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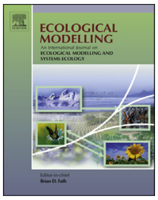

Simulating carbon dioxide exchange in boreal ecosystems flooded by reservoirs

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ABSTRACT

A process-based reservoir model of Flooded Forest Denitrification Decomposition (FF-DNDC) was developed to simulate carbon dioxide (CO_2) exchange from flooded boreal landscapes. The reservoir model is based on Forest-DNDC, a terrestrial biogeochemistry model which supports detailed soil carbon (C) processes including redox chemistry, with modification to represent the disturbed soil and vegetation C dynamics due to the presence of an overlying water column on the ecosystems. Soil decomposition rates and temperature and oxygen profiles were changed, and sedimentation to the soil surface was added. FF-DNDC was evaluated using CO_2 exchange measurements from the newly created Eastmain-1 reservoir in northern Quebec, Canada. For the first four years of the reservoir (2006 to 2009), simulated daily CO_2 emissions averaged $1.42\,g\,C\,m^{-2}\,d^{-1}$ (ranging from 0.75 to $3.24\,g\,C\,m^{-2}\,d^{-1}$) from the flooded forest and $0.74\,g\,C\,m^{-2}\,d^{-1}$ (ranging from 0.51 to $1.09\,g\,C\,m^{-2}\,d^{-1}$) from the flooded peatland. The simulated emissions were smaller than the thin-filmed boundary layer exchanges based on measured partial pressure of carbon dioxide (pCO_2) but were larger than the exchanges measured using an eddy covariance system. However, the temporal patterns of simulated and measured exchanges were similar. We simulated potential CO_2 emissions over 100 years, the expected operating lifetime of the reservoir, with assuming no change in climate. Simulated CO_2 emissions decreased with time since flooding especially for the first four decades. The 100-year cumulative emissions from the flooded peatland were larger than those from the flooded forest. Sensitivity analysis indicated that vegetation and soil inputs and parameters controlling the quality and/or quantity of decomposable soil C in flooded ecosystems (e.g. woody vegetation biomass, soil organic carbon in organic and mineral layers, and carbon:nitrogen ratio in woody vegetation and soil) were important to the reservoir CO_2 emission.

1. Introduction

Freshwater bodies, such as rivers, lakes, and reservoirs, are typically supersaturated with carbon dioxide (CO_2) relative to the atmosphere and are therefore net heterotrophic systems (e.g. Cole et al., 1994; del Giorgio et al., 1999; Jonsson et al., 2003; Hanson et al., 2006). Reservoirs result in flooding of terrestrial ecosystems and generally have a greater potential in emitting carbon (C) compared to natural lakes, but this potential varies depending on the duration of inundation (e.g. Soumis et al., 2004; Cole et al., 2007). Approximately 0.7% of the land surface of boreal biomes (~80,000 km^2) has been inundated by reservoirs created for hydroelectric power production (Barros et al., 2011). This has changed landscape-scale C exchanges, but a small number of studies have focused on gas exchange between boreal hydroelectric reservoirs and the atmosphere (e.g. Tremblay et al., 2004; Teodoru et al., 2011, 2012).

It is widely accepted that CO_2 emissions from reservoirs are linked to decomposition of soil and plant biomass which were stored in ecosystems prior to flooding. The largest CO_2 emissions occur during the first few years following inundation (Teodoru et al., 2012), supported by the decomposition of fresh organic matter of the flooded soil and vegetation (Matthews et al., 2005).

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[†] We dedicate this paper to the memory of Changsheng Li.

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Measurements from flooded peatlands suggested that higher CO_2 emissions are sustained for several decades after flooding, before declining to rates similar to those of boreal lakes (Kelly et al., 1997; St. Louis et al., 2000; Tremblay et al., 2004). Although studies in the experimental reservoirs, related to boreal reservoir biogeochemistry (e.g. Bodaly et al., 2004; Matthews et al., 2005), have provided valuable knowledge on the spatial and temporal dynamics of net CO_2 exchange, questions of scale remain regarding the application of this knowledge to reservoirs created for hydroelectric production. Hydroelectric reservoirs are larger and deeper than experimental reservoirs, have annual water level variations, and experience hydrodynamics not found in experimental reservoirs. Ecosystem models, including the appropriate physical conditions and biogeochemical processes and considering the variations in ecosystem type and standing biomass prior to flooding, are useful for estimating CO_2 exchange over the lifetime of boreal hydroelectric reservoirs. By modifying existing ecosystem models which contain the basic physical processes and some representation of redox conditions, the models can be used to simulate CO_2 exchange from the boreal reservoirs.

To date, three types of reservoir models have been developed from the boreal regions. The first is based on lake biogeochemical processes where internal water column nutrient cycling and food web dynamics are simulated, but within the model, a simple treatment of benthic processes is included (Romero et al., 2004). The second focuses on the physical mechanisms of vertical C transport in the water column and empirical functions to describe the air–water exchange (Dionne and Thérien, 1997; Barrette and Laprise, 2002). The third involves C budget calculations which focus on shoreline erosion and the C inputs of a reservoir rather than the internal dynamics from the benthic layer and water column (Weissenberger et al., 2010). Three approaches are limited in effectiveness in their role for long-term simulations of reservoir C dynamics, since they lack biogeochemical processes in the benthic layer where the major store of terrestrial C exists, which is arguably the main source of CO_2 emissions after flooding (e.g. ~70% of the surface emissions: Teodoru et al. (2011)). Ideally, a model to simulate the C dynamics in reservoirs should simulate the exchanges in boreal ecosystems prior to flooding and use the living and soil C pools as initial conditions for the simulation of the flooded ecosystems. This allows for the simulation of the change in CO_2 exchange due to the reservoir creation.

In this study, the Forest-DNDC biogeochemistry model (Li et al., 2000; Zhang et al., 2002; Miehle et al., 2006) was adapted to simulate the fate of terrestrial C following flooding and estimate CO_2 emissions from flooded ecosystems. Forest-DNDC is well-suited to simulate soil biogeochemical processes as simulating changes in redox chemistry in relation to oxygen (O_2) diffusion and moisture conditions in both upland and wetland soils. This enables simulation under flooded conditions where the supply of O_2 is restricted by the presence of several meters of overlying water. To apply Forest-DNDC to flooded ecosystems, the model was modified to incorporate environmental and plant physiological changes which occur following flooding as well as water column C processes.

Our study objectives were to: (1) develop a new process-based reservoir model by modifying modules and parameters of a terrestrial biogeochemical model and including aquatic biogeochemical processes in the terrestrial model; (2) simulate CO_2 emissions in a flooded mature black spruce forest and a flooded peatland for a period from 2006 to 2009 and compare the model outputs to observations of CO_2 exchanges between the water surface and the atmosphere; and (3) examine how CO_2 emissions from the flooded forest and peatland change over the expected lifetime of a boreal hydroelectric reservoir (i.e. ~100 years, Gagnon and van de Vate, 1997). A young reservoir in Quebec, built in 2006, was used as a case study for CO_2 exchange simulations over 100 years of flooding.

2. Materials and methods

2.1. Study area

The study area is the Eastmain-1 (EM-1) hydroelectric reservoir (Lat. 52°0′ to 52°30′N, Long. 75°30′ to 76°10′W) located in northern Quebec, Canada (Fig. 1). It is situated on the Canadian Shield with local maximum elevations of ~150 m ASL. Precambrian bedrock and surface Quaternary deposits from the Wisconsin Glacial Episode represent the geology of the area. This region is located within the boreal ecoclimatic zone characterized by moist, warm summers and dry, cold winters (Loisel and Garneau, 2010). From 2006 to 2009, average of annual mean air temperature was −0.5 °C and average of annual total precipitation was 692 mm. Mean air temperature during the warm seasons (May to October) and cold seasons (November to April) was, respectively, 10.4 and −11.5 °C. Mean total precipitation for the two seasons was 592 and 100 mm, respectively. Generally, the reservoir is covered with ice from mid-December to mid-May. Land cover comprises 65% forests (dominated by mature black spruce forests), 14% peatlands, and 21% lakes, rivers, and exposed bedrock. Nearly one-third of forested land has been burnt over the last few decades, and almost all lakes are connected to wetlands and rivers (Teodoru et al., 2011).

The EM-1 reservoir was created on the Eastmain River which flows 800 km before draining into James Bay (total drainage area of 46,400 km^2). The surface area of the reservoir is 603 km^2, 89% of which was previously terrestrial ecosystems. Water impoundment began in late 2005, and the reservoir was filled in early 2006. Its average water depth is 11 m, and the maximum operational drawdown is 9 m. Forty-six percent of the reservoir area includes 0–10 m of water depth; 39% of the area includes 10–20 m; and the rest 15% does 20–57 m. The reservoir was designed with a mean hydraulic residence time of 135 days at a flow rate of 595 $m^3\,s^{-1}$. Flooded terrestrial ecosystems are: mature forests (30%), secondary growth and recently burned forests (19%), and peatlands (18%). The remaining flooded area is composed of lakes and rivers (25%) and exposed bedrock (8%) (Teodoru et al., 2011).

For model application, a mature black spruce forest (forest site: EM-1 BS) (Lat. 52°6′N, Long. 76°11′W) and a patterned ombrotrophic bog (peatland site: EM-1 bog) (Lat. 52°17′N, Long. 75°50′W) adjacent to the reservoir, and an island within the reservoir (reservoir site) (Lat. 52°7′N, Long. 75°56′W) were selected as study sites (Fig. 1). The forest and peatland site are characteristic of the soil and vegetation types found in the area prior to flooding. Soil properties (e.g. soil type and pH) were observed, and climate, soil and vegetation C storage, and CO_2 flux were measured at these two sites (Kim et al., 2014). Climate and CO_2 flux data from the reservoir surface were collected at the reservoir site.

The forest site is covered by ~90-years-old mature black spruce (*Picea mariana*) with an understory of shrubs (e.g. *Kalmia* and *Rhododendron* spp.), feather mosses (*Pleurozium* spp.), and lichens (*Cladonia* spp.). There is an 8 to 16-cm thick organic soil layer over well-drained sandy mineral soils (Ullah et al., 2009; Lemieux, 2010). At the peatland site, ericaceous shrubs (*Chamaedaphne* and *Ledum* spp.), sedges (*Carex* and *Eriophorum* spp.), and *Sphagnum* mosses cover the surface. Tree species (e.g. *P. mariana* and *Larix laricina*) are sparsely scattered. Approximately 110 kg C m^{-2} peat is present with a thickness varying between 1 and 5 m (van Bellen et al., 2011). The reservoir site is on an island in the northwestern part of the reservoir, and land cover of this island was previously mature black spruce. An eddy covariance (EC) tower installed on the site sees open water to the north and west in an arc exceeding 150° with