current and future projections of the DC (Student's *t*-tests, $P < 0.05$).

burn were projected to vary from −0.6 to 8.4 cm depending on the models and IPCC emission scenarios. In contrast, the DC increase should not be sufficient to permit moisture limits to reach 140% in SpSp stands or to greatly modify depth of burn in SpSp stands, varying from −0.09 to 1.23 cm when burning soil moisture conditions were 500%.

Discussion

This study reports on the soil moisture content dynamics of Clay Belt stands during a year of particularly dry conditions. A fire weather-based gravimetric moisture model with *in situ* soil moisture data from deep forest floor layers was parameterised to calculate and project future depth of burn potential. Analysis of moisture contents confirmed our first hypothesis that soil moisture dynamics in spruce–*Sphagnum* (SpSp) stands are less sensitive to drought severity than in spruce–feather moss (SpMo) stands. A decrease in GMC with seasonal drought in SpMo stands is consistent with information acquired from analyses in other boreal stands (e.g. Lawson and Dalrymple 1996, Otway *et al.* 2007). As previously observed by Waddington *et al.* (2012), GMC of SpSp stands showed a steady-state with high values during the fire season. This 'resistance to drought' is probably related to the presence of *Sphagnum* species (Dai *et al.* 1974) that act as a physical soil isolating barrier from atmospheric temperature variations, notably by air spaces in the *Sphagnum* layer (Gornall *et al.* 2007). The *Sphagnum* species are also composed of internal hyaline cells (water tanks) (Silvola 1991) in which stocked water acts as insulation. This internal structure provides better protection against atmospheric temperature variations in comparison with the external structure found in feather moss (Busby and Whitfield 1978), allowing lower evaporation and increasing isolative effects.

Modelling analysis highlighted, first, that drier weather conditions are required in SpSp stands to burn the same amount of organic layer as in SpMo forests. The water retention characteristics of some *Sphagnum* species protect forest soils not only from drought but also from high organic layer consumption during wildfire (Benscoter and Wieder 2003; Harden *et al.* 2006; Shetler *et al.* 2008; Kasischke *et al.* 2010; Benscoter *et al.* 2011; Turetsky *et al.* 2011*a*). Second, depth of burn in SpSp stands was independent from date of burn. DOB in SpSp stands should thus be less affected by an increase in DC, as projected with the 2071–2100 climate change scenarios. Our results in Clay Belt forested peatlands hence contrast with previous studies conducted in peatlands located in the discontinuous permafrost. Therein it was suggested that DOB may increase in response to climate change (e.g. Kasischke *et al.* 2010; Turetsky *et al.* 2011*a*, 2011*b*). This may be explained by the different mechanisms responsible for the poor drainage noted in this study. In the case of sites on the discontinuous permafrost, saturated soil conditions are promoted by the maintenance of ground temperatures below the freezing point of water (Bonan and Shugart 1989). Climatic warming in recent years has induced permafrost degradation (Vitt *et al.* 2000) and affected water storage, leading to a decrease in moisture content (Zoltai *et al.* 1998; Frolking *et al.* 2011). In our case, flat topography and clay substrate, which originate from long geological processes, are the mechanisms responsible for poor drainage (Fenton *et al.* 2005) and may not be directly alterable by climate change. Moisture conditions are mainly created by the accumulation of the organic layer leading to a rise in the water table (Fenton *et al.* 2006). A study encompassing peatlands from different global regions could improve our knowledge about the importance of drainage mechanisms.

Other processes induced by climate change could provide feedback on the high depth of burn risk in the future by further contributing to the loss of the *Sphagnum* layer. Notably, an increasing number of fires (e.g. Amiro *et al.* 2009; Le Goff *et al.* 2009; Bergeron *et al.* 2010; Wotton *et al.* 2010; Terrier *et al.* 2013) and area burned (e.g. Le Goff *et al.* 2008, 2009) could lead to successive fire events, which may in turn reduce the organic layer and eventually promote a switch from SpSp stands to SpMo stands. The *Sphagnum* layer could also be effected by the direct effects of climate change even without fire regime changes. For instance, increasing drought duration could lead to a lowering of the water table and a shift from SpSp to SpMo covers (Breeuwer *et al.* 2009) and an increase in tree cover (Gignac and Vitt 1994; Breeuwer *et al.* 2009). Temperature could also increase decomposition rate if saturation soil moisture reaches 25 to 75%, thereby further contributing to the loss of the *Sphagnum* layer (Wickland and Neff 2008). That being said, increases in temperature could stimulate *Sphagnum* growth (Loisel *et al.* 2012) and therefore counteract these potential effects.

Efforts are needed in data acquisition to improve estimates and knowledge of global effects of climate change on peatlands (Zoltai *et al.* 1998; Frolking *et al.* 2011). This study represents only 1 year of data from four sites, which were used for model calibration. A larger number of soil moisture probes at more depths at each site would have been preferred, but this was limited by equipment availability. Additional data are also needed to estimate moisture limits that allow a fire to ignite and spread in Clay Belt stand types. The GMC of SpSp stands never reached values lower than 140% in either 2010 or 2071–2100, and the limit of 500% was overestimated for SpMo as this moisture threshold was predicted to be deeper than the total organic layer depth. Weather conditions would probably not be sufficient for SpSp stands to reach this independent ignition limit. However, once a fire is started in peat, such as by lightning or by a larger sustained burning source like a burning log or other dead woody debris, the peat will continue to burn by smouldering combustion at GMC of 140–500%. As the results of this study indicate, these conditions can occur within the Clay Belt region.

Conclusions

The effects of climate change on the depth of burn in stands of the Clay Belt of eastern Canada were examined. *Sphagnum* layers protect soils from drought and consequently from increasing depth of burn risks. These results have important implications for forest management in the context of climate change adaptation. Climate change would increase depth of burn of spruce–feather moss stands. However, spruce–*Sphagnum* stands in the boreal Clay Belt should be more resistant to an increase in the depth of burn risk. Managers should consider that they could increase potential depth of burn if they apply practices to reduce *Sphagnum* establishment and favour the development of more productive spruce–feather moss stands. Peatland protection (such as reducing or preventing peatland drainage) could be an alternative way to increase forest resistance to fire and reduce future fire carbon emissions in eastern Canadian forests.

Given the uncertainties associated with field data and carbon cycle knowledge, these results should be seen as a first estimate of the effects of climate change on depth of burn in the boreal forest of the eastern Canadian Clay Belt. Future studies should focus on the role of *Sphagnum* species in soil moisture content and how it could be affected by climate change by monitoring over multiple sites and years. Future studies should also be extrapolated to a larger scale by a meta-analysis of existing data according to the different regions to understand the role of poor drainage mechanisms.

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Appendix 1. Calibration of GMC with duff moisture code

Duff Moisture Code (DMC) represents the average moisture content of loosely compacted, decomposing organic layers of moderate depth weighing ~5 kg m^{-2} when dry. It relates to the probability of lightning ignition and fuel consumption. The DMC model is an exponential model of moisture exchange wherein layers gain moisture from precipitation and dry depending on relative humidity and air temperature (Wotton 2009). The equivalent moisture Q can be calculated from DMC with the equation developed by Van Wagner (1987):

$$Q = 20 + \ln\left(\frac{DMC - 244.73}{-43.43}\right) \tag{A1}$$

For a temperature of 25°C, relative humidity of 30% and wind speed of 10 km h^{-1}, the response times of DMC and DC are ~10 days (Wotton 2009). Table A1 shows coefficients and fit statistics for the model of gravimetric moisture content (GMC) with DMC.

Table A1. Coefficients and fit statistics for model of gravimetric moisture content (GMC) with duff moisture code (DMC) as a predictor variable

$$\log(GMC_{jkdr}) = \beta_0 + \beta_1 D + \beta_2 DMC_{jkdr} + \beta_3 ST + \beta_4 DMC_{jkdr} ST + b_r + b_{dr} + b_{kdr} + e_{jkdr}$$

	Values	Standard error	P
Fixed effects			
β_0 (Intercept)	4.90	0.11	≤0.0001
β_1	0.02	0.007	≤0.05
β_2	−0.002	0.0002	≤0.0001
β_3	1.25	0.11	≤0.0001
β_4	0.0013	0.0002	≤0.0001
Random effects			
Region	0.05		
Depth in region	0.00005		
Replicates in depth in region	0.0003		

Appendix 2. Temperature and precipitation change projected with global climate models

Table A2. Change in mean temperature (°C) or total precipitation (%) projected by global climate models (GCMs) and their greenhouse gas forcing scenarios for the period 2071–2100 at the study area

Data were downloaded from the Canadian Climate Change Scenarios Network (CCCSN) data portal, www.cccsn.ec.gc.ca, accessed 23 February 2014

Centre	Model	Forcing	Temperature change (°C)	Precipitation change (%)
Bjerknes Centre for Climate	BCM2.0	A1B	3.6	9.3
		A2	3.5	14.8
		B1	2.3	3.2
Canadian Centre for Climate Modelling and Analysis (CCCma)	CGCM3T63	A1B	4.1	16.8
		A2	5.3	18.7
		B1	2.8	8.8
Australia's Common-wealth Scientific and Industrial Research Organisation (CSIRO)	CSIROMk3.5	A1B	4.1	14.1
		A2	4.8	16.4
		B1	3.2	9.1
GISS	GISSAOM	A1B	3.3	13.3
		B1	2.3	10.9
Institute for Numerical Mathematics	INMCM3.0	A1B	3.6	4.8
		A2	4.9	11.9
		B1	3.6	8.8
National Institute for Environmental Studies	MIROC3.2 medres	A1B	5.7	7.9
		A2	6.2	3
		B1	4.2	8.6