The net carbon footprint of a newly created boreal hydroelectric reservoir

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We present here the first comprehensive assessment of the carbon (C) footprint associated with the creation of a boreal hydroelectric reservoir (Eastmain-1 in northern Québec, Canada). This is the result of a large-scale, interdisciplinary study that spanned over a 7-years period (2003–2009), where we quantified the major C gas (CO2 and CH4) sources and sinks of the terrestrial and aquatic components of the pre-flood landscape, and also for the reservoir following the impoundment in 2006. The pre-flood landscape was roughly neutral in terms of C, and the balance between pre- and post-flood C sources/sinks indicates that the reservoir was initially (first year post-flood in 2006) a large net source of CO2 (2270 mg C m−2 d−1) but a much smaller source of CH4 (0.2 mg C m−2 d−1). While net CO2 emissions declined steeply in subsequent years (down to 835 mg C m−2 d−1 in 2009), net CH4 emissions remained constant or increased slightly relative to pre-flood emissions. Our results also suggest that the reservoir will continue to emit carbon gas over the long-term at rates exceeding the carbon footprint of the pre-flood landscape, although the sources of C supporting these emissions have yet to be determined. Extrapolation of these empirical trends over the projected life span (100 years) of the reservoir yields integrated long-term net C emissions per energy generation well below the range of the natural-gas combined-cycle, which is considered the current industry standard.


1. Introduction

There are currently more than 45,000 large dams constructed worldwide with the purpose of power generation, agricultural and domestic use, and their number continue to increase globally at a fast pace [World Commission on Dams, 2000; Downing et al., 2006]. Among the multiple environmental, ecological, biogeochemical and social impacts associated with reservoir development [Rosenberg et al., 1995, 1997; Vörösmarty et al., 1997; Friedl and Wüest, 2002], the emission of carbon (C) gases is steadily becoming a focus of both scientific and economic concerns. Hydroelectric production was until quite recently, considered for all practical purposes as relatively C-neutral with close to zero-emission [Hoffert et al., 1998; Victor, 1998], but there is mounting evidence that hydroelectric reservoirs may in fact emit significant amounts of both carbon dioxide (CO2) and methane (CH4). Over the last decade, there have been increasing efforts to understand the complex interplay between biogeochemical and physical processes responsible for elevated levels of CO2 and CH4 emission that have been recorded following reservoir creation. Emissions of CO2 and CH4 vary greatly within and among reservoirs depending on geographic location, climate, morphometry and age of impoundments, watershed properties, and management practices [St. Louis et al., 2000; dos Santos et al., 2004; Barros et al., 2011] making it difficult, if not impossible, to extrapolate observations from one reservoir to another.

The magnitude of global C emissions from reservoirs has been a longstanding debate, in part due to the scarcity of robust quantitative estimates, a lack of common methodologies for measurements, and the lack of process based
models to extend the observational data based beyond reservoirs where measurements have been made [Rosa and Schaeffer, 1994, 1995; Fearnside, 1996; St. Louis et al., 2000; Giles, 2006]. A recent meta-analysis of published data from reservoirs with a worldwide distribution suggests globally, hydropower reservoirs emit in the range of 48 Tg C-CO2 y−1, and 3 Tg C−CH4 y−1 [Barros et al., 2011], substantially less than previous reports [St. Louis et al., 2000], mostly due to differences in the estimate of global reservoir surface. Although still substantial, these estimates are entirely based on the emissions measured at the surface and do not take into account the C sinks and sources of the natural ecosystems that were flooded. Thus, the current data do not allow effective assessments of the true impact of reservoirs in regional or global C budgets, or to place hydropower generation in the context of net emissions due to the actual reservoir construction and operation, over and above the natural regional fluxes.

4 A realistic assessment of the actual C footprint of hydropower reservoirs, and thus of C emissions associated with hydropower energy generation requires, in addition to reliable estimates of reservoir CO2 and CH4 emissions taken over space and time, robust estimates of the C sinks and sources from the terrestrial and natural aquatic ecosystems that existed in the pre-flood landscape and which are lost due to flooding [St. Louis et al., 2000; Teodoru et al., 2011]. In spite of the increasing awareness of the significance of reservoir C emissions, to our knowledge no such pre-, post flooding C balance has ever been carried out.

5 The overall aim of our study was to: 1) determine the complete pre-flood C sink/source balance of the reservoir basin; 2) determine the post-flood C balance including an estimate of spatial and temporal variability in CO2 and CH4 emissions from the reservoir; and finally, 3) combine these two estimates to calculate the net C footprint of a reservoir basin. The study focuses on the Eastmain-1 reservoir that was created in 2006 in the boreal region of Northwestern Québec. The research we present here represents a synthesis of a large cross-disciplinary collaborative project carried out by a team of scientists from several universities, consulting companies and industry (Hydro-Québec). Launched in 2003, and spanning a 7-year period, the project involved a combination of extensive empirical studies of the pre-flood ecosystems, detailed follow-up of the reservoir, and modeling of the landscape C sink/source balance. During the initial phase of the project, from 2003 to 2005, the team monitored and quantified the CO2 and CH4 sources and sinks of the pre-flood landscape, including C storage and CO2 and CH4 emission from forests, peatlands, lakes, streams and rivers. The basin was flooded at the end of 2005, and over the next four years (2006 to 2009), we quantified C gas emissions from the reservoir, by integrating detailed spatial and temporal surveys of surface water CO2 and CH4 concentrations and fluxes. In addition to diffusive fluxes, we measured methane bubbling and degassing fluxes at the powerhouse. We also determined C sedimentation and net storage in the reservoir, and continued to monitor the net C exchange by the surrounding terrestrial landscape. The net C emissions due to the reservoir, for each of the first four years after flooding, were determined from the difference between the pre- and post-flood C sink/source budgets over the entire surface of the flooded landscape, and these initial net emissions were projected over the next decades and further validated with existing data from older reservoirs in the region. These results represent, to the best of our knowledge, the first comprehensive, pre- and post-flood net C balances ever carried out for a hydropower reservoir, and provide robust estimates of the net C footprint directly associated with hydropower generation of a northern reservoir.

2. Experimental Section

2.1. Study Site

6 The Eastmain-1 reservoir (51 to 52°N and 72 to 76°W) lies within the James Bay lowland of boreal Québec, Canada (Figure 1 and see full description of the area in auxiliary material).1 The Eastmain River is one of the major boreal rivers in northern Québec. It originates in the North-Central Québec region, and flows west across 800 km, draining a total area of about 46,400 km2 and discharging into James Bay. The Eastmain-1 reservoir is located about 200 km upstream of the river mouth. It has a surface area of 602.9 km2, an average depth of 11 m, and a total storage capacity of 6.94 km3 (drawdown 9 m, active storage 4.21 km3). The theoretical hydraulic residence time (HRT) of the reservoir at a rated design flow of 550 m3 s−1 is on average 145 days. With an installed capacity of 485 MW, this hydropower station generates an annual output of 2.7 TWh. The total energy output is however expected to increase with the completion of the second powerhouse (Eastmain-1A, 768 MW) anticipated by the end of 2012.

7 Filling up of the reservoir at the end of 2005 flooded a heterogeneous landscape composed of a diversity of terrestrial, wetland and aquatic ecosystems: approximately 182 km2 of the pre-flood landscape consisted of mature forest (91% coniferous and 9% deciduous), 114 km2 was burned forest (95% 17-year-old burned and 5% 2-year-old burned), 46 km2 was non-forest soil, and 111 km2 was wetlands (1% fens, 77% bogs, and 22% swamps/marshes) (Table 1). Additionally, there were 827 lakes of widely varying sizes, totaling an area of 67 km2, there were 82 km2 of main riverbed, and more than 827 stream segments with a total surface of 1.3 km2 (Table 1).

2.2. General Approach

8 Our approach was to quantify the major carbon sources and sinks of both the pre-flood and post-flood landscape, and derive the net impact of this land cover transformation as the difference between the two. The pre-flood landscape was divided into three major components: Terrestrial (which includes forests and non-forest soils), wetlands (which include fens, bogs, swamps/marshes) and aquatic systems (which include streams, rivers and lakes). We estimated C sink/sources for each of these individual components. In the case of terrestrial and wetland components, the C source/sink was determined as the net flux of CO2 and CH4 to the atmosphere. Aquatic systems however function simultaneously as net source of C gas to the atmosphere and net C sink to the landscape through sedimentation and storage. The latter is only possible because lakes receive substantial inputs of C from the watershed as well, and thus, the net C source/sink

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1Auxiliary materials are available in the HTML. doi:10.1029/2011GB004187.
balance of lakes cannot be derived only from net gas exchange but is instead determined as the difference between CO₂ and CH₄ emissions to the atmosphere and the rate of C burial in the sediment. As previous studies in boreal regions suggest that CH₄ release during forest fire is negligible relative to CO₂ representing only between 0.3 to 0.4% of the CO₂ flux [Kasischke and Bruhwiler, 2002], fire CH₄ flux was not included in the overall computation and the pre-flood balance was thus calculated as:

\[ 9 \] Pre-flood C sink/source balance = (Net terrestrial CO₂ and CH₄ exchange + fire CO₂ flux) + (Net wetland CO₂ and CH₄ exchange) + (Aquatic CO₂ and CH₄ emissions − lake sediment C burial).

\[ 10 \] We followed the same general approach for the post-flood landscape. The net post-flood C source/sink balance was thus calculated as:

\[ 11 \] Reservoir C sink/source balance = CO₂ exchange (diffusive + turbine) + CH₄ exchange (diffusive + bubbling + turbine) − net C sedimentation.

\[ 12 \] The degrading soils contained within the reservoir constitute an additional unquantified source of carbon to the system, a portion of which can ultimately be the source of the

**Table 1.** Weighted-Average and Range Variability of Diffusive Fluxes and C Storage in Natural Aquatic and Terrestrial Ecosystems Prior to Flooding

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Class</th>
<th>Area (km²)</th>
<th>Diffusive Flux (mg C m⁻² d⁻¹)</th>
<th>C Storage (mg C m⁻² d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>CO₂</td>
<td>CH₄</td>
</tr>
<tr>
<td>Natural aquatic</td>
<td>river</td>
<td>82.0</td>
<td>398 (279/445)</td>
<td>1.0 (0.8/1.1)</td>
</tr>
<tr>
<td></td>
<td>lake</td>
<td>66.9</td>
<td>239 (229/247)</td>
<td>2.8 (0.9/4.2)</td>
</tr>
<tr>
<td></td>
<td>stream</td>
<td>1.3</td>
<td>2751 (1115/6019)</td>
<td>ND</td>
</tr>
<tr>
<td>Total aquatic</td>
<td></td>
<td>150.2</td>
<td>335 (241/399)</td>
<td>1.8 (0.9/2.5)</td>
</tr>
<tr>
<td>Forest</td>
<td>coniferous</td>
<td>166.6</td>
<td>−159 (−376/−1)</td>
<td>−0.24 (−0.31/−0.17)</td>
</tr>
<tr>
<td></td>
<td>deciduous</td>
<td>15.6</td>
<td>−471 (−729/−214)</td>
<td>−0.08 (−0.09/−0.07)</td>
</tr>
<tr>
<td></td>
<td>burned</td>
<td>113.8</td>
<td>−9 (−88/71)</td>
<td>−0.24 (−0.30/−0.18)</td>
</tr>
<tr>
<td>Total forest</td>
<td></td>
<td>296.0</td>
<td>−117 (−250/15)</td>
<td>−0.22 (−0.29/−0.17)</td>
</tr>
<tr>
<td>Non-forest soil</td>
<td></td>
<td>45.9</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>Wetland</td>
<td>peatland: fen</td>
<td>1.1</td>
<td>1278 (954/1603)</td>
<td>35 (30/40.5)</td>
</tr>
<tr>
<td></td>
<td>peatland: bog</td>
<td>85.4</td>
<td>−120 (−233/−6)</td>
<td>39 (33/45.5)</td>
</tr>
<tr>
<td></td>
<td>swamp:marsh</td>
<td>24.4</td>
<td>−102 (−218/14)</td>
<td>39 (33/45.5)</td>
</tr>
<tr>
<td>Total wetland</td>
<td></td>
<td>110.9</td>
<td>−102 (−218/14)</td>
<td>39.3 (33.1/45.5)</td>
</tr>
<tr>
<td>Total terrestrial (including non-forest soil)</td>
<td>452.8</td>
<td>−102 (−217/14)</td>
<td>9.5 (7.9/11.0)</td>
<td>ND</td>
</tr>
<tr>
<td>Total pre-flood ecosystem</td>
<td></td>
<td>602.9</td>
<td>7 (−103/110)</td>
<td>7.6 (6.2/8.9)</td>
</tr>
</tbody>
</table>

*Negative values represent C sink. Values between parentheses correspond to lower and upper limit estimates. ND denotes not determined.*
sedi
et is
and the reservoir
C budget was calculated by accumulating the NEE over each


[14] Data collected both before and after flooding showed that dissolved organic carbon (DOC), particulate matter and partial pressure of CO$_2$ ($p$CO$_2$) concentrations in the Eastmain River upstream and downstream of the flooded basin remain similar (within $±10\%$), which suggest small changes in the net export via the river from the study basin. In our calculations of net reservoir impact we have therefore only considered changes in CO$_2$ and CH$_4$ emissions and C storage within the flooded basin, and have not included differences between the input and outputs of C to and from the basin via the Eastmain River, which were too small to be resolved, and which were small also relative to other fluxes.

[15] We used a single, average Pre-flood C sink/source balance for all calculations, whereas we calculated the reservoir C sink/source balance for each of the 4 study years post flooding. The net reservoir C footprint represents the net changes in CO$_2$ and CH$_4$ flux which includes the actual measured emissions plus the loss of the sinks or sources of CO$_2$ and CH$_4$ that were present in the pre-flood landscape, and thus represent the “excess” emissions directly associated with the creation and operation of the reservoir.

[16] The results presented here combine multiple research components that were carried out in parallel by the different groups within the team over the 7-year study period. Portions of the data used in this final mass balance have been published before (as referenced), others are in the process of being published, and yet other data components are unpublished and presented here for the first time.

2.3. Flux Measurements and Calculations

2.3.1. Streams, Rivers, and Lakes

[17] We sampled a wide range of natural aquatic ecosystems, including lakes, streams and rivers of varying sizes, starting in 2005 (one year before flooding), and continuing until 2009, including winter sampling carried out in 2008 (see section S2 in Text S1 in the auxiliary material for details of aquatic sampling). Diffusive air-water CO$_2$ and CH$_4$ fluxes can be adequately modeled as a Fickian diffusive process (also known as the Thin Boundary Layer method, TBL) and were determined from the difference in partial pressures of CO$_2$ ($p$CO$_2$) and of CH$_4$ ($p$CH$_4$) in the surface water relative to that of the atmosphere combined with an appropriate gas transfer coefficient ($k_{H0}$) [Hesslein, 2005; Cole and Prairie, 2009]. The surface water $p$CO$_2$ was measured using a non-dispersive infrared (NDIR) instrument (PP-System EGM-4) coupled to a gas equilibrator, and $p$CH$_4$ using gas chromatography (see section S3 in Text S1 for details on gas measurements and diffusive flux calculations). In addition, we made direct measurements of diffusive fluxes in lakes using floating chambers (see section S3 in Text S1 for full description of approach and calculations). The chamber measurements may be affected by turbulence and chamber design [Vachon et al., 2010], whereas the TBL estimates are strongly influenced by assumptions concerning wind speed and gas exchange coefficients [Duchemin et al., 1995; Matthews et al., 2003], so we combine both types of estimates to better bracket aquatic emissions.

[18] Annual values were estimated from daily summer fluxes by assuming an average ice-free period in the region of 215 days, and that the C pool which has accumulated under the winter ice is released rapidly within the first month following the ice break and represents 30% of the annual emission as suggested by gas partial pressure data from both natural lakes (V. Ducharme-Riel et al., The contribution of winter under-ice and summer hypolimnetic CO$_2$ accumulation to the annual CO$_2$ budget of temperate and boreal lakes in Quebec, submitted to Ecosystems, 2011) and the reservoir [Demarty et al., 2009; Bastien et al., 2011a].

[19] We further measured the C sedimentation rates in lakes using sediment traps (two traps per mooring) deployed for more than two months during the summer period of 2008 at the deepest locations of eleven reference lakes situated in the immediate vicinity of the reservoir (C. R. Teodoru et al., Depositional fluxes and sources of particulate carbon and nitrogen in natural lakes and a young boreal reservoir in Northern Quebec, submitted to Biogeochemistry, 2012). Long-term C sequestration rates were calculated as the difference between these gross C sedimentation rates and the fraction of C that is eventually respired in the benthos [Brothers et al., 2011]. While the mean rates of C sequestration represent an area-weighted average, the upper and lower limits of C accumulation correspond to the minimum and maximum recorded values.

2.3.2. Forests

[20] We estimated the net ecosystem exchange (NEE) of CO$_2$ for the major forest types that are present in the Eastmain region. The dominant forest is represented by coniferous black spruce (Picea mariana Miller BSP) closed canopy for which we measured NEE continuously starting in August 2006 up to 2009 using eddy covariance tower (see section S4 in Text S1 for details). An overall annual CO$_2$ budget was calculated by accumulating the NEE over each year of measurements. Details of eddy covariance data processing and flux calculations are described by Bonneville et al.[2008] and Barr et al.[2004]. Since there was a relatively large variation in stand ages and stand types (i.e., black spruce, jack pine) of the coniferous forest in the region, a more robust calculation of the regional CO$_2$ budget for the coniferous forest within the Eastmain-1 was obtained by combined our measured NEE (eddy covariance tower – three years data for black spruce) with literature value from other representative boreal black spruce forests (i.e., jack pine - Pinus banksiana Lamb.) of different ages [Arain et al., 2002; Amiro et al., 2006; Yuan et al., 2008]. The area-weighted average value for the entire coniferous forest was derived taking into account the spatial and temporal variability in NEE for these different coniferous forest types. For deciduous forests, the CO$_2$ budget was derived from literature data on eddy covariance NEE measurements made in boreal aspen forests [Arain et al., 2002; Amiro et al., 2006; Barr et al., 2007]. Literature data from similar regions were also used to estimate the CO$_2$ budget for burned forests of different ages [Amiro et al., 2006; Mkhabela et al., 2009]. Since it is recognized that the forest fire cycle in this region is around 100 years [Bergeron et al., 2004], we assumed that about 1% of the total area (coniferous + deciduous + previously burnt), would burn every year, and that 50% of the related biomass
series measurements over 4 years period [Teodoru et al., 2011; Bastien et al., 2011a].

[23] Besides estimating diffusive fluxes, we used empirical estimates of degassing fluxes at the turbines and spillway from the time series pCO₂ and pCH₄ concentrations of the inlet water of the turbines measured continuously from September 2006 to December 2009 with an automated system installed at the Eastmain-1 powerhouse [Bastien et al., 2011a]. The assumption used in degassing flux calculations was that all the excess pCO₂ and pCH₄ (relative to the atmospheric values of 380 ppmv for CO₂ and 1.77 ppmv for CH₄ [Forster et al., 2007]) was emitted into the atmosphere at the turbines or immediately downstream the powerhouse [Roehm and Tremblay, 2006]. The measured pCO₂ and pCH₄ during 2010 and 2011 in the river downstream of the dam was in the range of about 600 ppmv CO₂ and 2 ppmv CH₄ [Bastien et al., 2011b], suggesting a slight overestimation of the degassing flux. These relatively high river concentrations may also have been the result of lateral inputs and high rates of replenishment as observed in most boreal rivers in Quebec (C. R. Teodoru et al., manuscript in preparation, 2012). Annual degassing emissions were thus calculated as the product of monthly mean water excess CO₂ and CH₄ concentrations and the mean water discharge. Upper and lower limits were estimated using the standard deviation values from the mean. Details on the equations and calculations are given by Demarty et al. [2009].

[24] Bubble-mediated CH₄ fluxes were measured in the Eastmain-1 reservoir from June to September 2008 using 50 submerged inverted funnels deployed along eight transects to cover four major flooded ecosystems: forest, peatland, lakes and river. The accumulated gas was sampled every 2 to 3 weeks (156 samples) and analyzed for CH₄ concentration using a gas chromatograph. As CH₄ bubbles were extremely rare (only three funnels trapped CH₄ bubbles and only one funnel had detectable concentrations), the range variability of gross bubble emissions (lower, mean and upper limits) for the entire reservoir was estimated by multiplying the average measured flux with 1%, 5% and 10%, respectively, of the reservoir surface of 603 km². This percentage range described best the variability in the relative contribution of shallow waters to the total reservoir surface, where increased water temperature due to shallower conditions may favor CH₄ bubble production.

[25] As with natural lakes, net C accumulation in the reservoir was estimated from the gross C sedimentation flux measured in fourteen sediment traps installed at various locations in the reservoir during the summer period of 2008 minus the fraction that is eventually respired in the benthos. As with the other fluxes, we calculated the mean annual sediment C accumulation in the reservoir by extrapolating the open water measurements to 215 days, assuming that sediment C accumulation during the ice-cover (150 days) represents 30% of the annual sink. The upper and lower estimates correspond to the maximum and minimum measured rates of C deposition, whereas the mean value is integrated (weighted average) over the reservoir area. Detailed information on trends, rates and the origin of C in the reservoir as well as the eleven reference lakes are described by Teodoru et al. (submitted manuscript, 2012).

[26] All gas concentrations or fluxes are reported as C-CO₂ and C-CH₄, respectively. In this paper we use the atmospheric
convention – i.e., C fluxes to the atmosphere are expressed with a positive sign, and net C uptake from the atmosphere is expressed with a negative sign. For the calculation of net C emissions per unit energy generated, we transformed C-CH\textsubscript{4} to C-CO\textsubscript{2} equivalents (C-CO\textsubscript{2}, eq.) using a conversion factor of 8.384 combining the ratio of their molecular weights, and 100 years global warming potential (GWP) of methane of 23 [Intergovernmental Panel on Climate Change, 1996]. Annual estimates were calculated using mean values assuming a normal distribution of variables.

[27] The entire basin was mapped using digitized maps (National Topographic Data Base, scale 1:50,000, www. geogratis.cgdi.gc.ca/) and characterized for different terrestrial and aquatic types using the hydrological and topographical extensions in ArcMap GIS 9.2. Statistical analyses of all variables presented here (i.e., errors in the analytic methods, errors in the temporal interpolations, errors in the interpretation of the land classes, etc), were carried out using JMP®7 (SAS Institute, Cary, NC, USA).

3. Results and Discussion

3.1. Pre-Flood Fluxes

[28] All three major components of the aquatic network (rivers, lakes and streams) were consistently net sources of both CO\textsubscript{2} and CH\textsubscript{4} to the atmosphere. On an annual basis, gross surface CO\textsubscript{2} emissions for the Eastmain River were estimated to fluctuate from 280 to 445 mg C m\textsuperscript{-2} d\textsuperscript{-1} (mean 398 mg C m\textsuperscript{-2} d\textsuperscript{-1}), while much smaller CH\textsubscript{4} fluxes ranged between 0.8 and 1.1 mg C m\textsuperscript{-2} d\textsuperscript{-1} (mean 1.0 mg C m\textsuperscript{-2} d\textsuperscript{-1}). Area-weighted average CO\textsubscript{2} emissions from the lakes in the region varied within a very narrow range of between 230 and 247 mg C m\textsuperscript{-2} d\textsuperscript{-1} (mean 240 mg C m\textsuperscript{-2} d\textsuperscript{-1}), and again CH\textsubscript{4} fluxes were much lower but slightly higher than river emissions, ranging between 0.9 and 4.2 mg C m\textsuperscript{-2} d\textsuperscript{-1} (mean 2.7 mg C m\textsuperscript{-2} d\textsuperscript{-1}). These estimates are in good agreement with previous studies of similar boreal systems [Tremblay et al., 2005a; Roehm et al., 2009; Tranvik et al., 2009; Karlsson et al., 2010; Bastviken et al., 2011]. The estimated net C accumulation rates in lake sediments were in the order of −10 to −51 mg C m\textsuperscript{-2} d\textsuperscript{-1} (mean −27 mg C m\textsuperscript{-2} d\textsuperscript{-1}), and thus represented only around 10% of lake C emissions, a pattern that has also been previously reported [Kortelainen and Pajunen, 2000; Kortelainen et al., 2004; von Wachenfeldt and Tranvik, 2008]. Stream areal emissions were the highest among all natural aquatic ecosystems, with CO\textsubscript{2} fluxes ranging from 1115 to over 6000 mg C m\textsuperscript{-2} d\textsuperscript{-1} (mean 2750 mg C m\textsuperscript{-2} d\textsuperscript{-1}), consistent with previous observation [Jonsson et al., 2007; Teodoru et al., 2009]. However, due to their small areal extent relative to other types of aquatic system in this particular basin, the overall contribution of streams to total aquatic CO\textsubscript{2} emissions was relatively small (about 7%). We did not measure CH\textsubscript{4} fluxes in streams. However, based on the above example of CO\textsubscript{2} fluxes we have assumed that stream CH\textsubscript{4} emissions, even if higher than river or lake fluxes, did not represent a major component of the overall aquatic CH\textsubscript{4} balance. Subsequent work of our group in other boreal areas tends to support this assumption (P. del Giorgio, unpublished data, 2011).

[29] We used the areal coverage of each type of aquatic system within the pre-flood basin (Table 1) to estimate the area-weighted average CO\textsubscript{2} and CH\textsubscript{4} emissions for the entire aquatic network that existed prior to flooding, which ranged from 240 to 400 mg C m\textsuperscript{-2} d\textsuperscript{-1} of CO\textsubscript{2} (mean 335 mg C m\textsuperscript{-2} d\textsuperscript{-1}), and between 0.9 and 2.5 mg C m\textsuperscript{-2} d\textsuperscript{-1} of CH\textsubscript{4} (mean 1.7 mg C m\textsuperscript{-2} d\textsuperscript{-1}), respectively (Figure 2).

[30] The estimated total NEE for the entire forest components ranged from −250 to 15.5 mg C m\textsuperscript{-2} d\textsuperscript{-1} (mean −117 mg C m\textsuperscript{-2} d\textsuperscript{-1}, Table 1), in good agreement with previous reports for similar boreal landscapes [Blais et al., 2005; Amiro et al., 2006; Barr et al., 2007; Yuan et al., 2008; Mkhabela et al., 2009]. The range of NEE for the wetland components was similar to that of the forest, in the order of −218 to 14.2 mg C m\textsuperscript{-2} d\textsuperscript{-1} (mean −102 mg C m\textsuperscript{-2} d\textsuperscript{-1}) and similar with previous estimates for northern peatlands [Jonsson et al., 2007; Roulet et al., 2007; Nilsson et al., 2008; Koehler et al., 2009; Buffam et al., 2011]. Taken together, the terrestrial (forest + wetland) ecosystems prior to flooding were collectively a moderate sink of CO\textsubscript{2}, in the order of −113 mg C m\textsuperscript{-2} d\textsuperscript{-1} (between −241 to 15 mg C m\textsuperscript{-2} d\textsuperscript{-1}) or −102 mg C m\textsuperscript{-2} d\textsuperscript{-1} (between −217 to 14 mg C m\textsuperscript{-2} d\textsuperscript{-1}) if the Non-Soil Forest area is included (Table 1 and Figure 2). These average values are twice as high compared to terrestrial NEE calculated for a subarctic Swedish catchment [Christensen et al., 2007], three to five times lower than similar catchments in boreal Sweden [Jonsson et al., 2007], and northern temperate USA [Buffam et al., 2011], and close to the global estimate of about 80 mg C m\textsuperscript{-2} d\textsuperscript{-1} [Battin et al., 2009]. Considering that forest fires in this region contribute annually on the order of 15 to 28 mg C m\textsuperscript{-2} d\textsuperscript{-1} of CO\textsubscript{2} (mean 21 mg C m\textsuperscript{-2} d\textsuperscript{-1}), the rate of CO\textsubscript{2} uptake by the terrestrial ecosystems would decrease slightly to an average of −88 mg C m\textsuperscript{-2} d\textsuperscript{-1} (−207 to 32 mg C m\textsuperscript{-2} d\textsuperscript{-1}) if fire is incorporated. Due to the relatively large CH\textsubscript{4} flux from wetlands of 39 mg C m\textsuperscript{-2} d\textsuperscript{-1} (in agreement with −28 mg C m\textsuperscript{-2} d\textsuperscript{-1} of Buffam et al. [2011]) relative to the low sink in forest soils (−0.22 mg C m\textsuperscript{-2} d\textsuperscript{-1}), the pre-flood combined terrestrial (forest + wetland + mineral soil) components of the landscape were on average a source of approximately 9.5 mg C m\textsuperscript{-2} d\textsuperscript{-1} of CH\textsubscript{4} (Table 1).

[31] The balance of all C sources and sinks of the aquatic and terrestrial ecosystems, integrated over the entire landscape, suggests that the pre-flood basin was a small source of both CO\textsubscript{2} and CH\textsubscript{4}, of approximately 7 mg C m\textsuperscript{-2} d\textsuperscript{-1} of CO\textsubscript{2} (or 17 mg C m\textsuperscript{-2} d\textsuperscript{-1} if forest fires are considered) and of 7.6 mg C m\textsuperscript{-2} d\textsuperscript{-1} of CH\textsubscript{4} (Figure 2). The upper and lower limits around this central value of the pre-flood C balance (Table 1, numbers in parentheses) were determined by combining the lowest emission estimates with the highest C uptake estimates (to determine the upper limit), and the highest emission estimates with the lowest C uptake estimates (to determine the lower limit). Although these confidence limits represent the most extreme scenarios possible within the confines of our measurements (and thus are not statistical intervals), it is clear that the calculated small net CO\textsubscript{2} source of the overall landscape cannot be distinguished from zero and that the reservoir area as a whole can be considered carbon-neutral prior to flooding. This is unlikely to be a general characteristic of the entire region however, for it is highly influenced by the high emissions of the Eastmain River, which itself occupies about 14% of the pre-flood basin area. Large rivers in northern Québec occupy less than 1.5% of the boreal landscape, so this overall boreal landscape is probably a net sink for carbon as indicated by the results of
similar studies of Swedish subarctic and boreal catchments [Christensen et al., 2007; Jonsson et al., 2007], and northern temperate USA [Buffam et al., 2011].

3.2. Post-Flood Fluxes

Surface water gas concentrations and air/water gas emissions in the reservoir were highly variable, both spatially and temporally over the 4-year study period. The various ecosystems that existed prior to impoundment have now been incorporated in the Eastmain-1 Reservoir, and have been shown to influence strongly both the magnitude and the spatial patterns of CO$_2$ emissions in the reservoir [Teodoru et al., 2011; Brothers et al., 2012]. The highest CO$_2$ fluxes were measured during the first year after flooding (2006) when the largest spatial heterogeneity was also encountered (up to one order of magnitude) [Teodoru et al., 2011].

Areal-weighted average CO$_2$ fluxes for the entire reservoir reached 2364 mg C m$^{-2}$ d$^{-1}$ in 2006 and decreased to 1420 mg C m$^{-2}$ d$^{-1}$ in 2007, 1056 mg C m$^{-2}$ d$^{-1}$ in 2008 and 888 mg C m$^{-2}$ d$^{-1}$ in 2009 (Table 2). Despite this relatively sharp decrease with reservoir age, surface CO$_2$ fluxes in 2009 were still 3 to fourfold higher than the average fluxes observed for lakes in the region (Table 1) [see also Brothers et al., 2011]. Applying the inverse relationship between $p$CO$_2$ and lake size [Roehm et al., 2009], the degree of supersaturation and the corresponding fluxes observed in the reservoir are much larger than what would be expected of a lake of similar size. Due to the relatively shallow and predominantly oxic nature of the reservoir, diffusive CH$_4$ fluxes were generally low and quite stable, ranging from 7.3 mg C m$^{-2}$ d$^{-1}$ in 2006, 6.2 mg C m$^{-2}$ d$^{-1}$ in 2007, 6.9 mg C m$^{-2}$ d$^{-1}$ in 2008 and 10.5 mg C m$^{-2}$ d$^{-1}$ in 2009 (Table 2).

Although those diffusive CH$_4$ fluxes in the reservoir seems low, they were fourfold higher than the CH$_4$ emissions for lakes in the region, and similar to those of pre-flood terrestrial (forest + wetland + mineral soil) components of the landscape (Table 1).

We explored bubble-mediated fluxes in the reservoir, but out of 50 funnels and 156 samples analyzed during the summer period of 2008, only three funnels collected CH$_4$
Diffusive Fluxes, C Storage, CH₄, Ebulition and Degassing Fluxes Together With Annual Post-Flood C Budgets for the Eastmain-1 Reservoir During the Period of 2006 and 2009.

Table 2. Diffusive Fluxes, C Storage, CH₄, Ebulition and Degassing Fluxes Together With Annual Post-Flood C Budgets for the Eastmain-1 Reservoir During the Period of 2006 and 2009.

<table>
<thead>
<tr>
<th>Year</th>
<th>CO₂</th>
<th>CH₄</th>
<th>Ebulition</th>
<th>Degassing</th>
<th>Post-flood C balance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg C m⁻² d⁻¹</td>
<td>mg C m⁻² d⁻¹</td>
<td>mg C m⁻² d⁻¹</td>
<td>mg C m⁻² d⁻¹</td>
<td>mg C m⁻² d⁻¹</td>
</tr>
<tr>
<td>2006</td>
<td>1234 (1230/1235)</td>
<td>784 (782/785)</td>
<td>32 (31/33)</td>
<td>23 (22/24)</td>
<td>1234 (1230/1235)</td>
</tr>
<tr>
<td>2007</td>
<td>1356 (1354/1356)</td>
<td>678 (676/678)</td>
<td>42 (41/43)</td>
<td>31 (30/32)</td>
<td>1356 (1354/1356)</td>
</tr>
<tr>
<td>2008</td>
<td>1478 (1476/1480)</td>
<td>890 (888/892)</td>
<td>55 (54/56)</td>
<td>41 (40/42)</td>
<td>1478 (1476/1480)</td>
</tr>
<tr>
<td>2009</td>
<td>1600 (1598/1602)</td>
<td>1012 (1010/1014)</td>
<td>68 (67/69)</td>
<td>49 (48/50)</td>
<td>1600 (1598/1602)</td>
</tr>
</tbody>
</table>

The net balance between gross reservoir surface fluxes, sediment C fluxes, degassing, and bubble-mediated emissions indicates that during the first year after flooding (2006), the Eastmain-1 reservoir was an overall net source of both CO₂ and CH₄, in the order of 2280 mg C m⁻² d⁻¹ and 7.8 mg C m⁻² d⁻¹, respectively (Table 2). The net CO₂ emissions declined steeply in subsequent years, to 1390 mg C m⁻² d⁻¹ in 2007, 1032 mg C m⁻² d⁻¹ in 2008 and 843 mg C m⁻² d⁻¹ in 2009, whereas CH₄ emissions increased steadily to 8 mg C m⁻² d⁻¹ in 2007, 8.8 mg C m⁻² d⁻¹ in 2008 and 11.9 mg C m⁻² d⁻¹ in 2009. As in the case of pre-flood C sink/source balance, the lower and upper ranges of the post-flood balance of each year (Table 2, numbers in parentheses) were calculated by combining the lowest recorded emissions with the highest C accumulation rates (to derive the lower emission range), and the highest recorded emissions with the lowest C accumulation rates (to derive the upper emission range). The results of the post-flood balance...
clearly show that reservoir C emissions were dominated by CO\textsubscript{2} diffusive fluxes from the water/air interface, that CH\textsubscript{4} emissions (both diffusive and ebullition) were small relative to CO\textsubscript{2} fluxes, and that the former declined steeply with time after flooding, agreeing with previous reports for boreal and temperate reservoirs [St. Louis et al., 2000; Tremblay et al., 2005a, 2005b].

3.3. Net Reservoir C Footprint

The net reservoir C footprint represents the actual CO\textsubscript{2} and CH\textsubscript{4} fluxes to the atmosphere over and above the exchanges that existed in the pre-flood landscape, and thus represent the emissions that can be directly attributed to the creation and existence of the reservoir. As stated in the Methods section, these were calculated by subtracting the pre-flood C sink/source balance of the basin, from the post-flood C sink/source balance of the reservoir. If overall the pre-flood basin was a net sink of C, then the integrated pre-flood landscape fluxes need to be added to the net post-flood reservoir fluxes to account for the total change in landscape scale CO\textsubscript{2} exchange. Conversely, if the landscape was a source of C to the atmosphere then the landscape flux needs to be subtracted from the reservoir emissions. We bracketed our best estimates (the mean value) of net reservoir C footprint, with likely upper and lower limits, by creating two contrasting extreme scenarios: 1) a low emission scenario that combines the lowest reservoir fluxes and highest pre-flood emissions; and 2) a high-emission scenario that combines the highest reservoir fluxes plus the highest pre-flood sinks (or minus the lowest pre-flood emissions). This approach intrinsically provides wider confidence intervals than standard error propagation calculations would yield and we are thus confident that the uncertainty in our projected emissions are both conservative and robust.

The pre-flood emissions suggests that the basin was a small source of both CO\textsubscript{2} and CH\textsubscript{4}, in the range of 7 and 7.6 mg C m\textsuperscript{-2} d\textsuperscript{-1}, respectively (Table 1), while the post-flood C sink/source balance indicates that the reservoir was a large net source of CO\textsubscript{2}, and a relatively small source of CH\textsubscript{4} (Table 2). However, taking into consideration the analytical and all the interpolation errors, it is safe to assume that the landscape prior to flooding was effectively carbon neutral. The difference between the pre-flood and post-flood fluxes indicates that the net reservoir C footprint for Eastmain-1 was initially (2006) a large net source of around 2270 mg C m\textsuperscript{-2} d\textsuperscript{-1} of CO\textsubscript{2}, and of only 0.2 mg C m\textsuperscript{-2} d\textsuperscript{-1} of CH\textsubscript{4} (Figures 3a and 3b). The upper and lower scenarios for 2006 suggest a range of variability around these mean
values of about ±14% for CO₂ (+343/−339), and of ±94% (+3.6/−3.7) for CH₄. On an annual base, this translates into a net C release to the atmosphere due to the Eastmain-1 reservoir of around 5 × 10¹¹ t C-CO₂ and approximately 45 t C-CH₄. The same calculation for subsequent years indicates that net reservoir sink/source balance of CO₂ decreased to 1390 (+180/−165) mg C m⁻² d⁻¹ in 2007, 1025 (+180/−170) mg C m⁻² d⁻¹ in 2008, and 835 (+215/−200) mg C m⁻² d⁻¹ in 2009 (Figure 3a). Incorporating CO₂ fluxes due to forest fires in these calculations results in only a 1% change in the estimated net reservoir CO₂ sink/source balance. The net reservoir C sink/source balance of CH₄ increased with the reservoir age, ranging from 0.5 (+3.6/−3.8) mg C m⁻² d⁻¹ in 2007, 1.2 (+6.4/−6.0) mg C m⁻² d⁻¹ in 2008 and 4.3 (+9.4/-5.8) mg C m⁻² d⁻¹ in 2009 (Figure 3b).

[40] It is difficult at this point to accurately project the course of the reservoir net CO₂ sink/source balance beyond the initial four years of this study. The initial trajectory of net CO₂ emissions fits extremely well (R² > 0.99) both a negative exponential with threshold [F = C + exp(−k × T)] and a power function (F = a × T⁻b). Although the fit of these two models is identical in the initial years, they differ markedly over time and there are no statistical reasons for choosing one model over the other. The power model predicts near zero emissions within less than 25 years whereas the exponential model predicts long-term emissions of around 700 mg C m⁻² d⁻¹. It is clear however that the former scenario is rather unrealistic, since there is empirical evidence that older reservoirs in the same boreal region of northern Québec still emit at rates that vary between 300 and 900 mg C m⁻² d⁻¹ of CO₂, even after 25 to 75 years [Tremblay et al., 2005a]. Therefore, the negative exponential model was considered more appropriate for the projection with reference to the overall objective of the study. Similarly, the early trajectory of CH₄ emissions fits a positive linear model, which predicts extremely high CH₄ fluxes within 25 years. This is equally unrealistic since gross CH₄ fluxes for the same reservoirs rarely exceed 35 mg C m⁻² d⁻¹.

[41] To further examine the projected long-term trend, we combined our data for the Eastmain-1 reservoir with existing pCO₂ and pCH₄ data from older reservoirs in the same boreal region of Québec to model the potential trajectory of the net reservoir C emissions (Figures 3c and 3d). Since these reported data represent gross fluxes, we had to estimate the corresponding net fluxes so that the data would be comparable to that of Eastmain. First, we derived CO₂ fluxes for these older reservoirs based on the measured pCO₂ using a TBL model, which provide a lower limit estimate of CO₂ fluxes (as described in the Methods section and in section S2 in Text S1). We then developed an empirical linear relationship between the lower gross CO₂ fluxes and the net CO₂ sink/source balance for the Eastmain-1 reservoir, based on our own estimates, and assumed that this same relationship applies to other boreal reservoirs in the same region. Finally, we applied this empirical relationship to the gross CO₂ fluxes calculated for the older boreal reservoirs, in order to obtain an estimate of net CO₂ sink/source balance for these reservoirs, and we used these estimates to reconstruct the potential trajectory of net CO₂ emissions with time for the Eastmain-1 reservoir.

[42] The model that best fits the combination of Eastmain-1 data (first four years, Figure 3a) and the data from older boreal reservoirs is also a first-order exponential decay with an additive intercept (equation 1) and Figure 3c, rather than either a negative power or normal exponential decline:

\[ NMF_{(CO₂)} = 433.8 + 3195.9 \times \exp(Age/−1.76), \quad R^2 = 0.86 \]  

where NMF_{(CO₂)} is the net mean CO₂ flux in mg C m⁻² d⁻¹, and Age represent the number of years after flooding.

[43] We further assumed that the relative differences between the lower, mean and upper emission estimates of the first four years are maintained in time, so that we could extrapolate likely upper and lower limits for the projected fluxes. This empirical modeling of net CO₂ fluxes suggests that, after the initial steep decrease during the first five to seven years, the decline in the reservoir net CO₂ sink/source balance will decelerate and the fluxes will stabilize after twelve to fifteen years, around a threshold level of about 435 (+140/−120) mg C m⁻² d⁻¹ (Figure 3c). This level is somewhat lower than that projected only from the initial four years (approx. 40% lower) but still two orders of magnitude higher than the integrated emissions of the pre-flooded ecosystem that we estimated for this boreal region (assuming that the terrestrial exchange would not have changed in time). Even though there is a large degree of uncertainty associated with the method assumptions, this approach, which also consider the evolution in time of C emissions in other (older) reservoirs in the region, adds extra level of confidence to the overall long-term projection. Most certainty, it is therefore safe to assume that this trajectory resemble better the true situation rather than would have been if directly extrapolated from our initial four years alone.

[44] In the case of CH₄, we based our projections of net CH₄ sink/source balance from Eastmain-1 on pCH₄-derived fluxes from older reservoirs in the region with ages between five to eighty years (average twenty years). The results indicate a range variability of gross lower fluxes between 1.7 and 37.5 mg C m⁻² d⁻¹. In the absence of any significant correlation with the reservoir age, an average gross lower flux of 8.4 mg C m⁻² d⁻¹ was considered representative for all older reservoirs (Figure 3d, yellow star). Following the same steps described above for CO₂ fluxes, the exercise suggests that after an initial exponential increase characteristic of the first six to seven years, reservoir net CH₄ emissions would reach a plateau level of around 7.0 (+13.4/−7.1) mg C m⁻² d⁻¹ (equation 2) and Figure 3d). The resulting model is described by:

\[ NMF_{(CH₄)} = 6.97 − 6.72/\left[1 + \exp\left(\left(Age − 3.80\right)/0.46\right)\right], \quad R^2 = 0.99 \]  

where NMF_{(CH₄)} represents the net mean CH₄ flux in mg C m⁻² d⁻¹, and Age is the number of years after flooding. These results suggest that reservoirs continue to emit C (both CO₂ and CH₄) at a rate that exceeds that of the pre-flood ecosystem. The empirical modeling results presented here represent a first attempt at projecting the long-term net C emissions resulting from the creation of a hydroelectric reservoir. We are currently developing a process-based model that incorporates, among other factors, climate effects over the lifetime of the reservoir that should allow us to confirm
1. Contributing approximately 10%. Although there is still Tremblay et al. Rosenberg et al. and CH in 2006 and C emissions per in 2007 (Figure 4a), using the curve in 2009, which are 20% and 40%, respectively, below the NGCC level (Figure 4a). Our projections for the following years suggest that these emissions will continue to decline over the next ten to fifteen years, likely reaching an asymptote around an average value of around 40 t C-CO$_2$ eq GWh$^{-1}$ (Figure 4a), but the exact pattern of decline has yet to be determined. Extrapolating these trends over the life span of the reservoir (100 years) results in a long-term average net C emission per energy generation in the range of 43 t C-CO$_2$ eq GWh$^{-1}$, with CH$_4$ contributing approximately 10%. Although there is still much uncertainty in these long-term estimates, the upper and lower bands that we propose (64 and 28 t C-CO$_2$ eq GWh$^{-1}$, Figure 4a), represent extreme scenarios so that emissions are likely to be within this bracket.

2. These calculations also raise the question as to the sources of carbon sustaining the projected higher emissions relative to the pre-flood conditions over such long-term. Whereas there is consensus that the initial post-flood upsurge in CO$_2$ and CH$_4$ emissions is the result of the decomposition of labile plant and soil organic matter [Bodaly et al., 2004; Galy Lacaux et al., 1997; Rosenberg et al., 1997], the processes that sustain the long term are less clear and need further exploration. For instance, if the elevated rates are sustained largely by the slow degradation of the flooded soil material, then it is rightly assigned as a consequence of the reservoir creation. If, on the other hand, it is mostly sustained by the biological and photo-chemical mineralization of allochthonous carbon inputs (enhanced because of the longer water residence time of the reservoir) that would have otherwise occurred elsewhere downstream, then it is arguable whether these emissions can be rightfully attributed to the creation of the impoundment or should instead simply viewed as a geographical displacement of these natural emissions. This point is seldom addressed in the current literature on long-term emissions from man-made impoundments but is critical to the proper assessment of human-induced changes to the landscape. We are unable to project empirically the relative importance of these two processes or how it will change over the long-term, but back-of-the-envelope calculations based on an average apparent mass transfer coefficient of 3.2 m yr$^{-1}$ for DOC [Dillon and Molot, 1997] suggests that only 10–20% of the projected long-term C emissions from the Eastmain reservoir can be attributed to natural but displaced emissions. A process-based model is currently under development to further address such question (N. T. Roulet et al., manuscript in preparation, 2012).

3. Net C Emissions per Energy Generation

3.4. Net C Emissions per Energy Generation

The net C footprint of this boreal reservoir discussed in previous sections translates into net C emissions per energy generation of 183 t C-CO$_2$ eq GWh$^{-1}$ in 2006 and 119 t C-CO$_2$ eq GWh$^{-1}$ in 2007 (Figure 4a), using the currently installed capacity of 2.7 TWh$^{-1}$. Those rates are about 77% and 15% higher, respectively, than the equivalent emissions of around 104 t C-CO$_2$ eq GWh$^{-1}$ of the most efficient thermal power plants using a natural-gas combined-cycle (NGCC) [Spath and Mann, 2000; Tremblay et al., 2005b]. These high initial emissions declined steeply over the following years to 84 t C-CO$_2$ eq GWh$^{-1}$ in 2008 and 65 t C-CO$_2$ eq GWh$^{-1}$ in 2009, which are 20% and 40%, respectively, below the NGCC level (Figure 4a). Our projections for the following years suggest that these emissions will continue to decline over the next ten to fifteen years, likely reaching an asymptote around an average value of around 40 t C-CO$_2$ eq GWh$^{-1}$ (Figure 4a), but the exact pattern of decline has yet to be determined. Extrapolating these trends over the life span of the reservoir (100 years) results in a long-term average net C emission per energy generation in the range of 43 t C-CO$_2$ eq GWh$^{-1}$, with CH$_4$ contributing approximately 10%. Although there is still much uncertainty in these long-term estimates, the upper and lower bands that we propose (64 and 28 t C-CO$_2$ eq GWh$^{-1}$, Figure 4a), represent extreme scenarios so that emissions are likely to be within this bracket.

While the above results suggest how the annual net emissions per energy production vary through time, for a more direct comparison of energy production alternatives it is more relevant to express how the cumulative C emissions per unit electricity generation vary throughout the lifespan of the reservoir. According to our calculations and models, it will take over five years (and not only two years as indicated by Figure 4a) before the integrated emissions fall below the threshold level of the most efficient thermal power plant (Figure 4b).
Furthermore, the comparison of C emissions for different types of energy generation is dependent on the time scale considered. For instance, while during the first year, the Eastmain-1 reservoir was emitting up to 77% more C than NGCC, after only 5 years, the emissions were at par with NGCC, and after 25 years, reservoir emissions will be 50% lower than those of NGCC (Figure 4b). These projections suggest that over its entire projected lifespan (100 years), the Eastmain-1 reservoir will emit the equivalent of 40% (11,700 × 10^3 t C-CO\(_2\)-eq) of the C emissions that the currently most efficient thermal power plant would have for an equivalent amount of energy production (NGCC: 28,000 × 10^3 t C-CO\(_2\)-eq) [Tremblay et al., 2005b] (Figure 4b).

These estimated C emissions related to energy generation that we present here are by no means fixed or invariant. In addition to variations related to natural climate and hydrology, these net emissions are also likely to vary with the actual management and operation of the reservoir. For example, an additional power station (Eastmain-1A) is planned to go online in 2012, which will add approximately 768 MW of capacity to the currently installed 485 MW. Assuming an equivalent operation efficiency to that of the current power house (approximately 63%), this would generate an additional 4.2 TWh to the current 2.7 TWh, which will be fueled by the diversion of another large river (Rupert River) into the existing Eastmain-1 reservoir. Assuming that such changes in hydrological regime and in the surrounding landscape will not alter the basic C sink/source balance of the reservoir, this increased power generating capacity could result in long-term GHG emissions in the order of 17 t C-CO\(_2\)-eq GWh\(^{-1}\), as opposed to the 43 t C-CO\(_2\)-eq GWh\(^{-1}\), in the current scenario described above. This represents a very significant increase in generation efficiency of the reservoir in terms of C emissions, but the C sink/source balance of the reservoir and the affected surrounding landscape must be revisited once the water diversion has been finalized, to assess potential deviations from the basic budget proposed here.

Regardless of the scenario considered, the long-term net C emissions from the Eastmain-1 reservoir are projected to be well below the emissions of the NGCC and all other current fossil-fuel based technologies, for similar amounts of energy produced. The results that we present here are specific for this particular flooded basin, but are likely to roughly represent reservoirs across the circumboreal region, which share many of the features of Eastmain-1 [Barros et al., 2011]; our results, however, should not be extrapolated to reservoirs in non-boreal regions. In the case of the Eastmain-1 reservoir, net C emissions are mostly as CO\(_2\), with CH\(_4\) contributing very little, as is the case for most northern reservoirs [Tremblay et al., 2005b]. There are two main reasons for this: 1) These boreal reservoirs tend to be relatively shallow and well mixed, and also on average colder, and thus do not develop extensive or permanent bottom anoxia that could generate greater CH\(_4\) fluxes [Tremblay et al., 2005a]; 2) The boreal landscape itself has significant coverage of peatbogs and other wetlands, which naturally generate significant fluxes of CH\(_4\), so flooding may actually reduce the overall CH\(_4\) emissions from the landscape and not increase them. In contrast, in tropical and subtropical reservoirs, CH\(_4\) is proportionately much more important, because the combination of basin morphometry and climate lead to extensive anoxia and often extremely high CH\(_4\) emissions [Galy Lacaux et al., 1997; Abril et al., 2005; Tremblay et al., 2005a].

We conclude that the creation of this boreal reservoir resulted in a significant shift in the C sink/source balance of the landscape that was flooded, with initially high net C emissions to the atmosphere, mostly as CO\(_2\), directly attributable to the reservoir itself. We have also shown that the effect of this reservoir is highly dynamic in time, with net reservoir emissions rapidly declining in the years following flooding, but our projections suggest that these C emissions will tend to stabilize at values that are nevertheless higher than those from the surrounding landscape. Calculations of C emissions associated with hydroelectric energy production must take these long-term dynamics into consideration. We have further shown that in this particular landscape, the integrated (terrestrial + wetland + aquatic) pre-flood net C exchange with the atmosphere was small, relative to the reservoir fluxes that were measured during the first four years after flooding, so subtraction of this baseline had a relatively minor influence on the apparent reservoir net fluxes. However, this may not be the case for all types of landscapes, and certainly not the case for the Eastmain-1 reservoir at longer time scales once the initial pulse subsides. For example, whereas flooding results in the loss of terrestrial primary production (therefore loss of a potential sink) and to conditions that may favor increased decomposition of soil organic C (therefore increase C flux to the atmosphere), it also impedes logging and fire, which are major structuring forces in the boreal biome [Lecomte et al., 2006], and thus lessens a major regional sink/source of atmospheric C [Amiro et al., 2009]. Long-term shifts in fire regime [Bergeron et al., 2004], and thus in the regional terrestrial and peatland C exchange as well as changes in the general forest management practices could significantly shift the frame of reference and thus alter the apparent reservoir impact. The results of this project thus highlight the importance of understanding the C exchanges of the natural landscapes prior to flooding, and understanding the actual C balance and the long-term dynamics of the reservoir itself, when determining the net C footprint of hydroelectric reservoirs.

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