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Can the Canadian drought code predict low soil moisture anomalies in the mineral soil? An analysis of 15 years of soil moisture data from three forest ecosystems in Eastern Canada

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ABSTRACT

The Canadian Drought Code (CDC) is an empirical soil-drying model adapted to high-latitude forests and commonly used by Canadian fire managers and researchers to predict the water content of the organic soil layer. Better knowledge of the capacity of the CDC to predict the effect of droughts on the water content of the mineral soil could improve our capacity to predict the future response of Canadian boreal forests to future changes in drought frequency and intensity.

We tested the capacity of the CDC to predict mineral soil water content (SWC) and droughts against long-term (14–16 years) daily mineral SWC data from time domain reflectometry probes in multiple stations within three forest ecosystems of Eastern Canada respectively dominated by sugar maple, balsam fir and black spruce. Droughts were defined as SWC values lower than one standard deviation from their historical mean. The drought intensity and frequency of each growing season were computed as the sum of daily SWC departures from normal and the sum of days of drought, respectively.

Our results show that the CDC is a reliable predictor of mineral SWC ($r = 0.6$–0.8), drought frequency ($r = 0.5$–0.9) and intensity ($r = 0.7$–0.9) for high-latitude forest ecosystems of Eastern Canada. Lower correlations were due to the poor accuracy of the model at predicting mild droughts at the sugar maple stand due to the SWC values close to the drought threshold. We detected a higher susceptibility to droughts at the black spruce stand due to a 1-month-earlier occurrence of severe droughts.

KEY WORDS Canadian Drought Code; Canadian Forest Fire Weather Index System; soil water content; drought; high-latitude forests; podzol

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INTRODUCTION

Soil water plays a vital role in the regulation of many forest ecosystem processes, including the movement of nutrients in plants and soils and the provision of electrons for plant photosynthesis. An increasing number of cases of forest die-off related to droughts or high temperature in cold, temperature-limited environments as well as in mesic temperate forests suggest that a majority of forest species are vulnerable to droughts and that this vulnerability is not limited to dry, water-limited ecosystems (Allen *et al*., 2010). The 20–40% reduction in soil moisture projected by climate models for forest ecosystems of Eastern Canada by the end of the 21st century (Houle *et al*., 2012) will probably increase the intensity and the duration of droughts and should have major effects on forest ecosystem primary productivity (e.g. D'Orangeville *et al*., 2013). For instance, the summer drought and heat wave of 2003 in Europe reduced gross primary productivity by 30% and increased mortality, cancelling in a single year the equivalent of 4 years of net ecosystem carbon sequestration (Ciais *et al*., 2005). Drought impact should be integrated into predictive models in order to accurately predict future changes in forest productivity. This requires good knowledge of physiological thresholds for stomatal closure, embolism formation and eventually carbohydrate starvation (Choat *et al*., 2012). The acquisition of such knowledge is made difficult by the variability in drought responses because of the varying combinations of drought intensity and duration as well as the species-specific and site-specific responses. Crossing datasets of tree growth and survival over large temporal and spatial scales with extreme climate events is a promising approach providing significant empirical knowledge on tree species resistance (e.g. Babst *et al*., 2012; Carrer *et al*., 2012).

Various drought indices integrating climate or hydrological variables can be used to quantify drought frequency

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and intensity at various temporal (e.g. months, years) or spatial scales (e.g. regional, continental; Heim, 2002). However, drought indices have often been developed to reflect the conditions of the region for which they were designed. The most common drought index, the Palmer Drought Severity Index, was developed in the United States for semiarid and dry subhumid climates and does not incorporate snowmelt in its calculations (Keyantash and Dracup, 2002). Other common drought indices like the Standard Precipitation Index also exclude snowmelt water from their calculations. Hence, the most common drought indices are not adapted to the several months of continuous snow cover, short growing season and major influence of spring snowmelt on the seasonal soil water content (SWC) that characterize high-latitude forests (Barnett *et al.*, 2005).

The Canadian Drought Code (CDC) is an empirical soil-drying model commonly used by Canadian fire managers and researchers in order to estimate the soil flammability. This index, developed by Turner (1966), uses daily temperature and precipitation data and accounts for the effect of snowmelt in its calculation (Lawson and Armitage, 2008). Because of its empirical nature, the CDC does not explicitly reproduce hydrological processes. However, the CDC integrates two simple variables (precipitation and temperature) that are well correlated to soil moisture. While precipitation is mainly responsible for the increases in soil moisture, temperature controls evapotranspiration losses (although the soil moisture absolute values depend on other factors such as soil texture). For large-scale studies, empirical-drying models requiring easily available data of input variables, such as the CDC, can be advantageous compared with process-based models that require many input variables (forest composition, soil texture, soil horizon thicknesses, etc.).

The use of the CDC as a surrogate of SWC has been repeatedly validated against SWC values of organic soil horizons from Western Canada (Lawson and Dalrymple, 1996; Abbott *et al.*, 2007; Otway *et al.*, 2007; Johnson *et al.*, 2013). Despite the fact that the CDC was not originally designed to represent any particular soil horizon, it is commonly considered to represent the water content of deep, compact organic horizons in average 18-cm deep and 25 kg m^{-2} in dry weight, although such characteristics are not associated with a majority of forest soils in north-eastern North American forests (Van Wagner, 1987).

Increasing evidence suggests that water availability from mineral horizons may be crucial for drought tolerance in trees, as they are less sensitive to climate variations and may act as a more reliable water reservoir for trees (Schenk & Jackson, 2002, Warren *et al.*, 2005). For mature Scots pine and Norway spruce trees growing in the Swedish boreal forest, Bishop and Dambrine (1995), using hydrological isotopic tracers, observed that most of the tree water uptake was from a depth of 8–17 cm in the upper B horizon, lower than where most fine roots are located. In order to use the CDC to study boreal ecosystems response to soil water limitations, it is therefore essential that the CDC predicts accurately the SWC of mineral horizons, although this remains to be verified.

So far, only a few attempts have been made to use the CDC in order to predict hydric stress in boreal vegetation. Monthly CDC outputs were significantly correlated with the radial growth of tree populations in Central Canada (Girardin *et al.*, 2008). A significant relationship was also established between maximal CDC values and tree-ring chronology of northern white cedar (Bergeron and Archambault, 1993). However, the same seasonal CDC value can reflect a wide variety of drought conditions, e.g. intensity and length. A better characterization of tree species thresholds for drought tolerance could be drawn by converting raw CDC outputs into CDC anomalies relative to corresponding historical ranges of SWC values. This would provide a more detailed characterization of the droughts and allow the study of species drought tolerance over sites with naturally contrasting SWC. The capacity of the CDC to predict droughts has never been thoroughly tested, perhaps because of the scarcity of long-term daily SWC datasets.

The main objective of this study was thus to validate the accuracy of the CDC as a potential tool to predict low soil moisture anomalies in the mineral soil horizon of boreal forest ecosystems for the study of tree species drought tolerance. We compared the CDC output, computed from the weather data recorded at three forest ecosystems of Eastern Canada, with contrasting vegetation types growing on podzols, with replicated daily measurements of mineral SWC over a period of 14–16 years. Our specific objectives were as follows: (i) to compare the behaviour of CDC-modelled moisture with observed SWC in the top mineral soil during the growing season and (ii) to analyse the capacity of the CDC to predict the frequency, intensity and timing of low soil moisture anomalies.

METHODS

Site description

The three study sites are located on the Boreal shield ecozone in the province of Quebec, Canada, developed on the granitic gneiss series of the Grenville Province (Figure 1). Because of altitudinal and latitudinal gradients, each site has a distinct vegetation type. The Lake Clair watershed (46°57′N, 71°40′W, 270–390 m above sea level) covers 226 ha and is a typical northern hardwood forest of north-eastern North America, dominated by sugar maple (SM; *Acer saccharum* Marsh.), American beech (*Fagus grandifolia* Ehrh.) and yellow birch (*Betula alleghaniensis* Britton). The vegetation is growing on a ferro-humic podzol, with a 5-cm-deep forest floor and a 53-cm mineral

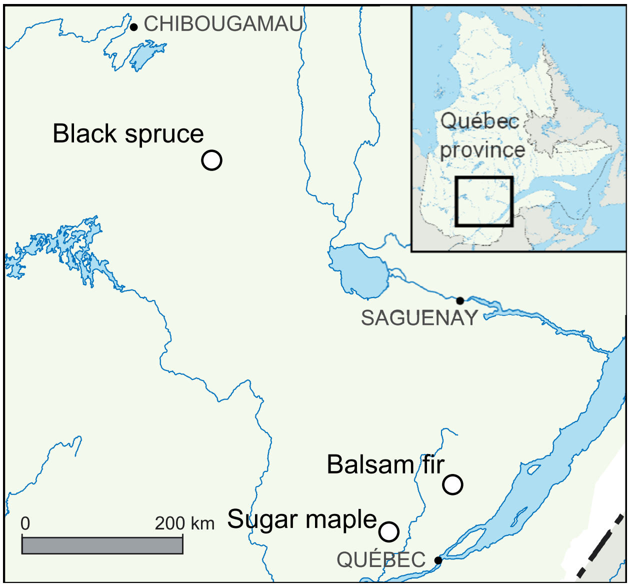

Figure 1. Location of the three watersheds in Quebec, Canada.

B horizon of sandy loam texture. The site receives 1392 mm of precipitation annually (31% as snow), and the annual catchment runoff is 855 mm. September is the month with the most precipitations.

The Lake Laflamme watershed (47°19′N, 71°07′W, 68 ha) is located at higher altitude (770–860 m above sea level) and is dominated by balsam fir (BF; *Abies balsamea* (L.) Mill.) with white birch (*Betula papyrifera* Marsh.) and white spruce (*Picea glauca* (Moench) Voss) as companion species. The vegetation lays on an orthic humo-ferric podzol on a sandy loam, with a 17-cm organic horizon over a 63-cm mineral horizon. Average precipitation is 1451 mm annually (41% as snow), and the annual catchment runoff is 914 mm. September is also the month with the most precipitation.

Finally, the Lake Tirasse watershed (49°12′N, 73°39′W, 400–450 m above sea level) is at higher latitude and covers 56 ha, and the forest is composed mainly of black spruce (BS; *Picea mariana* (Mill.) Britton, Sterns & Poggenburg) with some jack pine (*Pinus banksiana* Lamb.) growing on a humo-ferric podzol developed on a loamy sand with a 13-cm forest floor and a 50-cm mineral B horizon above a cemented horizon. The site receives 919 mm of precipitation annually, including 312 mm in the form of snow, and the annual catchment runoff is 610 mm. The highest monthly precipitation usually occurs in July. More details on the three watersheds soil characteristics can be found in the study of Ouimet and Duchesne (2005). The Lake Clair, Lake Laflamme and Lake Tirasse study sites will be named hereafter by their dominant vegetation type, i.e. SM, BF and BS. Each site is equipped with a complete meteorological station. The mean air temperature at SM, BF and BS (1998-2012) is 4.4 °C, 1.5 °C and 1.5 °C, respectively.

Data collection

Meteorological stations used to monitor weather conditions were located in a clearing next to each site. Data collection was started in 1995 at SM, in 1997 at BS and in 1999 at BF and is ongoing. Air temperature and relative humidity were measured at a height of 3.3 m (HMP35CF, Campbell Scientific Inc., Logan, UT, USA). Measurements were made every 5 s and hourly averages were recorded by the data logger (CR-1000, Campbell Scientific Inc.). Precipitation was measured hourly with a precipitation gauge (35-1558, Fisher and Porter, Albany, NY, USA). During the growing season, the readings from a tipping bucket rain gauge (TE-525, Texas Electronics, Dallas, TX, USA) were used to complete the missing data. Snowpack height was monitored weekly by averaging the readings from multiple vertical rulers anchored in the ground within the studied stands (six at BF and BS, 12 at SM).

At each site, daily volumetric SWC (referred hereafter as SWC_{obs}) was measured using time-domain reflectometry (CS615, Campbell Scientific) with sensor rods inserted horizontally with insertion guides in the top mineral B horizon, 34-cm deep at SM and 22-cm deep at BF and BS. Before insertion, the good functioning of each sensor was tested in air (0% SWC) and water (100% SWC). The soil dielectric measurements were converted to estimates of volumetric SWC according to the manufacturer standard calibration curve. In addition, the converted SWC measurements were corrected for temperature bias according to the manufacturer correction curves. Because the goal of this paper is to evaluate the potential of the CDC to detect temporal soil water variations, especially droughts in the form of low soil moisture anomalies relative to normal values, the use of calibrated SWC_{obs} values was not necessary to answer our research questions. To account for spatial variability, soil moisture was measured at two stations within the SM site (SM1 and SM2), four stations within the BF site (BF1, BF2, BF3 and BF4) and three stations within the BS site (BS1, BS2 and BS3). At SM, the soil profiles are 110 m apart, while profiles from BF and BS are 20–28 m apart. For all sites, daily weather and soil moisture data are available for 14–16 years.

Data correction

Abnormal SWC data were observed at BF2 and BF3 at BF. Starting on July 2006, SWC_{obs} measurements at BF2 became more variable. After comparing different corrective approaches, dividing SWC values by the ratio of standard deviation of the means before and during that period was found to remove completely the anomaly. At BF3, the SWC_{obs} suddenly increased on November 2008 following the replacement of a broken probe. We calculated the average difference between values before and during that period and subtracted that difference to correct the data (Supporting information). Corrections were validated by comparison of data from other stations at the site.

In order to obtain stationary time series without long-term trends required for the analyses used in our study (Legendre and Legendre, 1998), a linear regression was applied to each SWC_{obs} time series. Significant linear trends (at $P < 0.05$) were detected with a *t*-test in four out of the nine stations (SM1, BF1, BF3 and BS1), in which case they were removed (Appendix 1). Following correction, the stations were averaged to obtain a single time series for each site. The field water-holding capacity associated with each site was estimated by averaging the spring soil recharge values following snowmelt or high precipitation episodes (Dane *et al*., 2002). SWC relative to field capacity (0–1) was computed by subtracting the minimal SWC observed at the site, taken as the permanent wilting point, to the SWC_{obs} and dividing the result by the field capacity (Bréda *et al*., 2006).

Drought code

Daily observations of air temperature and 24-h rainfall were used to calculate the CDC component of the Canadian Forest Fire Weather Index System for each site, according to Van Wagner's algorithm (Van Wagner 1987), using the function 'fwiBAT' from the 'fwi.fbp' package (Wang *et al*., 2013) in R software (R Development Core Team, 2014).

As the CDC algorithm tracks the amount of water in and out of the layer during the growing season, its calculation relies on the value from the previous day. Therefore, missing data for temperature (1.8–6.3% of values) and precipitation (6.4–25.4% of values) due to device malfunctions were replaced with data generated by the BioSIM model, which uses the four closest geo-referenced weather stations to the specified location and adjusts the data for the differences in longitude, latitude and elevation (Régnière, 1996). Daily temperature and precipitation data generated with BioSIM are generally highly correlated ($r \geq 0.99$) with observed values (Régnière and St-Amant, 2007).

The growing season was set to start on the third day after complete snowmelt and to end in the fall when snow covered the ground, a standard approach for the calculation of the CDC (Lawson and Armitage, 2008). With average winter precipitations exceeding 200 mm, the soil at our study sites is considered completely saturated with water following snowmelt (Lawson and Armitage, 2008). Thus, we applied the recommended default initial CDC value of 15 at the start of the season, corresponding to about 3 days of drying from complete moisture saturation. In order to compare the observed data with the predicted CDC values, the CDC was converted to a SWC (SWC_{pred}) equivalent (gravimetric SWC, in $g\,g^{-1}$) with a theoretical maximum moisture content of 400% using the following standard model (Van Wagner, 1987):

$$SWC_{pred} = 400 * exp^{-CDC/400} \quad (1)$$

Drought identification

Using the departure-from-normal approach used in major drought indices like the Palmer Drought Severity Index, predicted and observed droughts were defined as SWC values lower than one standard deviation from their respective predicted or observed historical mean. The mean and standard deviation were obtained for each site by averaging all SWC_{obs} or SWC_{pred} values corresponding to each day of the year for the entire period of record (on average, $N = 78$) using a moving average with a 7-day window centred on the day of interest. For example, the historical mean for 6th July at station BF1 would be calculated by averaging the SWC from 3 to 9 July for the years 1999–2012.

For each growing season, drought frequency was computed as the sum of days of drought. In addition, each day of drought was characterized for its intensity by computing the SWC difference with the normal value. In order to compare the predicted with observed values on the same scale, moisture differences were divided by the normal value. Daily intensity values were summed by growing season.

Statistics

The predictions of the CDC were compared with the observed values with ordinary-least-square type II regressions because of the fact that both observed and predicted variables are random (Legendre and Legendre, 1998). The conversion of the CDC output into soil water equivalent with Equation (1) has been proven to linearize the relationship between the CDC and field SWC (Van Wagner, 1987). This assumption was confirmed by the visual inspection of the relationship between the two variables (Figure 3); thus, a linear regression model was used. The significance associated with the slope parameter and the correlation coefficient was tested with 999 permutations. Daily values were used to compare SWC_{obs} with SWC_{pred}, while annual values were used to compare the predicted with observed seasonal droughts (frequency, intensity and timing of most intense drought). All analyses were computed using the R software (R Development Core Team, 2014).

RESULTS

Temporal and spatial variability

Spring snowmelt was completed by late April at SM (DOY 115 ± 8; mean annual value ± standard deviation) and mid-May at BF and BS (DOY 134 ± 8 and 129 ± 9, respectively).

In the fall, the ground was covered with snow in late October at BF and BS (DOY 302 ± 10 at both sites) and 2 weeks later at SM (DOY 318 ± 15).

All stations displayed a typical seasonal pattern of elevated SWC_{obs} in the spring because of snowmelt, followed by a declining trend until September (DOY 250), when higher precipitation and lower plant water uptake contributed to the increase in SWC_{obs} (Figure 2). Fall SWC_{obs} at SM and BF reached values similar to spring, while soils at BS did not recharge to spring SWC_{obs} levels. Soils from BS displayed the lowest SWC_{obs} during the snow-free season, with monthly SWC_{obs} of 16% ± 2%, compared with 33% ± 4% at SM and 37% ± 6% at BF (Figure 2).

Despite a general agreement in the temporal patterns of SWC_{obs} at the three sites, the differences in SWC_{obs} and synchronicities were observed. At SM, the two stations displayed contrasted SWC_{obs} levels with averages of 43% ± 6.8% and 20% ± 3.1% (Figure 2), although their seasonal synchronicity was high ($r = 0.93$). At BF, large spatial differences in snowmelt water among stations reduced their spring synchronicity, with average seasonal correlation between stations of 0.70–0.92. Soil water content of BF1 remained high until the end of July (DOY 200), while at BF4, it decreased rapidly from snowmelt until September, and stations BF2 and BF3 displayed intermediate patterns. In addition, the autumn water recharge was different at BF4: in contrast with BF1, BF2 and BF3, SWC_{obs} was not fully replenished by the end of the season. As for BS, the synchronicity in SWC_{obs} between stations was also variable, with correlations ranging from 0.57 to 0.91. BS2 and BS3 displayed very similar SWC_{obs} patterns over time ($r = 0.91$), including a major peak during snowmelt, which was not observed at BS1 (Figure 2a). This is consistent with the lower correlation of BS1 with BS2 ($r = 0.57$) and BS3 ($r = 0.67$).

Correlation between predicted and observed soil moisture

At the three sites, the SWC_{pred} followed the typical seasonal pattern described earlier with high spring and fall water contents and lower summer values with a minimum reached in early September (Figure 2). The relationship between SWC_{pred} and SWC_{obs} was generally linear with correlations of 0.62, 0.73 and 0.84 at BS, BF and SM, respectively (Figure 3). The lower correlation found at BS is mostly due to an inverse relationship observed between SWC_{pred} and SWC_{obs} at high SWC (for $SWC_{pred} > 3.5$, $r = -0.10$). This unusual relationship was caused by the lag between the observed and predicted values in the spring. While the CDC predicted a soil at field capacity at the beginning of the snow-free season, we rather observed a rapid increase in the amount of stored water in the first weeks of the season (Figure 2).

Identification of droughts

The number of days of drought was highly variable between years, ranging from 0 to 64, 0 to 115 and 1 to 93 days at SM, BF and BS, respectively (Figures 4 and 5). The driest years, in terms of the number of days of drought and intensity, were 2002, 2010 and 2012 at SM and BF and 2000, 2005 and 2010 at BS. The average SWC_{obs} during the 2010 drought, common to all study sites, ranged from

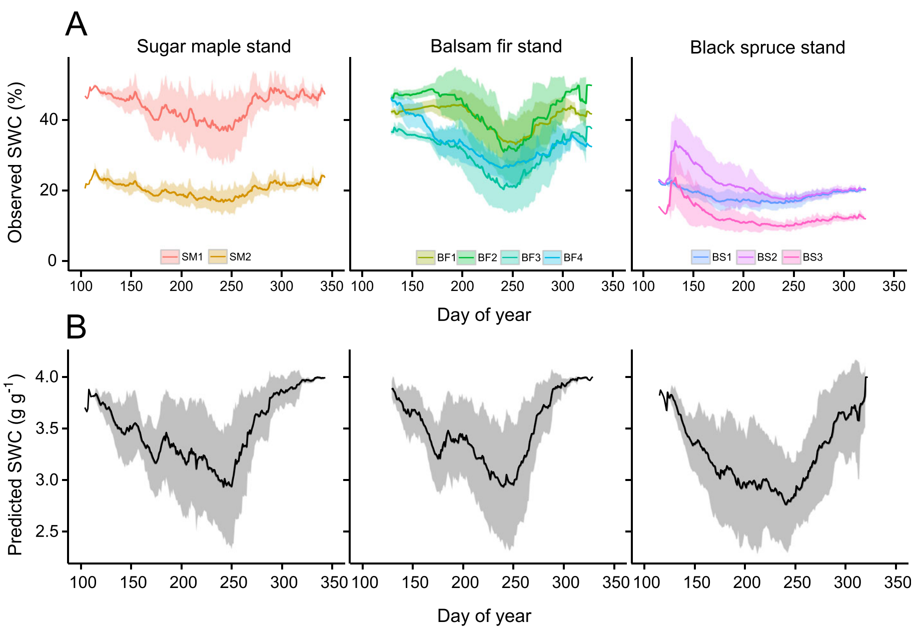

Figure 2. A. Average volumetric soil water content (SWC_{obs}) during the snow-free season in the upper B horizon of each station at sugar maple, balsam fir and black spruce. B. Canadian Drought Code gravimetric soil water content (SWC_{pred}) predicted for each site. Shaded areas represent the standard deviation from the mean.

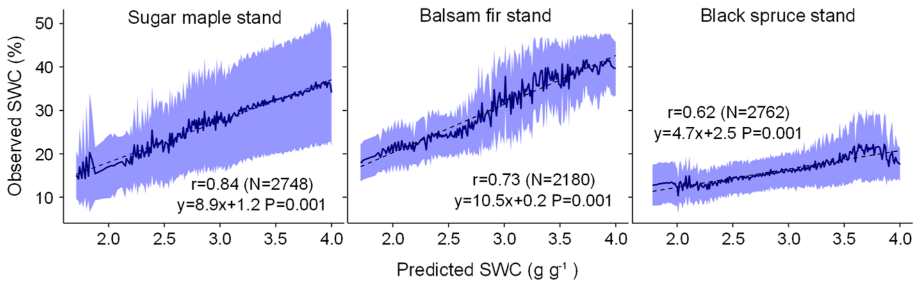

Figure 3. Canadian Drought Code gravimetric soil water content (SWC_{pred}) and corresponding average of observed soil water content (SWC_{obs}) at each site. Coloured ribbons correspond to the standard deviation from the mean. Correlation values, linear regression coefficients and their probability are shown.

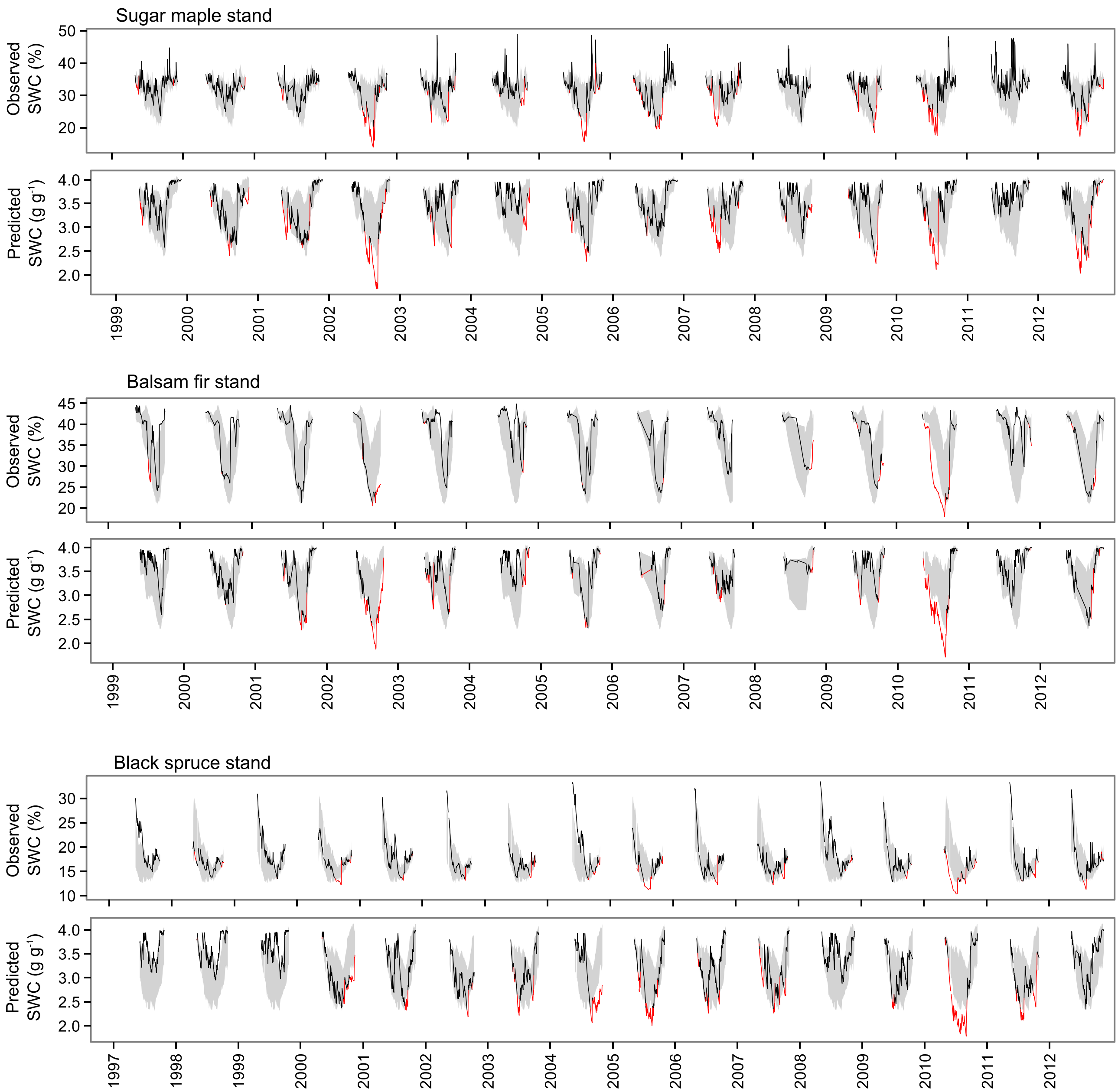

Figure 4. Observed and predicted soil water content during the snow-free season at sugar maple, balsam fir and black spruce watersheds for the entire period of observation. Black curves are the daily observed or predicted value averaged for each site, while shaded areas represent the corresponding range of historical normal values (mean ± 1 standard deviation). Droughts, defined as daily soil water content below its historical normal range of values, are in red.

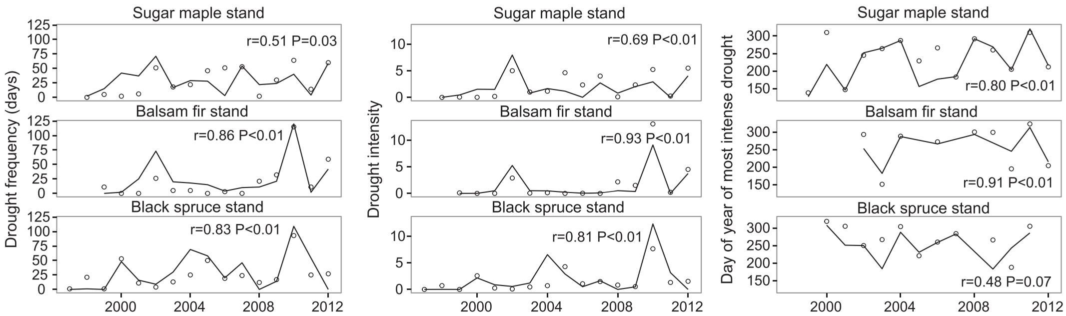

Figure 5. Mean annual observed (circles) and predicted (lines) number of days of drought, relative drought intensity and day of year of most intense drought during the growing season at sugar maple, balsam fir and black spruce. Pearson correlations between the observed and predicted values at each site are shown, as well as their associated probability.

12% at BS to 27% at BF, although the SWC_{obs} of all profiles was 21–26% lower than the normal SWC_{obs} for that period.

The success of the CDC at predicting drought frequency, intensity and timing was variable among ecosystems. The most accurate results were found at BF, with correlations for drought frequency, intensity and timing of 0.86, 0.93 and 0.91, respectively (Figures 4 and 5). Drought frequency and intensity were also well predicted at BS, with correlations of 0.83 and 0.81, respectively, but the model did not predict accurately the most intense day of drought ($r = 0.48$). The CDC was less accurate at SM, with correlations of 0.51 and 0.69 for drought frequency and intensity, respectively, although the model predicted successfully the timing of the most intense drought ($r = 0.80$; Figure 5). The years with the worst predictions at that site, with 40% + relative error rate for drought frequency, were associated with mild droughts with SWC_{pred} only 0.01–0.14 g g^{-1} less than the threshold, while better predicted droughts had SWC_{pred} 0.14–0.35 g g^{-1} less than the threshold.

Relative to field capacity, the intensity of droughts differed between sites, with mean SWC_{obs} equivalent to 30.1%, 25.1% and 17.2% of the water-holding capacity at SM, BF and BS, respectively (Figure 6). If we define severe droughts as those with SWC_{obs} less than 20% relative to field capacity, such droughts were recorded from June to September at SM (86 days), from July to October at BF (104 days) and from May to October at BS (138 days). At SM and BF, relative SWC_{obs} during droughts was generally above 40% in April–May and decreased steadily until September, when the lowest SWC values were recorded (Figure 6). In the following weeks, the SWC values rapidly rose back to spring levels. At BS, not only did the droughts displayed generally lower SWC relative to field capacity, but the most intense droughts occurred in July, 2 months earlier than at the other sites. In the following months, the relative SWC observed during droughts steadily increased until the end of the growing season similarly to the two other sites (Figure 6).

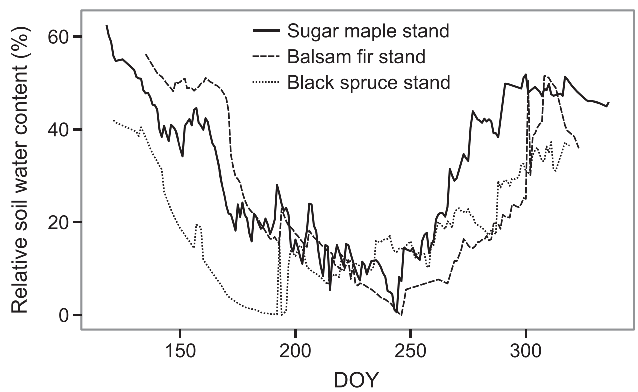

Figure 6. Mean daily observed soil water content during droughts relative to the field water capacity observed at sugar maple, balsam fir and black spruce.

Influence of the date of snow disappearance on the Canadian Drought Code

Inaccurate dates of snow disappearance generally reduced the predictive power of the CDC, but this adverse effect was mostly limited to the first month of the season (Table I). An earlier date of snowmelt of 1–3 weeks reduced the correlation between SWC_{obs} and SWC_{pred} by 80–87% during the first week of the growing season. The effect decreased in the following weeks, with a 12–16% negative effect in the fourth week. Later dates of snowmelt reduced the correlation by 3–41% in the first week, but the negative effect was reduced to 3–4% during the fourth week of the growing season. No differences were detected later in the season.

DISCUSSION

Capacity of the Canadian Drought Code to predict soil moisture variations

Considering the large spatial heterogeneity of the water-holding capacity (field capacity) within each study site, the significant overall linear relationship between SWC_{obs} and

Table I. Effect of a change in the date of snowmelt on the predictive power of the Canadian Drought Code, expressed as weekly correlation estimates between predicted and observed soil water content, averaged for all stations, since the beginning of each growing season.

	Earlier snowmelt				Delayed snowmelt		
	3 weeks	2 weeks	1 week	No lag	1 week	2 weeks	3 weeks
Week 1	0.03	0.02	0.02	0.15	—	—	—
Week 2	0.28	0.28	0.28	0.36	0.35	—	—
Week 3	0.33	0.34	0.31	0.39	0.38	0.21	—
Week 4	0.41	0.43	0.43	0.49	0.48	0.41	0.29
Week 5	0.44	0.45	0.46	0.51	0.49	0.44	0.36
Week 6	0.57	0.56	0.58	0.62	0.63	0.59	0.53
Week 7*	0.69	0.69	0.70	0.72	0.72	0.70	0.70

*The following weeks are not displayed as the differences in correlation coefficients were negligible.

SWC_{pred} (r = 0.6–0.8 among sites) demonstrates that the CDC is capable of predicting the SWC in the mineral soil horizon of boreal forest ecosystems. The weaker relationship found at BS (r = 0.62) is mostly due to the poor fit of the model during the first weeks of the growing season. Although the coarse texture of the BS soil would suggest a rapid drainage of the snowmelt water in spring, increases in SWC have been associated with rises in the groundwater table (Laudon *et al.*, 2004), but the presence of a cemented horizon at the bottom of the mineral soil probably could also have delayed drainage of the snowmelt water (Moore, 1976). An alternative possibility that soil frost could have altered the snowmelt water flow paths is not supported by the soil temperature data (not shown).

Like all drought indices that use meteorological data as input, the CDC does not take into account the spatial variability of SWC caused by the microtopography and the associated variability in soil texture, soil organic matter content or drainage. Forest soil are typically highly heterogeneous (Wilson, 2000), and our study sites are no exception: previous analyses of mineral B soil horizons sampled at various depths from five to seven soil profiles at each study site revealed variable levels of stoniness (23–80% at SM, 6–40% at BF and 2–25% at BS) as well as organic matter content (2–27% at SM, 1–20% at BF, 1–8% at BS, unpublished data). This can probably explain the high spatial variability in SWC_{obs} between nearby stations within each forest stand. Our data reveal that the largest differences in SWC_{obs} between stations occur in the spring, as spring snowmelt is the most important hydrological event in areas with significant snow cover such as our study sites (Barnett *et al.*, 2005). Differential water flow paths of melt water, combined with variable drainage capacity and groundwater table heights, maintained a high SWC_{obs} at some stations until July, as observed at BF and BS, while the SWC_{obs} of other stations steadily decreased from the start of the season.

The high spatial variability of the SWC_{obs}, within the otherwise homogeneous forest canopies of our study, sheds light on one of the limitations of drought indices to predict SWC. Although the SWC_{pred} correlates relatively well with the mean SWC_{obs} at the stand scale, it does not take into account the spatial variability at a smaller scale and, therefore, does not necessarily reflect the SWC_{obs} at the tree scale.

Capacity of the Canadian Drought Code to predict droughts

From the 14–16 years of data analysed, our study shows that the CDC can predict the frequency (r = 0.5–0.9) and intensity (r = 0.7–0.9) of droughts in temperate and boreal forest ecosystems of Eastern Canada. The lower success of the CDC at predicting droughts frequency and intensity at SM was mainly due to a high number of droughts with SWC_{obs} close to the threshold value. Such events, which can fall within the 'drought' or 'non-drought' status, are more likely to be incorrectly categorized by the CDC. When using the CDC to study past drought impact on the environment, we suggest that the years characterized by drought levels close to the threshold value be excluded in order to minimize the model error.

Although droughts were evenly distributed within the snow-free season, their corresponding SWC varied greatly among sites and during the growing season, which should reflect on the vegetation response. In terms of water potential and plant stress, droughts occurring in the first weeks of spring and characterized by a relatively high SWC_{obs} could have a limited physiological significance for plants. Therefore, when using the CDC to predict droughts and their effects on vegetation, one could assess such effects using the predicted SWC. In addition, the average SWC during droughts as well as the seasonal peak in drought severity displayed interesting differences between sites. Both SM and BF shared similar seasonal patterns, with the most severe droughts (SWC_{obs} <20% of FC) occurring mostly in July, August and September, at least 2 months after the end of the snowmelt. At BS, however, severe droughts occurred as soon as the end of May, only 3 weeks after snowmelt and 25–36 days earlier than at the more southern sites. This pattern could be due to the coarser soil texture at BS as well as the lower precipitations and reduced snowpack, which would reduce the buffering effect of spring snowmelt water on the intensity of early droughts. The first weeks of the growing season are critical in high-latitude forests as they use this time to rehydrate before the beginning of growth (Turcotte *et al*., 2009). Such early droughts could delay the trees rehydration and potentially reduce the season favourable for tree growth.

Computing the CDC necessitates daily temperature and precipitation data as well as the dates when snow covers the ground. While temperature and precipitation data can be relatively easy to obtain, snow cover data are rarely available. Moreover, the timing of snow disappearance under forest cover can vary spatially because of the variations in canopy structure, ground cover, slope or altitude. In the current study, snow cover was measured *in situ* using snow rulers. However, such ideal situation is not always met. The supply of snowmelt water can affect soil moisture for several months in the growing season (Barnett *et al*., 2005). As seen here, the biased estimates of the date of snow disappearance can significantly reduce the accuracy of the CDC but only during the first weeks of spring, when the risks of plant water stress are limited by the important input of snowmelt water.

CONCLUSIONS

In this study, we tested the ability of the CDC and its moisture converting function to predict mineral SWC using 14–16 years of daily observations from three different forest ecosystems of Eastern Canada. Our results show that the CDC is a reliable predictor of mineral SWC_{obs} ($r = 0.6$–0.8). Focusing exclusively on low soil moisture anomalies, or droughts, we show that the CDC can predict with good accuracy the frequency ($r = 0.5$–0.9) and intensity ($r = 0.7$–0.9) of such events. The earlier occurrence of severe droughts observed at the black spruce stand, a probable effect of coarser soil texture and reduced snowpack, suggests a higher susceptibility to droughts. Our results support the use of the CDC as a drought indicator for high-latitude forest ecosystems, although certain mild droughts can be less accurately predicted by the model because of their proximity to the drought-detecting SWC threshold. In addition, an inaccurate date of snowmelt can reduce the capacity of the CDC to predict SWC, but this effect only lasts a few weeks at the beginning of the growing season, when risks of drought are tempered by the input of snowmelt water.

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