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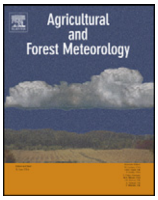

A simple soil moisture index for representing multi-year drought impacts on aspen productivity in the western Canadian interior☆

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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 (θ_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 θ_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 drought impacts on the productivity of aspen and other forest types.

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 ($e^*_{T_{dew}}$):

$$VPD = 0.5(e^*_{T_{\max}} + e^*_{T_{\min}}) - e^*_{T_{dew}} \tag{1}$$

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^{-1}):

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

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:

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

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

$$E_{day} = k_m PE_{day} \tag{4}$$

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 $k_m = 1$