Ecological Modelling 321 (2016) 98–109

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Evaluating the impacts of climate variability and cutting and insect defoliation on the historical carbon dynamics of a boreal black spruce forest landscape in eastern Canada

Bin Chen[a,c,*], M. Altaf Arain[b], Jing M. Chen[c], Holly Croft[c], Robert F. Grant[d], Werner A. Kurz[e], Pierre Bernier[f], Luc Guindon[f], David Price[g], Ziyu Wang[d]

[a] *International Institute for Earth System Science, Nanjing University, Nanjing, China*
[b] *McMaster Centre for Climate Change and School of Geography and Earth Sciences, McMaster University, Hamilton, ON, Canada*
[c] *Department of Geography and Program in Planning, University of Toronto, Toronto, ON, Canada*
[d] *Department of Renewable Resources, University of Alberta, Edmonton, AB, Canada*
[e] *Canadian Forest Service, Pacific Forest Centre, Natural Resources Canada, Victoria, BC, Canada*
[f] *Canadian Forest Service, Laurentian Forestry Centre, Natural Resources Canada, Quebec, QC, Canada*
[g] *Canadian Forest Service, Northern Forestry Centre, Natural Resources Canada, Edmonton, AB, Canada*

ARTICLE INFO

Article history:
Received 24 August 2015
Received in revised form
20 November 2015
Accepted 23 November 2015
Available online 11 December 2015

Keywords:
Net biome productivity
Climate sensitivity analysis
Scenario analysis
Canadian land surface scheme

ABSTRACT

In this study, the Carbon and Nitrogen coupled Canadian Land Surface Scheme (CN-CLASS) was used to investigate the impact of climate variability, seasonal weather effects, disturbance, and CO_2 fertilization effects on the historical carbon (C) dynamics of an eastern Canadian boreal forest landscape (6275 ha) from 1928 to 2008. The model was parameterized with ecological, soil texture, forest inventory and historical disturbance data and driven by hourly meteorological data constructed from the historical climate records. Before performing the landscape-level simulation, model results were evaluated against site-level eddy covariance (EC) measurements. Landscape-level simulated C fluxes showed that the forest ecosystem was a small C sink in all of the years prior to cutting and insect defoliation in 1963, which resulted in the removal of 23849 Mg C from the forest landscape. As a consequence, the study area was a large C source in 1963 (net biome productivity, NBP = $-537\ \mathrm{g\,C\,m^{-2}\,yr^{-1}}$). After that, the forest landscape was mainly a net annual C sink, with total ecosystem C stocks increasing from 14.8 to 16.0 $\mathrm{kg\,C\,m^{-2}}$ by 2008, during which total biomass increased from 3.1 to 4.2 $\mathrm{kg\,C\,m^{-2}}$. Analysis of landscape-level, age-detrended, simulated C fluxes for the undisturbed forest landscape from 1928 to 2002 indicated that summer temperature was the dominant control on C fluxes with higher temperature causing a much faster increase in landscape-level annual R_e than that of GPP (i.e. 12.3 vs. 1.3 $\mathrm{g\,C\,m^{-2}\,yr^{-1}\,{}^{\circ}C^{-1}}$, respectively). Scenario analysis suggested that forest disturbances had a less profound impact on landscape-level C fluxes and stocks compared to inter-annual climate variability in this landscape. Climate sensitivity analysis revealed that landscape-level simulated C fluxes and stocks were sensitive to the change of air temperature, while only dead organic matter (DOM) and soil organic matter (SOM) were sensitive to the change of precipitation. This study will help to explore the impact of future climate change scenarios and forest management on boreal forest landscapes.

1. Introduction

Boreal forests cover circumpolar areas in the Northern Hemisphere in both North America and Eurasia, occupying 16.6 million $\mathrm{km^2}$ area worldwide (Canadian Forest Service, 2005) and accounting for half of the terrestrial biosphere's carbon (C) stocks (Dixon et al., 1994). In Canada, boreal forests occupy 3.3 million $\mathrm{km^2}$ and around 37% of the country's landmass, which is about 77% of Canada's forested land (Brandt, 2009). In 1989, Canada's boreal forest contained approximately 335.5 $\mathrm{Mg\,C\,ha^{-1}}$ (Kurz and Apps, 1999). The ability of boreal forests to sequester C is governed by both climate and disturbance regimes (Chertov et al., 2009; Kang et al., 2006). The productivity of boreal forests is influenced by short-term (Bergeron et al., 2007) and long-term

* Corresponding author at: International Institute for Earth System Science, Nanjing University, 22 Hankou Road, Gulou, Nanjing, Jiangsu, China.
E-mail address: classgg.temp@gmail.com (B. Chen).

http://dx.doi.org/10.1016/j.ecolmodel.2015.11.011
0304-3800/

variability in climate (Kang et al., 2006; Wang et al., 2013), as warmer springs tend to increase the yearly CO_2 uptake due to the earlier beginning of the growing season (Barr et al., 2004; Bergeron et al., 2007; Tanja et al., 2003). In contrast, autumn warming can enhance respiration more than photosynthesis and thus decrease the yearly CO_2 uptake of the forest ecosystems (Piao et al., 2008). In addition, higher summer air temperature (T_a) may reduce net ecosystem productivity (NEP) (Brooks et al., 1998; Dang and Lieffers, 1989; Tang et al., 2010) through concurrent declines in gross primary productivity (GPP) and increases in ecosystem respiration (R_e) (Grant et al., 2009; Griffis et al., 2003). The increases in NEP from higher spring or summer T_a are likely the more important responses in cooler or wetter climates, while the decreases in NEP resulting from higher summer T_a are likely to be more important in warmer or drier climates (Hofgaard et al., 1999; Nishimura and Laroque, 2011).

In Canada, black spruce (*Picea mariana* (*Mill.*) *B.S.P.*) stands constitute a large portion of Canadian boreal forest landscapes (Pavlic et al., 2007), and have a greater total ecosystem C content than any other major forest ecosystems in this biome (Gower et al., 1997). Over the last few decades, boreal black spruce forests have been impacted by both natural and anthropogenic disturbances, which have an effect on the forests' C cycle. Bergeron et al. (2008) compared carbon dioxide (CO_2) fluxes of an old black spruce site in eastern Canada with a black spruce site that was harvested in 2000 (HBS00) near Chibougamau, Quebec, Canada. They found that the C budget of boreal black spruce forests was much more affected by the disturbance regime, which consequently affected stand age, than the inter-annual climate variability (Bergeron et al., 2008). Bond-Lamberty et al. (2004) measured all the components of net primary productivity (NPP) and NEP in seven black spruce sites which comprised a boreal forest wildfire chronosequence near Thompson, Manitoba, Canada. This study indicated that site-level total NPP was lowest (50–100 g C m^{-2} yr^{-1}) immediately after fire, highest (332 and 521 g C m^{-2} yr^{-1} in the dry and wet stands, respectively) 12–20 years after fire, but around 50% lower than this level in the oldest stands (Bond-Lamberty et al., 2004). This study demonstrated the profound impact of wildfire on the rate of C exchange between forest and atmosphere and the need to account for soil drainage, bryophyte production and species succession when modeling boreal C fluxes (Bond-Lamberty et al., 2004). However, most studies in literature are stand specific and, with very few studies investigating the impact of disturbance on the historical C dynamics of boreal forests at landscape scale, particularly for the black spruce landscape that dominates the Canadian boreal forests (Bernier et al., 2010; Wang et al., 2013).

In this study, we incorporated the disturbance matrix of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) carbon accounting model into the Carbon and Nitrogen coupled Canadian Land Surface Scheme (CN-CLASS) and applied it to a 6275 ha forest landscape in Chibougamau, Quebec from 1928 to 2008. The specific objectives of this study are to (1) compare model predictions of C fluxes with contemporary flux tower measurements at the Eastern Old Black Spruce (EOBS) site within this study area; (2) to investigate the impacts of climate variability, disturbance events and long-term trends in atmospheric CO_2 concentrations on the landscape-level historical C dynamics, and (3) to explore how the interaction of climate variability with disturbance events and CO_2 fertilization affect landscape-level C fluxes and stocks.

2. Materials and methods

2.1. Study landscape and its disturbance history

The Chibougamau study area (centered at 49°41′32.9" N, 74°20′31.3" W) is located about 30 km south of Chibougamau, Quebec, Canada and is dominated by black spruce forests. Most of the forests in Chibougamau area were originated from major forest fires in late 1800s, although about 22 ha of 120-year old balsam fir (*Abies balsamea* (L.) Mill) stands are still present in the study area. The study landscape covers 6275 ha area with UTM co-ordinates (Zone 18, NAD 83). The elevation of the study area varies from 368 m in the southwest to 444 m in the north. The major soil types in the study area include sand, sandy loam and organic. Five surface deposit types (fluvio-glacial deposits, deep glacial till, shallow glacial till, deep organic and shallow organic) were indentified in the Chibougamau study area from a vector map of surface deposit type and soil texture properties (Wang et al., 2013). The drainage of these soil ranges from well drained sand to very poor drained organic soils. The 30-year (1971–2000) mean annual air temperature (MAT) and precipitation are 0.0 °C and 961 mm, respectively, at Chapais which is less than 30 km away from EOBS Flux Station main tower site located in this landscape (Bergeron et al., 2007, 2008; Coursolle et al., 2006).

The historical disturbance data of Chibougamau forest landscape in Quebec was created and validated at Laurentian Forestry Centre of Canadian Forest Service (Bernier et al., 2010). Six intermediate mosaics of black and white aerial photos (taken during survey flights in 1953–1954, 1959, 1965, 1967–1968, 1969–1970 and 1982) were interpreted to retrieve the disturbance layers (clear cut, partial cut, insect defoliation and infrastructure) for the period of 1928–2003. Moreover, three decennial provincial forest inventory maps (1970–2005) and Quickbird Pansharped Multispectral images (2003) with 0.6 m resolution were also used to obtain more precise disturbance information after the mid 1970s.

Currently, the majority of this disturbed landscape (4601 ha) is dominated by different-aged black spruce stands, among which there are 3857 ha pure black spruce stands and approximately 744 ha black spruce stands are mixed with trembling aspen (*Populus tremuloides*). In the rest of the landscape, there are 123 ha pure trembling aspen forest stands, 984 ha of non-productive area and 455 ha is covered by water. In 2005, the area-weighted mean stand age was 121 and 43 years for undisturbed, and disturbed stands, respectively. This was determined from the photo-interpretation of the 1998 provincial forest cover map at 1:20,000 scale (Bernier et al., 2010).

Fig. 1 shows the levels and types of forest disturbance that was recreated from inventory and remote sensing data. There was no wood exploitation in this area until 1950s, after which the study area was partially disturbed. Major disturbance events include partial cuts (25–75% forest crown density removal) in 1950, 1953, 1957 and 1963 in about 130, 14, 11 and 75 ha areas, respectively (Fig. 1). In the 1950s, about 155 ha of the forest were partially cut (<75% removal) and 11 ha forest was clear cut (> 75% removal) (Fig. 1). In 1963, around 683 ha forest was harvested, of which 608 ha was clear cut and 75 ha was partial cut (Fig. 1). In the same year, approximately 6 ha forest was affected by mild insect defoliation (Fig. 1). From 1966 to 1969, about 95 ha forest was clear cut (Fig. 1). From 1982 to 1991, 12 ha forest was clear cut, of which 10 ha of the forest had regeneration protection (Fig. 1). Approximately, 222 ha stands were converted into infrastructure development (Bernier et al., 2010), causing the permanent reduction of forest area (deforestation). These grid cells were not included in the simulations.

2.2. Model overview

CN-CLASS is the carbon and nitrogen coupled version of Canadian Land Surface Scheme (CLASS), which was originally developed for coupling with the Canadian Global Climate Model, CGCM (Verseghy et al., 1993; Verseghy, 1991, 2000). CLASS may have up to five surface/vegetation types in each grid cell including