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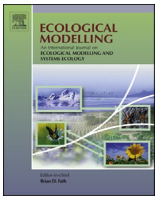

Incorporating weather sensitivity in inventory-based estimates of boreal forest productivity: A meta-analysis of process model results

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ABSTRACT

Weather effects on forest productivity are not normally represented in inventory-based models for carbon accounting. To represent these effects, a meta-analysis was conducted on modeling results of five process models (*ecosys*, *CN-CLASS*, *Can-IBIS*, *InTEC* and *TRIPLEX*) as applied to a 6275 ha boreal forest landscape in Eastern Canada. Process model results showed that higher air temperature (T_a) caused gains in CO_2 uptake in spring, but losses in summer, both of which were corroborated by CO_2 fluxes measured by eddy covariance (EC). Seasonal changes in simulated CO_2 fluxes and resulting inter-annual variability in NEP corresponded to those derived from EC measurements. Simulated long-term changes in above-ground carbon (AGC) resulting from modeled NEP and disturbance responses were close to those estimated from inventory data. A meta-analysis of model results indicates a robust positive correlation between simulated annual *NPP* and mean maximum daily air temperature (T_{amax}) during May–June in four of the process models. We therefore, derived a function to impart climate sensitivity to inventory-based models of NPP: $\mathrm{NPP'}_i = \mathrm{NPP}_i + 9.5\,(T_{amax} - 16.5)$ where NPP_i and $\mathrm{NPP'}_{i;}$ are the current and temperature-adjusted NPP, 16.5 is the long-term mean T_{amax} during May–June, and T_{amax} is that for the current year. The sensitivity of net CO_2 exchange to T_a is nonlinear. Although, caution should be exercised while extrapolating this algorithm to regions beyond the conditions studied in this landscape, results of our study are scalable to other regions with a humid continental boreal climate dominated by black spruce. Collectively, such regions comprise one of the largest climatic zones in the 450 Mha North American boreal forest ecosystems.

1. Introduction

Boreal forests account for about 14% of the earth's vegetation cover (Kang et al., 2006) and contain large amounts of carbon (C) (D'Arrigo et al., 1987; Sun et al., 2008). The capability of boreal forests to capture and release C is governed by climate and disturbance (Amiro et al., 2001; Banfield et al., 2002; Rapalee et al., 1998). In Canada, the influence of climate and disturbance on boreal forests has drawn much attention (Chertov et al., 2009; Bergeron et al., 2007), given that about 30% of the world's boreal forests are located in Canada (Canadian Forest Service, 2009). Improved understanding of the responses of boreal forest productivity to climate and disturbance is necessary to project future changes in forest C productivity and storage in a region exposed to rapid changes in climate.

The productivity of the boreal forest, and hence its C dynamics, are influenced by short-term and long-term variability in climate. For example, higher spring air temperatures (T_a) create longer growing seasons which have been found to raise seasonal productivity through earlier net CO_2 uptake (Arain et al., 2002; Barr et al., 2004; Bergeron et al., 2007; Brooks et al., 1998; Delpierre et al., 2009; Grant et al., 2009a,b; Wilmking et al., 2004). On the other hand, higher summer T_a has been found to reduce productivity (Brooks et al., 1998; Dang and Lieffers, 1989; Tang et al., 2010) through concurrent declines in gross primary productivity (GPP) and increased ecosystem respiration (R_e) (Grant et al., 2009b; Griffis et al., 2003; Morgenstern et al., 2004), and through adverse effects on tree water status (Barber et al., 2000; Goetz et al., 2005;

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Savva et al., 2008). Gains in productivity from higher spring or summer T_a are likely the more important responses in cooler or wetter climates, while losses in productivity resulting from higher summer T_a are likely to be more important in warmer or drier climates (e.g. Hofgaard et al., 1999; Nishimura and Laroque, 2011).

In Canada, the accounting and reporting on the state of, and changes in, forest C are done using the *CBM-CFS3* model (Kurz et al., 2009), which constitutes the core component of Canada's National Forest Carbon Monitoring, Accounting, and Reporting System (NFCMARS, Kurz and Apps, 2006). In this inventory-based model, estimates of forest productivity are generated from forest growth curves and do not explicitly consider variability in climate (Kurz et al., 2009). One question that was raised in the Fluxnet-Canada Research Network/Canadian Carbon Program (FCRN/CCP) (Margolis et al., 2006) was whether and how climatic sensitivity should be incorporated into *CBM-CFS3*. The FCRN/CCP therefore conducted a meta-analysis of results from multiple process models as applied to two contrasting forest landscapes centered on FCRN/CCP flux measurement sites: a coastal temperate forest landscape in British Columbia, and a continental boreal forest landscape near Chibougamau, in Quebec. Results from the coastal temperate forest modeling analysis (Wang et al., 2011) showed a convergence of climate sensitivity among process models for simulating weather effects on CO_2 exchanges. The result of the meta-analysis was a simple temperature-based equation to adjust CBM-CFS3 estimates of productivity to climate. However, the adjustment was considered appropriate only for the Pacific coastal region and not suitable for application in other climatic regions of Canada.

The current study builds on this work, but with a focus on the boreal forest landscape. The objectives of this study were (1) to determine the extent to which seasonal variability in weather affects modeled and measured productivity at seasonal to annual time scales, and (2) to extract a robust relationship between seasonal variability in weather and interannual variability in productivity that could be used to impart climate sensitivity to inventory models of forest productivity. Central to this investigation was an initial evaluation of the capacity of our suite of process-based models to reproduce the CO_2 flux measurements made at the boreal forest site at hourly and daily time scales. All abbreviations in the text below are listed in Table 1. In this analysis, total ecosystem C is defined as the sum of above-ground biomass (living) C (AGC), surface dead C (SDC), and below-ground organic live or dead C (BGC).

Table 1
List of abbreviations.

AGC	Above-ground biomass (living) C
APAR	Absorbed photosynthetically active radiation
BGC	Below-ground C (live roots, dead roots, and soil)
Can-IBIS	Canadian version of the Integrated Biosphere Simulator
CBM-CFS3	Carbon Budget Model of the Canadian Forest Service
CCP	Canadian Carbon Program
CN-CLASS	Carbon–Nitrogen version of the Canadian Land Surface Scheme
D	Vapor pressure deficit
EOBS	Eastern Old Black Spruce FCRN flux tower site at Chibougamau
DIC	Dissolved inorganic C
DOC	Dissolved organic carbon
DOM	Dead organic matter carbon
EC	Eddy covariance
ε_g	Gross photosynthetic efficiency
FCRN	Fluxnet Canada Research Network
GIS	Geographic information system
GPP	Gross primary productivity
g_c	Canopy conductance
g_l	Leaf conductance
InTEC	Integrated Terrestrial Ecosystem C-budget model
J	Electron transport rate
LAI	Leaf area index
LE	Latent heat flux
MAT	Mean annual air temperature
MSC	Meteorological Service of Canada
NPP	Net primary productivity
NEP	Net ecosystem productivity
NBP	Net biome productivity
OR	Oyster River region of Vancouver Island
Ω_a	Root axial resistance
Ω_r	Root radial resistance
PFT	Plant functional type
R_a	Autotrophic respiration
R_e	Ecosystem respiration
R_g	Growth respiration
R_h	Heterotrophic respiration
RMSD	Root mean square for difference
R_m	Maintenance respiration
SDC	Surface dead carbon (standing dead, stumps, forest floor)
SLC	Soil Landscapes of Canada
T_a	Air temperature
T_{amax}	Mean daily maximum air temperature during May – June
T_c	Canopy temperature
T_s	Soil temperature
θ_s	Available water content in soil
V_c	Canopy CO_2 fixation rate
V_r	Rubisco-limited CO_2 fixation rate
ψ_r	Root water potential
ψ_T	Canopy turgor potential
ψ_C	Canopy water potential

2. Model descriptions

The model intercomparison involved one inventory model *CBM-CFS3* (Kurz et al., 2009) and five process models developed in Canada: *ecosys* (Grant et al., 2007), *CN-CLASS* (Arain et al., 2006), *Can-IBIS* (Liu et al., 2005), *InTEC* (Chen et al., 2003) and *TRIPLEX* (Peng et al., 2002). The choice of the process models was based on their demonstrated ability to simulate climate effects on boreal ecosystem productivity (Grant et al., 2005, 2009a,b; Arain et al., 2002, 2006; Liu et al., 2005; Chen et al., 2000; Sun et al., 2008). The inventory model *CBM-CFS3* and the process models *ecosys*, *CN-CLASS*, *Can-IBIS* have also been used in the coastal temperate forest landscape intercomparison exercise and are therefore described in Wang et al. (2011). For the sake of parsimony, we provide below only descriptions of the two new models for this exercise: *InTEC* and *TRIPLEX*. Further details on algorithms used in all process models are provided in the Supplementary Material for this paper.

2.1. Integrated Terrestrial Ecosystem C-budget model (InTEC)

InTEC (Integrated Terrestrial Ecosystem C-budget model) was developed to simulate the integrated effects of disturbances, management practices, climate, and atmospheric factors at regional and global scales (Chen et al., 2000, 2003). The model simulates the dynamics of forest carbon stocks at an annual step through an up-scaling algorithm for the leaf-level model and combines the upscaled results with an age-NPP relationship. Inputs include climate, soil texture, nitrogen deposition, forest stand age and vegetation parameters (e.g. leaf area index and land cover type which can be generated from remotely sensed data).

2.2. TRIPLEX

The *TRIPLEX* model was developed at the Ontario Forest Research Institute of the Ontario Ministry of Natural Resources through collaboration with the Faculty of Natural Resources Management of Lakehead University. The model was developed on the basis of three models, namely *3PG* (Landsberg and Waring, 1997), *TREEDYN* 3.0 (Bossel, 1996) and *CENTURY* 4.0 (Parton et al., 1993) to simulate forest growth and the dynamics of carbon and nitrogen. Modeling processes of *TRIPLEX* have been described in detail by Peng et al. (2002) and Liu et al. (2002).