Uncovering the minor contribution of land-cover change in upland forests to the net carbon footprint of a boreal hydroelectric reservoir

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Key abbreviations:

CBM-CFS3, Carbon budget model of Canadian Forest Service (third version); CD, carbon disturbance; CE, carbon equivalent; CO_2e, carbon dioxide equivalent; CS, carbon sink; CWFIS, Canadian Wildland Fire Information System; D, decay; DOM, dead organic matter; GHG, greenhouse gas; HQ, Hydro-Québec; IPCC, Intergovernmental Panel on Climate Change; KP, Kyoto Protocol; LUCC, Land use and cover change; MRN, Ministère des ressources naturelles; NBP, net biome productivity; NEP, net ecosystem productivity; NPP, net primary productivity.

ABSTRACT

Hydropower in boreal conditions is generally considered the energy source emitting the least greenhouse gas per kWh during its life cycle. The purpose of this study was to assess the relative contribution of the land-use change on the modification of the carbon sinks/sources following the flooding of upland forested territories to create the Eastmain-1 hydroelectric reservoir, in Quebec's boreal forest using Carbon Budget Model of the Canadian Forest Sector (CBM CFS3). Results suggest a carbon sink loss after 100 years of 300 000 ± 100 000 Mg CO_2e. A wild fire sensitivity analysis revealed that the ecosystem would have acted as a carbon sink as long as < 75 % of the territory had burned over the 100 year-long period. Our long-term net carbon flux estimations resulted in emissions of 4 ± 2 g CO_2e kWh^{-1} as a contribution to the carbon footprint calculation, eight times less than what was obtained in a recent study (Teodoru et al., 2012) that used less precise and sensitive estimates. Consequently, this study significantly reduces the reported net carbon footprint of this reservoir, and reveals how negligible the relative contribution of the land-use change in upland forests to the total net carbon footprint of a hydroelectric reservoir in the boreal zone can be.

1. Introduction

With its 62 hydroelectric power plant and its production capacity of 36.5 GW (Hydro Québec, 2015), Hydro-Québec (HQ) is one of the most important electricity producers in North-Eastern America. HQ claims that its hydro-electricity is among the lowest C-intensive technologies worldwide. However, assessing the carbon (C) footprint of a given unit of electricity needs a complete life cycle analysis of emissions/sinks of greenhouse gases. In 2002, HQ, reported a secondary data-based C footprint of the full energy chain associated with the Eastmain-1 hydroelectric plant to other types of electricity generation (Tremblay et al., 2005). The data showed that with emissions of approx. 15 t CO_2e GWh^{-1} over 100 years for average boreal reservoirs (and up to 33 t CO_2e GWh^{-1} for the larger La Grande Complexe), boreal hydroelectricity is largely advantageous over others. However, this report (Tremblay et al., 2005) took only into account the gross GHG emissions created by a reservoir, i.e., without the variation in C fluxes associated with the land-use change caused by the flooding of a large forested territory to create the reservoir (IPCC, 2003), as required by the Kyoto Protocol (KP) (UNFCCC, 1998).

More recently, Teodoru et al. (2012) used direct observations, new modeling approaches and data from the literature to estimate reservoir net emissions, including an estimation of the loss of C sink to complete the net C footprint of the newly created Eastmain-1 reservoir. They assessed the loss of C sink from flooded upland forests to be 32 t CO_2e GWh^{-1} (range of 76 to –11 t CO_2e GWh^{-1}) or 20% of the overall and long-term (100 year) C footprint of the reservoir (158 t CO_2e GWh^{-1}) (Teodoru et al., 2012). Though their approach provided valuable and conservative results, a more detailed and sensitive methodology is deemed necessary to mitigate the uncertainty around the upland forest land-use cover change (LUCC) estimated impact on the net GHG emissions of hydroelectric reservoirs. This is particularly relevant given the importance of this energetic issue in North America – where the C footprint of different types of energy production is increasingly becoming strategic (Edenhofer et al., 2011) and considering that natural upland forests account for approx. 49% of the flooded territory and 20% of the net C fluxes calculated in Teodoru et al. (2012).

In Canada and elsewhere around the world, the Carbon Budget Model of the Canadian Forest Sector 3 (CBM-CFS3) (Kurz et al., 2009) is used to simulate the dynamics of forest C stocks as required under the KP (IPCC, 2003). CBM-CFS3 is an aspatial, stand and landscape-level modeling framework used to simulate the dynamics of all forest C stocks required under the Kyoto Protocol, and is compliant with the C estimation methods outlined in the IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry report (2003). This model uses information from forest inventories, growth and yield tables, natural disturbances and stand regeneration dynamics to estimate upland forest C fluxes and stocks. Hence, this model can be used to estimate the LUCC portion of the C footprint for different forest management scenarios, natural disturbances and changes in land use, like flooding for the creation of a water reservoir (Kurz et al., 2009).

Natural disturbances are the first cause of GHG emissions in managed forests of Canada by changing C accumulation in the affected areas (Carlson et al., 2010 and Chertov et al., 2009). In Canada, forest fires were assessed to be responsible for the emission of 2.7 Tg of C between 1959–1999, and annual burned forest area is expected to increase by 74–118 % by the end of the century (Amiro et al., 2001 and Flannigan et al., 2005). Hence, taking into account fire cycle – defined as the time needed to burn an area equivalent to a given territory (Bergeron et al., 2001) – is essential to adequately simulate C stock evolution over a large territory and long period of time as they are known to vary spatiotemporally and to be influenced by anthropic activities (forest management, fire control and recreational use) (Bergeron et al., 2001 and 2010, Lauzon et al., 2006 and Le Goff et al., 2009). The Eastmain-1 hydroelectric reservoir area had an estimated fire cycle varying between 132-153 years over the last century (burning rate of 0.65 to 0.76 % per year), and the annual burned area could increase by 7 % by 2100 (Le Goff et al., 2007). Other fire cycle studies covering extended territories, but always including the Eastmain river watershed, revealed that during the last century fire cycles varied from 191 to 325 years (Bergeron et al., 2001). As fire cycles vary greatly it makes any flooded upland forest C balance prediction difficult, thereby demonstrating the necessity to use sensitivity analyses while integrating wild fire risk in the C footprint calculation of the upland forest part of an hydroelectric reservoir.

In this study, the absence of the reservoir, and thus the natural dynamic of the upland forest ecosystems, constitutes the baseline scenario, while the reservoir creation and the resulting forested land flooding (with the concomitant loss of C fluxes from the forested lands) will be considered as the project scenario, *sensu* ISO 14064-2 (ISO, 2006) and in accordance with the same two scenarios in Teodoru et al. (2012). The objective of this study is therefore to estimate the net C balance of the flooded upland forest for the creation of the Eastmain-1 reservoir (see Figure 1) over a period of 100 years, using fire cycles data, forest inventory derived from photo interpretation and model simulations with CBM-CFS3, and then to translate this net C balance – the project scenario minus the baseline scenario, i.e., C fluxes with and without the reservoir – in terms of C footprint in CO_2e per kWh for the life expectancy of the installation. For the baseline scenario, sensitivity analyses are performed to evaluate the impact of different fire regimes, forest productivity and regeneration patterns following disturbance on the C balance of the unflooded upland forest territory. It is expected that the land use cover change caused by the flooding of the upland forest territories induces a net loss of C sink, as the forest at the moment it was flooded would have sequestered more C then it would have emitted despite fire disturbances. Other C sources resulting from the reservoir creation, i.e. the major C gas (CO_2 and CH_4) sources and sinks of the terrestrial (other than upland forests) and aquatic components of the pre- and post-flood landscape are not considered since they were thoroughly covered in Teodoru et al. (2012). A concomitant objective is to provide for the first time a detailed estimation of the relative contribution of the upland forest C sink/source change to the net C footprint of a newly flooded boreal hydroelectric reservoir.

2. Methods

2.1. Description of the study area

The study site is located in the Eastmain river watershed (50°59’50’’N and 76°02’28’’W; (Figure 2) which lies at the transition of two bioclimatic domains of the boreal zone in Québec, spruce-moss to the south and spruce-lichen to the north (Saucier, 2009). Annual average temperatures vary between 0 and -2.5º C, with 600 to 1000 mm of annual precipitation (for more details on the study site biophysical characteristics see Teodoru et al. (2012).

In 2003, a vast territory of 59 100 ha, of which 43 161 ha (73 %) were upland forested areas, was used to create the Eastmain-1 hydroelectric plant reservoir. The plant has three turbine-groups of a 485 MW power with a mean annual production of 2.7 TWh (Teodoru et al., 2012). In 2012, Hydro-Québec added approximately 768 MW of capacity by the diversion of the large Rupert river into the existing Eastmain-1 reservoir to the previous 485 MW, without any significant change to the initial reservoir area. The flooded areas also encompassed lakes, streams and rivers (~15 %), and wetlands (~12 %) (Teodoru et al., 2012), but the present model simulations focused exclusively on upland forests, for which CBM-CFS3 is fully parameterized (Kurz et al., 2009). Simulations were performed for the 43 161 ha (73%) of flooded forested areas to estimate C balance.

A forest inventory of this area was made using 253 aerial photos (1: 20 000) taken in 1999 before the area was flooded. From these photos, species, age class, tree density and mean tree height were photointerpreted for each distinct forest stand and recent disturbances noted. The 253 aerial photos and the 2 700 resulting stands were then scanned and georeferenced [NAD_1983_UTM_Zone_9N] and Arc GIS 9.0 [ESRI, Redland, USA, 2006] was used to determine their corresponding surface area.

The flooded territory was dominated by six species: black spruce (*Picea mariana* Mill.), jack pine (*Pinus banksiana* Lamb.), tamarack (*Larix laricina* (Du Roi) K. Koch), balsam fir (*Abies balsamea* (L.) Mill.), paper birch (*Betula papyrifera* Marsh) and trembling aspen (*Populus tremuloïdes* Michx). Black spruce covered 50 % of the territory, jack pine 35 % and 23 % of the area was in regeneration, i.e., stands were between 0–30 years old.

Stands with similar species, densities and ages were pooled so the initial 2700 stands resulted into 231 different groups of stands in order to simplify the model simulation. Growth and yield tables of corresponding stand types within the allowable cut territory (MRN, 2000) – less than 100 km southward and corresponding to the nearest region where comparable production data were available – were then used as CBM-CFS3 inputs.

2.2. Simulations

The C balance simulations were performed using the standard importation tool of the CBM-CFS3 (v. 1.2 beta) developed by the Canadian Forest Service (Kurz et al., 2009). This model simulates the dynamic of forest C stocks and complies with the approved methods of C stock estimations by the Intergovernmental Panel on Climate Change (IPCC) (Solomon et al., 2007). The model was feed with growth and yield tables according to forest inventory data (i.e. disturbance, species, age, area, stem density) (MRN, 2000). The absence of the reservoir, and thus the natural dynamic of the upland forest ecosystems, constitutes the baseline scenario, while the reservoir creation and the resulting forested land flooding (with the concomitant loss of C fluxes from the forested lands) will be considered as the project scenario, *sensu* ISO 14064-2 (ISO, 2006) and in accordance with the same two scenarios in Teodoru et al. (2012).

Simulations were carried out over a 100 year period in the Eastern Boreal Shield ecozone with CBM-CFS3 default soil parameters of this area. We used Bergeron et al. (2010) 0.45% annual burning rate to simulate a 222 year-long fire cycle (baseline scenario), as the flooded territory was included in their field study. This fire cycle was chosen because it represents a projection for the next 100 years. A fire pattern emulating natural variability was created using data from the Large Fire Database (LFDB) from Natural Resources Canada (1959–1999) (CWIFS, 2012). These data were extracted for a 10000 km^2 area centered over the Eastmain-1 reservoir. The 40 year fire sequence extracted from the database (1959–1999) was repeated 2.5 times to obtain a 100 year sequence and the result was then standardized to correspond to 45 % of burned area after a 100 year modeling, in order to relate to a fire cycle of 222 years (Bergeron et al., 2010). The model used did not account for multiple fires in the same area, so each hectare could only burn once during the 100 years modeling. Regeneration delay was set to begin the year following the fire disturbance without any modification to the forest inventory other than age class which was zeroed after a fire event. Stand composition transition was not taken into account as it had a negligible effect on C stocking. This pattern of fire variability was used in all simulations and resulted in 0–7% of yearly burned land in the study area (see Figure S1a in the Supporting Information).

2.3. Sensitivity analyses

Different factors were tested for their effects on the model output variability. Volume yield, fire cycle and stand composition following wild fire have been tested in sensitivity analyses.

Sensitivity analyses on volume yield were performed to evaluate the variability created by the simulations over a long period. Three simulations with different volume yields: original, original plus 20 %, original minus 20 % were carried out while fire cycle was kept constant at 222 years.

Different fire cycles were also used to ascertain the gain and losses in C stocks due to the uncertainty on the 222 year cycle (Bergeron et al., 2010) established for this area, and to estimate volume yields if the territory did not burn. The following scenarios were modeled: 1- no disturbance, 2- 313 year fire cycle (fire affects 32 % of the territory after 100 years), 3- 222 years (fire affects 45 % of the territory after 100 years), and 4- 170 years (fire affects 59 % of the territory after 100 years) (Bergeron et al., 2010). An additional analysis was conducted with a 127 year fire cycle (fires affects 79 % of the territory after 100 years), inferred from the photo interpretation performed for this study. This last scenario represents an instantaneous picture of the study area; however, it does not correspond to a science based fire cycle and should be considered as an extreme case in our range of tested scenarios.

Sensitivity analyses on stand regeneration were also performed to monitor the possible effects of a lack of regeneration with certain species and/or species switch following a fire event. See the Supporting Information for details on post-fire regeneration patterns tested.

2.4. Net biome productivity

Net biome productivity (NBP) of the flooded territory was calculated using these formulas:

$NEP = NPP + DOM_D$ (1)

$NBP = NEP + CD$ (2)

Where NEP is the sum of annual net primary productivity (NPP) and annual decay of dead organic matter (DOM_D), and NBP is the sum of the annual net ecosystem productivity (NEP) and the annual loss from C disturbance (CD), which includes any simulated disturbance affecting C stock, primarily fire.

2.5. Carbon sink/source per GWh

Tons of C equivalent (CE) obtained from the calculations of NBP were transformed into tons of C dioxide equivalent (CO_2e) using the formula CO_2e = CE * 3.67.

To calculate the C sink/source per GWh, overall upland C flux (in CO_2e) was divided by the Eastmain hydroelectric plant average annual production (2.7 TWh) and multiplied by the 100 years life expectancy of a hydroelectric plant in the boreal forest. The C sink/source per GWh was then calculated using Equation 3 (Tremblay et al., 2005):

$CS_{GWh} = NBP_{cumul} \times \mathbf{3.67}/(\mathbf{P} \times \mathbf{100})$ (3)

Where:

CS_{GWh} = Carbon sink/source per GWh (Mg CO_2 e GWh^{-1})

NBP_{cumul} = Cumulated NBP (Mg CO_2 e)

P = GWh produced per year at the Eastmain plant (GWh y^{-1})

100 = Life expectancy of an hydroelectric plant in the boreal zone (in years)

3. RESULTS

3.1. Initial carbon stocks

Dead organic matter represented up to 81% of the total upland forest C stocks (5 751 069 Mg), compared to 19 % for the biomass (Table 1). In total, C stock density was 133 Mg C ha^{-1} for all the C pools with 108 Mg C ha^{-1} in the dead organic matter pools.

3.2. Evolution of stand age

Average stand age went from 59 to 111-year-old during the simulated period with small variations corresponding to fire events (Figure S2 in the Supporting Information). Without wildfires scenario, stands would have reached 159 years on average.

3.3. Carbon flux and stock variations

During the years with fires burning large territories, emissions almost reached 40 000 Mg C $year^{-1}$ for the 43 161 ha flooded territory, or 0.9 Mg C ha^{-1} y^{-1}. In addition, C emissions increased over time as C stocks (biomass and dead organic matter) increased with stand age. On average, forest fires (C Disturbance) accounted for emissions of 0.08 (0.00/0.90) Mg C ha^{-1} y^{-1} (Table 2). Net primary production (NPP) of the flooded forest varied between 80 000 to 100 000 Mg C $year^{-1}$ and tended to increase slightly with time, but halted after 90 years of simulation. It also leveled off during the years of important fires, as the latter strongly affected age class structure of the territory. Overall, mean annual NPP was 2.12 (2.28/1.86) Mg C ha^{-1} $year^{-1}$ (Table 2). The simulated forest built up from 60 000 to 90 000 Mg C $year^{-1}$ in dead organic matter and this accumulation rate tended to increase over time. Overall, dead organic matter accumulation rate increased to a mean rate of 1.90 (1.51/2.15) Mg C ha^{-1} $year^{-1}$ (Table 2). Decomposition rate of organic matter increased over the years and varied from 78 000 to 90 000 Mg C $year^{-1}$ corresponding to emissions of 1.97 (1.81/2.09) Mg C ha^{-1} $year^{-1}$ (Table 2), with the lowest values during the years where burnt areas were large. Net ecosystem production (NEP) increased until year 35 then sharply declined with significant variations (in accordance with fire occurrence and extent) for thirty years. After year 65, the NEP tended to decrease with little variation caused by forest fires. The general trend was to decrease, but the mean NEP was 0.15 (-0.01/0.32) Mg C ha^{-1} y^{-1} (Table 2).

Net biome production followed the pattern of fire and NEP. Annual Net biome productivity was on average 0.07 (-0.89/0.32) Mg C ha^{-1} $year^{-1}$ (Table 2).

Cumulated NBP over the course of the 100 years simulation period (Figure 3a) showed the same leveling off around 90 years, in accordance with forest fires as in the other figures (Figure 3b, c, d). After 100 years the flooded forest would have sequestered 303 489 Mg C or 7 Mg C ha^{-1}.

3.4. Sensitivity tests

3.4.1. Yield tables variations

C gains (cumulative NBP) over the 100 years simulated varied between 270 251 to 326 463 Mg C when modifying the wood volume yield by ± 20% (Figure 3b), which corresponds to -11% to +8% compared to cumulated NBP with the volume yield used in the basic assumption.

3.4.2. Fire cycle variations

After 100 years, average stand age varied markedly according to the fire cycle, going from 74 years for a 127 year fire cycle to 125 years for a 313 year fire cycle (see Figure S2 in the Supporting Information). Shorter fire cycle resulted in less C sequestration (Figure 3c). Using the confidence intervals suggested in Bergeron et al. (Bergeron et al. 2010), C gains varied from 164 232 Mg C (170 year fire cycle) to 433 251 Mg C (313 year fire cycle), which correspond to variations of -46% and +43% of the NBP with the 222 year fire cycle used for the basic assumption. In the absence of fires over the course of 100 years, C sequestered would have been 738 318 Mg C. On the other hand, if fire frequencies remained as observed on the pre-flooded territory in the last 100 years (127 year cycle with 79% of the territory burned), the flooded forest would have been a net source of C over 100 years, with emission of 34 378 Mg C. The threshold for capture/emission balance was 75 % of burned territory; above that the territory became a net source.

3.4.3. Regeneration variations

The eleven stand regeneration hypotheses tested had a slight impact on cumulated net biome productivity (Figure 3d), with an increase of 7% from the basic assumption, to reach 325 042 Mg C.

3.5. Carbon sink/source per GWh

As per equation 2, the C footprint associated with land-use change for the Eastmain-1 flooded forested territory corresponds to a total C sink loss of 303 489 Mg C after 100 years. Expressed as a C sink loss per unit of produced energy based on equation 3, it corresponds to a C footprint of 4 ± 2 t CO_2 eq. GWh^{-1}. The uncertainty (± 2 t CO_2 eq. GWh^{-1}) corresponds to the confidence interval (170-313 years) proposed by Bergeron et al. (2010) for fire cycles.

$$CS_{GWh} = 303\,489\ Mg\ C \times \mathbf{3.67}/(\mathbf{2700\ GWh} \times \mathbf{100\ years}) = 4.1\ Mg\ CO2\ eq.GWh^{-1}$$

4. DISCUSSION

4.1. Pre-flooding carbon stocks evaluation

Estimated pre-flooding C stocks using CBM-CFS3 are similar to those obtained by Paré et al. (2011) on a small selection of stands from nearby sites which shows that the selection of growth and yield table to feed the model were adequate. Dead organic matter (DOM) C stocks in the simulation were 108 Mg C ha^{-1}, 29 Mg C ha^{-1} higher than that of field measurements in Paré et al. (2011). However, annual rates of litter accumulation are similar: first year of simulation with 1.5 Mg C ha^{-1} $year^{-1}$ (mean stand age 59 years) compared to observed 1.4 ± 0.2 Mg C ha^{-1} an^{-1} (mean stand age 41 years) in Paré et al. (2011) suggesting that the decay rate observed in the field is faster than what the model uses. Using the latter result and projecting it at a mean stand age of 59 years, we obtain a potential increase of accumulated litter of 25 ± 4 Mg C ha^{-1}, and total C stocks of 104 ± 4 Mg C ha^{-1}. Our simulated density of DOM is also near the range of 75 to 100 Mg C ha^{-1} predicted in Tremblay et al. (2005) for the same area (see Figure 4 therein) once again suggesting that the model behave adequately and that the growth and yield table selection were appropriate.

According to our simulations of the flooded territory, 19 % of the C stock was in the biomass. These results are within the 14 % to 33 % of C stocks in the biomass found in field-based observations from the literature for the boreal forest (Bergeron et al., 2007 and Moroni et al., 2010).

4.2. Carbon fluxes and stocks

The estimated net primary productivity (NPP) of 2.12 (2.28/1.86) Mg C ha^{-1} y^{-1} does not always concur with field observations in the literature. A study on the semi-arid boreal forest, using data from circumpolar flux towers, obtained a mean NPP of 3.3 ± 0.6 Mg C ha^{-1} y^{-1} (Bergeron et al., 2007). Another study, near Chibougamau, Québec (approx. 300 km south-east from the study area) estimated that a 91-year-old black spruce stand had a NPP of 5.84 ± 0.07 Mg C ha^{-1} y^{-1} (Luyssaert et al., 2007). Differences in stand age and low productivity (low site index) of the study area can explain this variation in NPP. It has also been shown that the CBM-CFS3 model may underestimate biomass net growth by 10 % (Bernier et al., 2009), which may explain some of the difference in NPP observed between our study and that of Bergeron et al. (2007).

The estimated net ecosystem productivity (NEP) value of our study of 0.15 (-0.01/0.32) Mg C ha^{-1} y^{-1} contributes to a large array of values from the literature reporting NEP in boreal ecosystems: from -2.5 to 2.0 Mg C ha^{-1} y^{-1} (Amiro et al., 2010, Bergeron et al., 2007 and Luyssaert et al., 2007). The values vary mostly with the methodology used, growth conditions, occurrence of disturbances and stand age. Simulated decomposition (DOM_D) emissions of 1.97 (1.81/2.09) Mg C ha^{-1} y^{-1} was lower than reported field observations for the same type of forest, with 2.5 ± 0.3 Mg C ha^{-1} y^{-1} or 5.8 ± 0.1 Mg C ha^{-1} y^{-1} (Bergeron et al., 2007 and Luyssaert et al., 2007). The fact that these latter stands are located in the central part of Québec’s boreal forest, warmer and more productive than those near the Eastmain reservoir, might explain much of this difference in heterotrophic decomposition.

To our knowledge, it is the first time that simulated values of forest C fluxes (NPP, NEP and HR) and stocks are provided to such a northerly region of the boreal forest.

4.3. Sensitivity tests

Of the three factors tested for their effects on the model (volume yields, fire cycles and stand regeneration), fire cycles was by far the most influential with a +43 % to -46 % variation in NBP; to keep the model conservative, the confidence interval around the calculated NBP was set according to that of the 222 year fire cycle range. In the absence of any fires during the 100 year life expectancy of the power plant (unrealistic scenario), the flooded territory would have accumulated 738 318 Mg C, or 0.17 Mg C ha^{-1} y^{-1} (corresponding to 10 Mg CO_2 éq GWh^{-1}) which is somewhat similar to the net ecosystem productivity suggested in the literature for more productive boreal ecosystems (Amiro et al. 2010, Bergeron et al. 2007 and Luyssaert et al. 2007). Conversely, simulating the observed shorter fire cycle of the flooded area over the next hundred years resulted in a modelled territory that would be a net source of emissions (-34 378 Mg C or -0.5 Mg CO_2 eq GWh^{-1}) instead of a net sink. In other words, in the case of a 127 year-long fire cycle scenario, the creation of the reservoir resulted in fewer emissions than the natural forest (without anthropogenic disturbance). The simulation without any fire pattern, whereby the percentage of burned territory remained the same year after year, only reduced the NPB by 5 000 Mg C, indicating that fire pattern is not an issues in this simulation. Hence, the submerged territory was possibly a net source during the century before the flooding, given the observed 127 year fire cycle. Using the 222 year fire cycle from Bergeron et al. (2010) as a conservative measure in this C footprint calculation, we estimated that this territory would have sequestered a net 300 000 Mg C after 100 years, with a ± 150 000 Mg C range, which corresponds to 4 ± 2 Mg CO_2 éq GWh^{-1}. To sum up, this modeling approach has shown how crucial it is to include fire disturbance dynamics in models for the boreal zone, as it is the principal source of variability and a major cause for concern given the expected impacts of climate change on fire cycle regime in this area (Le Goff et al., 2009).

4.4. Forest inventory and yield tables

The upland forest inventory used in this study (from pre-flooding aerial photographs taken in 1999), yielded C stocking results comparable to a field inventory on a nearby site (Paré et al., 2011), which further warrants the reliability of our simulations.

Volume yield estimates were obtained from growth and yield tables southward of the study area, which could have led to an overestimation of C stocking. However, sensitivity tests performed on volume yield tables showed that ± a 20 % variation created much less fluctuation than fire cycles (Figure 3d vs. 3c), which was then chosen as the range for the confidence interval of the model output, consequently including all the possible variation pertaining to the volume yield tables and to the photo interpreted forest inventory. Stand age class used (0, 30, 50, 70, 90 and 120+ years) could also be a source of error, with mean age obtained by photo interpretation of 59 years as opposed to the 41 years measured in the field by Paré et al. (2011). Should average stand age be 41 years, wood volume from production tables would correspond to 20 m^3 ha^{-1} less than that in the model; again, this is well within +43 % to -46 % range applied to the model outputs, given the variability induced by fire cycles.

4.5. Carbon sink/source per unit of electricity produced

The 73% forested territory in this study was permanently transformed into a hydroelectric reservoir, corresponding to a change in land use according to the IPCC (Solomon et al., 2007). Hence, this impact should be included in the C footprint of the production of 1 kWh by Hydro-Québec, following the ISO 14 067 guidelines (ISO/DIS 14067, 2013). The estimated C balance associated with the upland forest cover change of the Eastmain-1 flooded territory correspond to emissions (or a loss of C sink) of 4 ± 2 Mg CO_2e GWh^{-1}. This is 8 times less than the ≈32 Mg CO_2e GWh^{-1} estimated from Teodoru et al. (2012), but remains within the wide range they reported, i.e. a C sink of 76 Mg CO_2e GWh^{-1} to a source of 11 Mg CO_2e GWh^{-1}. They also estimated NEP to be 117 mg C m^2 d^{-1} with a range from 250 to -15 mg C m^{-2} d^{-1} (Teodoru et al., 2012). Their estimates of net ecosystem exchange are based on three years of sampling (2006-2009) with one Eddy covariance flux tower in black spruce closed canopy completed by available data in the literature. The emissions caused by forest fires were extracted from the literature with 21 mg C m^{-2} d^{-1} (ranging from 15 to 28 mg C m^{-2} d^{-1}). However, forest stands evolution over time and fire dynamics are not accounted for in their estimates. We believe that our methodology to evaluate the impact of upland forest cover change improves our ability to evaluate the GHG fluxes of upland forest of the flooded territories and better ascertain the C intensity of the Eastmain-1 hydroelectric plant. In 2012, electricity production from Eastmain-1a increased with the diversion of the Rupert River into the Eastmain reservoir. The hydroelectric plant now generates 6.9 TWh per year. When integrating the added energy produced since 2012 by the Eastmain-1A in our calculations, the loss of upland forest C sink per unit of energy becomes 1.6 ± 0.8 Mg CO_2e GWh^{-1}.

The resulting emission factor per unit of energy produced is a measure of the forest C sinks loss for the Eastmain-1 reservoir. Our methodology can be used for other reservoirs, given a certain number of adjustments to the model in accordance with local characteristics. Important local adjustments include the reservoir surface area, forest stand types, productivity and age structure, but principally, as shown in this study, the fire cycle. Forest can also be vastly affected by other important disturbances, such as insect infestation like the spruce budworm (Dymond et al., 2010). The eventual modelling of this biotic disturbance is of interest, as it would modify forest C fluxes differently.

5. Conclusion

In conclusion, the creation of the Eastmain-1 reservoir represents a loss of the upland forest C sink of 4 ± 2 Mg CO_2e per GWh of electricity produced, because of the upland forest cover change caused by the flooding. Our estimations substantially increase the precision of recent figures for the upland forest C sink/source fluxes of this hydroelectric reservoir using a Eddy covariance flux tower and data from the literature (Teodoru et al., 2012), resulting in a marked reduction of the upland forest cover change contribution to the net C footprint of this boreal hydroelectric reservoir. From 20% of the total C footprint calculated in Teodoru et al. (2012), our study scales down the upland forest contribution to the net C footprint of the reservoir to a mere 3%. Consequently, the long-term net C footprint of the Eastmain-1 hydroelectric reservoir would be 130 t CO_2e GWh^{-1} rather than 158 presented in Teodoru et al. (2012). This study also suggests that the relative contribution of land-use change to the C balance of the creation of a hydroelectric reservoir in the boreal zone can be considered minor, if not negligible, relative to the long-term net C footprint of such boreal hydroelectric reservoirs.

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References

Amiro, B.D., Barr, A.G., Barr, J.G., Black, T.A., Bracho, R., Brown, M., Chen, J., Clark, K.L., Davis, K.J., Desai, A.R., Dore, S., Engel, V., Fuentes, J.D., Goldstein, A.H., Goulden, M.L., Kolb, T.E., Lavigne, M.B., Law, B.E., Margolis, H.A., Martin, T., McCaughey, J.H., Misson, L., Montes-Helu, M., Noormets, A., Randerson, J.T., Starr, G., Xiao, J., 2010. Ecosystem carbon dioxide fluxes after disturbance in forests of North America. J. Geophys. Res. -Biogeosciences 115, 2005-2012.

Amiro, B.D., Stocks, B.J., Alexander, M.E., Flannigan, M.D., Wotton, B.M., 2001. Fire, climate change, carbon and fuel management in the Canadian boreal forest. Int. J. Wildland Fire 10, 405-413.

Bergeron, O., Margolis, H.A., Black, T.A., Coursolle, C., Dunn, A.L., Barr, A.G., Wofsy, S.C., 2007. Comparison of carbon dioxide fluxes over three boreal black spruce forests in Canada. Glob. Chang. Biol. 13, 89-107.

Bergeron, Y., Cyr, D., Girardin, M.P., Carcaillet, C., 2010. Will clilmate change drive 21st century burn rates in Canadian boreal forest outside of its natural variability: collating global climate model experiments with sedimentary charcoal data. Int. J. Wildland Fire 19, 1127-1139.

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P., Lesieur, D., 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. Can. J. Forest Res. 31, 384-391.

Bernier, P.Y., Guindon, L., Kurz, W.A., Stinson, G., 2009. Reconstructing and modelling 71-years of forest growth in a Canadian boreal landscape- a test of CBM-CFS3 carbon accounting model. Can. J. Forest Res. 40, 109-118.

Carlson, M., Chen, J., Elgie, S., Henschel, C., Montenegro, A., Roulet, N., Scott, N., Tarnocai, C., Wells, J., 2010. Maintaining the role of Canada's forests and peatlands in climate regulation. Forest. Chron. 86, 434-443.

Chertov, O., Bhatti, J.S., Komarov, A., Mikhailov, A., Bykhovets, S., 2009. Influence of climate change, fire and harvest on the carbon dynamics of black spruce in Central Canada. Forest Ecol. Manag. 257, 941-950.

CWIFS, 2012. Large Fires Data Base. Natural Resources Canada, Canada Government, Canada.

Dymond, C.C., Neilson, E.T., Stinston, G., Porter, K., MacLean, D., Gray, D., Campagna, M., Kurz, W.A., 2010. Future spruce budworm outbreak may create a carbon source in eastern Canadian Forest. Ecosystems 13, 917-931.

Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, D. Arvizu, T. Bruckner, J. Christensen, J.-M. Devernay, A. Faaij, M. Fischedick, B. Goldstein, G. Hansen, J. Huckerby, A. Jäger-Waldau, S. Kadner,

D. Kammen, V. Krey, A. Kumar, A. Lewis, O. Lucon, P. Matschoss, L. Maurice, C. Mitchell, W. Moomaw, J. Moreira, A. Nadai, L.J. Nilsson, J. Nyboer, A. Rahman, J. Sathaye, J. Sawin, R. Schaeffer, T. Schei, S. Schlömer, R. Sims, A. Verbruggen, C. von Stechow, K. Urama, R. Wiser, F. Yamba, T. Zwickel, 2011: Summary for Policy Makers. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. v. Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Flannigan, M.D., Logan, K.A., D., A.B., Skinner, W.R., Stocks, B.J., 2005. Future area burned in Canada. Clim. Chang. 72, 1-16.

Hydro Québec. 2015. Annual Report 2014. Hydro-Québec, Affaires corporatives et secrétariat General, Montréal (QC), Canada. ISBN 978-2-550-72312-7, 2014G27SF. 118 p.

ISO, 2006. Greenhouse gases–Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions of removal enhancements. ISO, Geneva, Switzerland.

ISO, 2013. ISO 14067 : Empreinte carbone des produits: exigences et lignes directrices pour la quantification et la communication, in: ISO (Ed.). International Standardisation Organisation Genève, Suisse.

Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J., Apps, M.J., 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol. Model. 220, 480-504.

Lauzon, E., Bergeron, Y., Gauthier, S., Kneeshaw, D., 2006. Fire Cycles and Forest Management: An alternative Approach for Management of the Canadian Boreal Forest. Sustainable Forest Management Network, Edmonton, Alberta.

Le Goff, H., Flannigan, M.D., Bergeron, Y., 2009. Potential changes in monthly fire risk in the eastern Canadian boreal forest under future climate change. Can. J. Forest Res. 39, 2369-2380.

Le Goff, H., Flannigan, M.D., Bergeron, Y., Girardin, M.P., 2007. Historical fire regime shifts related to climate teleconnections in the Waswanipi area, central Quebec, Canada. Int. J. Wildland Fire 16, 607-618.

Luyssaert, S., Inglima, I., Jung, M., Richardson, A.D., Reichstein, M., Papale, D., Piao, S.L., Schulze, E.-D., Wingate, L., Matteucci, G., Aragao, L., Aubinet, M., Beer, C., Bernhofer, C., Black, K.G., Bonal, D., Bonnefond, J.-M., Chambers, J., Ciais, P., Cook, B., Davis, K.J., Dolman, A.J., Gielen, B., Goulden, M., Grace, J., Granier, A., Grelle, A., Griffis, T., Grünwald, T., Guidolotti, G., Hanson, P.J., Harding, R., Hollinger, D.Y., Hutyra, L.R., Kolari, P., Kruijt, B., Kutsch, W., Lagergren, F., Laurila, T., Law, B.E., Le Maire, G., Lindroth, A., Loustau, D., Malhi, Y., Mateus, J., Migliavacca, M., Misson, L., Montagnani, L., Moncrieff, J., Moors, E., Munger, J.W., Nikinmaa, E., Ollinger, S.V., Pita, G., Rebmann, C., Roupsard, O., Saigusa, N., Sanz, M.J., Seufert, G., Sierra, C., Smith, M.-L., Tang, J., Valentini, R., Vesala, T., Janssens, I.A., 2007. CO_2 balance of boreal, temperate, and tropical forests derived from a global database. Glob. Chang. Biol. 13, 2509-2537.

Moroni, M.T., Shaw, C.H., Kurz, W.A., Rampley, G.J., 2010. Forest carbon stocks in Newfoundland boreal forests of harvest and natural disturbance origin II: model evaluation. Can. J. Forest Res. 40, 2146-2163.

MRN, 2000. Mise à jour, Manuel d'aménagement forestier : Document d'annexes, Annexe 1, in: Québec, G.d. (Ed.). Gouvernement du Québec, Québec.

Paré, D., Banville, J.L., Garneau, M., Bergeron, Y., 2011. Soil carbon stocks and soil carbon quality in the upland portion of a boreal landscape, James Bay, Quebec. Ecosystems 14, 533-546.

Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner, F., 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. The Intergovernmental Panel on Climate Change (IPCC), Institute for Global Environmental Strategies (IGES) for the IPCC.

Saucier, J.-P., Grondin, P., Robitaille, A., Gosselin, J., Morneau, C., Richard, P.J.H., Brisson, J., Sirois, L., Leduc, A., Morin, H., Thiffault, É., Gauthier, S., Lavoie, C., Payette, S., 2009. Chapitre 4: Écologie forestière, in: Multimonde, É. (Ed.), Manuel de foresterie, 2e ed. ed. Ordre des ingénieurs forestiers du Québec, Québec, Canada.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., (eds.), H.L.M., 2007. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change., in: Press, C.U. (Ed.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA p. 996.

Spath, P.L., Mann, M.K., 2000. Life-cycle assessment of a natural gas combine-cycle power generation system. National Renewable Energy Laboratory, Golden, Colorado.

Teodoru, C., Bastien, J., Bonneville, M.-C., del Giorgio, P., Demarty, M., Garneau, M., Hélie, J.-F., Pelletier, L., Prairie, Y., Roulet, N., Strachan, I., Tremblay, A., 2012. The net carbon footprint of a newly created boreal hydroelectric reservoir. Global biogeochem. cy. 26, GB2016, doi:10.1029/2011GB004187.

Tremblay, A., Varfalvy, L., Roehm, C., Garneau, M., 2005. Greenhouse Gas Emissions - Fluxes and Processes: Hydroelectric Reservoirs and Natural Environments. Springer, Berlin, Germany.

United Nations Framework Convention on Climate Change (UNFCCC), 1998. Kyoto Protocol to the United Nations framework convention on climate change, in: Nations, U. (Ed.). United Nations framework convention on climate change, Bonn, Germany.

Tables

Table 1

Carbon stock estimates (CBM-CFS3) in the biomass and dead organic matter pool at year 0 for the flooded Eastmain-1 forest area.

Carbon pools	C stocks (Mg)	C stocks (%)
Aerial biomass	889 387	15%
Below ground biomass	207 558	4%
Dead organic matter above ground	2 013 477	35%
Dead organic matter below ground	2 640 647	46%
Total	5 751 069	100%

Table 2

Weighted-Average (min/max) of annual carbon flux estimates of the flooded forested land [a]

Type of Carbon flux	Carbon flux Mg C ha^{-1} y^{-1}
Net primary production (NPP)	-2.12 (-2.28/-1.86)
Litter	1.90 (1.51/2.15)
Decomposition (DOM_D)	1.97 (1.81/2.09)
Net ecosystem productivity (NEP)	-0.15 (0.01/-0.32)
Disturbance (CD)	0.08 (0.00/0.90)
Net biome productivity (NBP)	-0.07 (0.89/-0.32)

[a]Negative values in the table represent C sink. Values between parentheses correspond to lower and upper limit estimates.

Figures

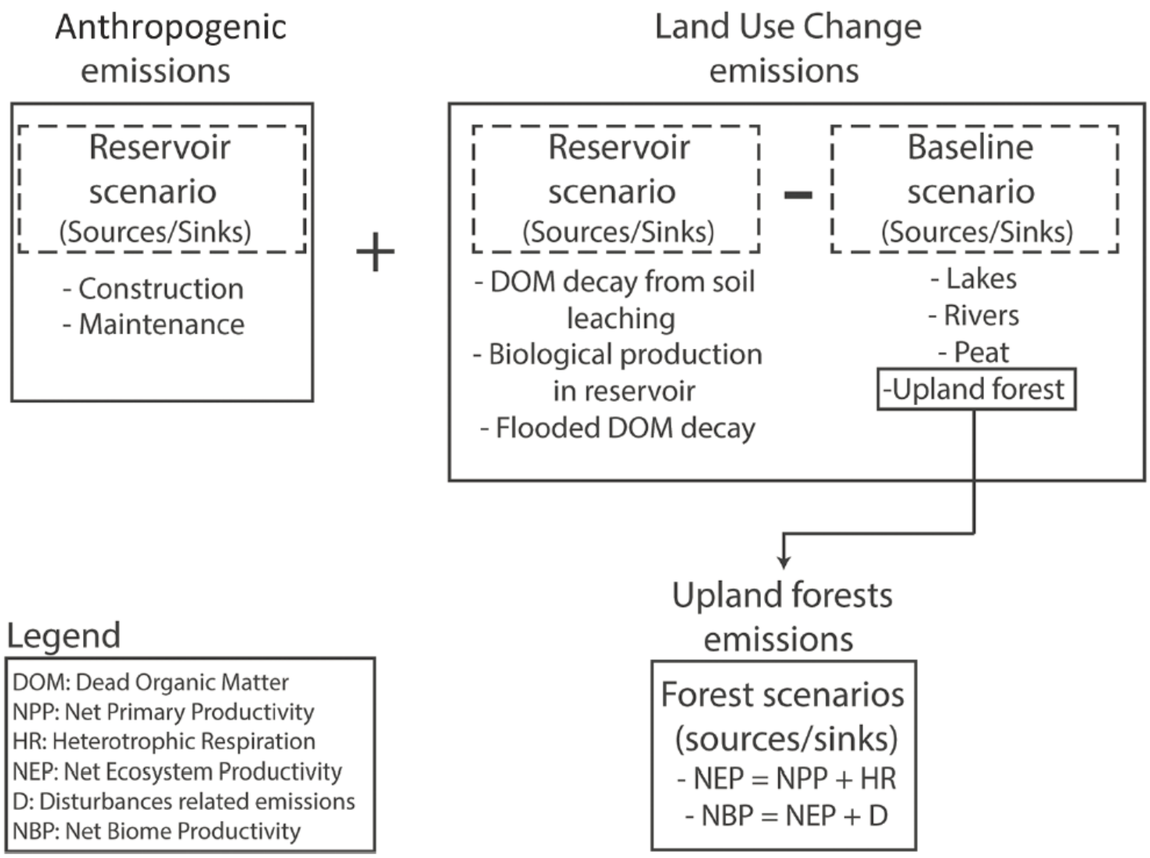

Fig. 1. Schematic representation of the C footprint assessment in this study, showing where the upland forest sources/sinks specific contribution in the overall net C footprint stands.

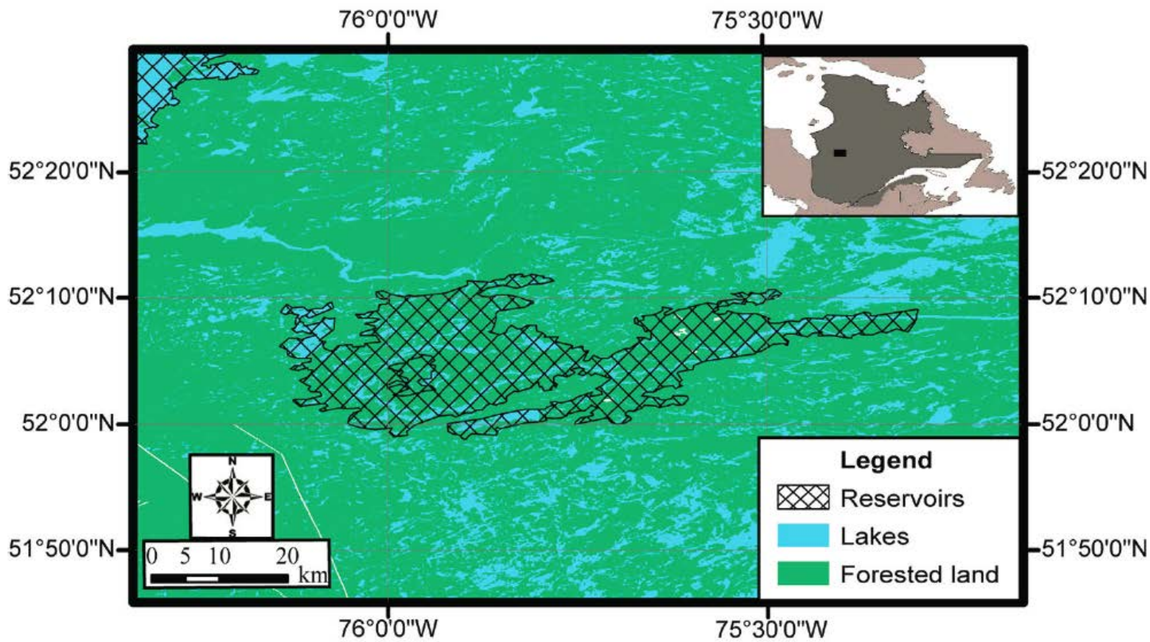

Fig. 2. Location of the study area in Québec, Canada (upper right). The squared area in the middle corresponds to the flooded territory, and the whole area represents the sector from which fire data were extracted from the Natural Resources Canada large fire database.

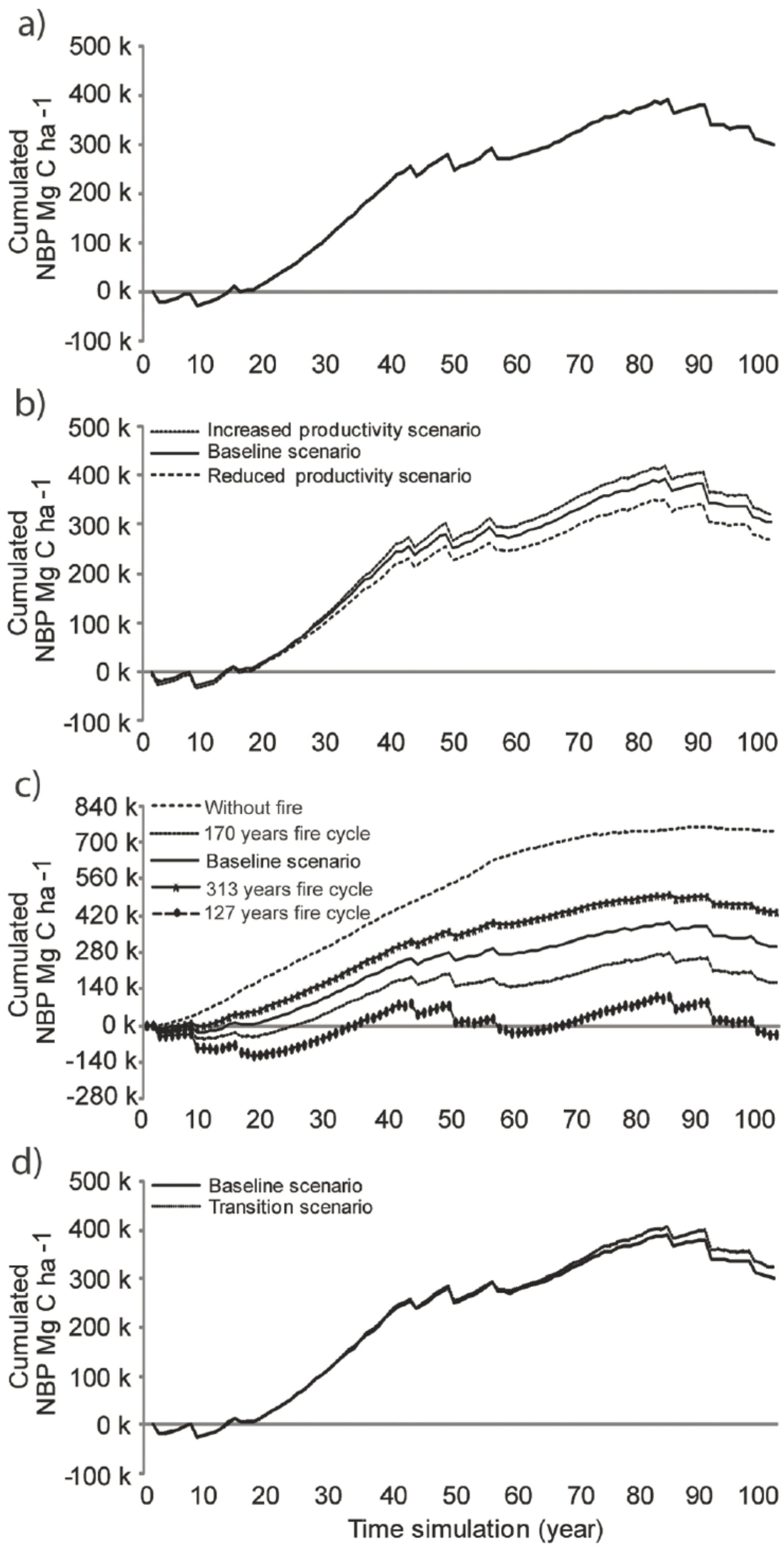

Fig. 3. Cumulated Net biome productivity (NBP) (Mg C ha^{-1}) of the flooded forested land over 100 year following (a) baseline scenario, and sensitivity analysis on (b) growth and yield table, (c) fire cycle length and (d) stand composition following fire event.

Supplemental information

on the article

Uncovering the minor contribution of land-cover change in upland forests to the net carbon footprint of a boreal hydroelectric reservoir

by

Pierre-Luc Dessureault, Jean-François Boucher, Pascal Tremblay, Sylvie Bouchard, Claude Villeneuve

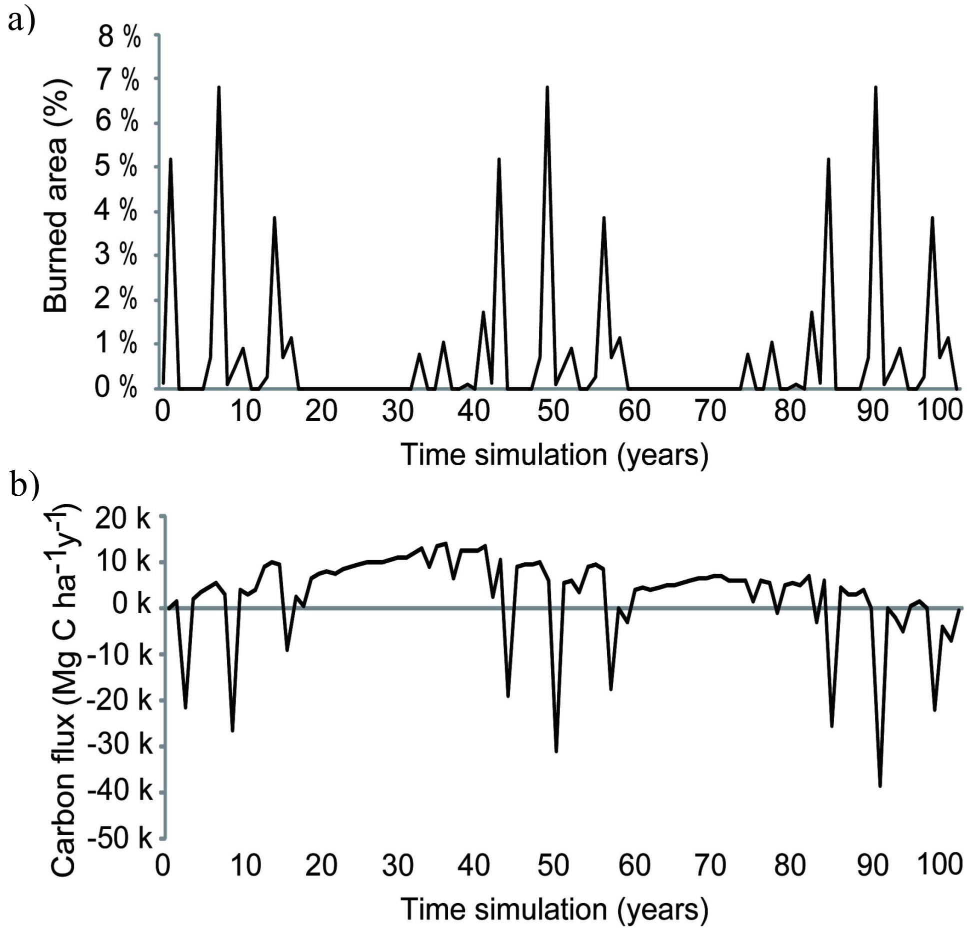

Figure S1. Percentage of yearly burned area (a) of the 43 161 ha flooded forested land inferred from the Large Fire Database from Natural Ressources Canada and (b) its relative impact on yearly Net Biome Productivity.

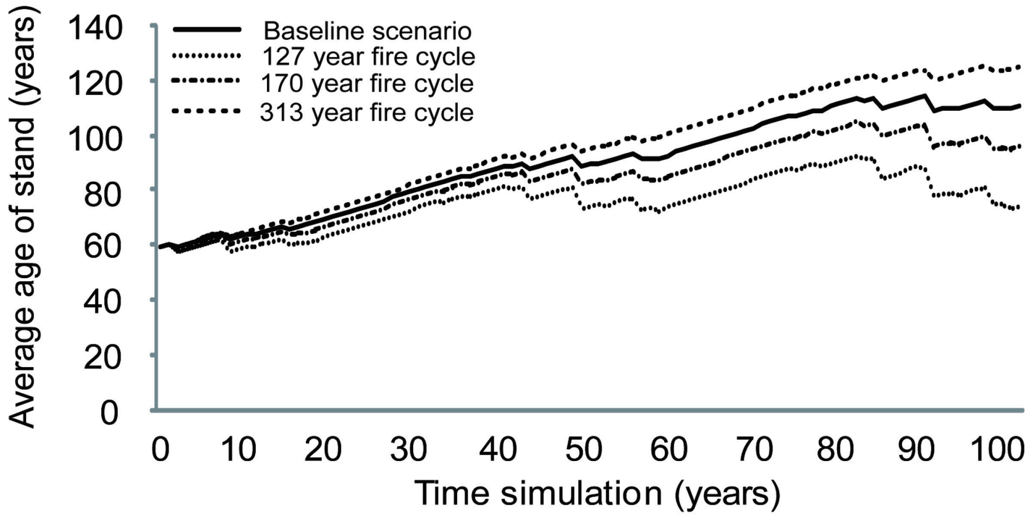

Figure S2. Average stands age under different fire cycle scenarios.

Precision on sensitivity analyses performed on stand regeneration patterns

The following cases, based on the available literature on post-fire regeneration in the boreal forest, were tested: 1) no switch in species and no loss in volume yield; 2) fire occurs in a < 60-year-old black spruce stand and tree density (and consequently volume yield) diminishes towards a low tree density stand (28,29,30); 3) balsam fir within a mature black spruce stand disappears after a fire (31); 4) if a fire occurs in < 60-year-old black spruce with jack pine as a companion species, jack pines dominates after the fire (31, 32); 5) if a fire occurs in < 60-year-old black spruce with birch and trembling aspen as companion species, deciduous trees becomes dominant after the fire (31); 6) if a fire occurs in a < 60-year-old spruce-tamarack stand it remains the same (33); 7) if fire occurs in a < 10-year-old jack pine stand, tree density (and volume yield) diminishes towards a low tree density stand (34); 8) if fire occurs in a jack pine stand with black spruce as a companion species < 60-year-old, the latter disappears (31, 32); 9) if fire occurs in a < 10-year-old jack pine stand with trembling aspen as a companion species, jack pine disappears (34); 10) if a fire occurs in a mixed conifer stand < 60-year-old, the balsam fir, tamarack and black spruce disappear and are replaced by jack pine (31, 33); 11) if a fire occurs in a deciduous stand or a mixed conifer stand, it remains the same after fire (35).

Table 1: Attributes table of the 231 forest strata resulting from the grouping of the 2700 initial upland forest stands of the flooded territory.

Stands Attributes					
Species	**Density class**	**Height class**	**Age class**	**Last known disturbance**	**Area (ha)**
BBPE	B	5	50		7
PEBB	B	5	50		11
PEPE	A	3	50		2
BB1PG	C	4	30		10
BBPG	C	4	30		4
BBE	B	4	50		24
BBPG	A	4	30		12
BBPEPG	C	3	50	BRP	12
PGPGBP	B	4	30		6
PGPGBP	B	4	30		27
EBB	B	4	70	BRP	12
EBB	D	4	70		14
EPE	B	3	70		58
EPE	C	4	50		6
EPE	D	4	50		10
EPE	D	4	50	BRP	26
EPE	D	4	70		45
EPE	D	4	70	BRP	31
PEE	D	3	70		15
PEPEE	C	3	70		22
PEPEE	D	3	70		16
PEPE	C	3	70		20
PEPE	D	3	70		30
PGBB	B	4	30		10
PGBB	C	4	30		7
EPE	C	3	70	BRP	10
PEBBE	C	3	50		16
PEBBE	C	3	50	BRP	46
PEBBPG	C	3	50		14
M6	B	4	30		30
M6			30	BR	381
M	A	5	30	BR	67
M	B	5	30	BR	699
M	B	5	90	BR	12
M	C	3	30	BR	21
M	C	5	30	BR	830
M	D	5	120	BR	17
M	D	5	30	BR	1425
EE	A	4	70		6
EE	B	3	50		12
EE	B	3	70		223
EE	B	4	50		70
EE	B	4	70		273
EE	B	4	90		24
EE	B	3	90		35
EE	B	3	120		286
EE	B	4	30		12
EE	B	4	120		190
EE	C	3	120		1367
EE	C	3	70-120		61
EE	C	4	120		1037
EE	C	4	70-120		19
EE	C	3	120		568
EE	C	3	90		81

Species	Density class	Height class	Age class	Last known disturbance	Area (ha)
EE	C	4	70		430
EE	D	4	VIN		10
EE	C	3	50		8
EE	C	4	30		10
EE	C	4	50		5
EE	D	3	120		509
EE	D	4	120		1540
EE	D	3	50		15
EE	D	3	70		157
EE	C	4	90		52
EE	D	3	90		50
EE	D	4	50		109
EE	D	4	70		969
EE	D	4	90		49
EPG	D	3	120		120
EPG	D	3	50		54
EPG	D	3	70		684
EPG	D	3	90		64
EPG	D	4	120		26
EPG	D	4	30		60
EPG	D	4	50		821
EPG	D	4	70		1336
EPG	D	5	50		1
EME	B	3	120		6
EME	B	3	120	BRP	6
EME	B	4	120		7
EME	C	3	120		140
EME	C	3	120	BRP	13
EME	C	3	70		11
EME	C	3	90		2
EME	C	4	120		21
EME	D	3	120		99
EME	D	3	120	BRP	8
EME	D	3	70		28
EME	D	4	120		93
EME	D	4	120	BRP	5
MEE	C	3	120		5
MEE	D	3	120		45
MEE	D	3	120	BRP	18
MEE	D	4	120		27
MEME	D	3	120		26
EPG	B	4	120		17
EPG	B	4	30		47
EPG	B	4	70		227
EPG	C	4	120		47
EPG	C	4	30		54
EPG	C	4	50		186
EPG	C	4	70		462
EPG	C	4	90		6
EPG	C	5	120		2
EPG	B	3	120	BRP	24
EPG	B	3	50		7
EPG	B	3	70		425
EPG	B	3	90		38
EPG	B	4	50		44
EPG	C	3	120		116
EPG	C	3	70		534
EPG	C	3	90		111
ES	B	3	120		15

Species	Density class	Height class	Age class	Last known disturbance	Area (ha)
ES	B	3	30		1
ES	B	3	70		45
ES	B	3	90		41
ES	B	4	50		6
ES	B	5	70		6
ES	C	3	120		330
ES	C	3	70		72
ES	C	4	70		45
PGE	B	3	50		154
PGE	B	3	70		13
PGE	B	3	120		36
PGE	B	3	70		466
EPG	B	3	50		38
PGE	B	3	50		214
BR				BR	5030
PGE	B	4	30		117
PGE	B	4	50		56
PGE	B	4	70		10
PGE	C	4	30		99
PGE	C	4	50		220
PGE	C	4	70		91
R6			30	BR	970
R	A	5	30	BR	27
R	A	5	30	BR	9
R	B	5	30	BR	218
R	C	5	30	BR	306
R	C	0	30	BR	44
R	D	3	30	BR	68
R	D	5	30	BR	3294
PGE	D	3	120		43
PGE	D	3	50		248
PGE	D	3	70		573
PGE	D	4	30		178
PGE	D	4	50		273
PGE	D	4	70		206
PGPG	D	3	50		125
PGPG	A	3	70		49
PGPG	A	4	30		124
PGPG	A	4	50		25
PGPG	C	4	30		416
PGPG	C	4	50		101
PGPG	C	4	70		29
PGPG	D	4	30		581
PGPG	D	4	50		166
PGPG	D	4	70		33
PGE	C	3	120		114
PGE	C	3	120		566
PGE	C	3	90		11
PGPG	B	3	30		5
PGPG	B	3	50		441
PGPG	B	3	70		427
PGPG	B	4	30		434
PGPG	B	4	50		209
PGPG	B	4	70		11
PGPG	C	3	50		156
PGPG	C	3	70		297
PGPG	D	3	70		394
EE	C	3	120	CHP	21
EE	C	3	70	CHP	5

Species	Density class	Height class	Age class	Last known disturbance	Area (ha)
EE	D	3	120	CHP	80
ES	C	3	VIN	CHP	37
ES	C	3	70	CHP	23
ES	C	3	120	BRP	50
ES	D	3	120	BRP	45
ES	D	3	120	CHP	13
EE	C	4	50	BRP	2
EE	C	4	70	BRP	21
EE	C	4	90	BRP	21
EE	C	5	120	BRP	10
EE	D	4	120	BRP	685
EE	D	4	50	BRP	91
EE	D	4	70	BRP	302
ME	D	5	120	BRP	9
ES	C	3	70	BRP	14
ES	C	4	70	BRP	26
ES	C	4	70	CHP	16
ES	D	4	120	BRP	18
ES	D	4	70	BRP	37
EE	D	5	120	BRP	12
ES	D	3	70	BRP	20
EPG	B	3	50	BRP	11
EPG	B	4	70	BRP	16
EPG	C	4	50	BRP	6
EPG	C	4	70	BRP	14
EE	B	3	120	BRP	50
EE	C	2	120	BRP	12
EE	C	3	120	BRP	943
EE	C	3	70	BRP	174
EE	C	3	90	BRP	54
EE	C	4	120	BRP	326
EE	D	3	120	BRP	2052
EE	D	3	50	BRP	38
EE	D	3	70	BRP	445
EE	D	3	90	BRP	45
EPG	C	3	120	BRP	10
EPG	C	3	70	BRP	17
EPG	C	3	90	BRP	9
EPG	D	3	50	BRP	41
EPG	D	3	70	BRP	100
EPG	D	3	90	BRP	10
EPG	D	4	50	BRP	276
EPG	D	4	70	BRP	77
EPG	D	5	30	BR	14
PGE	B	3	70	BRP	30
PGE	C	3	30	BRP	15
PGE	C	3	50	BRP	8
PGE	C	4	30	BRP	25
PGE	C	4	50	BRP	25
PGE	C	5	70	BRP	8
PGE	D	3	120	BRP	49
PGE	D	3	50	BRP	52
PGE	D	4	50	BRP	33
PGPG	C	3	70	BRP	4
PGPG	C	4	30	BRP	10
PGPG	C	4	50	BRP	32
PGPG	D	3	120	BRP	5
PGPG	D	3	50	BRP	27
PGPG	D	4	30	BRP	9

Table 2: Description of species codes used to describe the forest strata of Table 1 in the supporting information

Species Code	Species
BB1PG	White Birch, Jack pine
BBE	White Birch, Black spruce
BBPE	White birch, Trembling aspen
BBPEPG	White birch, Trembling aspen, Jack pine
BBPG	White Birch, Jack pine
BR	N.A.
EBB	Black spruce, White birch
EE	Black spruce
EME	Black spruce, Tamarack
EPE	Black spruce, Trembling aspen
EPG	Black spruce, Jack pine
ES	Black spruce, Balsam fir
M	Mixed
ME	Tamarack
MEE	Tamarack, Black spruce
PEBBE	Trembling aspen, White birch, Black spruce
PEBBPG	Trembling aspen, White birch, Jack pine
PEE	Trembling aspen, Black spruce
PEPE	Trembling aspen
PEPEE	Trembling aspen, Black spruce
PGBB	Jack pine , White birch
PGE	Jack pine, Black spruce
PGPG	Jack pine
PGPGBP	Jack pine, White birch
R	N.A.
R6	N.A.

N.B.: Species order of appearance in the species codes column represents their relative contribution to the stand wood volume (m^3)

Table 3: Description of density class used to describes the forest strata of Table 1 in the supporting information

Density Class	Cover (%)
A	80-100
B	60-80
C	40-60
D	25-40

Table 4: Description of Height class used to describes the forest strata of Table 1 in the supporting information

Height Class	Height (m)
0	0
2	17-22
3	12-17
4	7-12
5	4-7

Table 5: Description of Age class used to describes the forest strata of Table 1 in the supporting information

Age Class	Age (years)
30	21-40
50	41-60
70	61-80
90	80-100
120	100+
70-120	61-80 & 100+
VIN	Multi cohort

Table 6: Description of the disturbance type used to describes the forest strata of Table 1 in the supporting information

Disturbance type	Description
BR	Fire
BRP	Partial fire
CHP	Partial windthrow