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Modelling CO_2 emissions from water surface of a boreal hydroelectric reservoir

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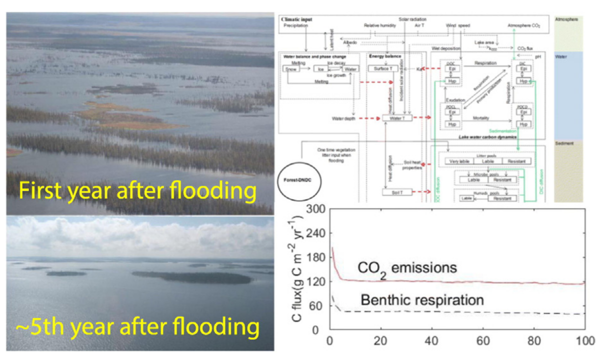
HIGHLIGHTS

- Hydroelectric reservoirs shaped by flooding terrestrial organic carbon emit CO_2.
- A daily time-step reservoir biogeochemistry model was developed.
- The 1-D model predicted CO_2 fluxes well compared to eddy covariance measurements.
- The annual effluxes steeply declined in the first three years after flooding.
- Physical and biogeochemical processes co-determine the CO_2 flux pattern.

GRAPHICAL ABSTRACT



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ABSTRACT

To quantify CO_2 emissions from water surface of a reservoir that was shaped by flooding the boreal landscape, we developed a daily time-step reservoir biogeochemistry model. We calibrated the model using the measured concentrations of dissolved organic and inorganic carbon (C) in a young boreal hydroelectric reservoir, Eastmain-1 (EM-1), in northern Quebec, Canada. We validated the model against observed CO_2 fluxes from an eddy covariance tower in the middle of EM-1. The model predicted the variability of CO_2 emissions reasonably well compared to the observations (root mean square error: 0.4–1.3 g C m^{-2} day^{-1}, revised Willmott index: 0.16–0.55). In particular, we demonstrated that the annual reservoir surface effluxes were initially high, steeply declined in the first three years, and then steadily decreased to ~115 g C m^{-2} yr^{-1} with increasing reservoir age over the estimated "engineering" reservoir lifetime (i.e., 100 years). Sensitivity analyses revealed that increasing air temperature stimulated CO_2 emissions by enhancing CO_2 production in the water column and sediment, and extending the duration of open water period over which emissions occur. Increasing the amount of terrestrial organic C flooded can enhance benthic CO_2 fluxes and CO_2 emissions from the reservoir water surface, but the effects were not significant over the simulation period. The model is useful for the understanding of the mechanism

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of C dynamics in reservoirs and could be used to assist the hydro-power industry and others interested in the role of boreal hydroelectric reservoirs as sources of greenhouse gas emissions.

1. Introduction

Hydroelectric reservoirs have become a focus of attention since these artificial lakes that were formed by flooding land (e.g., forests and wetlands) emit CO_2 and other greenhouse gases (GHGs) (Barros et al., 2011; Deemer et al., 2016; St. Louis et al., 2000). Flooding terrestrial ecosystems eliminates terrestrial uptake of carbon (C) and converts stores of terrestrial C to water-saturated sediments where the organic matters (e.g., plant biomass, litter, and soil organic matter) decompose and then emit to the atmosphere (Brothers et al., 2012b). Such land-use change can rapidly alter and create novel environmental conditions that fundamentally alter the C cycle (Teodoru et al., 2012). Because hydro-electricity is proposed as a viable non-fossil fuel based source of energy for the future, managers and policy-makers require GHG emission assessments from reservoirs (Liden, 2013).

Young reservoirs may emit higher GHGs than old ones (Barros et al., 2011; St. Louis et al., 2000), because flooded terrestrial organic matters not only directly contribute large amounts of dissolved CO_2 but subsequently provide the water column with plentiful dissolved organic C (DOC) that could enhance water column respiration in young reservoirs (Brothers et al., 2012b). However, the effects of flooding terrestrial ecosystems to create a reservoir on C processing in the flooded soil and the water column are still poorly understood and the change of CO_2 emissions with reservoir age is highly uncertain (Barros et al., 2011; Kim et al., 2016). Given that reservoirs have a lifetime of up to 100 years, it is essential to develop a mechanistic-based model that is able to simulating the CO_2 exchange over their life-time considering the physical and biogeochemical dynamics in the water column and land-use change from terrestrial ecosystems to a reservoir.

This presents a number of problems. To assess the impact of creating a reservoir on greenhouse gas exchange with the atmosphere a model needs to be able to determine the net change due to the conversion of terrestrial ecosystems to a reservoir. This requires, in addition to simulating a reservoir's C dynamics, the model has to be able to deal with a large amount terrestrial C that becomes sediments on flooding and also the model needs to be able to simulate the terrestrial C exchanges and stores prior to flooding. The net change from an atmospheric perspective is the difference between a reservoir exchange and the landscape exchange prior to flooding. The magnitude of sink of CO_2 in the terrestrial ecosystems of the boreal can be as large as the emissions from older reservoirs but with the opposite sign (Teodoru et al., 2012). To reduce uncertainty *r* it is desirable to have a model that is capable simulating both systems – i.e. the same basic biogeochemical functions to process C but in the different physical and ecological setting. While there are good reservoir models (see below) none that we know of can simulate the landscape exchanges if the reservoir did not exist or is capable of dealing with the terrestrial C input when the terrestrial ecosystems become sediments.

Lake ecosystem models that simulate spatial and/or temporal distributions of water quality parameters such as heat and nutrient budgets of a lake or a reservoir have been developed during the past four decades (Mooij et al., 2010). However, only a handful of models such as CE-QUAL-W2 (Cole and Wells, 2006) and Delft3D-ECO (Los et al., 2008) have the ability to simulate C dioxide balance of a water body (Menshutkin et al., 2014). Even fewer modelling studies have reported the quantity of emissions of CO_2 or CH_4 across the air-water interface using process-based models (e.g., Chanudet et al., 2012; Hanson et al., 2004; Kim et al., 2016; Weissenberger et al., 2010). Many of the existing reservoir models require a suite of high frequency input data to define the surface boundary conditions. For much of the Canadian northern boreal region only daily temperature, precipitation and wind run might be collected at remote weather stations but the density of weather stations in the region is <1 station/700 km^2.

To address these problems for estimating the net change in emissions due to reservoir creation in the northern region of the Canadian boreal biome we develop, a process-based biogeochemical model that can simulate interactions between physical and biogeochemical processes for terrestrial ecosystem (Kim et al., 2014a) and for reservoirs with a daily time-step that requires basic weather inputs is developed. The model, *F*orest *Aq*uatic-*Den*itrification *Dec*omposition (FAQ-DNDC), was integrated from a well-known terrestrial biogeochemical model developed by Li et al. (1992), a zero-dimension lake C model developed by Hanson et al. (2004), and a one-dimensional water thermal dynamic model (Wang et al., 2016). Eventually, we wish to simulate the possible long-term (~century) net CO_2 emissions (i.e., differences between post- and pre-impoundment balance of CO_2 emissions) from northern boreal landscapes following procedures and protocols to quantitatively analyze net GHG emissions (International Energy Agency, 2015). We thus developed the new model rather than using existing reservoir models such as CE-QUAL-W2 and Delft3D-ECO because we want the model that uses the same structure and functions for the processing of C before and after the land-use change and secondly, we need a model that required less inputs since there is a dearth of climate data in most boreal locations suitable for reservoir creation.

The objectives of this paper were to (1) describe the scientific foundation, mathematical formulation, and major assumptions of the FAQ-DNDC reservoir model, (2) demonstrate and assess inter-annual variability in CO_2 emissions, and (3) evaluate how and by what mechanisms, flooding alters the C fluxes across the air–water interface. We hypothesize that environmental factors such as air temperature and wind speed can regulate reservoir C dynamics by affecting the physical and biogeochemical processes and their interactions, and that the CO_2 emissions from the boreal reservoir surface will be the largest in the first one to two decades and will then show little secular change thereafter—i.e. year-to-year variability around a fairly constant mean.

2. Materials and methods

2.1. Study region and data collection

The Eastmain-1 reservoir (EM-1, 51 to 52°N and 72 to 76°W) in northern Quebec, Canada was constructed at the end of 2005 by damming at the Eastmain River (Fig. 1). The full reservoir has a surface area of 623 km^2 and a total storage capacity of 6.94 km^3. The surface elevation varies ~9 m over the reservoir operations. The mean depth of the reservoir is 11 m. The EM-1 power complex with 1248 MW of capacity can generate 6.3 TWh per year (from 2012 forward). The Eastmain River has an average discharge of 635 $m^3\ s^{-1}$. The EM-1 reservoir area has a continental climate with mean annual temperature of −1.5 °C (daily maximum and minimum temperature of 20.4 and −27 °C) and mean annual precipitation of 969 mm, with 32% falling as snow (measured for 15 years between 1981 and 2010 at Bonnard weather station, 50.73°N 71.05°W, http://climate.weather.gc.ca). Tree stems were removed in the first winter after the inundation by controlling icepack elevation through dam operations.

Pre-flooded landscapes were composed of forests, wetlands, lakes, and rivers. Black spruce (*Picea mariana* Mill. BSP) forests covered an area of 296 km^2, or ~50% of the pre-flooded landscape (Teodoru et al.,