Effects of invasion by birch on the growth of planted spruce at a post-extraction peatland

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SUMMARY

Planting forest on cutover peatlands may be regarded as a viable restoration technique in western Canada, where natural bogs are treed with a high density of Black Spruce, *Picea mariana*. Fertilizer is needed to promote *P. mariana* establishment on cutover peatlands; however, it also encourages spontaneous colonisation by non-peatland species such as Paper Birch, *Betula papyrifera*. This study aimed to assess the most appropriate fertilizer dose for *P. mariana* establishment and growth against the trade-off of birch invasion; consequently, we monitored the effect of *B. papyrifera* on *P. mariana* growth. Four levels of fertilizer dose were applied below-ground, but flooding of the site following planting allowed fertilizer to reach the surface and favoured the colonisation of *B. papyrifera*. Seven years after planting, fertilizer promoted *P. mariana* survival and the highest fertilizer dose improved both *P. mariana* and *B. papyrifera* growth, while the lowest fertilizer dose promoted spruce growth, to a lesser degree, without promoting birch growth as much as higher doses of fertilizer. Birch removal had a significant positive effect on the growth of *P. mariana*, possibly by allowing greater light penetration and higher near-surface soil moisture. Avoiding *B. papyrifera* colonisation on site is more effective than cutting due to the ability of birch to regenerate rapidly from stumps. In practice, if planting coniferous trees is the chosen restoration option, the risk of birch colonisation can be minimised by leaving a thicker remnant peat deposit, burying fertilizer near the planted seedlings, and planning planting to avoid flooding during the growing season post-planting whenever possible.

KEY WORDS: *Betula papyrifera*, cutover peatland, fertilizer dose, forest plantation, *Picea mariana*,

INTRODUCTION

To extract peat for horticultural use, the land needs to be drained and surface vegetation removed (Graf *et al*. 2012). Drainage of natural mires (living peat-forming ecosystems) can degrade them to a state of reduced habitat diversity (Raunio *et al.* 2008, Tarvainen *et al.* 2013) and reduced native mire species (Tarvainen *et al*. 2013). The regeneration process in cutover peatlands is slow; however, human intervention can facilitate adequate environmental conditions to promote recolonisation by the desired peatland species (González *et al.* 2014).

In western Canada, 80 % of undisturbed *Sphagnum* peatlands have coniferous forest cover (Vitt 2006). Black Spruce (*Picea mariana*) is a common naturally occurring species on North American *Sphagnum* bogs. This article relates to a first attempt to restore an extracted bog employing the action of coniferous tree planting as a means of speeding the recovery of a naturally treed peatland.

P. mariana does not grow readily on cutover peatland because residual peat is deficient in plant nutrients, with low phosphorus and potassium contents and relatively low nitrogen (Wind-Mulder 1998). However, this species has been shown to grow well in plantations on cutover peatland if fertilizers are added (Bussières *et al.* 2008). Indeed, to achieve good establishment and early growth of *P. mariana* seedlings, NPK fertilizer applications are essential (Caisse *et al.* 2008, Hugron *et al.* 2011). In 2005 a trial was initiated in western Canada to determine the best fertilizer application dose. However, within a few years of *P. mariana* planting, Paper Birch (*Betula papyrifera*) had invaded the site.

A main goal of peatland restoration is to recreate a wetland system that is able to accumulate organic matter in the form of peat (Graf *et al*. 2012), and colonisation by *B. papyrifera* may make it difficult to achieve this goal. The dispersal of *B. papyrifera* seeds is primarily wind-driven, allowing long-distance colonisation of new habitats (Campbell *et al.* 2003). Once established, it can tolerate a wide range of environmental conditions and rapidly absorb

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nutrients in open areas (Fay & Lavoie 2009). A dense colony of birch will alter the site's hydrology through transpiration (Fay & Lavoie 2009), lowering the water table and limiting mire recovery, especially the establishment of mosses (Lavoie & Saint-Louis 1999). Aeration of bare peat also facilitates invasion, particularly by vascular plants whose root systems need oxygen (Laine *et al*. 2011, Graf *et al*. 2012). In addition to drying of the substrate by lowering the water table, potential consequences of *B. papyrifera* colonisation on cutover peatlands undergoing the restoration described here include annual mulching with fallen leaves each autumn, shading of the ground, and competition for nutrients with *P. mariana* inhibiting growth of the desired plant species.

This study investigates the appropriate fertilization dose for *P. mariana* planted on cutover peat as part of a restoration strategy, and determines the effect of *B. papyrifera* colonisation on *P. mariana* growth.

METHODS

Study site

Paxson Bog is a 166 ha cutover peat bog located near the town of Athabasca (54° 40' 3.28" N, 113° 7' 24.57" W) in the east-central part of Alberta, Canada. According to data from the Athabasca weather station, average growing season (May–October) precipitation for the 30 years from 1981 to 2010 was 357.8 mm (Environment and Climate Change Canada 2019). In 2005, Premier Tech Ltd. and the Peatland Ecology Research Group (PERG; Université Laval) designed a restoration plan incorporating a *P. mariana* plantation, which was established on a 5 ha section of the bog. Two-year-old *P. mariana* saplings were planted in plugs between 25 and 30 July 2005. At planting, a dose of fertilizer was buried beneath each seedling in a small mesh bag. Four levels of fertilizer were tested. Further details of the treatment plots for the fertilization study are given in the later section 'Effect of fertilization on *P. mariana* establishment'. Beginning in September 2012 (seven years post-planting), tree performance was evaluated; and in 2013 a carbon exchange study was completed (Bravo *et al*. 2018).

Weather data were recorded during the study period in 2012 and 2013 (Table 1). The 2013 data (May to October) were recorded every 30 minutes from two meteorological stations containing temperature and precipitation sensors (HOBO sensors, Onset Inc., Cape Cod, MA, USA). Precipitation was relatively low during the growing seasons (264 and 292 mm), the wettest months being July (~100 mm), June (~70 mm) and August (~45 mm). The mean growing season temperature recorded was around 10 °C. In 2013, the mean peat pH was 4.06 ± 0.04, mean corrected electrical conductivity (EC) in the near-surface peat was 933 ± 139 µS cm^{-1}, with high values probably linked to the visible precipitation on the surface of solutes potentially sourced from the underlying mineral soil due to shallow peat depth. The remaining depth of peat post-extraction ranged from 40 cm to 90 cm.

In autumn 2012, the main ditch surrounding the experimental site was blocked in an attempt to raise

Table 1. Mean values for weather conditions, air temperature, relative humidity, and precipitation, in 2005 and 2013. Temp = air temperature at height above ground, PPT = precipitation, RH = relative humidity, ϴ = volumetric water content.

	2005			**2013**				
Month	**Temp at 5 cm (°C)**	**RH (%)**	**PPT (mm)**	**Temp. at 5 cm (°C)**	**Temp at 2 m (°C)**	**RH (%)**	**PPT (mm)**	**ϴ (%)**
April	6	57	6	-	-4	79	0	-
May	10	60	26	-	12	61	33	-
June	13	77	62	15	14	83	75	33
July	15	76	101	20	15	83	95	21
August	13	76	49	16	16	85	43	37
September	8	75	27	19	11	80	7	45
October	-	-	22	11	5	90	10	45
Growing Season	11	70	292	16	10	80	264	35

the water table and thus improve the hydrological conditions of the restored peatland, including the *P. mariana* plantation. In addition, all of the smaller ditches allowing outflow from the restored area were blocked 20 m away from the experimental plots by filling with local peat.

Environmental variables

Peat volumetric water content (ϴ) was measured monthly using a portable WET-Sensor (Delta-T Devices, HH2, Cambridge, UK) time-domain reflectometry device during the growing season from August to October in 2012 (prior to birch cutting) and from May to October in 2013 (post-cutting). Water content was recorded monthly at seven locations within each experimental unit (EU; see next section), in the middle of four trees, and averaged across the EU to obtain an EU-scale ϴ value for the 0–6 cm upper soil layer (Figure 1). The depth of the peat deposit was measured at three randomly chosen spots around each EU and then a mean was calculated for the EU.

Effect of fertilization on *P. mariana* establishment

The effect of nutrient additions on *P. mariana* establishment was examined within a completely randomised design testing four levels of fertilizer application in seven replicates, giving a total of 28 experimental units (EUs; Figure 1). The composition of the fertilizer was 20-10-15 (N-P_2O_5-K_2O) and the doses tested were: 1) non-fertilized (control), 2) 8.9 g/bag (low dose), 3) 17.9 g/bag (medium dose) and 4) 26.8 g/bag (high dose). Each EU consisted of a 400 m^2 (20 × 20 m) plantation of 100 *P. mariana* trees spaced 2 m apart, with one bag of fertilizer buried adjacent to each tree in fertilized EUs. As all treatment blocks were located within one peatland, the study was pseudoreplicated (*sensu* Hurlbert 1984) and this should be kept in mind when interpreting the results of the statistical analysis.

P. mariana performance was evaluated seven years post-planting in a 10 × 10 m quadrat in the central part of each EU to avoid edge effects. Thus, only the 36 central trees of the 100 planted per EU were surveyed (for survival, basal diameter and total height).

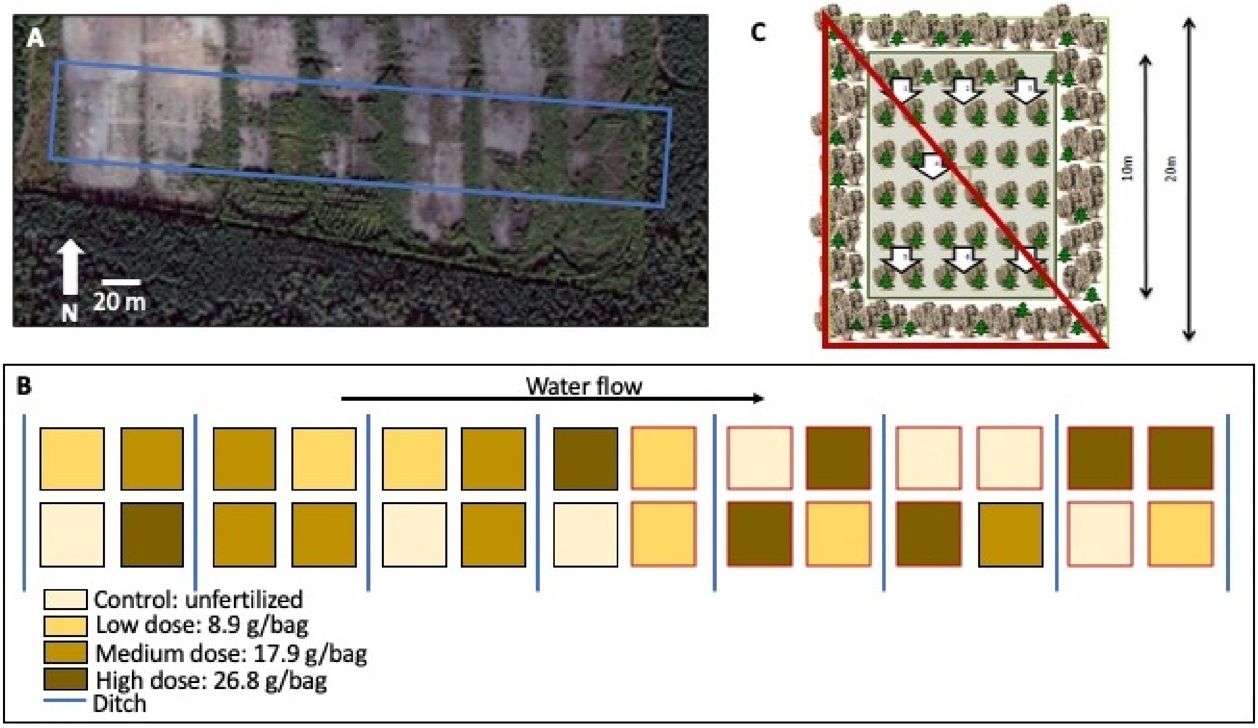

Figure 1. Map and schematics of the study site. (A) A satellite image of the study area with fertilizer treatment experimental units (EUs) and birch removal sub-units visible (source: maps.google.ca). The area outlined in blue is expanded as a schematic of the study areas in (B) showing the layout of the fertilizer doses and EUs used for birch removal (outlined in red). (C) A schematic of tree and soil measurements within the EU, within the 36 inner trees to avoid edge effects. *B. papyrifera* main stems present within a radius of 50 cm of the main planted *P. mariana* stem were assessed. Arrows show the positions for volumetric water content (ϴ) measurements. The red triangle outlines the random selection of birch removal where the above-ground *B. papyrifera* were cut down around the planted *P. mariana* in selected EUs.

Unexpected effect of fertilizer and remediation trial

Wetter-than-average spring weather following planting flooded the experimental site and brought the fertilizer to the surface, leading to spontaneous colonisation by *B. papyrifera* in subsequent years. *B. papyrifera* grew around each fertilized *P. mariana* sapling and at high density along the sides of former drainage ditches. Some *B. papyrifera* was also present in unfertilized EUs, but at much lower density. A note of caution is necessary because not all of the birch individuals that colonised the site have been identified. The majority are *B. papyrifera* and all birch are referred to as *B. papyrifera* throughout this article. However, although western Canada is not part of the usual distribution of Grey Birch (*Betula populifolia*), seedlings of this species have been identified on Paxson Bog; *B. populifolia* has been described as a pioneer species in extracted peatlands elsewhere (Lavoie & Saint-Louis 1999).

Seven years post-planting, we conducted a split-plot birch removal experiment in order to assess the effect of *B. papyrifera* presence on *P. mariana* growth and on ground microclimatic conditions (ϴ, relative humidity (RH) and insolation by photosynthetically active radiation (PAR)). In August 2012, all *B. papyrifera* were removed (by cutting the main stem at ground level) from around the planted *P. mariana* within a randomly chosen half (sub-unit) of each selected EU. We utilised only the eastern part of the restored site, which showed the highest levels of birch invasion (Figure 1). Therefore, for the birch removal study, the high-dose fertilizer treatment was replicated five times and the low-dose and control treatments four times. The medium fertilizer treatment was not included in the birch removal experiment.

The *B. papyrifera* survey measured height, basal diameter, and number of branches growing from each birch stem within 50 cm of a planted *P. mariana*. Prior to removal of a *B. papyrifera* tree, basal diameter and total length of every branch from the main stem was measured.

The effect of birch removal on microclimate and *P. mariana* growth

In July 2013, eleven months after *B. papyrifera* removal, the microclimatic variables RH and PAR were measured on birch removal and non-removal sub-units at ground level and 1.30 m height, with 50 cm distance between measurements. Twenty measurements were made within each sub-unit (Figure 1) using a portable infrared gas analyser with a PAR sensor attached (EGM4, PP systems, Massachusetts, USA), which reports RH in air drawn into the instrument through an input port on the side. At the same time and locations, ϴ was measured using a portable WET-Sensor (Delta-T Devices, Cambridge, UK). Thirteen months post-removal, basal diameter, height and annual height growth (elongation of the leader stem) of the central 6 × 6 planted *P. mariana* trees were measured in the EUs subject to *B. papyrifera* removal only. Basal diameter post-removal of birch was compared to the 2012 *P. mariana* survey and the annual increase in basal diameter was computed. Annual elongation of leader stem was obtained by measuring the distance between successive terminal buds scars (internode) downwards from the sampling year (2013) until secondary growth of stems (thick bark) hampered counting of bud scars (Gamache & Payette 2004).

Statistical analyses

All statistical analyses were performed using R (R Core Team 2019). The tree survey was used to evaluate the effect of fertilizer dosage on tree growth and to determine whether fertilizer improved *P. mariana* and *B. papyrifera* growth (Normality Shapiro-Wilk test, $p < 0.05$). In order to account for environmental variation between EUs that may have also contributed to tree growth, we included EU as a random intercept in linear mixed effects models assessing the effect of fertilizer dose on survival, basal diameter and height for *P. mariana* and on height of *B. papyrifera* growing within 50 cm of planted *P. mariana*. Linear mixed effects modelling was completed with the package nlme (Pinheiro *et al.* 2019).

To evaluate the effect of *B. papyrifera* removal on *P. mariana* growth (basal diameter and elongation of the leader stem) and microclimatic conditions (ϴ, RH and PAR) we used a linear mixed effects model with EU as a random intercept and fertilizer dose and removal treatment as fixed effects. If the interaction between fertilization and *B. papyrifera* removal was significant, the effect of removal was evaluated independently within each fertilizer dose.

RESULTS

Environmental conditions

In 2005, the mean ϴ during the summer as measured by Premier Tech was 26 % and in 2012 the mean ϴ was 23 %. In 2013 after blocking the ditches, mean ϴ was 35 ± 0.8 %.

Effect of fertilizer on tree growth after seven years

Seven years after *P. mariana* seedlings were planted on the cutover peat field, 845 (84.5 %) of the 1008 surveyed trees (in the central parts of 28 EUs) had survived. When fertilized, 90 % of the trees survived compared to 65 % when not fertilized (Table 2; $F_{3, 24} = 5.81$, $p = 0.004$). Within each fertilizer treatment, birch trees were taller than spruce trees (Table 2). Fertilizer application promoted *P. mariana* growth as indicated by both height ($F_{3, 24} = 21.80$, $p < 0.001$) and basal diameter ($F_{3, 24} = 7.33$, $p = 0.001$); the degree of difference was proportional to the doses tested in this study. Fertilizer treatment also had a significant effect on *B. papyrifera* tree height ($F_{3, 943} = 49.46$, $p < 0.001$), which showed an increase with higher doses (Table 2).

Effect of *B. papyrifera* invasion on microclimate

B. papyrifera cutting induced responses in the annual elongation of *P. mariana* leader stems as a function of the fertilizer dose; there was a significant interaction between *B. papyrifera* removal and fertilizer treatments ($F_{2, 224} = 4.59$, $p = 0.011$). At unfertilized EUs, elongation of the leader stem was significantly greater in sub-units where *B. papyrifera* remained intact (Figure 2; $F_{1, 67} = 4.57$, $p = 0.036$). In contrast, at low and high fertilizer doses there was no significant difference in annual leader elongation but there was a trend towards greater growth following

Table 2. Mean (± SE) of survival, basal diameter and height of *P. mariana* and height of *B. papyrifera* seven years after planting of *P. mariana* saplings in relation to their fertilization treatment. Doses are significantly different for a given factor if they do not share a common letter; statistical values are given in the text.

Fertilizer dose (g/bag)	***P. mariana* survival (%)**	***P. mariana* height (cm)**	***P. mariana* basal diameter (cm)**	***B. papyrifera* height (cm)**
High (26.8)	88 ± 2 ^{a}	136 ± 2 ^{a}	2.0 ± 0.04 ^{a}	201 ± 5.3 ^{a}
Medium (17.9)	93 ± 2 ^{a}	113 ± 2 ^{ab}	1.8 ± 0.04 ^{a}	175 ± 6.6 ^{ab}
Low (8.9)	90 ± 2 ^{a}	103 ± 3 ^{b}	1.7 ± 0.04 ^{a}	160 ± 6.0 ^{b}
Control (0)	65 ±10 ^{b}	52 ± 1 ^{c}	1.2 ± 0.04 ^{b}	50 ± 3.7 ^{c}

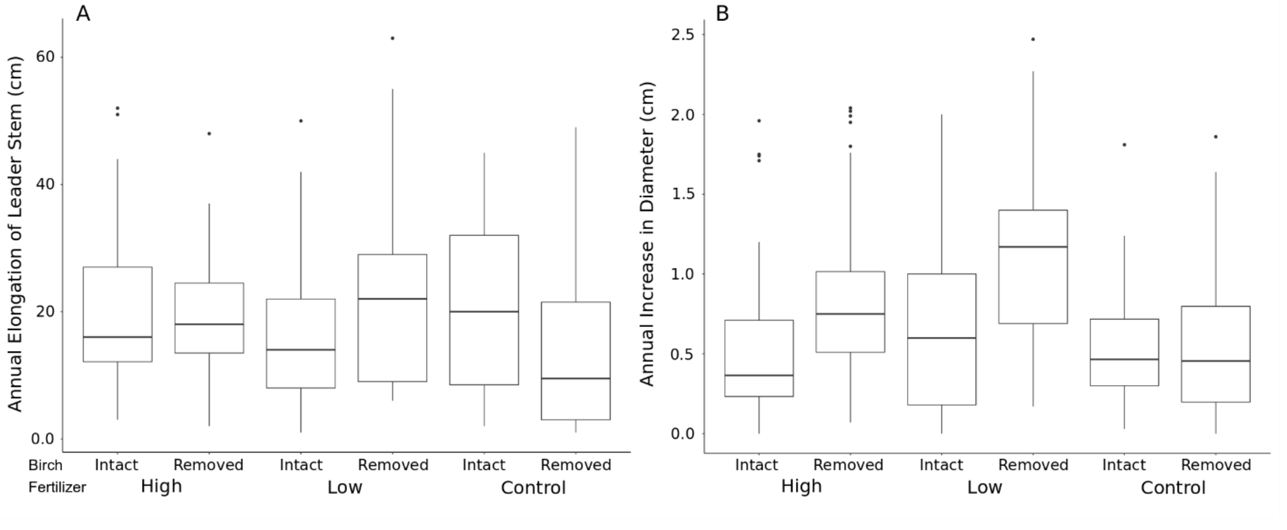

Figure 2. Annual elongation of leader stem (A) and increase in basal diameter of *P. mariana* (B) as a function of doses of fertilizer within plots where *B. papyrifera* were removed or left intact. The line in the middle of each box represents the median, the edges of the box the 25th and 75th percentiles, and the error bars 95 % of the data. There was a significant interaction effect between annual elongation of *P. mariana* leader stem with fertilizer treatment and birch removal ($p < 0.001$), such that the presence of intact birch trees within no-fertilizer controls did not reduce the growth of *P. mariana* compared to higher fertilizer doses. Increase in basal diameter was significantly less for *P. mariana* adjacent to intact *B. papyrifera*.

B. papyrifera removal (Figure 2). Similarly, increases in *P. mariana* basal stem diameter following *B. papyrifera* removal depended on fertilizer dose (interaction: $F_{2, 278} = 3.16$, $p = 0.044$). The removal of *B. papyrifera* had little effect on basal diameter growth of *P. mariana* in unfertilized EUs ($F_{1, 83} = 1.82$, $p = 0.181$), while the increase in basal diameter was greater in *B. papyrifera* removal sub-units for fertilized EUs, with the difference statistically significant only for the low fertilizer dose (high dose: $F_{1, 120} = 1.41$ $p = 0.238$; low dose: $F_{1, 70} = 11.44$, $p = 0.001$).

Removal of *B. papyrifera* increased soil moisture (ϴ) in the birch removal plots, with birch-removed plots having mean ϴ across all measurements of 30.57 % compared to 30.04 %, but this difference was not significant ($F_{1, 75} = 0.76$, $p = 0.37$). The presence of invasive *B. papyrifera* around the planted *P. mariana* significantly reduced PAR at ground level ($F_{1, 681} = 42.4$ $p < 0.001$) by an average of 0.200 mmol m^{-2} s^{-1} (Figure 3). There was also a significant interaction between birch removal and fertilizer dose, with greater reductions in PAR at the soil surface for higher fertilizer doses ($F_{2, 681} = 3.82$, $p = 0.022$). Similarly, PAR at 130 cm height was significantly increased by *B. papyrifera* removal ($F_{1, 681} = 17.54$, $p < 0.001$), also with a significant interaction with fertilizer dose ($F_{2, 681} = 5.31$, $p = 0.005$). Birch removal had a small but significant effect on microclimatic conditions by increasing RH at ground level to 43.9 % from 40.6 % (Figure 3; $F_{1, 681} = 25.49$, $p < 0.001$). There was also a significant interaction between fertilizer dose and birch removal ($F_{2, 681} = 5.45$, $p = 0.004$), where ground-level RH decreased slightly under the highest fertilizer dose but consistently increased with *B. papyrifera* removal at the low-dose fertilized and unfertilized plots. The RH at 130 cm above the ground also increased slightly following birch removal, from 33.9 % to 35.6 % ($F_{1, 680} = 6.02$, $p = 0.01$), and this effect was consistent across fertilizer treatments.

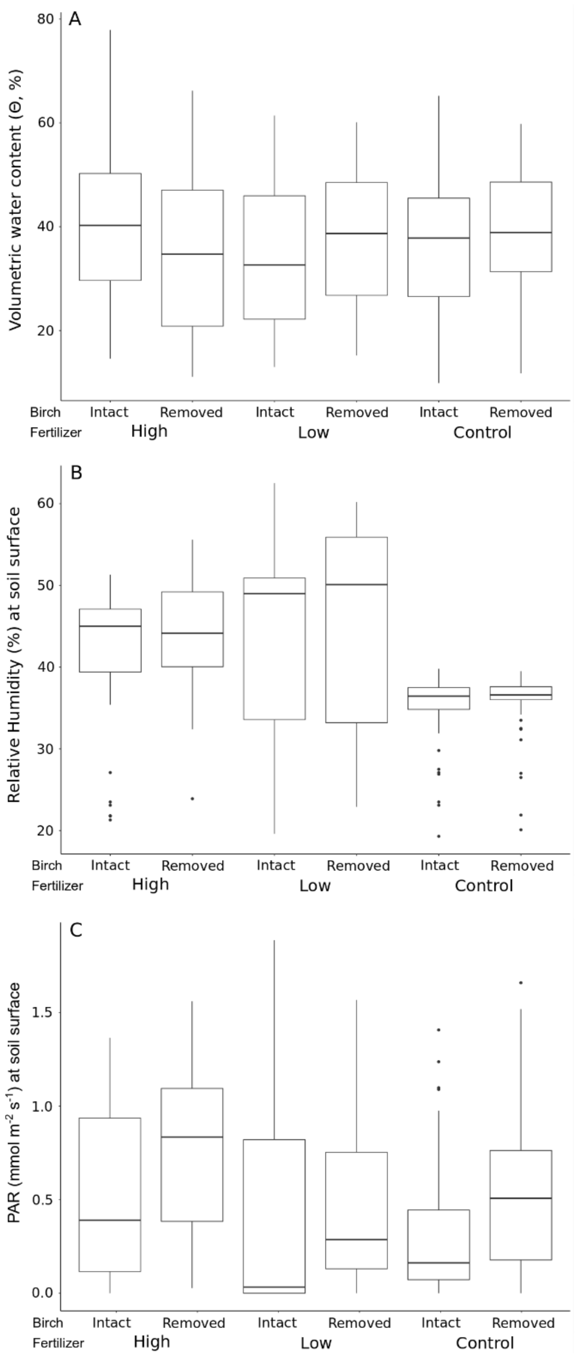

Figure 3. Volumetric water content (ϴ; A) was significantly increased by birch removal ($p < 0.001$). Relative humidity (RH; B) at ground level varied significantly with fertilizer dose and there was a significant interaction between birch removal and fertilizer dose ($p < 0.001$); RH is not different between birch-removed and intact plots, except for low fertilizer dose, where RH is higher where birch was removed. PAR (C) at ground level was significantly higher following birch removal and there was a significant interaction between birch removal and fertilizer doses, with fertilized birch removal plots showing the highest median values ($p < 0.001$).

DISCUSSION

This study demonstrated that fertilizer application through the use of buried bags improved *P. mariana* survival, establishment and subsequent growth, but the upward movement of this fertilizer, in this case caused by flooding, had the unfortunate effect of favouring *B. papyrifera* colonisation around the planted spruce trees that reduced the benefits of fertilization and restricted *P. mariana* growth. However, by using a low dose of application, the effects of birch invasion can be mitigated in relation to *P. mariana* growth. Our results support the pattern of previous afforestation studies that have described fertilization as required on cutover peatlands to promote the growth and survival of coniferous tree seedlings (Bussières *et al.* 2008, Hugron *et al.* 2011, Renou-Wilson 2011). Seven years after planting, the fertilizer still had an effect on the growth of *P. mariana*, with better survival and larger trees on fertilized compared to unfertilized plots (Table 2). The establishment and growth of *P. mariana* trees in the drier climate of western Canada was as good with the low dose of NPK fertilizer treatment (8.9 g/bag) as with the higher dose (26.9 g/bag), as previously found in afforestation trials in eastern Canada (Bussières *et al*. 2008). Therefore, using lower doses of fertilizer can be effective for *P. mariana* establishment on cutover peat while having a lower probability for the applied fertilizer to reach water outflows, less chance to increase mineralisation of the residual peat (Bravo *et al.* 2018) and a lower operational cost. Furthermore, the marginal benefit to *B. papyrifera* of increasing fertilizer doses, i.e. the greater growth observed in birch at medium and high-dose plots compared to control and low-dose plots, is greater than the marginal benefit to *P. mariana* (Table 2). The low dose provides a reasonable trade-off between promoting the target species for restoration, *P. mariana*, while minimising the additional growth of the undesirable Paper Birch.

Removal of the competitor species, *B. papyrifera*, improved basal diameter growth and, in some cases, annual elongation of the leader stem of *P. mariana*, possibly by improving microclimatic conditions (ϴ, RH and PAR; Fay & Lavoie 2009). The highest values of RH were recorded at the low-fertilizer plots where birch had been removed. This is a somewhat puzzling result because the link between fertilizer, birch removal and near-ground humidity is not obvious. It is difficult to disentangle effects driven by changes in microclimate from other effects of competition by species such as *B. papyrifera* that may also compete with *P. mariana* and other peatland species for multiple resources (Roy *et al*. 2000, Limpens *et al.* 2003, Hotanen *et al.* 2006, Préfontaine & Jutras 2017).

Although fertilization is important for *P. mariana*, the resulting *B. papyrifera* colonisation negatively affected *P. mariana* growth. One growing season after birch removal and blocking the ditches, annual elongation of *P. mariana* leader stems was improved, and was associated with a small increase of mean ϴ compared to sub-units where birch remained intact. High density of *B. papyrifera* invasion elevates evapotranspiration from the site (Mäkiranta *et al.* 2007) and may change soil moisture content, while litter accumulating on the ground could inhibit the establishment of other peatland understorey species (e.g., mosses). If the restoration goal is to restore a forested wetland habitat, the high evapotranspiration of *B. papyrifera* becomes important to the restoration. Typically, when the water table is more than 50 cm below the soil surface, groundwater ceases to contribute to evapotranspiration and the soil moisture of the surface peat layers can become exhausted (Price 2003, Fay & Lavoie 2009). Although some improvements in *P. mariana* growth were found following *B. papyrifera* removal, we observed that it regrew quickly from stumps and probably changed local hydrological conditions again. Furthermore, while birch and other fast-growing species have been proposed as nurse species for slower-growing target tree species, where the birch suppress the smaller vascular plants that compete with young target tree species by shading and other effects (Kelty 2006, Löf *et al.* 2014), the birch in this case invaded a site with well-established spruce trees that had most likely grown beyond serious competition from understorey plants. The significant interaction effect, where at unfertilized plots, the small *P. mariana* trees had greater elongation of the leader stem when birch were intact, while at fertilized plots *P. mariana* had improved growth following birch removal, does suggest that spruce trees may derive some benefit from adjacent birch under particular combinations of fertilizer dose and tree ages.

General management recommendations

Previous work had shown that the best way to favour the establishment and growth of trees in cutover peatlands was to insert the fertilizer below ground at planting, within a bag resembling a tea bag, in order to decrease the chance of undesirable plant colonisation around the planted tree (Hugron *et al*. 2011). In this study, we were surprised to find that the fertilizer had migrated to the surface following heavy rainfall events, allowing a competing deciduous tree to establish on the restoration site. If tree reintroduction is part of a restoration design, we recommend the tea bag fertilization method, particularly for areas to be restored with less water, such as elevated areas or former roads within an extracted peatland. Care should be taken to plan the timing of planting and fertilizing to avoid rapid water table rise/flooding soon after planting occurs. This will help to prevent the fertilizer from becoming available to non-target species.

In practice, the cutting of birch trees will not lead to long-term changes in microclimate as this practice has the potential to increase the vigour of regeneration (Wisconsin Department of Natural Resources 2016). Thus, during the year following birch removal, transpiration will increase again, along with shading. Therefore, it is desirable to prevent *B. papyrifera* colonisation in the first place rather than attempt to manage the birch once it is on site. A low dose of fertilizer (8.9 g/bag) was sufficient to favour the growth and survival of *P. mariana* and avoid high densities of *B. papyrifera* colonisation. Moreover, greater peat depth and ϴ had a negative effect on *B. papyrifera* volume (data not shown). Similarly, Hugron *et al*. (2011) suggested that peat depth greater than 40 cm can reduce *B. papyrifera* colonisation. This suggests that maintaining a thicker residual peat column post-extraction and keeping the site wetter by managing hydrology could help to prevent *B. papyrifera* colonisation. Thus, while we did not test the effects of hydrology here, control of water levels is suggested for peatland restoration (Price 2003, Nwaishi *et al*. 2015), and it is clear that fertilizing with a minimal dose should result in better outcomes for a forest plantation on a cutover peatland.

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AUTHOR CONTRIBUTIONS

TGB, MS, LR developed the study design and objectives, TGB conducted the field research and preliminary data analysis, MB and MS completed final data analysis. All authors contributed to manuscript writing and editing.

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