

# A simple soil moisture index for representing multi-year drought impacts on aspen productivity in the western Canadian interior



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## ABSTRACT

Tree ring studies have shown that drought is a major factor governing growth of aspen (*Populus tremuloides* Michx.) forests in western Canada. Previous analyses showed that interannual variation in aspen radial growth is moderately well-correlated with a climate moisture index (CMI), calculated annually as the difference between precipitation ( $P$ ) and potential evapotranspiration ( $PE$ ). However, there are multi-year lags, where current year growth is significantly related to CMI over each of the preceding 5 years. We postulated that such lags arise because of tree growth responses to soil water content, which in deep soils may change slowly in response to interannual variation in  $P$  and  $PE$ . To address this, a model was developed that simulates changes in a soil moisture index (SMI) from inputs of  $P$  and  $PE$  only. The SMI represents the quantity of available soil water (mm) for aspen forest evapotranspiration and growth, and also provides a measure of relative soil water content ( $\theta_r$ ). Model performance was tested using measurements made at an intensively instrumented boreal aspen stand in Saskatchewan, Canada, over a 9-year period that included an exceptionally severe drought (2001–2003). Following optimization of the equations describing soil water limitations on evapotranspiration, the model was successful in simulating the observed, monthly variation in  $\theta_r$  ( $r^2 = 0.86$ – $0.88$ ). The model was then used to estimate historic variation in the SMI across a regional network of aspen stands where historical variation in growth was reconstructed from tree-rings. Subsequent analyses showed that average SMI during the current growing season was comparable to the CMI in its ability to explain temporal variation in aspen growth. However, the multi-year lags associated with the CMI were no longer statistically significant when the SMI was used as the independent moisture variable. In a case study of aspen stands that had been free of significant defoliation by insects, tree-ring analysis showed that growth was significantly related to CMI in each of the preceding 5 years, but was significantly related to SMI only in the current year and the preceding year. Thus, hydrological lags can explain much of the apparent delay in aspen growth responses to moisture, and future tree-ring studies may benefit from using modeled SMI as a more realistic index for assessing

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## 1. Introduction

Over the past decade, there has been a notable increase in reporting of drought-related impacts on forests at regional (Breshears et al., 2005; van Mantgem et al., 2009) and global (Allen et al., 2010) scales. In the North American boreal forest, the reported

impacts include large-scale increases in tree mortality (Peng et al., 2011) and decreases in forest growth (Beck et al., 2011), net primary production (Bunn et al., 2007) and net biomass increment (Ma et al., 2012).

One of the affected species is trembling aspen (*Populus tremuloides*), which is the most widely distributed tree in North America. Following the exceptional, subcontinental drought of 2001–2003, massive dieback and mortality of aspen forests was documented across large areas of Colorado (Worrall et al., 2010) and western Canada (Michaelian et al., 2011). In both regions, tree-ring studies have shown that aspen growth is also negatively affected by moisture deficits (Hogg et al., 2005; Hanna and Kulakowski, 2012).

One of the major challenges and knowledge gaps is the spatial and temporal scaling of drought effects on aspen and other forest types across large areas (Hogg, 1997; Michaelian et al., 2011). Such

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knowledge is needed, for example, for reporting on climate-related impacts on forest carbon cycling (Kurz et al., 2009) and for long-term planning of forest practices to achieve a sustainable supply of wood fiber from managed forests (Bernier and Schoene, 2009).

Previous studies (Hogg, 1994, 1997) reported on a simple, climate-driven index of water balance that was developed as a method to assist in the understanding of processes affecting forest distribution in western Canada. This index, referred to as the Climate Moisture Index or CMI, is calculated annually as the difference between precipitation ( $P$ ) and potential evapotranspiration ( $PE$ ). One of the useful features of the CMI is that the zero isoline of this index (where  $P=PE$  over the long term) corresponds remarkably well to the forest–grassland boundary in the region (Hogg, 1997). Thus over the long term, positive CMI values denote moist climates capable of supporting closed-canopy forests, whereas negative values indicate drier climates where forest cover is typically patchy (parkland) or absent (prairie) (Hogg and Bernier, 2005). To facilitate the reporting of the CMI across remote forested areas where long-term meteorological observations are limited, the calculation of  $PE$  is based solely on the monthly means of daily maximum and minimum temperature, along with station elevation that is used to correct for barometric pressure effects (Hogg, 1997). Thus, the CMI can be readily calculated and mapped across large areas and over the multi-decadal periods of instrumental climate records.

The CMI has been successfully applied in the assessment of drought impacts on spatial and temporal variation in the growth, dieback and mortality of western Canadian aspen forests (Hogg et al., 2005, 2008; Michaelian et al., 2011). In each of these studies, the calculation of 12-month CMI values in successive “tree water years” ending 31 July was found to provide a good indicator of drought stress based on regressions with the variables describing aspen responses. However, it was found that there were often multi-year lags between the 12-month values of CMI and subsequent changes in aspen forest dynamics. For example, a regional tree-ring study on aspen showed that annual growth was significantly related to CMI in the current year and in each of the preceding 4 years (Hogg et al., 2005). We postulated that this is partly a consequence of tree growth responding directly to temporal variation in soil water content, which may be expected to change slowly in climatically dry regions with deeply rooted trees. If true, this would explain the apparent multi-year delays in growth responses to annual changes in forest water balance, i.e., inputs from precipitation and losses from evapotranspiration.

Drought-induced dieback and mortality of aspen and other trees may also occur as direct responses to soil water deficits through xylem cavitation (McDowell et al., 2008; Anderegg et al., 2012). Thus, the characterization of temporal variation in soil moisture within the tree rooting zone may be expected to provide a better measure of drought impacts on forest dynamics than that estimated by changes in  $P$ , CMI or other indicators of moisture.

The overall goal of this study was to develop a versatile, field-validated model of soil moisture variation that would be suitable for regional analyses of drought effects on stand dynamics of aspen and other boreal tree species in the west-central Canadian interior. For this purpose, we used the monthly water balance variables of the CMI (i.e.,  $P$  and  $PE$ ) as inputs to the soil moisture model because they can be readily mapped over large areas and multi-decadal time scales. The main output variables included monthly and annual totals of evapotranspiration ( $E$ ) and a soil moisture index (SMI, units in mm) that represents the quantity of available soil water in the tree rooting zone.

In the first portion of the study, the performance of the SMI model was examined using 9 years of measurements at an intensively instrumented flux tower site situated in a mature, boreal aspen stand in Saskatchewan, Canada. The measurement period included a wide range of climatic variation, notably the severe,

regional drought of 2001–2003 whose effects have been thoroughly documented in previous studies at this site (e.g., Kljun et al., 2006; Krishnan et al., 2006; Bernier et al., 2006; Barr et al., 2007; Zha et al., 2010). This provided an ideal opportunity to test the performance of the model under alternative parameters and equation forms describing soil water limitations on  $E$ .

We subsequently applied the SMI model to the regional analysis of multi-year drought effects on aspen growth in stem cross-sectional area based on tree-rings (Hogg et al., 2005). Most of the region's aspen stands have a history of severe defoliation by forest tent caterpillar (*Malacosoma disstria* Hbn.), which leads to strong growth reductions that may confound the characterization of drought impacts (Hogg et al., 2002a,b). Thus, we conducted a similar analysis in more northerly aspen stands near Fort Smith, NWT that were free of significant defoliation by insects over a prolonged period (87 years). In both of these case studies, we conducted regression analyses to determine the relative performance of the SMI and the CMI as indicators of drought impacts on aspen growth. Specifically, we examined the question of whether the multi-year effects of CMI are reduced or eliminated when the SMI is used as a more realistic indicator of drought stress during the seasonal period of stem growth in a given year.

## 2. Materials and methods

### 2.1. Soil moisture model structure

The SMI model was designed to estimate the temporal variation in soil water availability for tree growth using only temperature and precipitation as weather variable inputs. To achieve this, the SMI model was constructed as a one-layer “bucket” water balance model that uses the same inputs as those used in the “simplified Penman–Monteith” (SPM) method of estimating monthly  $PE$  for subsequent calculations of the CMI (Hogg, 1997).  $PE$  is defined as the expected rate of water vapor loss to the atmosphere from a well-vegetated landscape assuming adequate soil moisture in the plant rooting zone. The SPM method is based on the assumption that monthly  $PE$  is proportional to mean vapor pressure deficit ( $VPD$ ), which can be estimated from saturation vapor pressure (kPa) at the monthly mean values of daily maximum temperature ( $e_{T_{max}}^*$ ), minimum temperature ( $e_{T_{min}}^*$ ), and dewpoint temperature ( $e_{T_{dew}}^*$ ):

$$VPD = 0.5(e_{T_{max}}^* + e_{T_{min}}^*) - e_{T_{dew}}^* \quad (1)$$

Mean monthly  $e_{T_{dew}}^*$  was estimated as the saturation vapor pressure at the monthly mean value of  $T_{min}$  minus 2.5 °C (Hogg, 1997). The following equations (modified from Hogg, 1997) were then used to estimate daily  $PE$  ( $PE_{day}$ , mm d<sup>-1</sup>):

$$PE_{day} = 3.1 VPD k_t \exp\left(\frac{ALT}{9300}\right) \quad (2)$$

where  $ALT$  is the site altitude (m) and  $k_t$  is a cold temperature modifier that decreases linearly from its maximum value of 1.0 when mean monthly temperature ( $T_{mean}$ ) ≥ 10 °C, to 0.0 when  $T_{mean} \leq -5$  °C:

$$k_t = \max\left(\min\left(\frac{T_{mean} + 5}{15}\right), 1\right), 0 \quad (3)$$

The values of  $PE_{day}$  were used in the estimation of actual evapotranspiration ( $E_{day}$ ), a key variable used in the model:

$$E_{day} = k_m PE_{day} \quad (4)$$

where  $k_m$  is a soil moisture modifier ranging from 0 to 1. This variable, also referred to as the  $E:PE$  ratio, was calculated monthly as a function of the SMI, which is the available soil water content (mm) in the tree rooting zone. In the model, it was assumed that  $k_m = 1$

(i.e.,  $E_{day} = PE_{day}$ ) when SMI exceeds a critical value (the parameter  $SMI_{crit}$ ), and that  $k_m = 0$  (i.e.,  $E_{day} = 0$ ) when  $SMI = 0$ . A second model parameter,  $SMI_{max}$ , gives the maximum possible value of SMI.

Two alternative equation forms were used to simulate the decrease in  $k_m$  for  $SMI < SMI_{crit}$ : In the bilinear (BL) equation,  $k_m$  was calculated as  $SMI/SMI_{crit}$ , whereas in the quadratic + linear (QL) equation,  $k_m$  was calculated as:

$$k_m = 2 \left( \frac{SMI}{SMI_{crit}} \right) - \left( \frac{SMI}{SMI_{crit}} \right)^2 \quad (5)$$

The BL equation was based on the assumption of a linear relationship between  $E_{day}$  and the fraction of plant-extractable soil water in the rooting zone (e.g., Spittlehouse and Black, 1981; Zha et al., 2010), whereas the QL equation implies a quadratic relationship between these variables (Bernier et al., 2006).

In principle, the SMI model can be run on a daily time step but for the current application (regional-scale tree-ring analysis) we used a monthly time step. As a default, the initial value of the soil moisture index ( $SMI_0$ ) was set to its maximum value ( $SMI_{max}$ ) at the beginning of each simulation. Simulations were initiated using climatic variable inputs starting at least 5 years prior to the period of interest (e.g., the earliest tree ring) so that the value of  $SMI_0$  had a negligible effect on SMI in subsequent analyses. To achieve model stability, each month was subdivided into 30 “pseudo-days” (hereafter referred to as “day”), each having equal values of daily precipitation ( $P_{day}$ ) and calculated as the monthly total precipitation divided by 30. On each day of the simulation, SMI was calculated as:

$$SMI = \min(SMI_{day-1} + P_{day} - E_{day}, SMI_{max}) \quad (6)$$

where  $SMI_{day-1}$  is the value of SMI on the previous day. To achieve water balance, daily water runoff ( $R_{day}$ ) is calculated as:

$$R_{day} = \max(SMI_{day-1} + P_{day} - E_{day} - SMI_{max}, 0) \quad (7)$$

In the model output, SMI was reported at the end of the last day of each month. Although the model does not specifically differentiate between solid and liquid water (e.g., snow and rain), it was assumed that this simplification has a minimal influence on SMI during the snow-free season when soils in the region are normally thawed or nearly so (end of April or May to the end of October).

## 2.2. Field measurements

This study used 9 years of field measurements from the Old Aspen (OA) flux tower site that was originally established as part of the Boreal Ecosystem-Atmosphere Study (BOREAS) and has continued to operate since 1997 under the BERMS and Fluxnet-Canada research programs (Barr et al., 2004). The flux tower is located within an extensive forest dominated by mature trembling aspen (*P. tremuloides* Michx.) in Prince Albert National Park, Saskatchewan (53.7° N, 106.2° W). The overstory aspen originated from fire in 1919 and have an average height of about 22 m, while the understory is composed mainly of dense hazelnut (*Corylus cornuta* Marshall) shrubs about 2 m tall. The terrain is generally level to gently rolling and the soil is an Orthic Gray Luvisol with an 8–10 cm surface organic layer overlying sandy clay loam in the uppermost 120 cm of mineral soil. Further details on site characteristics are given by Barr et al. (2004) and Bernier et al. (2006). Water table depths as deep as 4 m have been recorded at the site (Barr et al., 2007). Maximum rooting depth is not known but aspen roots were found at soil depths down to 130 cm or more in similar boreal stands (Strong and La Roi, 1983) and aspen sinker roots may descend to depths of about 3 m or more in some cases (Gifford, 1966).

The 9-year period of 1997–2005 included three consecutive years of severe drought (2001–2003) followed by several years of exceptionally wet conditions starting in 2004 (Barr et al., 2007; Zha et al., 2010). For the current analysis we constructed daily

time series of soil moisture measurements from the organic (LFH) surface layer at depths of 2.5 and 7.5 cm (soil water content reflectometer probes, CS616, Campbell Scientific Inc., Logan, UT) and from the 0–15, 15–30, 30–60, 60–90 and 90–120 cm depths of mineral soil (segmented time-domain reflectometry probes, Moisture Point type B, Gabel Corp., Victoria, Canada). Further details on instrument specifications and deployment at the OA site are given by Barr et al. (2007). From the original measurements made every 4 h, daily values of total water content in the uppermost 129 cm of soil (ca. 9 cm LFH layer plus 120 cm of mineral soil) were calculated for the period 30 April–31 October each year, when soils were generally free of frost. These daily values were also expressed as mean volumetric soil water content ( $\theta_v$ ,  $m^3 m^{-3}$ ) of the 129 cm soil profile.

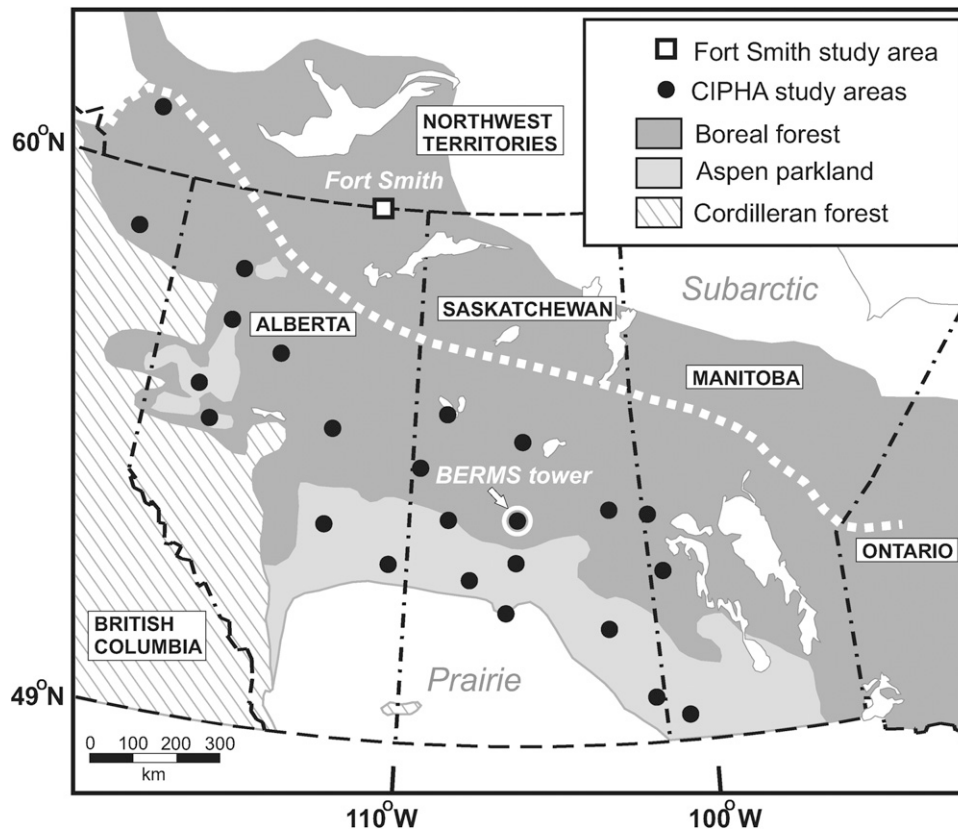
For this study, we used the data sets of daily evapotranspiration and precipitation along with daily maximum and minimum air temperature within the aspen canopy at a height of 18 m. Daily totals of measured evapotranspiration ( $E$ ) from the aspen forest were obtained from continuous, half-hourly eddy-covariance measurements of water vapor flux densities made at the 39-m height on a twin scaffold tower. The sensors included a three-dimensional sonic anemometer–thermometer for measuring wind velocity and temperature fluctuations (R3, Gill Instruments Ltd., Lymington, UK) and a temperature-controlled closed-path infrared gas analyzer (LI-6262 or LI-7000, LI-COR Inc., Lincoln, NE) for measuring water vapor mixing ratio fluctuations. Further details on the eddy-covariance measurements can be found in Blanken and Black, 2004. After exclusion of low friction–velocity data at night, energy balance closure of half-hour data averaged 0.89 (Barr et al., 2006) but varied according to year (Barr et al., 2012). For the current study we used yearly totals of measured  $E$  that included site-specific, annual adjustments to achieve energy balance closure (Barr et al., 2012). Precipitation was measured using an accumulating gauge located in a clearing near the flux tower (Zha et al., 2010). The daily maximum and minimum temperature measurements from the aspen canopy were adjusted by adding 0.3 °C and subtracting 1.4 °C, respectively so that their average values during May–September of 1997–2005 matched those derived from a spatial interpolation of measurements from adjacent climate stations.

## 2.3. Field testing of the soil moisture model

Previous analyses at the OA flux tower site indicated that  $E$  was strongly limited during periods when soil water content declined below a certain threshold value (Barr et al., 2007; Zha et al., 2010). In the current study, this effect was modeled through the application of the soil moisture modifier  $k_m$ , as indicated above (Eq. (4)). To facilitate the comparison of modeled and measured variation in  $\theta_v$ , we expressed both time series as relative water content ( $\theta_r$ ) as defined by Bernier et al. (2006). From the field measurements of  $\theta_v$ ,  $\theta_r$  was calculated as:

$$\theta_r = \frac{\theta_v - \theta_{wp}}{\theta_{fc} - \theta_{wp}} \quad (8)$$

where  $\theta_{wp}$  and  $\theta_{fc}$  are the values of  $\theta_v$  ( $m^3 m^{-3}$ ) at the permanent wilting point and at field capacity, respectively. Initially, we used the values of  $\theta_{wp} = 0.14$  and  $\theta_{fc} = 0.36$  that were derived by Bernier et al. (2006) from their analysis at the OA site that covered the period 1998–2003. During the exceptionally wet year of 2005, however, the measured soil water content (up to  $0.41 m^3 m^{-3}$ ) was substantially greater than  $\theta_{fc}$ . Given the likelihood that soil water content exceeded field capacity in 2005, we assumed an intermediate value of  $\theta_{fc} = 0.38$  for modeling purposes. This corresponds to an estimated  $0.24 m^3 m^{-3}$  of maximum available soil water (i.e., the difference between  $\theta_{fc}$  and  $\theta_{wp}$ ).



**Fig. 1.** Location of aspen stands included in this study, including the BERMS Old Aspen (OA) tower site, the regional network of CIPHA study areas, and the Fort Smith study area. The dotted white line shows the approximate northern limit of moderate to severe defoliation by forest tent caterpillar based on annual surveys by the Canadian Forest Service during 1937–1997.

In the model, the SMI was reported as available soil water (mm) in the aspen rooting zone. For the purpose of comparison with field measurements, the model outputs were also expressed as relative water content, where  $\theta_r = \text{SMI}/\text{SMI}_{\max}$ . Initially, it was assumed that the aspen rooting zone was limited to the uppermost 129 cm of soil (including the 9 cm LFH layer), so that  $\text{SMI}_{\max}$  corresponds to the maximum available water ( $1290 \text{ mm} \times 0.24 = 310 \text{ mm}$ ) within this depth of soil. However, the analysis by Bernier et al. (2006) showed that over several rain-free periods, the amount of water lost from the soil measurement profile accounted for only 82% of total  $E$  from the tower-based eddy covariance measurements. These results strongly suggested that water was being drawn from soil deeper than the soil water measurement profile, and implied that  $\text{SMI}_{\max}$  was approximately 378 mm (i.e.,  $310 \text{ mm}/0.82$ ). Together with analyses reported by Barr et al. (2007) and Zha et al. (2010), this served as a guide for selecting the following ranges of parameter values in the model simulations of  $\theta_r$ , using both the BL and QL equations: 300–500 mm for  $\text{SMI}_{\max}$  and 100–400 mm for  $\text{SMI}_{\text{crit}}$ . Model outputs were tested against field measurements using linear regressions of modeled versus observed monthly  $\theta_r$  under alternative parameter values and equation forms. Similar comparisons were also made between modeled and observed values of  $E$  (monthly and annual totals). These comparisons were used to select the best-fitting combinations of parameter values and equation forms for subsequent application to tree-ring studies of aspen growth responses to soil moisture variation (see below).

#### 2.4. Model application for tree-ring analysis

In a previous study (Hogg et al., 2005), the CMI was used as an indicator of tree water stress in the tree-ring analysis of factors affecting regional-scale variation in aspen growth during

1951–2000. In the analysis, lag effects of moisture were examined by including five additional independent variables where the annual CMI series was offset forward in time by 1, 2, 3, 4 or 5 years. These additional variables did not introduce any concerns about multicollinearity because there was no significant serial autocorrelation in CMI values ( $r = -0.13$ ,  $p = 0.369$ , result from Hogg et al., 2005). Regional aspen growth was based on average detrended values of annual increment in stem cross-sectional area in a total of 72 aspen stands (6 trees sampled per stand) representing the 24 Climate Impacts on Productivity and Health of Aspen (CIPHA) study areas across the western Canadian interior (Fig. 1). Further details on the CIPHA study, including methods of tree-ring sampling and analysis are given by Hogg et al. (2005).

In the present study, the SMI model was applied to provide a more realistic alternative measure of tree water stress. Soil water-holding capacity is largely a function of soil texture (Saxton and Rawls, 2006) and measurements indicated that on average, soil texture across the regional network of 24 aspen sites (44% sand, 34% silt and 22% clay, Hogg et al., 2008) was similar to that previously measured at the OA site (50% sand, 28% silt and 19% clay, Bernier et al., 2006). Thus, we assumed that the model parameters derived from measurements at the OA site should be generally applicable across the regional network.

As in the previous analysis based on the CMI, SMI values were calculated for each of the 24 CIPHA study areas using reconstructed monthly values of mean daily maximum and minimum temperature and monthly total precipitation at the nearest weather stations (as described by Hogg et al., 2005). Other than using SMI rather than CMI, the current analysis followed the methods of Hogg et al. (2005), in which linear regression analysis was used to examine the combined influences of moisture (CMI), growing degree days during 1 April–31 July ( $GDD$ ) and insect defoliation ( $D$ ) on average



**Table 1**

Linear regressions of measured versus modeled values of monthly relative soil water content ( $\theta_r$ ) and annual evapotranspiration ( $E$ ) at the BERMS Old Aspen flux tower site under alternative values of model parameters ( $SMI_{max}$  and  $SMI_{crit}$ ) for each of the two model equation forms (BL and QL). All analyses are based on the years 1997–2005; for  $\theta_r$ , analyses are based on available data for the last day of each month between April and October of these 9 years ( $N = 56$  months).

Equation form	$SMI_{max}$	$SMI_{crit}$	Measured vs modeled $\theta_r$ (monthly)		Measured vs modeled $E$ (annual)	
			$r^2$	Slope	$r^2$	slope
BL	500	400	0.796	0.873	0.817	1.014
	500	250	0.835	0.947	0.855	0.973
	400	300	0.849	0.899	0.765	1.024
	<b>400</b>	<b>200</b>	<b>0.881</b>	<b>0.978</b>	<b>0.832</b>	<b>0.988</b>
	400	100	0.749	1.002	0.822	0.974
	300	150	0.854	0.854	0.738	1.015
QL	500	400	0.828	0.932	0.861	0.982
	400	400	0.860	0.912	0.806	1.024
	<b>400</b>	<b>300</b>	<b>0.864</b>	<b>0.961</b>	<b>0.844</b>	<b>0.996</b>
	400	200	0.802	0.998	0.849	0.978
	300	150	0.768	1.015	0.786	1.001

Bold value the best-fitting model for each equation form.

detrended aspen growth ( $A'$ ). The procedure used in the calculation of detrended aspen growth is given by Hogg et al. (2005).  $GDD$  was calculated as the sum of positive departures in mean daily temperature from a base of 5 °C; and  $D$  was calculated as the percentage of trees affected by moderate to severe defoliation each year based on the presence of distinctive, pale colored tree-rings (referred to as “white rings”, Hogg et al., 2002b).

Monthly SMI was estimated as the average of modeled SMI values reported on the final days of the previous and current months. Annual values of SMI were calculated from mean monthly SMI values over all possible periods of 1–5 months during the growing season for aspen (May–September). Initial regression analyses showed that the strongest relationships with  $A'$  were obtained using average SMI over the summer months of June–August; thus only the results based on SMI over this 3-month period are reported.

In the previous tree-ring study of aspen in the regional network of CIPHA study areas, Hogg et al. (2005) found that 84% of the 432 sampled aspen trees had a history of moderate to severe defoliation that was primarily caused by forest tent caterpillar (*Malacosoma disstria*). This led to strong reductions in  $A'$  during the years of large-scale insect outbreaks, raising concerns that insect defoliation might confound the analysis of growth responses to soil moisture variation.

Thus, we conducted a similar analysis on six additional aspen stands near Fort Smith, NWT, located beyond the historical northern range limit of major outbreaks of forest tent caterpillar (Fig. 1). The analysis confirmed that there was minimal insect defoliation in these stands prior to sampling in 2003 based on the absence of “white rings”. The landscape around Fort Smith is level to gently undulating and the aspen forests are on well-drained sites with acid brown wooded soils (Dystric Brunisols) developed on calcareous alluvial sediments; soil texture in the upper 1 m ranges from loam to sandy loam (Day and Leahey, 1957). Fort Smith has a relatively dry climate with only 350 mm of mean annual precipitation compared to about 450 mm at OA. The mean July temperature of 16 °C is comparable to that at OA but colder winters result in a mean annual temperature that is lower (−3 °C) than at OA (0 °C). Permafrost occurs sporadically in peaty lowland areas but is absent from the mineral soils underlying the upland forests of aspen and jack pine (*Pinus banksiana* Lamb.).

The six aspen stands were located within distances of 1–29 km from the Fort Smith climate station, which has had nearly complete (97%) monthly records of temperature and precipitation since 1914. This provided a high degree of confidence in the reconstructed climate histories for these stands. The small number of data gaps from Fort Smith were filled from the nearest reporting climate stations

(Fort Chipewyan and Hay River) using the method described by Hogg et al. (2005).

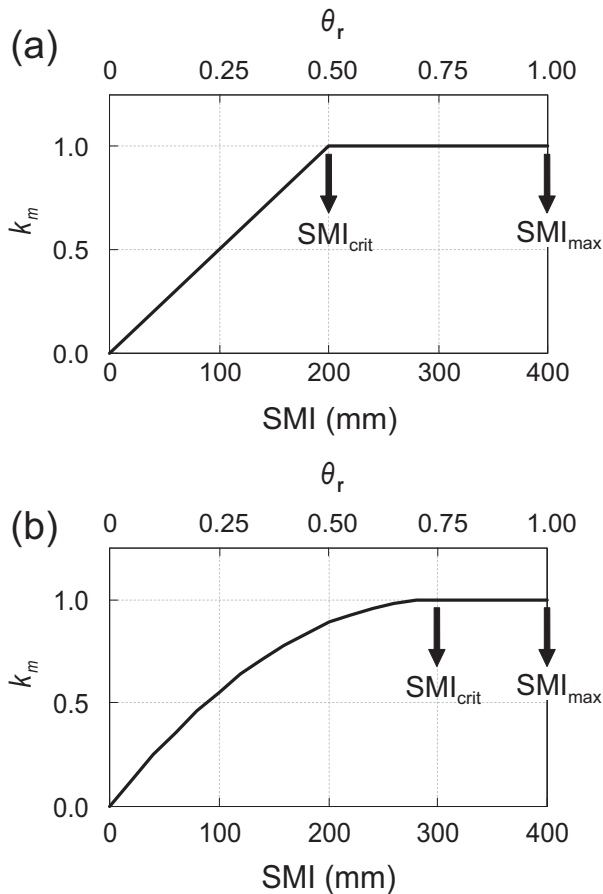
The six stands at Fort Smith were considerably older (ca. 90–130 years) than those in the regional CIPHA network (ca. 40–80 years in 2000), which enabled a longer period of analysis (1916–2002). Many of the old trees had heart rot near the base, and thus the sampling was conducted at a height of 2 m rather than the standard sampling height of 1.3-m. An increment borer was used to obtain two cores from each of three aspen trees at each site (total of 18 trees). Cores were prepared and ring widths were measured and cross-dated using methods described previously (Hogg et al., 2002a, 2005). For each tree, relative growth was calculated as increment in stem basal area divided by total stem cross sectional area. Stand-level estimates of annual relative growth ( $A$ ) were obtained by averaging the relative growth of the three trees sampled within each stand. The effects of age and stand development were then removed using the detrending procedure described previously (Hogg et al., 2005; Hogg and Wein, 2005) in which detrended growth ( $A'$ ) was calculated as  $A$  divided by the expected growth from a best-fitting quadratic equation. In this study, the period used for the detrending procedure started 10 years after the earliest tree ring in each stand (1883–1915) and ended in the year of sampling (2003). Finally, the annual values of  $A'$  from the six stands were averaged to produce the chronology used in the regression analyses of growth responses to interannual variation in the CMI and modeled values of SMI. The methods for these regression analyses were the same as those used in the study of regional-scale responses from the CIPHA plot network (Hogg et al., 2005). As in the regional study, there was no significant serial autocorrelation in annual CMI values over the period of analysis (1916–2002) at Fort Smith ( $r = 0.13$ ,  $p = 0.220$ ).

### 3. Results and discussion

#### 3.1. Soil moisture model simulations

Given its simplicity, the model performed remarkably well in simulating both the observed monthly variation in  $\theta_r$  as well as the observed annual variation in  $E$  at the OA site. For the model forms shown in Table 1, the slopes of linear regressions through the origin were close to unity for both monthly  $\theta_r$  (0.873–1.015) and annual  $E$  (0.973–1.024), indicating that the magnitude of these variables could be successfully estimated by the model.

With the BL equation, the strongest relationship ( $r^2 = 0.881$ ) between measured and modeled  $\theta_r$  was obtained using  $SMI_{max} = 400$  mm and  $SMI_{crit} = 200$  mm (hereafter referred to

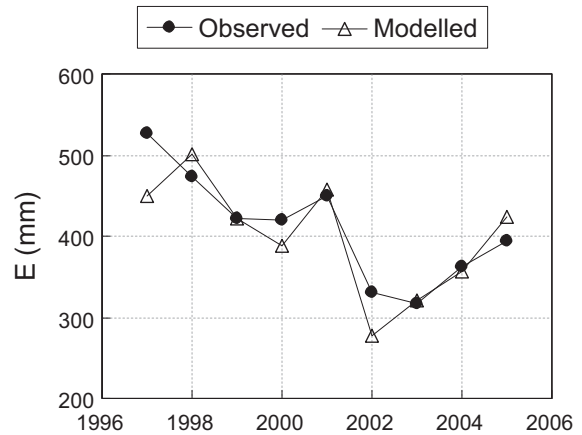


**Fig. 2.** Alternative equation forms for calculating the soil moisture modifier ( $k_m$ ) used in the modeling of evapotranspiration as a function of the soil moisture index (SMI): (a) bilinear (BL) and (b) quadratic + linear (QL).  $SMI_{crit}$  and  $SMI_{max}$  are model parameters. The SMI provides a measure of relative soil water content in the rooting zone ( $\theta_r$ ), as shown in the upper x-axis of each graph.

as the BL 400–200 model, Fig. 2A). With the QL equation, the relationship was marginally weaker ( $r^2 = 0.864$ ) using the best-fitting parameters of  $SMI_{max} = 400$  mm and  $SMI_{crit} = 300$  mm (QL 400–300, Fig. 2B). However, in the comparison of modeled and measured  $E$ , the QL 400–300 model gave a slightly stronger relationship ( $r^2 = 0.844$ ) than the BL 400–200 model ( $r^2 = 0.832$ ).

The period of analysis included the severe drought during 2001–2003, when annual precipitation amounts averaged only 260 mm per year or less than 60% of the long-term average (Barr et al., 2007). The resultant decreases in both  $\theta_r$  and  $E$  were successfully simulated by both the QL 400–300 model (Figs. 3 and 4, respectively) and the BL 400–200 model (nearly identical results, not shown). There was a generally strong match between modeled and measured seasonal variation in  $\theta_r$ , including, for example, the drawdown of  $\theta_r$  during the moderately dry year of 1997 (Fig. 4). The model underestimated the increase in  $\theta_r$  that was measured during the consecutive wet years of 2004 and 2005 (667 mm and 614 mm of annual  $P$ , respectively), which was likely a result of imperfect drainage so that the measured  $\theta_r$  would have likely exceeded  $\theta_{fc}$  at the measurement locations in 2005 and in subsequent wet years.

In the comparison of modeled and measured variation in  $\theta_r$ , we excluded the winter period of November to March when the ground is normally snow covered and soils are frozen, thus precluding reliable measurements of soil water content. Although the model does not differentiate between rain and snow as precipitation water inputs to the soil, there was generally good agreement in the simulation of  $\theta_r$  early in the growing season (30 April)



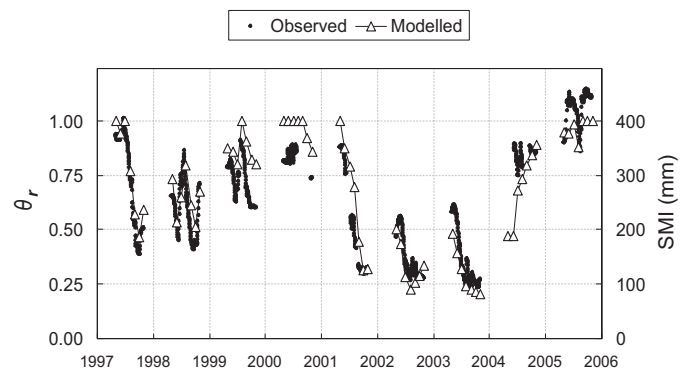
**Fig. 3.** Observed and modeled annual totals of evapotranspiration ( $E$ ) at the BERMS OA site during the years 1997–2005. Observed values are from tower-based, eddy-covariance measurements (Barr et al., 2007; Zha et al., 2010) and modeled values were obtained using the QL equation (Fig. 2b) with  $SMI_{max} = 400$  mm and  $SMI_{crit} = 300$  mm.

following spring snow melt (Fig. 4). Furthermore, the average modeled increase of 0.18 in  $\theta_r$  between 31 October and 30 April was similar to the measured increase of 0.17 over the years with unsaturated soils and available data on these dates (1997/1998–2003/2004).

Despite the close correspondence between the annual totals of modeled and measured  $E$  (Fig. 3), there were notable differences in the seasonal variation of modeled and measured  $E$  (not shown). On average, the model underestimated  $E$  by a total of  $37 \text{ mm yr}^{-1}$  (13%) during the summer months of June–August and overestimated  $E$  by a total of  $50 \text{ mm yr}^{-1}$  in spring (April–May) and autumn (September–November). These differences reflect the influence of seasonal changes in the leaf area of aspen and other deciduous species at this site (Barr et al., 2004) that strongly affect  $E$  (Barr et al., 2007; Zha et al., 2010) but are not specifically represented in the model.

### 3.2. Aspen growth responses to moisture variation

In the first case study, factors affecting interannual variation in aspen growth were examined using tree-ring analysis from the regional network of 72 CIPHA stands, which included three stands at OA located centrally within the CIPHA study region (Fig. 1). A previous analysis (Hogg et al., 2005) showed that detrended regional



**Fig. 4.** Observed and modeled variation in relative soil water content ( $\theta_r$ ) at the BERMS OA site during 1997–2005. Observed values are from daily average measurements of volumetric soil water content in the upper 120 cm of mineral soil and the overlying organic layer; modeled values are from the monthly output of the SMI model using the QL equation with  $SMI_{max} = 400$  mm and  $SMI_{crit} = 300$  mm (Figs. 2b and 3).

**Table 2**

Coefficients for regressions of factors affecting detrended aspen growth ( $A'$ ) in the regional network of CIPHA stands (1951–2000, results from Hogg et al., 2005) and for stands near Fort Smith (1916–2002). Regression equations are of the form  $A' = b + cCMI + c_{-1}CMI_{-1} + c_{-2}CMI_{-2} + c_{-3}CMI_{-3} + c_{-4}CMI_{-4} + dD + gGDD$ , where CMI is the climate moisture index for 12-month periods ending 31 July of the current year, and the variables designated as  $CMI_{-y}$  refer to CMI values  $y$  years previous to the current year. The variables  $D$  and  $GDD$  refer to insect defoliation (percentage of trees severely defoliated in the current year) and cumulative growing degree days (sum of daily mean temperatures exceeding 5 °C during 1 April–31 July of the current year), respectively (see Section 2.4 and Hogg et al., 2005).

	Regression coefficients								Adjusted $r^2$
	$b$	$c$	$c_{-1}$	$c_{-2}$	$c_{-3}$	$c_{-4}$	$d$	$g$	
CIPHA stands	0.629	0.0127	0.0072	0.0057	0.0060	0.0042	-0.0148	0.00062	0.733
Fort Smith stands	1.114	0.0118	0.0106	0.0080	0.0083	0.0058	nd	ns	0.432

ns: not significant ( $p > 0.05$ ); nd: no insect defoliation recorded in these stands.

**Table 3**

Coefficients for regressions of factors affecting detrended aspen growth ( $A'$ ) as in Table 2 but using the soil moisture index (SMI) rather than the CMI as a measure of interannual variation in moisture regimes. Regression equations are of the form  $A' = b + sSMI + s_{-1}SMI_{-1} + s_{-2}SMI_{-2} + s_{-3}SMI_{-3} + s_{-4}SMI_{-4} + dD + gGDD$ , where SMI is calculated from average monthly values during 31 May–31 August of the current year, and the variables designated as  $SMI_{-y}$  refer to SMI values  $y$  years previous to the current year. SMI values were calculated using two alternative model forms: the bilinear (BL) equation with  $SMI_{max} = 400$  mm and  $SMI_{crit} = 200$  mm (Fig. 2a), and the quadratic + linear (QL) equation with  $SMI_{max} = 400$  mm and  $SMI_{crit} = 300$  mm (Fig. 2b).

	SMI equation	Regression coefficients					Adjusted $r^2$
		$b$	$s$	$s_{-1}$	$d$	$g$	
CIPHA stands	BL	-0.425	0.00284	ns	-0.0166	0.00093	0.707
	QL	-0.432	0.00279	ns	-0.0168	0.00093	0.694
Fort Smith stands	BL	0.250	0.00161	0.00158	nd	ns	0.418
	QL	0.204	0.00160	0.00164	nd	ns	0.455

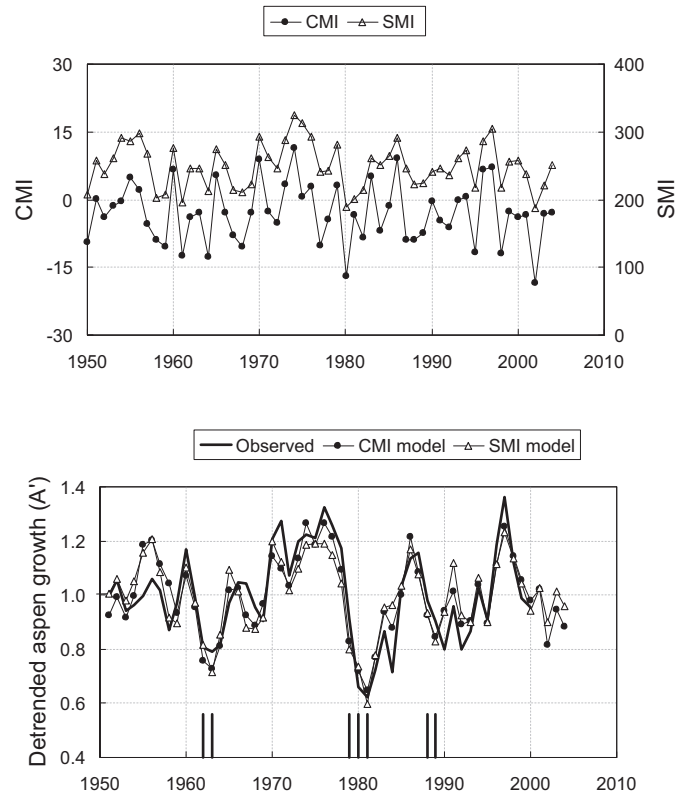
ns: not significant ( $p > 0.05$ ); nd: no defoliation recorded in these stands.

Note: the regression coefficients  $s_{-2}$ ,  $s_{-3}$ , and  $s_{-4}$  were not significant ( $p > 0.05$ ) in each of these regression equations.

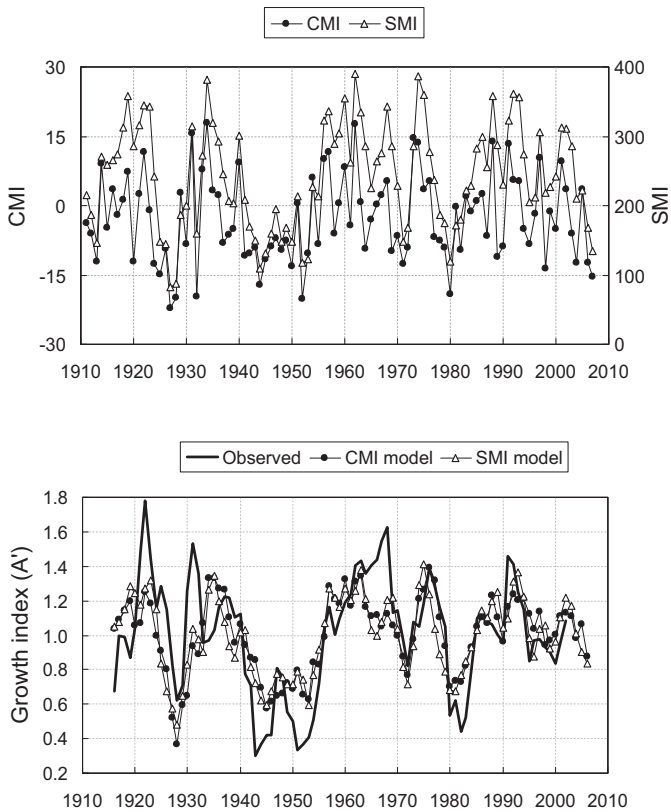
aspen growth ( $A'$ ) during 1951–2000 was significantly ( $p < 0.05$ ) related to the CMI in the current year and in each of the preceding 4 years, as shown in Table 2. However, when outputs from the SMI model were used, only the SMI value for the current growing season was significant using either the BL or QL equation (Table 3). Thus, applying the SMI model resulted in the elimination of the multi-year lag terms that occurred when CMI was used as an indicator of the moisture regime. The lag terms were eliminated because the SMI was more persistent than the CMI, capturing the deep drawdown of soil moisture reserves during drought and the need for multiple years to recharge them. Each of the regression models gave strong relationships with  $A'$ , although the relationships were slightly weaker for the models using the SMI ( $r^2 = 0.707$  and  $0.694$  for the BL and QL equations, respectively) compared to that based on the CMI ( $r^2 = 0.733$ ). As previously noted, however, insect defoliation ( $D$ ) led to strong reductions in  $A'$ , especially during the years with widespread defoliation by forest tent caterpillar during 1963–64, 1979–81 and 1988–89 (Fig. 5). Some of these years coincided with periods of drought, most notably in 1980. Furthermore, the analyses showed that in addition to the strong effects of soil moisture and defoliation, there was a positive (but relatively weak) influence of spring and early summer temperatures ( $GDD$ ) on  $A'$  (Tables 2 and 3). Thus despite the high  $r^2$  values, the regression coefficients for soil moisture (CMI or SMI) might have been confounded by variation in the other independent variables.

The sampling of tree rings at the six older aspen stands near Fort Smith provided the opportunity for conducting the second case study, in which growth responses to soil moisture variation were examined over a relatively long period of 87 years (1916–2002) in the absence of detectable defoliation by insects. Surprisingly, detrended growth ( $A'$ ) of these stands was not significantly related to  $GDD$ , so that the resultant regression equations included only the soil moisture variables (CMI or SMI). As in the regional analysis, the regressions based on the CMI included significant relationships with the current year and each of the preceding 4 years (Table 2).

In contrast, application of the SMI model (with either the BL or QL equation) resulted in significant relationships with SMI in the



**Fig. 5.** Interannual variation in moisture indices (CMI and SMI) and in the observed and modeled values of detrended aspen growth ( $A'$ ) at 24 CIPHA study areas across western Canada (locations shown in Fig. 1). Observed values of  $A'$  were derived from tree-ring analysis (Hogg et al., 2005) and modeled values were derived from the regression equations using the CMI (Table 2) and the SMI (QL equation, Table 3). Vertical bars (lower pane) denote the years with major defoliation by forest tent caterpillar (Hogg et al., 2005).

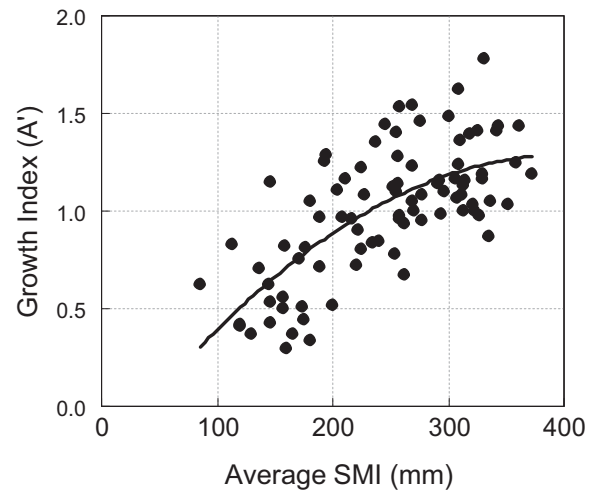


**Fig. 6.** Interannual variation in moisture indices (CMI and SMI) and in the observed and modeled values of average detrended aspen growth ( $A'$ ) in six aspen stands near Fort Smith (location shown in Fig. 1). Observed values of  $A'$  were derived from tree-ring analysis and modeled values were derived from the regression equations using the CMI (Table 2) and the SMI (QL equation, Table 3). There was no evidence of significant insect defoliation in these six stands prior to the year of tree-ring sampling (2003).

current and preceding year only (Table 3). When the QL equation was used, the regression based on the SMI gave a slightly stronger relationship ( $r^2 = 0.455$ , Table 3) with  $A'$  than that based on the CMI ( $r^2 = 0.432$ , Table 2), whereas the BL equation gave a slightly weaker relationship ( $r^2 = 0.418$ ).

Overall, the regression equations based on either the CMI or the SMI were remarkably successful in explaining the periods with exceptionally low aspen growth in the Fort Smith stands during the dry years of 1927–29, 1942–54, 1971–72, and 1980–83 (Fig. 6). On the other hand, the periods with exceptionally high growth (1921–23, 1930–32, and 1965–68) were not explained by the regression equations.

When the SMI model (with either the QL or BL equation) was used to estimate yearly variation in soil moisture, the magnitudes of the regression coefficients  $s$  and  $s_{-1}$  were similar (Table 3), indicating that aspen growth was influenced nearly equally by growing season soil moisture conditions in the current and preceding year. As expected, there was a high degree of serial autocorrelation in SMI ( $r = 0.661$ ,  $p < 0.001$ ) despite the lack of significant serial autocorrelation in CMI (see Section 2). Given the potential concerns about multicollinearity between SMI and  $SMI_{-1}$ , more robust results may be obtained by using the average of these variables ( $SMI_{avg[y, y-1]}$ ) as a combined measure of soil moisture, as shown in Fig. 7. Overall, there was a moderately strong relationship between  $A'$  and  $SMI_{avg[y, y-1]}$ , but there was a tendency for  $A'$  to level off at high values of soil moisture (Fig. 7). Thus, the relationship was slightly better for a quadratic equation ( $r^2 = 0.476$ ) than for a linear equation ( $r^2 = 0.462$ ).



**Fig. 7.** Average detrended aspen growth ( $A'$ ) for six aspen stands near Fort Smith in relation to the average SMI during 31 May–31 August of the current and previous year ( $SMI_{avg[y, y-1]}$ ), based on the QL equation. The best-fitting quadratic equation ( $A' = -0.299 + 0.00788 SMI_{avg[y, y-1]} - 9.8E-06 (SMI_{avg[y, y-1]})^2$ ,  $r^2 = 0.476$ ) is also shown.

### 3.3. Mechanisms leading to multi-year lags in aspen growth responses to drought

The results are consistent with previous tree-ring studies showing that droughts lead to strong, multi-year decreases in the growth of western Canadian aspen stands (Hogg et al., 2002a, 2005), even in the absence of significant insect defoliation (Hogg and Wein, 2005). In the current study, the application of the SMI model led to a reduction in the apparent duration of drought effects on aspen growth (1–2 years) compared to that obtained using the CMI (up to 5 years). This suggests that in western Canadian aspen stands, precipitation events or anomalies in CMI (or  $P - PE$ ) may have persistent, multi-year effects on soil moisture. Such persistence has been termed “soil moisture memory”, which has formed the basis for many studies of land surface feedbacks on the Earth’s climate system (e.g., Manabe and Delworth, 1990; Seneviratne et al., 2010). Most of these studies have reported on the effects of “soil moisture memory” over a few weeks or months, but soil moisture anomalies can be much more persistent in cold, dry regions such as Mongolia (Shinoda and Nandinsetseg, 2011). Climatic conditions are similarly cold and dry in the aspen stands examined in the present study (5–7 months per year of subfreezing temperatures and annual precipitation averaging  $430 \text{ mm yr}^{-1}$  across the CIPHA study region and  $340 \text{ mm yr}^{-1}$  at Fort Smith). The duration of “soil moisture memory” in these stands is further enhanced by the large quantity of available soil water within the aspen rooting zone (ca. 400 mm) compared with that typically used in previous models (e.g., 50–200 mm, Granier et al., 2000). An analysis derived from satellite data suggests that aspen-dominated forest types in western Canada are among those having the highest available soil water in western North America (Coops et al., 2012). The large soil water reserves are able to sustain high evapotranspiration during extended droughts through the deep drawdown of soil moisture (Zha et al., 2010). The corollary is that soil moisture often requires several years to recharge once a drought has ended.

As an alternative test of the interannual persistence of “soil moisture memory” in western Canadian aspen stands, a sensitivity analysis was conducted using SMI model simulations for the stands at Fort Smith that were free of significant insect defoliation effects. A total of 84 simulations were conducted, in which a negative SMI anomaly was induced by imposing a 10 mm decrease in the total July precipitation of a given year within the period



1916–1999. In each simulation, the persistence of the SMI anomaly was tracked over time and reported on 31 July for each of the following 3 years. As expected, the negative SMI anomaly was always eliminated (as water runoff) during subsequent wet periods when the soil reached saturation ( $SMI = SMI_{max} = 400$  mm). In contrast, the negative anomaly was maintained indefinitely during periods when  $SMI_{crit} < SMI < SMI_{max}$ , i.e., the range of conditions with no runoff and where  $E$  is insensitive to soil water content. Under drier soil conditions ( $SMI < SMI_{crit}$ ), there was a gradual loss of the negative SMI anomaly. As a result, the persistence of modeled soil water anomalies was highly variable, ranging from 0% to 100% from one July to the next. Over the 84 simulations (starting each year from 1916–1999), the modeled persistence of the negative SMI anomaly averaged 40% over one year (i.e., from July of the previous year to July of the current year), 20% over two years, and 10% over three years.

These results provide further evidence that “soil moisture memory” can provide a mechanism by which aspen growth is affected by periods of drought in previous years. This mechanism could only operate, however, in regions such as the western Canadian interior where the climate is sufficiently dry to induce chronically unsaturated soils (i.e.,  $\theta_r < 1$ ) within the tree rooting zone. From the tree-ring results, it was also apparent that “soil moisture memory” only explains part of the delayed responses of aspen growth to interannual variation in CMI. In the stands at Fort Smith, aspen growth was significantly affected by modeled soil moisture (SMI) in both the current and previous year’s growing seasons (Table 3), indicating that other factors were contributing to the apparent multi-year impacts of drought in these stands. These likely included physiological lags that may result from cavitation of xylem and/or carbohydrate exhaustion following periods of drought, leading to multi-year growth reductions through impairment of hydraulic conductivity, branch dieback and/or decreases in leaf area (Hogg, 1999; Frey et al., 2004; Anderegg, 2012). Ecological lags, notably drought-related increases in damage by wood-boring insects and fungal pathogens may also play a role in amplifying and prolonging the negative impacts of drought on aspen stands in this region (Hogg et al., 2002a, 2008) and elsewhere (Marchetti et al., 2011).

#### 4. Conclusions

The SMI model was very successful in simulating the observed changes in soil moisture within the rooting zone of a mature, boreal aspen site (OA) over a 9-year period. This may seem surprising, given that this is a simple model that does not specifically include many of the processes known to influence the water cycle of boreal deciduous forests, notably leaf phenology, stomatal responses, canopy interception of precipitation, snow accumulation and soil infiltration of water following snow melt. One of the advantages of the SMI model is that like the CMI (Hogg, 1997), it operates using only basic climatic inputs (daily maximum and minimum temperature and precipitation). Thus, the SMI can be calculated from existing historical observation records at specific climate stations or alternatively, can be interpolated and mapped across large areas using gridded climate data from programs such as ANUSPLIN (McKenney et al., 2006), BioSIM (Régnière and St-Amant, 2008) or PRISM (Daly et al., 2002). In this respect, the SMI model is comparable to the purely climate-driven, one layer “bucket” model of soil moisture developed in the US by Huang et al. (1996) that has been subsequently implemented at the global scale (Fan and van den Dool, 2004). In the present study, however, we have constrained the application of the SMI model to the simulation of soil moisture at similar aspen sites within a targeted region of western Canada. In this context, the SMI was found to provide a useful indicator of “soil

moisture memory” that partly explained the observed, multi-year lags in aspen tree-ring responses to drought in this region. Further development of the SMI model, including testing and validation against measurements at other sites would enhance its usefulness in simulating soil moisture and drought impacts across a wider range of forest types, soil characteristics and climatic moisture regimes.

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