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The Impact of Black Spruce (*Picea mariana*) Plantation on Carbon Exchange in a Cutover Peatland in Western Canada

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1 **The Impact of Black Spruce (*Picea mariana*) Plantation on Carbon Exchange in a**
2 **Cutover Peatland in Western Canada**

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Abstract

Northern peatlands are sinks for atmospheric carbon (C), but peat extraction converts these ecosystems to C sources. Due to a dry regional climate, undisturbed bog peatlands in western Canada often have a tree cover of *Picea mariana* (Mill.) B.S.P. Thus, coniferous forest plantation may be an appropriate land-use for cutover peatlands. This study determined the effect of a seven-year-old *P. mariana* plantation on C balance of a cutover peatland. We measured C stored in *P. mariana* biomass and carbon dioxide (CO₂) and methane (CH₄) fluxes from bare peat at each of four fertilizer doses. Carbon stored in biomass of *Betula papyrifera* (March.) that had spontaneously colonized the post-fertilized site was also determined. Given that the water table remained very deep, and that the Sphagnum-moss/ericaceous shrub peat-accumulating vegetation was not present, the site remained a source of C when only the planted *P. mariana* trees were considered, primarily in the form of CO₂ emissions by soil respiration. However, C accumulation in trees, including *B. papyrifera* biomass resulted in a net C sink in fertilized plots. Results from this study indicate that tree plantation on cutover peatland results may be a suitable land management strategy on sites difficult to effectively rewet.

Introduction

When a peatland is used for commercial peat extraction, vegetation is removed and open ditches are installed to dry the land. Drainage of peatland and extraction of peat leads to large carbon dioxide (CO₂) emissions while greatly reducing methane (CH₄) efflux (e.g., Waddington and Price 2000). The increased aeration of the remaining surface peat significantly enhances organic matter oxidation resulting in the increased CO₂ emission (Tuittila et al. 1999; Waddington and Price 2000). Previous research documents large carbon (C) emissions that remain after peat extraction (e.g., Strack et al. 2014; Waddington et al. 2002). The milled-extracted residual peat soil presents an environment too harsh to allow adequate plant community regrowth (see Poulin et al. 2005 for a review of the causal factors). Therefore, in order to return plant cover and to partly remediate these greenhouse gas (GHG) emissions, restoration techniques have been developed (e.g., Graf and Rochefort 2016) and recently tested in western Canada (Strack et al. 2014). In addition to restoration, forest plantation may be a suitable management option to partially return cutover peatlands' C storage function by C fixation in forest biomass (Renou and Farrell 2005; Mäkiranta et al. 2012), and may be appropriate in western Canada as undisturbed peatlands are largely treed in this region (Vitt 2006). This project assesses the C balance of a forest plantation on a cutover peatland in Alberta, Canada.

Ecological restoration is defined as “the process of assisting recovery of an impaired ecosystem” (Clewett and Aronson, 2007). In Canada, some stakeholders have included recovery of biodiversity, hydrological conditions, and C accumulation as peatland restoration goals (Price and Waddington 2000; Rochefort et al. 2003; Höper et

al. 2008; Nwaishi et al. 2015). This study particularly focuses on the return of carbon accumulating function to a cutover bog post-restoration. Although we consider forest plantation within a restoration context, planting trees on cutover peatland may also be accomplished for biomass harvesting for biofuel or wood products (e.g., Renou-Wilson et al., 2010).

The net accumulation of C in an ecosystem is the difference between inputs via photosynthesis and losses via plant respiration and organic matter decomposition. Ecosystem respiration (ER) includes both autotrophic (plant) and heterotrophic (largely microbial) respiration. The balance of photosynthesis and autotrophic respiration is assimilated to plant structures as net primary production (NPP). While northern peatlands are long-term net sinks for C at an average rate of $23.5 \text{ g C m}^{-2} \text{ yr}^{-1}$ (Loisel et al., 2014), extracted peatland remain large, persistent sources of C to the atmosphere ($90\text{--}400 \text{ g C m}^{-2} \text{ yr}^{-1}$, Waddington et al., 2002). Restoration can return a cutover peatland's C sink function (e.g., Tuittila et al., 1999; Strack et al., 2014). The abundance and the identity of species present at the restored peatland are important drivers of C exchange (Strack et al. 2016) and peat accumulation (Andersen et al. 2013).

Trees can colonize cutover peatlands. *Picea mariana* (Mill) B.S.P (black spruce) is one of the most abundant tree species occurring naturally on Canadian peatlands and has been recommended for plantation on cutover peatlands in Canada (Hugron et al. 2011). However, survival and growth of planted seedlings is frequently limited without suitable fertilization (Bussires et al. 2008). *Betula papyrifera* (March.) (paper birch), a deciduous tree commonly colonizing cutover peatlands (Lavoie & St. Louis 1998), is considered an invasive species on ombrotrophic bogs (e.g., Tomassen et al. 2004), and its

colonization may be encouraged by high fertilization doses (Bravo 2015). *B. papyrifera* colonization can affect the hydrology of a site, as mature birch stands intercept up to 30% of the precipitation and may draw down the water table by 20 cm (Price et al. 2003). Therefore, *B. papyrifera* invasion may also reduce the long-term resilience of peatlands (i.e., ability to withstand periodic stresses such as drought; Fay and Lavoie 2009). However, its rapid growth on cutover peatlands could provide a C sink. Fertilization might also impact the C balance due to changes in organic matter quantity and quality (FAO 2005), and changes in soil moisture due to evapotranspiration when there is high density of *B. papyrifera* colonization (Fay and Lavoie 2009). Very little data exists on the C balance of forest plantation on cutover peat (Maljanen et al., 2010), and thus there is a need to quantify sources and sinks of C in these ecosystems to help inform land management decisions. In particular, more information is required on productivity, accumulation of biomass, and peat soil C fluxes for forest plantations on peat.

Therefore, the objectives of this study were to: 1) determine the C stock in the biomass of *P. mariana* and *B. papyrifera* trees growing in a seven-year-old forest plantation on cutover peat, 2) quantify growing season soil CO₂ and CH₄ losses from the plantation, and 3) evaluate the effect of different fertilizer doses on biomass accumulation and soil C fluxes. The C balance in the study area is compared with other peatland restoration techniques from literature, and the overall result will provide information for land-management decisions. We hypothesized that the highest dose of fertilizer would be most effective in supporting biomass production through tree growth, and therefore offer the largest reduction in net C emissions.

Methods

Study Site

The study area, Paxson Bog (54°40'3.28"N; 113°7'24.57"W), is located near the town of Athabasca, in the east-central part of Alberta, Canada. The 30-year normal (1981-2010) annual precipitation is 479 mm of which 111 mm falls as snow, and average annual temperature is 2.3 °C (http://climate.weather.gc.ca/climate_normals/, Athabasca2 station).

The experimental site was located at the southern end of the cutover peatland. Seven years post-plantation (see below) in 2012, ditches were filled with peat material ~20 m north of the plantation to block the runoff and attempt to keep the plantation area wetter with the goal to improve overall restoration outcomes. There was no clear impact of the rewetting on water table position (remaining deeper than 60 cm below the surface), but peat volumetric water content increased from 23.5% in 2012 to 35.1% in 2013. Eight years post-plantation the study site had mean peat pH of 4.06 ± 0.04 , mean specific conductivity of $933 \pm 139 \mu\text{S cm}^{-1}$, and peat depth was 0.6 ± 0.2 m. The residual peat was weakly decomposed (von Post H3) and mean bulk density was $0.28 \pm 0.04 \text{ g cm}^{-3}$.

Experimental design and fertilization treatment

The restoration plan for Paxson bog was designed as a *P. mariana* plantation with four doses of fertilizer application. Each dose was replicated randomly seven times resulting in a complete randomized design with 28 experimental units. Each unit consisted of a 400 m² plantation of 100 (10 x 10) *P. mariana* seedlings. All planting and fertilization was completed in July, 2005.

The fertilizer used consisted of 20-10-15 (N-P₂O₅-K₂O) NPK fertilizer applied as:
1) high dose (26.8 g/bag), 2) mid dose (17.9g/bag), 3) low dose (8.9 g/bag), and 4) control (non-fertilized). During planting in 2005, each dose of fertilizer was buried beneath each seedling as a “tea bag”. Wet conditions due to precipitation at the time of planting brought the fertilizer to the surface, encouraging spontaneous colonization by *B. papyrifera*. Other than the planted *P. mariana* trees and birch colonization near these planted trees in response to fertilizer availability, little additional plant colonization occurred; most of the peat areas between the planted trees remained bare during the study period.

Environmental variables

During the 8th growing season post-plantation (May to October 2013), two meteorological stations recorded air temperature and precipitation (HOBOware sensors) on site every 30 minutes. During the 7th and 8th growing season post-plantation (July to October 2012 and May to October in 2013) and peat volumetric water content (Θ) was measured systematically seven times in each plot every month with a WET sensor (Delta-T devices). Water table position was deep at the site. Wells installed into the peat profile were nearly continuously dry (aside from May 2013) as water table was deeper than the remnant peat layer (60 cm on average). Therefore, water table is not reported.

Carbon balance of the plantation

The C exchange of the forest plantation was determined by estimating C stored in biomass and C lost from soil as fluxes of CO₂ and CH₄. Equation 1 describes the carbon

balance (ΔC) of the forest plantation considering both *P. mariana* (PM) and *B. papyrifera* (BP), including aboveground (AG) and belowground (BG) NPP and litter (L), and the soil losses of CO_2 and CH_4 measured in $g\ C\ m^{-2}\ d^{-1}$ and estimated as an annual value based on the growing season total (May-October). According to Saarnio et al. (2007), the growing season estimates for both CO_2 and CH_4 emissions have been converted to annual estimates by increasing them by 15% to account for non-growing season emissions. While simplistic, this correction factor has been used in numerous studies and in development of emission factors accounting for land-use change emissions from peatlands (Blain et al. 2014). Carbon balance was determined separately for each fertilizer dose.

$$\Delta C = (PM_{AG} + PM_{BG} + PM_L) + (BP_{AG} + BP_{BG} + BP_L) - (CO_2 + CH_4) \quad (1)$$

For individual carbon fluxes, we present all values as positive for clarity, but for the C balance we use the convention that positive values indicate accumulation of C in the ecosystem (tree + soils). The unit for all fluxes was $g\ C\ m^{-2}\ yr^{-1}$.

Biomass models

The basal diameter and height of all *P. mariana* within the central 6x6 planted trees of each plot was measured, resulting in an area of 100 m^2 for each plot. The *B. papyrifera* survey determined height, basal diameter, and number of branches growing from the same spot as *P. mariana* within a circle of radius of 50 cm. This accounted for >90% of *B. papyrifera* individuals within the 100 m^2 study zone at each plot. Tree surveys were conducted on the central 6x6 planted trees of each plot to avoid edge effects, particularly on the edge of the experimental units near remnant ditches. The main

colonizer species has been identified as *B. papyrifera*. In the present study, *B. papyrifera* density was high in many areas and for this reason not all the individuals that colonized the site were identified, but the majority were likely *B. papyrifera* and will be referred to as such throughout the paper. Although, western Canada is not a normal distribution of *Betula populifolia* (March) occasional seedlings have been identified on site, and this species has been described as a good pioneer species on cutover peatland (Lavoie and St. Louis 1998) and could account for some of the reported *Betula* biomass. Analysis of variance (ANOVA) was used to assess differences in seedling survival, basal diameter and height between the fertilizer treatments.

Aboveground biomass allometric relationships were based on 134 seven-year-old trees harvested for both species in August 2012, representing various fertilizer doses and basal diameter, including 76 *B. papyrifera* and 58 *P. mariana*. All the trees were cut at the stem base (soil surface). Biomass samples were dried for 72 hours at 40°C at the Northern Forest Centre in Edmonton, AB. The dry weight of samples was determined for the whole tree and then for each component (stem, branch, and leaves). Wood and bark were not separated. Loss of some material during separation of components led to their underestimation, particularly for *P. mariana* leaves (resulting in biomass components not summing to the total biomass; Table 1). Therefore, total biomass was estimated using the allometric equation for the whole sample to avoid underestimation. Since *B. papyrifera* litter production was estimated based on the allometric equation for leaves, it may be underestimated, but we estimate by less than 10%. Some root samples were collected, but due to the difficulty of the collection and low sample numbers, a previous model was used to estimate belowground biomass based on aboveground biomass (Li et al. 2003),

198 applying hardwood and softwood equations for *B. papyrifera* and *P. mariana*,
199 respectively (hardwood: belowground biomass = $1.576(\text{aboveground biomass})^{0.615}$;
200 softwood: belowground biomass = $0.222(\text{aboveground biomass})$). As the belowground
201 equations are not specific to peatland nor to young trees, this contributes additional error
202 to our total biomass estimate, but allows consistent estimation of belowground biomass
203 across all treatments.

204 Allometric equations based on Lambert et al. (2005) set nonlinear regression
205 equations for each biomass compartment, which we have also adopted in this study.
206 While many researchers have reported that diameter at breast height (DBH) is an
207 adequate biomass predictor for mature boreal tree species, the small size of the trees at
208 our research site suggested that the stem diameter at soil surface (basal diameter) would
209 be more appropriate, especially for the slow growing species in the boreal forest (Bond-
210 Lamberty et al. 2002). There was heteroscedasticity of residuals of the relationship
211 between diameter and height for *P. mariana* and *B. papyrifera* with fertilizer as an
212 additional fixed effect, and this often occurs in biomass data and is caused by an increase
213 of residual variance as basal diameter increases (Lambert et al. 2005). The
214 heteroscedasticity was addressed by $\log_{10}$ transformation. Since the difference between
215 different doses of fertilizer was not significant for total biomass (ANOVA, $p > 0.05$), all
216 fertilizer doses were combined as “fertilized” for the biomass models. Models were
217 performed with a 95% significance level (Lambert et al. 2005). A general linear model
218 (IBM SPSS version 21) was used to build a model with total biomass as the dependent
219 and continuous variable, and basal diameter as the predictor continuous variable,
220 considering fertilization (control vs. all fertilizer treatments grouped together) as a fixed,

221 categorial factor. Similar allometric equations were evaluated for each component for
222 each species (*i.e.*, stems, branches, leaves). Once developed, the models were applied for
223 each tree measured in the survey to estimate the total biomass of the forest plantation.

224 To estimate C stored in the tree biomass, C content in dry biomass was analysed
225 by combustion in a pure oxygen environment using a Perkin Elmer model 2400 series II
226 CNH analyzer (Chemistry Analytical Facility, University of Calgary). It was determined
227 that each dry gram of wood was equivalent to 0.51 gram of C for both tree species. Birch
228 leaves were 0.49 g C per dry gram biomass. The biomass models were used to estimate
229 the total tree aboveground biomass, and then biomass for each plot was summed,
230 converted to units of C and divided by the plot surface area (g C m^{-2}) and represents
231 forest plantation C uptake in $\text{g C m}^{-2} (\text{7 yr})^{-1}$. For birch trees only the wood components
232 (total biomass – leaf biomass) were included as the leaves were considered the litter
233 component (see below). These values were converted to an annual flux assuming a
234 constant growth of the trees every year and therefore it represents the average annual net
235 primary productivity (NPP) over this time period.

236 Litter for *B. papyrifera* was estimated based on the leaf biomass during the
237 sampling year. This does not account for litter produced in previous years, but as little to
238 no litter was observed on site, the underestimation is likely small; if most of the litter is
239 not deposited on site (*e.g.*, blown by wind) including all of the present year litter will
240 results in an overestimation. Litter production for *P. mariana* was estimated at 17% of
241 NPP according to Szumigalski and Bayley (1996). Belowground litter production was not
242 measured, but was assumed to be small given the young age of the stand and thus was not
243 included. This adds some uncertainty to the C balance estimates.

Carbon dioxide (CO₂) flux: soil respiration

Soil CO₂ fluxes were measured using closed chamber techniques (e.g., Strack et al. 2014) in the centre of each plot, monthly between May and October 2013. This location was equidistant from, and at least 50 cm away from the four closest trees and thus any contribution to respiration from tree roots is considered small. Excavation of several trees during collection of biomass samples supported this assumption although some root respiration may be included in high fertilizer dose plots and this will result in an underestimation of total C uptake by the plantation as a small portion of root respiration will be double counted. All plots on site were measured within 2-3 days during an intensive field campaign. A collar (60 cm x 60 cm x 15 cm deep) was inserted ~10 cm into the ground and an opaque chamber (60 cm x 60 cm x 30 cm high), equipped with a battery-powered fan to mix the headspace was placed on the collar. Water was added to the collar to create an air-tight seal with the chamber. Carbon dioxide concentration was measured every 15 seconds for 1.5–2 minutes in the chamber headspace using a portable infrared gas analyzer (IRGA; EGM4, PP systems) and flux was determined from the linear change in concentration over time. We inspected each flux measurement for evidence of CO₂ flushing effect that can result in non-linear trends in concentration change (e.g., Koskinen et al., 2014), but did not observe this in the data. Temperature of the peat profile at depths 2, 5, 10, 15 and 20 cm was also recorded using a thermocouple thermometer.

We estimated peat CO₂ emissions using an empirical model according to Lloyd and Taylor (1994):

267
$$SR = SR_{ref} \times e^{E0 \left[\frac{1}{T_{ref}-T_0} - \frac{1}{T_a-T_0} \right]}$$
 (2)

268 where SR_{ref} is soil respiration rate (SR) at the reference temperature ($T_{ref} = 283.5$ K), $E0$
269 is the activation energy, T_0 is the temperature at which biological processes start (237.48
270 K) and T_a is the air temperature (K) at the time of measurement. Although soil
271 temperature is likely a better predictor of SR than air temperature, our soil temperature
272 probe was damaged during the study and data was lost, leaving only a continuous record
273 of air temperature available. Data from all plots on all sampling dates for a given
274 fertilizer dose were combined to create one model per dose. Models were fit using non-
275 linear regression in R (nl; R Core Team, 2016). Error in modelled SR (E_{SR-mod}) was
276 determined according to Aurela et al. (2002):

277
$$E_{SR-mod} = \sqrt{\sum_{i=1}^n \frac{(SR_{obs}-SR_{mod})^2}{(n-1) \times n}}$$
 (3)

278 where SR_{obs} is the measured SR, SR_{mod} is the modelled SR and n is the number of
279 measurements. Daily error was estimated and multiplied by the number of days in the
280 study period to estimate error during the May-October period. Given that wintertime
281 fluxes were not measured, we assumed +/- 50% error on the 15% we added to account for
282 the winter period. Error in all other estimated components (e.g., biomass) of the C
283 balance was based on the standard error of the mean across the replicate plots. Error in
284 the C balance was assessed by summing the error estimated for each component.

285 To analyze the effect of fertilizer dose on SR a generalized linear mixed effects
286 model (LMM) analysis using the package *nlme* (Pinheiro et al., 2016) in R (R Core
287 Team, 2016) was completed with fertilizer dose as a fixed effect and plot as a random
288 factor to account for repeated measures. If a significant difference occurred, Tukey
289 pairwise comparisons were completed using the package *multcomp* (Hothorn et al.,

2008). We also used an LMM to assess the variance in SR explained by air temperature and soil moisture content. We used the package MuMIn (Barton, 2016) to determine the R^2 of the LMM models and report only the portion of variance explained by fixed factors.

Methane flux

During the intensive field campaigns each month, CH_4 flux was measured using the closed chamber method at 10 random plots in locations coincident with CO_2 flux measurement described above, and additionally at four remnant ditches over bare peat. The site was very dry such that even in the remnant ditches water table was far below the peat surface. An opaque plastic chamber (60 cm x 60 cm x 30 cm), equipped with a battery-powered fan to mix the headspace was placed on top of the collars on the ground, with water in the groove to create an airtight seal. Headspace samples were collected with a syringe equipped with a three-way valve at 7, 15, 25 and 35 minutes after sealing the chamber. The air samples were transferred to pre-evacuated Exetainers (Labco Ltd.). Samples were analyzed in the Department of Geography, University of Calgary using a Varian Gas Chromatograph 3800 (GC; Agilent Technologies Canada Inc.) equipped with a flame ionization detector. The GC was calibrated for potential instrumental errors or drift after every eight samples. Inside the chamber, air temperature was recorded at the same time the gas samples were collected using a thermocouple. Two ambient air samples were also collected to use as the reference for CH_4 concentration at the beginning of sample collection (i.e., 0 minute). Methane flux was estimated as the linear change in CH_4 concentration in the chamber over time, except in cases where the change in concentration was within the analytical precision of the GC (5%). In these cases, the

flux was considered to be zero. When a linear change in concentration was not observed and values varied greater than the GC precision, the value was removed from the analysis resulting in loss of 29% of the data. Soil temperature in the peat profile at 2, 5, 10, 15, 20, 25, and 30 cm depths were monitored during CH₄ flux measurement using thermocouple thermometers. Seasonal total CH₄ was estimated by multiplying the mean flux by the number of days in the study period and adding 15% to account for non-growing season release according to Saarnio et al. (2007).

In order to evaluate the effect of fertilizer and ditches on CH₄ flux, a LMM was used with fertilizer dose/ditch as a fixed factor and plot included as a random factor to account for repeated measures.

Results

Environmental conditions

Total precipitation during the year of assessment (May to October 2013) was 264 mm (Paxson meteorological station). The site received the most of precipitation (95 mm) in July (Figure 1). Mean air temperature during the study period was 15.5 °C. During the study period, mean peat volumetric water content (Θ) was $35.1 \pm 0.8\%$ with peat drying between May and July and then wetting up again into October (Figure 1). Water content had high variability both over the growing season and between plots. In general, the study site was dry despite blocking ditches near the plantation, seven years post-plantation (2012), with water table deeper than the remnant peat depth (~60 cm).

Effect of fertilizer dose on tree growth

Survival of *P. mariana* was greater at plots where nutrients were added to the tree plantation (ANOVA, $F_{3, 1007}=32.673$, $p<0.001$). However, there was no significant difference between the doses. Results were similar for basal diameter. Consequently, we pooled all the fertilized data as presented in Table 1. Non-fertilized areas had a significantly lower *P. mariana* survival of 65% whereas it was 91% for the fertilized plots. Seven years post-plantation trees in the *P. mariana* stand had a mean $\pm$ standard error basal diameter of 1.2 ± 0.1 and 1.8 ± 0.1 cm and height of 52 ± 2 and 117 ± 2 cm for unfertilized and fertilized plots, respectively. *B. papyrifera* basal diameter and height were on average 1.8 ± 0.1 cm and 79 ± 6 cm for unfertilized experimental units, while fertilized areas had average basal diameter and height of 2 ± 0.1 cm and 144 ± 3 cm (Table 1).

Aboveground biomass equations exhibited significant fits with basal diameter (Figure 2). In allometric equations, fertilizer was a significant factor for total biomass for both *P. mariana* and *B. papyrifera* suggesting that fertilization not only increased tree size, but also the total biomass present for a tree of a given basal diameter (Figure 2). Fertilization was also significant in the equations for some, but not all biomass components (Table 2).

Biomass of the plantation

Using the parameters from Table 2, biomass was estimated for all plots. Both tree species responded to fertilizer by more than doubling in biomass at fertilized compared to non-fertilized plots (Table 1). The mean equilibrium storage for a *P. mariana* individual aboveground biomass for fertilized plots was 343.2 ± 8.9 g of which 19% was stem

biomass, 21% was branch biomass and 33% leaf biomass, and for the non-fertilized plots biomass was 131 ± 10 g of which 11.4% was stem biomass, 17.8% was branch biomass and 33.1% was leaf biomass. The mean tree below ground biomass was 76.2 ± 2.0 g for the fertilized plots and 29.1 ± 2.2 g for non-fertilized plots. Considering all living trees in the plantation, mean *P. mariana* biomass was 29 ± 5 , 69 ± 10 , 64 ± 9 and 85 ± 8 g C m⁻² at unfertilized, low, mid and high fertilizer doses, respectively. Considering the 7 years since the plantation was established, total average annual biomass accumulation (net primary production, NPP) for *P. mariana* was between 3 ± 1 g C m⁻² yr⁻¹ at unfertilized plots and 10 ± 1 g C m⁻² yr⁻¹ at plots with the highest fertilizer dose (Table 4). Litter was estimated as 0.6 ± 0.1 to 1.7 ± 0.2 g C m⁻² yr⁻¹, depending on the dose of fertilizer (Table 4).

The total equilibrium aboveground biomass per main stem for the colonizer species, *B. papyrifera* was 223 ± 13 g for fertilized plots, of which 28% was stem biomass, 16% was branch biomass, and 12% was leaf biomass. For the non-fertilized plots total biomass was 89 ± 9 g of which 39% was stem biomass, 28% was branch biomass and 20% was leaf biomass. The *B. papyrifera* colonization on the edge of the plots, adjacent to ditches, has not been quantified, but had a higher density and would be expected to have a higher biomass than the fertilized plots. The mean of calculated belowground biomass per main stem was 37 ± 1 g for the fertilized plots and 23 ± 1 g for non-fertilized plots. Considering all individuals in the sample area, total *B. papyrifera* woody biomass (aboveground stem + branches + belowground) across the study plots was 112 ± 41 , 1320 ± 640 , 1760 ± 730 and 1880 ± 600 g C m⁻² at unfertilized, low, mid and high fertilizer doses, respectively. The mean annual woody tissue NPP for *B.*

papyrifera was between 14 ± 6 and 250 ± 81 g C m⁻² yr⁻¹ across the treatments (Table 4).

Litter was estimated as the leaf biomass in the year of study and ranged from 27 ± 1 at unfertilized plots to 350 ± 16 g C m⁻² yr⁻¹ at high fertilizer dose (Table 4).

Carbon dioxide (CO₂) flux

Seven years post-plantation, there was a significant effect of fertilizer dose on peat CO₂ flux ($F_{3,24} = 3.70$, $p=0.026$) where the medium dose had higher CO₂ emissions than all other treatments. As there were differences between doses, empirical models to estimate CO₂ emission according to air temperature were developed for each fertilizer dose separately (Figure 3). There was a significant effect of both air temperature (Figure 3) and soil moisture on CO₂ emissions (Figure 4a), where CO₂ emission was higher with higher temperature and lower soil moisture content. Soil temperature also explained a significant amount of the variation in ER (Figure 4b; $F_{1,82} = 97.6$, $p<0.001$, $R^2 = 0.42$).

All empirical models for estimating peat CO₂ emissions as soil respiration were significant. Parameters are reported in Table 3. Estimated CO₂ emissions during the study period (May 1 – October 7) were between 280 ± 120 g C m⁻² yr⁻¹ at unfertilized plots and 430 ± 240 g C m⁻² yr⁻¹ at the medium dose fertilized plots (Table 4). Emission of CO₂ during the non-growing season was estimated at 42-64 g C m⁻² yr⁻¹.

Methane flux

On average ($\pm$ standard error), CH₄ flux was 13 ± 7 mg CH₄ m⁻² d⁻¹. From field plots mean CH₄ flux was 14 ± 8 , 8 ± 6 , 17 ± 6 and 5 ± 10 mg CH₄ m⁻² d⁻¹ from unfertilized, high, mid and low fertilizer dose plots, respectively indicating net emission

of CH₄ in all cases. There was no significant difference between plots in ditches and field plots with any fertilizer dose, or between the fertilizer doses ($F_{4,25}=0.32$, $p=0.864$). Ditches were dry throughout the study period. As there were no significant differences among doses or between fields and ditches, we estimated total CH₄ flux from both fields and ditches using a mean value for all plots resulting in an annual estimate of CH₄ emission of $1 \pm 1 \text{ g C m}^{-2}$.

Net carbon balance of a forest plantation on a cutover peatland

To determine the total annual net C exchange of the plantation, the total biomass for *P. mariana* and *B. papyrifera*, including above and belowground NPP and litter were summed and then total soil respiration subtracted for both non-fertilized and fertilized plots (Equation 1; Table 4). Fertilization improved tree growth for both species. Particularly, *B. papyrifera* colonization increased with fertilizer dose and greatly increased C accumulation in biomass at fertilized plots. Since *B. papyrifera* colonization was an indirect effect within the forest plantation, net C balance was calculated considering: 1) *P. mariana* alone and 2) with the inclusion of *B. papyrifera* biomass.

The total net C balance for the *P. mariana* plantation alone was $-318 \pm 122 \text{ g C m}^{-2} \text{ yr}^{-1}$ at unfertilized plots and -485 ± 248 to $-367 \pm 172 \text{ g C m}^{-2} \text{ yr}^{-1}$ across the fertilized plots, depending on dose (Table 4), where negative values indicate a net source of C to the atmosphere. Considering biomass accumulated by *B. papyrifera* colonization, the unfertilized plots remained a carbon source with a C balance of $-275 \pm 122 \text{ g C m}^{-2} \text{ yr}^{-1}$. As higher doses of fertilizer resulted in greater *B. papyrifera* biomass, carbon uptake was greatest at the high fertilizer dose with a C balance of $249 \pm 191 \text{ g C m}^{-2} \text{ yr}^{-1}$.

Discussion

During the first seven years following planting of *P. mariana* seedlings, fertilization has had an effect on ecosystem C balance by supporting greater biomass production and therefore, offers a larger C storage capacity. The application of fertilizer was the principal variable that determined the *P. mariana* survival after seven years and its biomass production. Likewise, a study on black spruce plantations on cutover bogs in eastern Canada observed that tree survival was improved by 25 to 40% when fertilized and the biomass doubled to tripled (Caisse et al. 2008). Net primary production of *P. mariana* in the present study was estimated to be on average 9 ± 1 to 12 ± 2 g C m⁻² yr⁻¹ for fertilized plots and 4 ± 1 g C m⁻² yr⁻¹ for unfertilized plots, higher than values reported for the same species in eastern Canada planted on cutover peat ($0.3 - 0.9$ g C m⁻² yr⁻¹, Caisse et al., 2008), but much lower than NPP of 33 - 98 g C m⁻² yr⁻¹ reported from this species in western Canadian bogs (Wieder et al., 2009; Munir et al. 2014). Low rates of NPP determined in the present study are partially due to the density of the plantation, and its young age, but may indicate that conditions present on cutover bogs present additional challenges for growth of *P. mariana* seedlings (e.g., Caisse et al. 2008). Despite increased productivity in response to fertilization, when considering only the planted *P. mariana* seedlings, both fertilized and unfertilized plots remained net sources of atmospheric C during the study period likely due to low productivity and large losses of CO₂ from the soil.

While the addition of fertilizer enhanced *P. mariana* growth and helped increase total plantation biomass, it also helped support colonizing *B. papyrifera*. Dense *B.*

papyrifera colonization had a direct effect on C fixation through increasing tree NPP. In fact, in fertilized plots the high number of *B. papyrifera* stems resulted in biomass that was much greater than *P. mariana* biomass (Table 4) resulting in an estimated C sink at all fertilizer doses. However, this C sink depends on *B. papyrifera* litter production that was calculated as total leaf biomass during the study year. Since some leaf biomass was lost during processing of samples for allometric equations, litter contributions may be slightly underestimated, although we estimate this is less than 10%. Moreover, as little litter was observed on site from previous year's litter production, it is likely that many of the leaves are blown off site and may not contribute to the ecosystem C stocks. Even with this consideration and the high uncertainty in the C balance estimate due to uncertainty in soil CO₂ flux estimates and spatial variability between plots, it is likely that the high dose of fertilizer has resulted in a C sink. Most reported biomass values for planted trees on cutover peatlands are from Europe for fast growing species that could be used for biomass energy production and could be analogous to *B. papyrifera* in the present study. For example, Hytönen and Kaunisto (1999) report average dry biomass of 37.6 t ha⁻¹ for 14-year-old unfertilized stands of birch (*Betula pendula* and *Betula pubescens*) and willow (*Salix* spp.), while biomass reached 61.4 and 61.8 t ha⁻¹ in similar-aged ash and PK fertilized stands, respectively. Average carbon uptake in biomass of *Betula pubescens* on cutover peatlands in Ireland was 1.6 to 2.9 t C ha⁻¹ yr⁻¹ (Renou-Wilson et al. 2010), a similar rate to that measured in fertilized plots for *Betula papyrifera* in the present study of 191–266 g C m⁻² yr⁻¹ (~1.9–2.7 t C ha⁻¹ yr⁻¹). This rapid growth suggests that biomass energy production on cutover peatlands in Canada could also be an after-use option, although the ecosystem is likely to function as a woodland as opposed to a peatland.

While a dense population of *B. papyrifera* makes an important contribution to C uptake, it may also influence the site's hydrology, even during the early establishment phase (seedling) by increasing transpiration (Fay and Lavoie 2009). These drier conditions could indirectly affect the plantation C balance by increasing organic matter decomposition (Mäkiranta et al. 2012). Moreover, plots with high dose of fertilizer may also have increased heterotrophic soil respiration due to substrate supplied by birch litter and an increase of microbial activity (Mäkiranta et al. 2007). In fact, respiration rate was higher at fertilized plots in this study, resulting in greater soil C losses during this early period of plantation establishment. These increased losses should be balanced over time by increased litter additions to the soil.

Soil respiration during the 8th year post-plantation growing season at Paxson bog (and used to estimate mean C loss during the first seven years post-plantation) was estimated on average as 280–430 g C m⁻² yr⁻¹. Comparing these values with previous research, the soil respiration at Paxson was similar to cutover bare peat in Quebec with reported growing season soil respiration of 76–397 g C m⁻² season⁻¹ (Waddington et al. 2002; Waddington et al. 2010) and is also in the range of emissions of 126–680 g C m⁻² season⁻¹ on cutover bare peat reported for Alberta (Strack et al. 2014). Since soil respiration remained within the range of unrestored peatlands, this indicates that the ditch blocking activities had little impact on soil C emissions, not surprising given the dry conditions that remained on site during the study period. Soil moisture was monitored during soil respiration measurements, and although highly variable across each plot, it was correlated to soil respiration (Figure 4a) with higher respiration under drier

conditions. Therefore, the dry conditions that persisted on site throughout the study period contributed to the large soil C emissions.

Similarly, dry conditions resulted in low CH₄ flux at this site that did not make an important contribution to the net C balance. Studies on other abandoned cutover peatlands also report very low CH₄ flux and in some cases CH₄ consumption (e.g., Waddington and Day 2007; Strack and Zuback 2013). While several studies report that remnant drainage ditches can be hotspots for CH₄ flux (e.g., Waddington and Day, 2007; Cooper et al., 2014) and thus must be characterized, CH₄ flux from remnant drainage ditches was not higher than adjacent fields in the present study, also likely due to dry soil conditions that existed even in the ditches. The small emissions measured in the present study mainly result from wet conditions in spring.

For this study, dissolved organic carbon (DOC) was not measured. Although it could represent part of the C balance, DOC export was likely not important due to dry conditions that resulted in no water discharge from the site, at least during the growing season. However, further studies should measure DOC export to estimate its contribution to C balance of forest plantation on cutover peat.

Forest plantation on cutover peatlands is an alternative after-use technique to reduce GHG emissions through C storage in tree biomass, although the present study suggests that growth of the planted *P. mariana* alone does not result in a C sink over the first seven years. As the trees mature, increases in growth rate may create an annual C sink, but large soil C losses will still occur over this time period. As seen on fertilized sites where *B. papyrifera* invasive growth has been rapid, increasing aboveground biomass can balance the loss of C by peat oxidation (Bhatti et al. 2006), temporarily

preventing a change in C stocks in forested peatland ecosystems. However, if the trees within the forest plantation are later harvested for wood products, this C could be released to the atmosphere or stored in wood products (e.g., Minkinen et al. 2002) depending on the fate of the lumber and thus may not represent long term storage of C.

Strategies to improve C sequestration in the forest plantation

If plantation of *P. mariana* is considered as part of a restoration strategy that aims at returning a functional peatland ecosystem, strategies to enhance C uptake without relying on fast-growing trees such as *B. papyrifera* need to be considered. Fertilized plots were most effective in supporting biomass production through forest growth, and therefore offer the largest reduction in net C emissions, although care must be taken to prevent widespread movement of the fertilizer if colonization “weedy” species are to be avoided.

Since dry conditions on the site resulted in large soil C losses, more effective rewetting of the forest plantation could potentially reduce soil C losses, as rewetting organic soils reduces peat oxidation (Blain et al., 2014). In Europe, restoration measures are often limited to hydrological management (Yli-Petays et al. 2007), resulting in a reduction of C emission from soil (e.g. Tuittila et al. 1999). Nevertheless, rewetting may also lead to increased CH₄ emissions (e.g., Waddington and Day, 2007), particularly since input of C from root exudates and litter has the potential to increase rates of CH₄ production and emission (Trinder et al. 2008), and consequently increase decomposition of peat following restoration (Basiliko et al. 2007).

The reintroduction of understory vegetation could be an additional management activity to increase C uptake within the plantation. Previous research (e.g. Rochefort 2000; González and Rochefort, 2014; Strack et al. 2014) has demonstrated the effectiveness of “moss layer transfer” techniques on cutover peatland to establish wetland species and improve ecosystem services, including C uptake. Introducing forest floor vegetation during tree seedling plantation would likely help to improve C uptake and may also avoid colonization by undesirable species (Hugron et al. 2011).

Conclusions and general management recommendations

Any fertilizer dose tested in this study resulted in greater biomass accumulation, with fertilized sites acting as C sinks due to *B. papyrifera* colonization. When forest plantation is used as part of ecological restoration, the presence of *B. papyrifera* on site may have an impact on additional ecosystem services and ability to achieve restoration goals (e.g., by preventing return to wetland ecosystem, enhancing transpiration, etc.).

Fertilization is needed for tree establishment and growth on cutover peat in Canada (this study, Bussires et al. 2008, Caisse et al. 2008). Reducing the dose of fertilizer, and maintaining greater volumetric water content and peat depth could help reduce the density of *B. papyrifera* colonization (Fay and Lavoie 2009, Bravo 2015). Straw mulch may also reduce the high density of *B. papyrifera* colonization (Graf and Rochefort 2009), but was not tested in the present study. Rewetting is also important for limiting soil respiration. The ditches should be blocked close to the restored site to recover the hydrology and maintain shallow water table after restoration. The initial water supply after tree plantation could determine seedling survival and colonization by non-

target species. While the present study site was too dry on average (water table consistently deeper than the bottom, more than 60 cm below the surface, of the remnant peat) to determine the optimum water table for *P. mariana* growth and limitation of *B. papyrifera* colonization, Hugron et al. (2011) recommend a target water table of 40 cm below the surface.

Overall, peatland restoration using the moss layer transfer technique may be more desirable for returning peatland ecosystem services (e.g. Bonn et al. 2016; Strack and Zuback 2013); however, on some dry areas within cutover peatlands, restoration may not be a realistic target. In these cases, forest plantation might be appropriate when the recommendations above are followed, such that forest plantation activities within the restoration project also include rewetting and understory establishment.

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Tables

Table 1. Mean ($\pm$ standard error) by tree for survival, basal diameter, height, number of stems from the main trunk (central stem emerging from the soil), aboveground biomass divided by compartments and belowground biomass estimated Li et al. (2003) equations for *P. mariana* and *B. papyrifera* survey seven years after plantation by fertilizer treatment.

Species		<i>P. mariana</i>		<i>B. papyrifera</i>	
Treatment		No Fertilizer	Fertilizer	No Fertilizer	Fertilizer
Survival		65%	91%	n/a	n/a
Number of stems per main trunk per m ²		1 0.23 $\pm$ 0.04	1 0.33 $\pm$ 0.04	4 $\pm$ 1 1.6 $\pm$ 0.7	12 $\pm$ 1 8.5 $\pm$ 5
Height (cm)		52 $\pm$ 2	117 $\pm$ 2	79 $\pm$ 6	144 $\pm$ 3
Basal diameter (cm) ^a		1.2 $\pm$ 0.1	1.8 $\pm$ 0.1	1.8 $\pm$ 0.1	2.0 $\pm$ 0.1
Total ^b		131 $\pm$ 10	343 $\pm$ 9	89 $\pm$ 9	223 $\pm$ 13
Aboveground biomass (g)	Leaves	70 $\pm$ 5	113 $\pm$ 3	28 $\pm$ 2	39 $\pm$ 2
	Branches	40 $\pm$ 2	62 $\pm$ 1	42 $\pm$ 4	60 $\pm$ 3
	Stem	14 $\pm$ 1	69 $\pm$ 2	32 $\pm$ 3	94 $\pm$ 4
Belowground biomass (g)		29 $\pm$ 2	76 $\pm$ 2	23 $\pm$ 1	37 $\pm$ 1
Total biomass (g) ^b		160 $\pm$ 10	419 $\pm$ 9	113 $\pm$ 9	259 $\pm$ 13

a. Basal diameter of individual stems. For *P. mariana* this is the central stem (i.e., trunk), whereas for *B. papyrifera* this is the diameter of the individual stems emerging from the central trunk.

b. Total tree is the total aboveground biomass estimated using the allometric equation computed for the whole individual, where an individual consists of one stem with associated branches and leaves. As individual components were computed using component allometric equations, they may not sum to the total tree. Loss of some material during component separation results in their underestimation.

c. Total biomass is the sum of aboveground (total tree) and belowground biomass

Table 2. Parameters and statistical information for aboveground biomass allometric equations^{a,b}

Species/component	a	b	c	Std. Error
<i>P. mariana</i> / total biomass	1.656	2.102	0.144	0.066
<i>P. mariana</i> / leaves	1.596	1.728	n.s. ^c	0.072
<i>P. mariana</i> / branches	1.493	1.850	n.s.	0.054
<i>P. mariana</i> / stem	0.387	2.276	0.402	0.076
<i>B. papyrifera</i> / total biomass	0.989	2.492	0.218	0.118
<i>B. papyrifera</i> / leaves	0.774	2.256	n.s.	0.024
<i>B. papyrifera</i> / branches	0.890	2.250	n.s.	0.072
<i>B. papyrifera</i> / stem	0.565	2.060	0.346	0.176

a. Total biomass and stem biomass equations for *P. mariana* and *B. papyrifera* were of the form: $\log_{10}(\text{biomass component (g biomass/tree)}) = a + b \cdot \log_{10}(\text{basal diameter (cm)}) + c \cdot (\text{fertilization treatment})$, where fertilization treatment was a categorical variable indicating either no fertilization (control=1) or fertilization (all doses=2). Details of statistical model are given in Methods.

b. Leaf and branch biomass equations for *P. mariana* and *B. papyrifera* were of the form: $\log_{10}(\text{biomass component (g biomass/tree)}) = a + b \cdot \log_{10}(\text{basal diameter (cm)})$.

c. n.s. = not significant

Table 3: Parameter estimates for soil respiration empirical model^a

Fertilizer dose	SRref	p	E0	p
High	6.84 (1.07)	<0.0001	85.03 (38.48)	0.033
Mid	8.40 (1.46)	<0.0001	108.06 (40.29)	0.011
Low	6.87 (1.17)	<0.0001	67.83 (40.08)	0.098
Control (unfertilized)	5.66 (0.89)	<0.0001	87.99 (40.81)	0.037

a. Model is specified in Equation 2

Table 4. Mean $\pm$ standard error for net primary production for *P. mariana* and *B. papyrifera* above and belowground biomass and annual soil losses of CO₂ and CH₄ by fertilizer dose^a. Negative values for carbon balance indicate C losses from the soil/ecosystem.

		High dose	Mid dose	Low dose	Control (unfertilized)
		g C m ⁻² yr ⁻¹			
<i>Picea mariana</i>	Aboveground NPP	10 $\pm$ 1	7 $\pm$ 1	8 $\pm$ 1	3 $\pm$ 1
	Belowground NPP	2 $\pm$ 0.2	2 $\pm$ 0.2	2 $\pm$ 0.3	1 $\pm$ 0.1
	Litter	2 $\pm$ 0.2	1 $\pm$ 0.2	1 $\pm$ 0.2	1 $\pm$ 0.1
<i>Betula papyrifera</i>	Aboveground NPP	250 $\pm$ 81	240 $\pm$ 99	180 $\pm$ 88	14 $\pm$ 6
	Belowground NPP	16 $\pm$ 4	14 $\pm$ 5	11 $\pm$ 4	2 $\pm$ 1
	Litter	350 $\pm$ 16	330 $\pm$ 20	250 $\pm$ 18	27 $\pm$ 1
Soil CO ₂ flux (SR) ^b May 1 – Oct 7		330 $\pm$ 170	430 $\pm$ 240	330 $\pm$ 160	280 $\pm$ 120
Non-growing season CO ₂ flux		50 $\pm$ 25	64 $\pm$ 32	49 $\pm$ 24	42 $\pm$ 21
Annual soil CH ₄ flux		1 $\pm$ 1	1 $\pm$ 1	1 $\pm$ 1	1 $\pm$ 1
Carbon balance ^c		249 $\pm$ 191	99 $\pm$ 268	72 $\pm$ 185	-275 $\pm$ 122
Carbon balance <i>P. mariana</i> only ^c		-367 $\pm$ 172	-485 $\pm$ 248	-369 $\pm$ 161	-318 $\pm$ 122

a. Fertilizer doses are described in Methods. Standing biomass of *P. mariana* can be determined by multiplying the total aboveground NPP by 7 years (age of plantation) and for *B. papyrifera* by multiplying the aboveground NPP by 7 years for woody biomass and adding litter to obtain total biomass including leaves.

b. Error estimated according to equation 3

c. Error in C balance estimated based on the square root of the sum of squares of errors for each component.

Figure captions:

Figure 1. Air temperature (line graph, top), precipitation (bar graph, top) and soil moisture (bottom) over the study period. Soil moisture was measured in the top 0-6 cm of soil at all plots during an intensive 2-3 day field campaign each month.

Figure 2. Measured biomass versus basal diameter for *P. mariana* plantation and associated invasive *B. papyrifera* and estimated biomass model for each species between fertilized and non-fertilized plots.

Figure 3. Soil respiration versus air temperature for each fertilizer treatment. Lines shown are fitted according to Equation 2 with parameters given in Table 3.

Figure 4. Soil respiration versus a) soil moisture and b) soil temperature. Lines were fit with a linear mixed effect model including plot as a random factor and R² reported includes only the variability described by the fixed factor.