

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

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13 Key abbreviations:

14 CBM-CFS3, Carbon budget model of Canadian Forest Service (third version); CD, carbon disturbance; CE,
15 carbon equivalent; CO₂e, carbon dioxide equivalent; CS, carbon sink; CWFIS, Canadian Wildland Fire
16 Information System; D, decay; DOM, dead organic matter; GHG, greenhouse gas; HQ, Hydro-Québec;
17 IPCC, Intergovernmental Panel on Climate Change; KP, Kyoto Protocol; LUCC, Land use and cover change;
18 MRN, Ministère des ressources naturelles; NBP, net biome productivity; NEP, net ecosystem productivity;
19 NPP, net primary productivity.

20

21

22 ABSTRACT

23 Hydropower in boreal conditions is generally considered the energy source emitting the least greenhouse gas
24 per kWh during its life cycle. The purpose of this study was to assess the relative contribution of the land-use
25 change on the modification of the carbon sinks/sources following the flooding of upland forested territories
26 to create the Eastmain-1 hydroelectric reservoir, in Quebec's boreal forest using Carbon Budget Model of the
27 Canadian Forest Sector (CBM CFS3). Results suggest a carbon sink loss after 100 years of $300\,000 \pm$
28 $100\,000$ Mg CO_{2e}. A wild fire sensitivity analysis revealed that the ecosystem would have acted as a carbon
29 sink as long as $< 75\%$ of the territory had burned over the 100 year-long period. Our long-term net carbon
30 flux estimations resulted in emissions of 4 ± 2 g CO_{2e} kWh⁻¹ as a contribution to the carbon footprint
31 calculation, eight times less than what was obtained in a recent study (Teodoru et al., 2012) that used less
32 precise and sensitive estimates. Consequently, this study significantly reduces the reported net carbon
33 footprint of this reservoir, and reveals how negligible the relative contribution of the land-use change in
34 upland forests to the total net carbon footprint of a hydroelectric reservoir in the boreal zone can be.

35

36 1. Introduction

37 With its 62 hydroelectric power plant and its production capacity of 36.5 GW (Hydro Québec, 2015),
38 Hydro-Québec (HQ) is one of the most important electricity producers in North-Eastern America. HQ claims
39 that its hydro-electricity is among the lowest C-intensive technologies worldwide. However, assessing the
40 carbon (C) footprint of a given unit of electricity needs a complete life cycle analysis of emissions/sinks of
41 greenhouse gases. In 2002, HQ, reported a secondary data-based C footprint of the full energy chain
42 associated with the Eastmain-1 hydroelectric plant to other types of electricity generation (Tremblay et al.,
43 2005). The data showed that with emissions of approx. 15 t CO_{2e} GWh⁻¹ over 100 years for average boreal
44 reservoirs (and up to 33 t CO_{2e} GWh⁻¹ for the larger La Grande Complexe), boreal hydroelectricity is largely
45 advantageous over others. However, this report (Tremblay et al., 2005) took only into account the gross GHG
46 emissions created by a reservoir, i.e., without the variation in C fluxes associated with the land-use change
47 caused by the flooding of a large forested territory to create the reservoir (IPCC, 2003), as required by the
48 Kyoto Protocol (KP) (UNFCCC, 1998).

49 More recently, Teodoru et al. (2012) used direct observations, new modeling approaches and data
50 from the literature to estimate reservoir net emissions, including an estimation of the loss of C sink to
51 complete the net C footprint of the newly created Eastmain-1 reservoir. They assessed the loss of C sink from
52 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
53 long-term (100 year) C footprint of the reservoir (158 t CO_{2e} GWh⁻¹) (Teodoru et al., 2012). Though their
54 approach provided valuable and conservative results, a more detailed and sensitive methodology is deemed
55 necessary to mitigate the uncertainty around the upland forest land-use cover change (LUCC) estimated
56 impact on the net GHG emissions of hydroelectric reservoirs. This is particularly relevant given the
57 importance of this energetic issue in North America – where the C footprint of different types of energy
58 production is increasingly becoming strategic (Edenhofer et al., 2011) and considering that natural upland
59 forests account for approx. 49% of the flooded territory and 20% of the net C fluxes calculated in Teodoru et
60 al. (2012).

61 In Canada and elsewhere around the world, the Carbon Budget Model of the Canadian Forest Sector 3
62 (CBM-CFS3) (Kurz et al., 2009) is used to simulate the dynamics of forest C stocks as required under the KP
63 (IPCC, 2003). CBM-CFS3 is an aspatial, stand and landscape-level modeling framework used to simulate the
64 dynamics of all forest C stocks required under the Kyoto Protocol, and is compliant with the C estimation
65 methods outlined in the IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry report
66 (2003). This model uses information from forest inventories, growth and yield tables, natural disturbances
67 and stand regeneration dynamics to estimate upland forest C fluxes and stocks. Hence, this model can be
68 used to estimate the LUCC portion of the C footprint for different forest management scenarios, natural
69 disturbances and changes in land use, like flooding for the creation of a water reservoir (Kurz et al., 2009).

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

84 sensitivity analyses while integrating wild fire risk in the C footprint calculation of the upland forest part of
85 an hydroelectric reservoir.

86 In this study, the absence of the reservoir, and thus the natural dynamic of the upland forest
87 ecosystems, constitutes the baseline scenario, while the reservoir creation and the resulting forested land
88 flooding (with the concomitant loss of C fluxes from the forested lands) will be considered as the project
89 scenario, *sensu* ISO 14064-2 (ISO, 2006) and in accordance with the same two scenarios in Teodoru et al.
90 (2012). The objective of this study is therefore to estimate the net C balance of the flooded upland forest for
91 the creation of the Eastmain-1 reservoir (see Figure 1) over a period of 100 years, using fire cycles data,
92 forest inventory derived from photo interpretation and model simulations with CBM-CFS3, and then to
93 translate this net C balance – the project scenario minus the baseline scenario, i.e., C fluxes with and without
94 the reservoir – in terms of C footprint in CO₂e per kWh for the life expectancy of the installation. For the
95 baseline scenario, sensitivity analyses are performed to evaluate the impact of different fire regimes, forest
96 productivity and regeneration patterns following disturbance on the C balance of the unflooded upland forest
97 territory. It is expected that the land use cover change caused by the flooding of the upland forest territories
98 induces a net loss of C sink, as the forest at the moment it was flooded would have sequestered more C than
99 it would have emitted despite fire disturbances. Other C sources resulting from the reservoir creation, i.e. the
100 major C gas (CO₂ and CH₄) sources and sinks of the terrestrial (other than upland forests) and aquatic
101 components of the pre- and post-flood landscape are not considered since they were thoroughly covered in
102 Teodoru et al. (2012). A concomitant objective is to provide for the first time a detailed estimation of the
103 relative contribution of the upland forest C sink/source change to the net C footprint of a newly flooded
104 boreal hydroelectric reservoir.

105

106 **2. Methods**

107 *2.1. Description of the study area*

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

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

122 A forest inventory of this area was made using 253 aerial photos (1: 20 000) taken in 1999 before the
123 area was flooded. From these photos, species, age class, tree density and mean tree height were
124 photointerpreted for each distinct forest stand and recent disturbances noted. The 253 aerial photos and the
125 2 700 resulting stands were then scanned and georeferenced [NAD_1983_UTM_Zone_9N] and Arc GIS 9.0
126 [ESRI, Redland, USA, 2006] was used to determine their corresponding surface area.

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

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

137

138 2.2. Simulations

139 The C balance simulations were performed using the standard importation tool of the CBM-CFS3 (v.
140 1.2 beta) developed by the Canadian Forest Service (Kurz et al., 2009). This model simulates the dynamic of
141 forest C stocks and complies with the approved methods of C stock estimations by the Intergovernmental
142 Panel on Climate Change (IPCC) (Solomon et al., 2007). The model was feed with growth and yield tables
143 according to forest inventory data (i.e. disturbance, species, age, area, stem density) (MRN, 2000). The
144 absence of the reservoir, and thus the natural dynamic of the upland forest ecosystems, constitutes the
145 baseline scenario, while the reservoir creation and the resulting forested land flooding (with the concomitant
146 loss of C fluxes from the forested lands) will be considered as the project scenario, *sensu* ISO 14064-2 (ISO,
147 2006) and in accordance with the same two scenarios in Teodoru et al. (2012).

148 Simulations were carried out over a 100 year period in the Eastern Boreal Shield ecozone with CBM-
149 CFS3 default soil parameters of this area. We used Bergeron et al. (2010) 0.45% annual burning rate to
150 simulate a 222 year-long fire cycle (baseline scenario), as the flooded territory was included in their field
151 study. This fire cycle was chosen because it represents a projection for the next 100 years. A fire pattern
152 emulating natural variability was created using data from the Large Fire Database (LFDB) from Natural
153 Resources Canada (1959–1999) (CWIFS, 2012). These data were extracted for a 10000 km² area centered
154 over the Eastmain-1 reservoir. The 40 year fire sequence extracted from the database (1959–1999) was

155 repeated 2.5 times to obtain a 100 year sequence and the result was then standardized to correspond to 45 %
156 of burned area after a 100 year modeling, in order to relate to a fire cycle of 222 years (Bergeron et al.,
157 2010). The model used did not account for multiple fires in the same area, so each hectare could only burn
158 once during the 100 years modeling. Regeneration delay was set to begin the year following the fire
159 disturbance without any modification to the forest inventory other than age class which was zeroed after a
160 fire event. Stand composition transition was not taken into account as it had a negligible effect on C stocking.
161 This pattern of fire variability was used in all simulations and resulted in 0–7% of yearly burned land in the
162 study area (see Figure S1a in the Supporting Information).

163

164 2.3. Sensitivity analyses

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

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

170 Different fire cycles were also used to ascertain the gain and losses in C stocks due to the uncertainty
171 on the 222 year cycle (Bergeron et al., 2010) established for this area, and to estimate volume yields if the
172 territory did not burn. The following scenarios were modeled: 1- no disturbance, 2- 313 year fire cycle (fire
173 affects 32 % of the territory after 100 years), 3- 222 years (fire affects 45 % of the territory after 100 years),
174 and 4- 170 years (fire affects 59 % of the territory after 100 years) (Bergeron et al., 2010). An additional
175 analysis was conducted with a 127 year fire cycle (fires affects 79 % of the territory after 100 years), inferred
176 from the photo interpretation performed for this study. This last scenario represents an instantaneous picture

177 of the study area; however, it does not correspond to a science based fire cycle and should be considered as
 178 an extreme case in our range of tested scenarios.

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

182

183 *2.4. Net biome productivity*

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

$$185 \text{ NEP} = \text{NPP} + \text{DOM}_D \quad (1)$$

$$186 \text{ NBP} = \text{NEP} + \text{CD} \quad (2)$$

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

190

191 *2.5. Carbon sink/source per GWh*

192 Tons of C equivalent (CE) obtained from the calculations of NBP were transformed into tons of C
 193 dioxide equivalent (CO_2e) using the formula $\text{CO}_2\text{e} = \text{CE} * 3.67$.

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

$$198 \text{ CS}_{GWh} = \text{NBP}_{cumul} \times 3.67 / (\text{P} \times 100) \quad (3)$$

199 Where:

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

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

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

203 100 = Life expectancy of an hydroelectric plant in the boreal zone (in years)

204

205 **3. RESULTS**

206 *3.1. Initial carbon stocks*

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

210

211 *3.2. Evolution of stand age*

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

215

216 *3.3. Carbon flux and stock variations*

217 During the years with fires burning large territories, emissions almost reached $40\ 000\ Mg\ C\ year^{-1}$ for
218 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
219 (biomass and dead organic matter) increased with stand age. On average, forest fires (C Disturbance)

220 accounted for emissions of 0.08 (0.00/0.90) Mg C ha⁻¹ y⁻¹ (Table 2). Net primary production (NPP) of the
221 flooded forest varied between 80 000 to 100 000 Mg C year⁻¹ and tended to increase slightly with time, but
222 halted after 90 years of simulation. It also leveled off during the years of important fires, as the latter strongly
223 affected age class structure of the territory. Overall, mean annual NPP was 2.12 (2.28/1.86) Mg C ha⁻¹ year⁻¹
224 (Table 2). The simulated forest built up from 60 000 to 90 000 Mg C year⁻¹ in dead organic matter and this
225 accumulation rate tended to increase over time. Overall, dead organic matter accumulation rate increased to a
226 mean rate of 1.90 (1.51/2.15) Mg C ha⁻¹ year⁻¹ (Table 2). Decomposition rate of organic matter increased
227 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)
228 Mg C ha⁻¹ year⁻¹ (Table 2), with the lowest values during the years where burnt areas were large. Net
229 ecosystem production (NEP) increased until year 35 then sharply declined with significant variations (in
230 accordance with fire occurrence and extent) for thirty years. After year 65, the NEP tended to decrease with
231 little variation caused by forest fires. The general trend was to decrease, but the mean NEP was 0.15 (-
232 0.01/0.32) Mg C ha⁻¹ y⁻¹ (Table 2).

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

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

238

239 3.4. Sensitivity tests

240 3.4.1. Yield tables variations

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

244

245 3.4.2. Fire cycle variations

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

256 3.4.3. Regeneration variations

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

259

260 3.5. Carbon sink/source per GWh

261 As per equation 2, the C footprint associated with land-use change for the Eastmain-1 flooded
 262 forested territory corresponds to a total C sink loss of 303 489 Mg C after 100 years. Expressed as a C sink
 263 loss per unit of produced energy based on equation 3, it corresponds to a C footprint of 4 ± 2 t CO₂ eq. GWh⁻¹
 264 ¹. The uncertainty (± 2 t CO₂ eq. GWh⁻¹) corresponds to the confidence interval (170-313 years) proposed by
 265 Bergeron et al. (2010) for fire cycles.

$$266 \quad CS_{GWh} = 303\,489 \text{ Mg C} \times 3.67 / (2700 \text{ GWh} \times 100 \text{ years}) = 4.1 \text{ Mg CO}_2 \text{ eq. GWh}^{-1}$$

267

268 4. DISCUSSION

269 4.1. Pre-flooding carbon stocks evaluation

270 Estimated pre-flooding C stocks using CBM-CFS3 are similar to those obtained by Paré et al. (2011)
 271 on a small selection of stands from nearby sites which shows that the selection of growth and yield table to
 272 feed the model were adequate. Dead organic matter (DOM) C stocks in the simulation were 108 Mg C ha⁻¹,
 273 29 Mg C ha⁻¹ higher than that of field measurements in Paré et al. (2011). However, annual rates of litter
 274 accumulation are similar: first year of simulation with 1.5 Mg C ha⁻¹ year⁻¹ (mean stand age 59 years)
 275 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
 276 the decay rate observed in the field is faster than what the model uses. Using the latter result and projecting it
 277 at a mean stand age of 59 years, we obtain a potential increase of accumulated litter of 25 ± 4 Mg C ha⁻¹, and
 278 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
 279 ha⁻¹ predicted in Tremblay et al. (2005) for the same area (see Figure 4 therein) once again suggesting that
 280 the model behave adequately and that the growth and yield table selection were appropriate.

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

284

285 *4.2. Carbon fluxes and stocks*

286 The estimated net primary productivity (NPP) of 2.12 (2.28/1.86) Mg C ha⁻¹ y⁻¹ does not always
287 concur with field observations in the literature. A study on the semi-arid boreal forest, using data from
288 circumpolar flux towers, obtained a mean NPP of 3.3 ± 0.6 Mg C ha⁻¹ y⁻¹ (Bergeron et al., 2007). Another
289 study, near Chibougamau, Québec (approx. 300 km south-east from the study area) estimated that a 91-year-
290 old black spruce stand had a NPP of 5.84 ± 0.07 Mg C ha⁻¹ y⁻¹ (Luysaert et al., 2007). Differences in stand
291 age and low productivity (low site index) of the study area can explain this variation in NPP. It has also been
292 shown that the CBM-CFS3 model may underestimate biomass net growth by 10 % (Bernier et al., 2009),
293 which may explain some of the difference in NPP observed between our study and that of Bergeron et al.
294 (2007).

295 The estimated net ecosystem productivity (NEP) value of our study of 0.15 (-0.01/0.32) Mg C ha⁻¹ y⁻¹
296 contributes to a large array of values from the literature reporting NEP in boreal ecosystems: from -2.5 to 2.0
297 Mg C ha⁻¹ y⁻¹ (Amiro et al., 2010, Bergeron et al., 2007 and Luysaert et al., 2007). The values vary mostly
298 with the methodology used, growth conditions, occurrence of disturbances and stand age. Simulated
299 decomposition (DOM_D) emissions of 1.97 (1.81/2.09) Mg C ha⁻¹ y⁻¹ was lower than reported field
300 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
301 al., 2007 and Luysaert et al., 2007). The fact that these latter stands are located in the central part of
302 Québec's boreal forest, warmer and more productive than those near the Eastmain reservoir, might explain
303 much of this difference in heterotrophic decomposition.

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

306 *4.3. Sensitivity tests*

307 Of the three factors tested for their effects on the model (volume yields, fire cycles and stand
308 regeneration), fire cycles was by far the most influential with a +43 % to -46 % variation in NBP; to keep the
309 model conservative, the confidence interval around the calculated NBP was set according to that of the 222
310 year fire cycle range. In the absence of any fires during the 100 year life expectancy of the power plant
311 (unrealistic scenario), the flooded territory would have accumulated 738 318 Mg C, or 0.17 Mg C ha⁻¹ y⁻¹
312 (corresponding to 10 Mg CO₂ eq GWh⁻¹) which is somewhat similar to the net ecosystem productivity
313 suggested in the literature for more productive boreal ecosystems (Amiro et al. 2010, Bergeron et al. 2007
314 and Luyssaert et al. 2007). Conversely, simulating the observed shorter fire cycle of the flooded area over the
315 next hundred years resulted in a modelled territory that would be a net source of emissions (-34 378 Mg C or
316 -0.5 Mg CO₂ eq GWh⁻¹) instead of a net sink. In other words, in the case of a 127 year-long fire cycle
317 scenario, the creation of the reservoir resulted in fewer emissions than the natural forest (without
318 anthropogenic disturbance). The simulation without any fire pattern, whereby the percentage of burned
319 territory remained the same year after year, only reduced the NPB by 5 000 Mg C, indicating that fire pattern
320 is not an issues in this simulation. Hence, the submerged territory was possibly a net source during the
321 century before the flooding, given the observed 127 year fire cycle. Using the 222 year fire cycle from
322 Bergeron et al. (2010) as a conservative measure in this C footprint calculation, we estimated that this
323 territory would have sequestered a net 300 000 Mg C after 100 years, with a ± 150 000 Mg C range, which
324 corresponds to 4 ± 2 Mg CO₂ eq GWh⁻¹. To sum up, this modeling approach has shown how crucial it is to
325 include fire disturbance dynamics in models for the boreal zone, as it is the principal source of variability and
326 a major cause for concern given the expected impacts of climate change on fire cycle regime in this area (Le
327 Goff et al., 2009).

328

329 *4.4. Forest inventory and yield tables*

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

333 Volume yield estimates were obtained from growth and yield tables southward of the study area,
334 which could have led to an overestimation of C stocking. However, sensitivity tests performed on volume
335 yield tables showed that \pm a 20 % variation created much less fluctuation than fire cycles (Figure 3d vs. 3c),
336 which was then chosen as the range for the confidence interval of the model output, consequently including
337 all the possible variation pertaining to the volume yield tables and to the photo interpreted forest inventory.
338 Stand age class used (0, 30, 50, 70, 90 and 120+ years) could also be a source of error, with mean age
339 obtained by photo interpretation of 59 years as opposed to the 41 years measured in the field by Paré et al.
340 (2011). Should average stand age be 41 years, wood volume from production tables would correspond to 20
341 $\text{m}^3 \text{ha}^{-1}$ less than that in the model; again, this is well within +43 % to -46 % range applied to the model
342 outputs, given the variability induced by fire cycles.

343

344 4.5. Carbon sink/source per unit of electricity produced

345 The 73% forested territory in this study was permanently transformed into a hydroelectric reservoir,
346 corresponding to a change in land use according to the IPCC (Solomon et al., 2007). Hence, this impact
347 should be included in the C footprint of the production of 1 kWh by Hydro-Québec, following the ISO
348 14 067 guidelines (ISO/DIS 14067, 2013). The estimated C balance associated with the upland forest cover
349 change of the Eastmain-1 flooded territory correspond to emissions (or a loss of C sink) of $4 \pm 2 \text{ Mg CO}_2\text{e}$
350 GWh^{-1} . This is 8 times less than the $\approx 32 \text{ Mg CO}_2\text{e GWh}^{-1}$ estimated from Teodoru et al. (2012), but remains
351 within the wide range they reported, i.e. a C sink of $76 \text{ Mg CO}_2\text{e GWh}^{-1}$ to a source of $11 \text{ Mg CO}_2\text{e GWh}^{-1}$.
352 They also estimated NEP to be $117 \text{ mg C m}^2 \text{ d}^{-1}$ with a range from 250 to $-15 \text{ mg C m}^2 \text{ d}^{-1}$ (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 $21 \text{ mg C m}^{-2} \text{ d}^{-1}$ (ranging from 15 to $28 \text{ mg C m}^{-2} \text{ d}^{-1}$). 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 $1.6 \pm 0.8 \text{ Mg CO}_2\text{e GWh}^{-1}$.

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.

370

371 **5. Conclusion**

In conclusion, the creation of the Eastmain-1 reservoir represents a loss of the upland forest C sink of $4 \pm 2 \text{ Mg CO}_2\text{e per GWh}$ 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

376 literature (Teodoru et al., 2012), resulting in a marked reduction of the upland forest cover change
377 contribution to the net C footprint of this boreal hydroelectric reservoir. From 20% of the total C footprint
378 calculated in Teodoru et al. (2012), our study scales down the upland forest contribution to the net C
379 footprint of the reservoir to a mere 3%. Consequently, the long-term net C footprint of the Eastmain-1
380 hydroelectric reservoir would be 130 t CO₂e GWh⁻¹ rather than 158 presented in Teodoru et al. (2012). This
381 study also suggests that the relative contribution of land-use change to the C balance of the creation of a
382 hydroelectric reservoir in the boreal zone can be considered minor, if not negligible, relative to the long-term
383 net C footprint of such boreal hydroelectric reservoirs.

384

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393

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- 490

491 **Tables**

492

493 **Table 1**

494 Carbon stock estimates (CBM-CFS3) in the biomass and dead organic matter pool at year 0 for the
 495 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%

496

497

498

499 **Table 2**500 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)

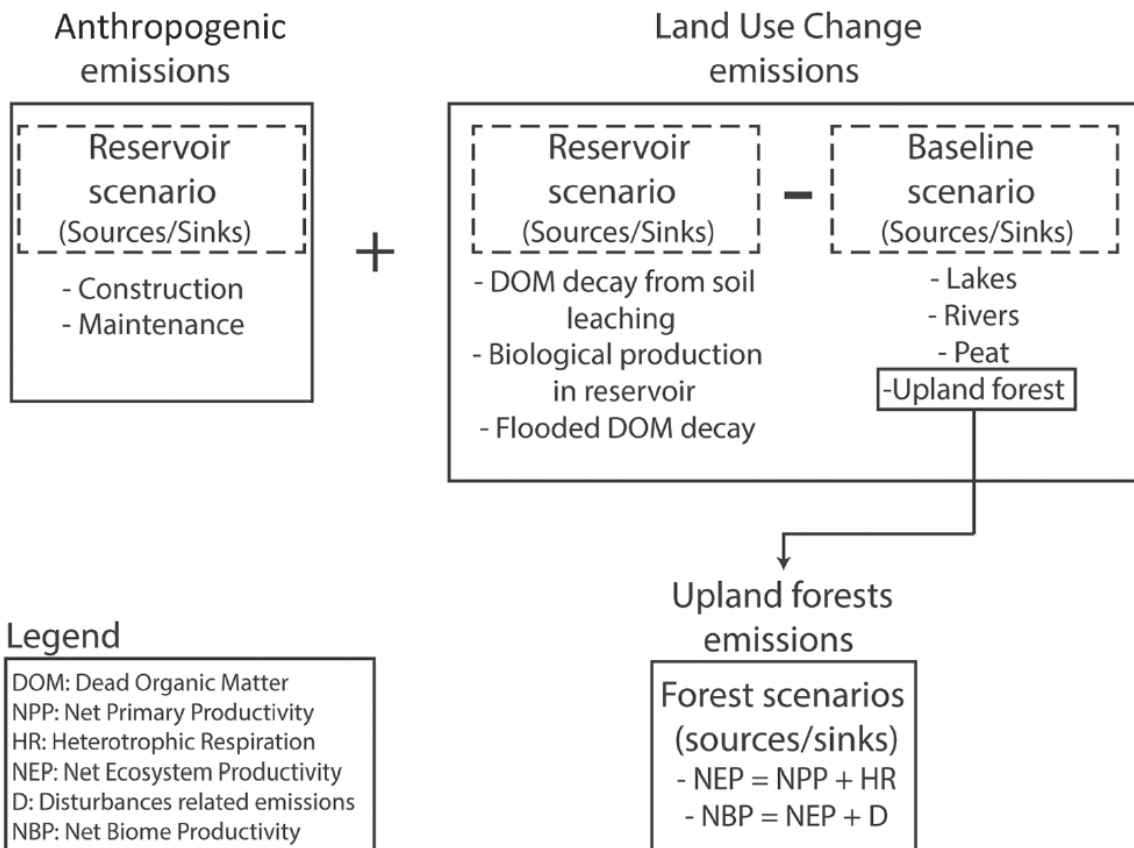
501 ^aNegative values in the table represent C sink. Values between parentheses correspond to

502 lower and upper limit estimates.

503

504 **Figures**

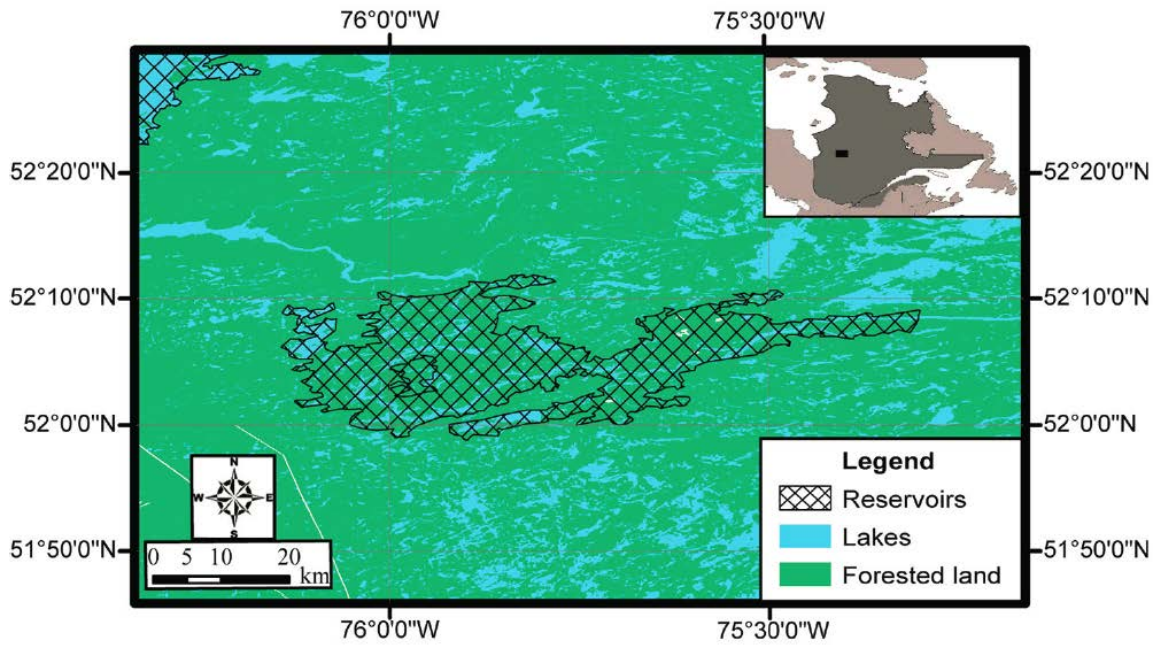
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507 **Fig. 1.** Schematic representation of the C footprint assessment in this study, showing where the upland forest
 508 sources/sinks specific contribution in the overall net C footprint stands.

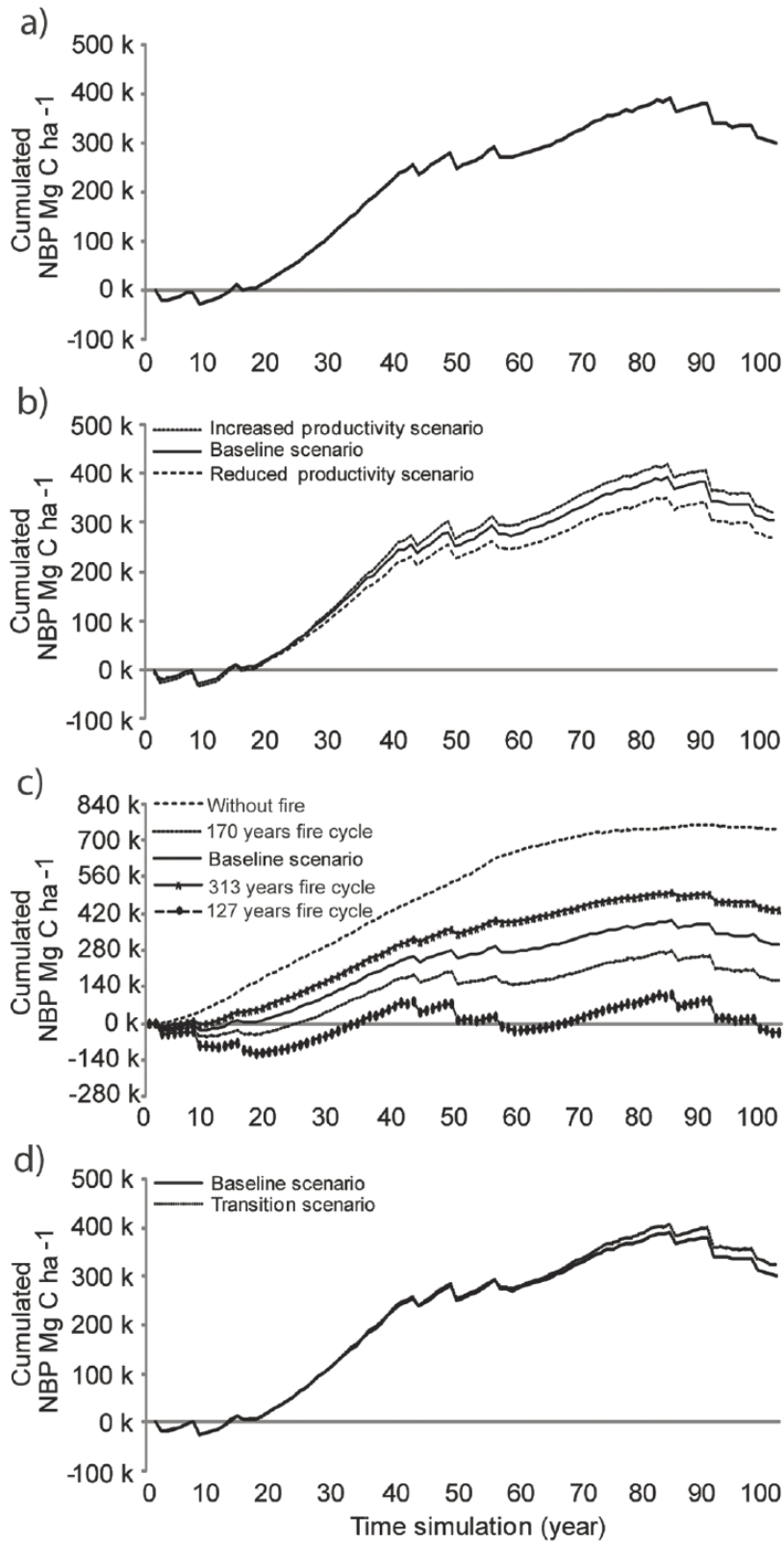
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511 **Fig. 2.** Location of the study area in Québec, Canada (upper right). The squared area in the middle corresponds
512 to the flooded territory, and the whole area represents the sector from which fire data were extracted from the
513 Natural Resources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

514



515

516 **Fig. 3.** Cumulated Net biome productivity (NBP) (Mg C ha^{-1}) of the flooded forested land over 100 year
 517 following (a) baseline scenario, and sensitivity analysis on (b) growth and yield table, (c) fire cycle length and
 518 (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**

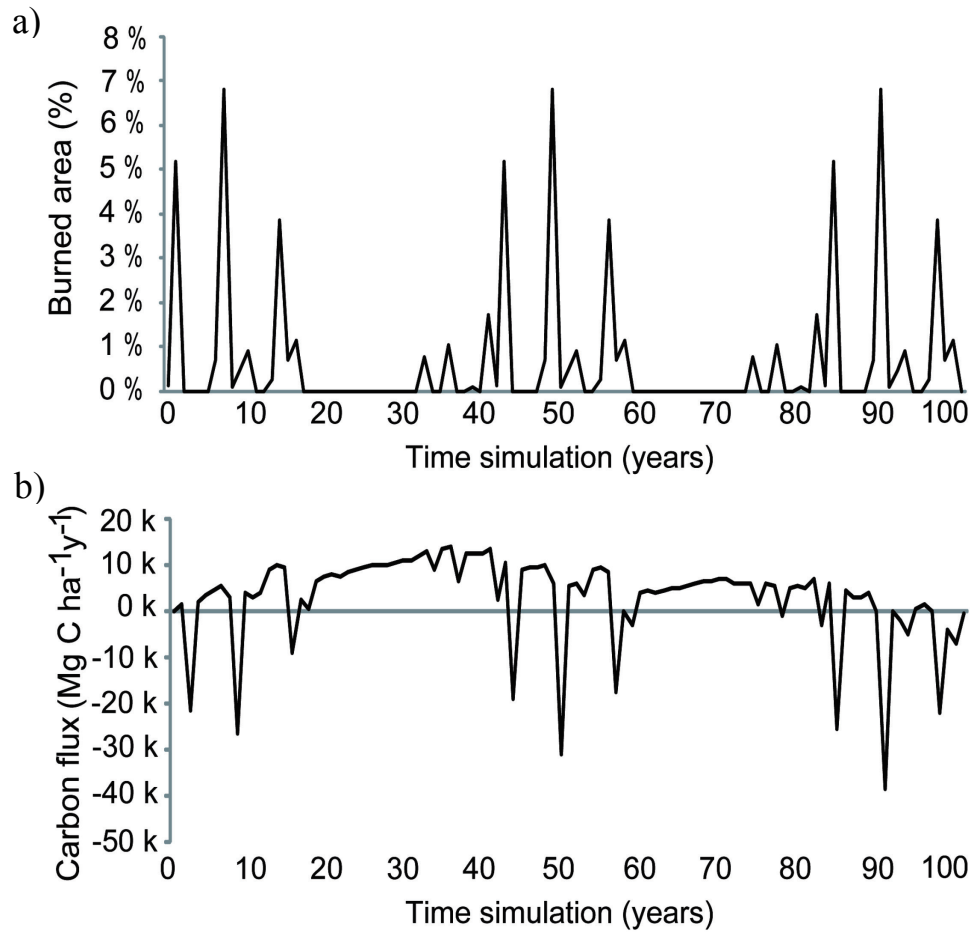


Figure S1. Percentage of yearly burned area (a) of the 43 161 ha flooded forested land inferred from the Large Fire Database from Natural Resources Canada and (b) its relative impact on yearly Net Biome Productivity.

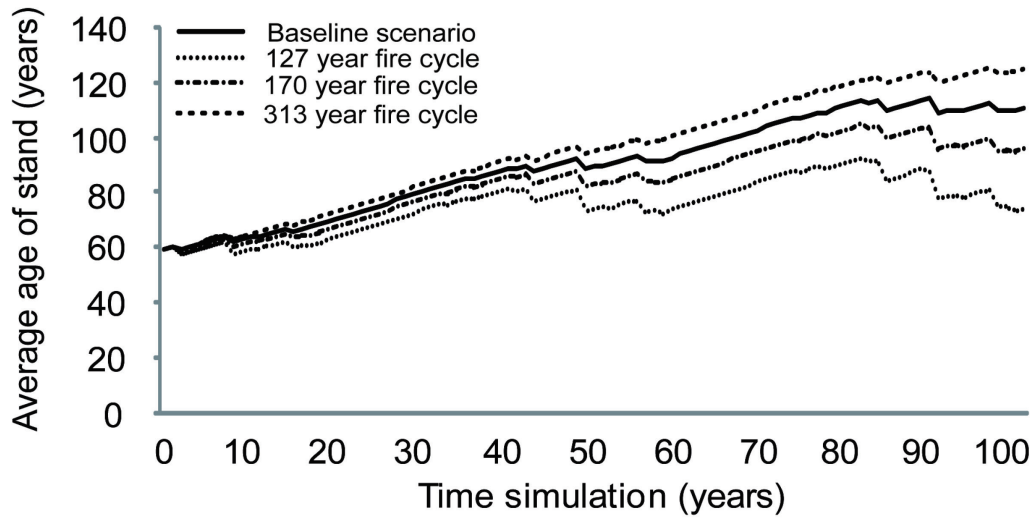


Figure S2. Average stands age under different fire cycle scenarios.

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 (m³)

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