UNIVERSITY OF CALGARY

Picea mariana (Mill.) B.S.P Plantation on Cutover Peatland in Alberta (Canada): Evaluating the Effect of Fertilization and Resulting Carbon Stocks.

by

Tania Garcia Bravo

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE

GRADUATE PROGRAM IN GEOGRAPHY
CALGARY, ALBERTA

APRIL, 2015

ABSTRACT

Horticultural peat extraction in Canada is mainly performed by vacuum-harvesting, leading to a residual peat soil limited in nutrients and seed bank, which does not allow adequate plant recovery once extraction ceases. Restoration techniques have been designed for the rehabilitation of open bog areas in eastern Canada, but in western Canada many undisturbed peatlands have high cover of forest and the reintroduction of trees should be part of restoration goals. This study is focused on *Picea mariana* (Mill.) B.S.P (black spruce) plantation. Previous studies have shown that fertilization is needed, but the adequate dose of fertilizer to create the preferred habitat structures remains unclear. Fertilizer dose could also affect the colonization of non-target species such as *Betula papyrifera* (March.) and consequently microclimate conditions and competition could affect the growth of *P. mariana*. Results showed that a low dose of fertilizer (8.9 g/ bag) allowed *P. mariana* to establish while controlling the *B. papyrifera* colonization. Higher rates of fertilization resulted in dense *B. papyrifera* communities having a direct effect on photosynthetically active radiation and relative humidity at ground level. Black spruce plantation on cutover peat will also affect the site's carbon (C) balance. The C balance was estimated using the C stock in biomass of the forest plantation and soil respiration measurement (CO_2 and CH_4). Although *B. papyrifera* fixed C though biomass, they also may influence the site hydrology by higher evapotranspiration. After seven years post-restoration, the study site was a source of C due to dry conditions and lack of understory, resulting in peat oxidation. These results can be used to assist in the choice of suitable treatments when the restoration goal is the recovery of ecological functions in cutover peatlands.

PREFACE

The thesis is presented in manuscript format and consists of two chapters, a broader introduction of the research context and conclusion. Naturally there is some repetition (e.g., study sites) between the chapters. The chapters will be published and represent collaborative work and the specific contributions of the candidate are described below.

Chapter Two

Title: Effect of fertilizer dose and *Betula papyrifera* colonization on success of a *Picea mariana* plantation on a cutover peatland

Authorship: Garcia Bravo T., Rochefort L., Strack M.

Status: In preparation for Mires and Peat.

Candidate contribution: All data in 2012 and 2013 were collected and all data analysis and manuscript preparation were completed by the candidate. Line Rochefort established the fertilization experiment in 2005 and participated in the current study design, and provided critical comments on drafts of the manuscript. M. Strack supervised the study and provided criticism of the manuscript.

Chapter Three

Title: The Impact of Forest Plantation on Carbon Exchange in Cutover Peatlands in Western Canada.

Authorship: Garcia Bravo T., Rochefort L., Strack M.

Status: To be submitted to Wetland Ecology and Management.

Candidate contribution: All data in 2012, 2013 and 2014 were collected and all data analysis and manuscript preparation were completed by the candidate. Line Rochefort designed the plantation trials in 2005 and provided critical comments on draft of the manuscript. M. Strack participated in study design, supervised the study and provided criticism of the manuscript.

ACKNOWLEDGEMENTS

It has been a great privilege to get to spend these years in the Department of Geography at the University of Calgary. Its members will always remain dear to me. I am most grateful to my advisor, Dr. Maria Strack for allowing me to work on this project and all that I have learned under her supervision. I am grateful for her guidance and for many opportunities that she provided me to broaden my professional experience. This thesis would not have been possible without her help, attention and patience, and I am giving her my heartfelt appreciation.

I would also like to acknowledge my thesis committee members, Dr. Line Rocherfort, Dr. Greg McDermid and Dr. Mary Reid. Many thanks for the recommendations and excellent advice to finish this thesis effectively. I gratefully acknowledge Dr. Bin Xu (NAIT), Marie Claire Leblanc and Dr. Rémy Pouliot (U. Laval), Dr. Kisa Mwakanyamale (Prairie Research Institute, University of Illinois) and Eduardo González (University of Denver) for their insightful suggestions, support and learning opportunities. Special thanks go to Jacques Gagnon (Premier Tech), Frederic Caron (Premier Tech), Scott Briscoe (Premier Tech) and Dr. Daniel Thompson (Northern Forestry Center in Edmonton) for field logistic support. To Ms. Paulina Mendori (University of Calgary), thank you for your tremendous help.

Many thanks to Brenda McDermott for all her support, input and stimulating conversations in this research. I also want to take this opportunity to express my appreciation to Gisela Engels and Tak Fung for the statistical advices and Robin Poitras for teaching me poster design.

Denise and Gail Brown, Brian Duclos and Wayne Staudt who make my family in Canada. Amaya González, Fernando Fernández de Bobadilla, Jaime García Verges, Elisabeth van Stam, Álvaro Recio, Luis Jasso, Andrés Puentes and Florian Bergoin to bring me wonderful moments to share and smile during this process.

I really appreciate Melanie Bird, Mendel Perkins, Elena Farries, Sasha Van Stavel, Jordan Zukowski, Jordanna Branham, Trent Schumann, Noelle Chin, Mark Caudill, Brendan Hart and Jessica Wang for assistance with fieldwork and lab analysis. Many thanks to Cristina G.Bravo and Isidro J. Garcia for all their time in this fieldwork research. Thanks all for sharing with me this motivation and passion.

This research was supported by the University of Calgary, Department of Geography and an Industrial Research Chair to Line Rochefort at Université Laval sponsored by NSERC and the Canadian Sphagnum Peat Moss Association and its members and by Environment Canada through the Grants and Contributions program funding to Maria Strack.

I am indebted to my fellow graduate students for providing an enjoyable environment to learn and grow. It has been a pleasure working with you. I am especially grateful to my lab mates Golnoush Hassanpour Fard, Tariq Munir, Bhupesh Khadka, Sharif Mahmood and Kim Murray.

Finally, I would like to express deep appreciation to my family and friends who provided so much needed support and encouragement throughout my education journey. To Beatriz Molero and Hala Kamaliddin, your friendship is indescribable, I can only say thank you. It is difficult to overstate my gratitude to my family Cristina Garcia Bravo, Noemí Bravo, Celsa Álvarez and my parents, Rocío and Isidro Juan for believing in me. And a big thanks to Jérémy Hecquet for your gentle support and help every day. This would not have been possible without their constant care and encouragement.

Tania Garcia Bravo
April 2015

Engineers, scientists, and policy makers need to recognize that Mother Nature (self-design) and Father Time (it takes time) are the parents and guardians of functional ecosystems

William J. Mitsch

Me gustan las palabras

Me gusta bajar por la mañana a comprarlas y elegir una a una, como si fueran albaricoques maduros.
Nunca se sabe qué palabras van a necesitar a lo largo del día.
Nunca se sabe cuáles sacar de la mochila o llevar en la maleta de viaje.
Cuántos adjetivos-blanco, doloroso, fértil-cuántos verbos y cómo conjugados: te quiero, conduzco, abriendo, he estado, supuse.....Cuántos artículos indefinidos. Cuántas preposiciones.
Yo digo que me gustan las palabras. Me gusta atesorarlas. Pero también dejarlas, a veces, como si no fueran mías.
Hay decenas de miles de palabras. Puede que más.
Palabras construidas en chapa, que suenan como el óxido al decirlas, esqueje; o como madera, tacón.
Palabras recortadas en papel de cebolla, sílfide o eliminar;
y palabras bastas como una tela vieja: lomera, bayeta, batanar.
Hay palabras que hay que masticar como si tuvieran nervios: duplicar, irreversible.
Y Mi palabra favorita es: Felicidad

Rocío Bravo

To my parents, Rocío and Juan.
Mil Gracias.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PHOTOGRAPHIC APPENDIX

LIST OF ABBREVIATIONS

ANOVA - Analysis of variance

BD - Bulk density

C - Carbon

CH_4 - Methane

CO_2 - Carbon Dioxide

DBH – Diameter at Breast Height

DOC - Dissolved Organic Carbon

EC - Electrical Conductivity

ER - Ecosystem Respiration

GC - Gas Chromatograph

GEE - Generalized Estimating Equation

GLM - General Lineal Models

GEP - Gross Ecosystem Photosynthesis

GHG - Greenhouse Gases

LMM - Linear Mixed Models

NEE - Net Ecosystem Exchange

NPP - Net Primary Production

PAR - Photosynthetically Active Radiation

Pp - Precipitation

RH - Relative Humidity

Temp - Temperature

Θ - Volumetric Water Content (VWC)

CHAPTER 1: Introduction and Study Context

1.1. Introduction

In Alberta, 16% of the total land is covered by peatlands (Locky, 2011), which provide ecosystem services including long term C capture, habitat and biodiversity. Even in remote areas of the province, around 0.6% of these peatlands has been damaged or destroyed (Wilson et al., 2001). Undisturbed peatlands are greenhouse gas (GHG) sinks (Frolking et al., 2011), while damaged peatlands may release GHG (carbon dioxide (CO_2) and methane (CH_4)) into the atmosphere (Moore et al., 1989, Waddington et al., 2002), largely because CO_2 emissions, as a result of peat oxidation, increase significantly under dry conditions (Waddington et al., 2002). Hydrology and biodiversity are also altered in disturbed peatland (Vitt et al., 2006). Peatlands cover an impressive 12% of Canada's territory. Canada is one of the largest producers of horticultural peat in the world (IPS, 2001), resulting in 25000 ha of peatland disturbed for this purpose (Environment Canada, 2010). The Canadian peat producers support guidelines to adhere to a responsible management code of conduct for horticultural peat production (http://www.peatmoss.com/blog/environment/preservation-reclamation-policy). Over the past 20 years, they have partnered with academics to develop ecological restoration methods specifically to restore open cutover bogs. However, lately more development of commercial activities is taking place in western Canada where naturally the bogs are treed; consequently restoration methods have to be adapted to include the recovery of the usual *P. mariana* (black spruce) cover of continental boreal bogs. However, *B. papyrifera* colonization has occurred on bare peat and could also impact the function of the ecosystem post-extraction.

Some afforestation trials have been carried out on cutover peatlands in eastern Canada (Bussières et al., 2008). The term *afforestation* referes to “the direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding and/or the human-induced promotion of natural seed sources” (LULUCF, 2005). However, no peatland forest plantations have been assessed in western Canada. Since a combination of factors, including location and environmental conditions, are the most important variables to evaluate success of cutover peatland management (González et al., 2013a), western

Canadian peatland restoration may require different techniques than their eastern counterparts. *P. mariana* plantation may be an appropriate after-use for peatlands in Alberta, where many undisturbed peatlands have extensive forest cover (Vitt, 2006). To evaluate forest plantation as a potential land-use management option on cutover peatlands, its impact on carbon exchange should also be considered. This research assesses the use of forest plantation to recover peatland ecosystem function in western Canada, including C storage, following horticultural peat extraction. The effect of fertilizer dose on both *P. mariana* and *B. papyrifera* growth is also considered.

In order to understand the importance of this study, a background about peatland ecosystems is provided to facilitate the study context.

1.1.1. Peatland ecosystems in Canada

Peatland are wetlands ecosystems where, over long time periods, vegetation growth (net primary production-NPP) overtakes organic matter decomposition, leading to the accumulation of "peat" (Vitt et al., 2006). Peatlands are principally important since they offer essential ecosystem services, such as carbon storage, biodiversity support, water regulation, and nutrient cycling (Ten et al., 2013). Northern peatlands store an estimated 500 ± 100 billion tonnes (Gt) of C (Yu, 2012). Peatlands also hold 10% of global freshwater resources and act as important water reservoirs for human populations and ecohydrological condition downstream (Parish et al., 2008). As soils, peat is material composed of more than 30% organic matter (dry mass) by weight in the upper 30 cm layer of soil (Rochefort et al., 2012).

Across Canada, peatlands are largely distributed in boreal and subarctic regions (Vitt et al., 2000). Environmental conditions and peat accumulation indicate that western Canadian peatlands are younger than those in eastern Canada (e.g. Glaser and Janssens, 1992); as a result peatlands in north-western prairie provinces are treed (Vitt et al., 2006). Furthermore, as the climate becomes more continental in western Canada, vascular plants become more abundant and water becomes less available at the bog surface (Vitt et al., 2000).

1.1.2. Peatland carbon cycle and greenhouse gas exchange

Peatland ecosystems by definition accumulate C through time. Peat producers want to develop optimum restoration techniques to rehabilitate the ecosystem post-exploitation including C storage. In this study, also, C storage function was assessed. In order to explain our measurements into context, it is useful to review the basic processes involved in the C cycle of peatlands.

1.1.2.1. Components of the peatland carbon cycle

The net accumulation of peat is the result of only a small difference between C inputs via photosynthesis and following distribution to the soil environment above and belowground, and C loss via decomposition of this organic matter (Aerts et al., 2006). C storage capacity in peatlands results from the balance between net exchange of CO_2 and CH_4, and hydrological losses of carbon including dissolved organic and inorganic C (Strack et al., 2008). Net ecosystem exchange of CO_2 (NEE) is the difference between gross ecosystem photosynthesis (GEP) and ecosystem respiration (ER) (Strack et al., 2008). Ecosystem respiration includes both autotrophic (plant) and heterotrophic (mostly microbial) respiration. The amount of CO_2 taken up and stored in a forest plantation on cutover peatland results from the difference between CO_2 taken up through GEP of the trees and CO_2 lost through tree and soil respiration. Therefore the contemporary peatland (ecosystem) C balance as expressed by Strack et al., 2008 is:

$$\Delta C = -(NEE + FCH_4 + FDOC + FDIC + FPOC)$$

Where ΔC represents net change in C storage, while F is flux, CH_4 is methane, DOC is dissolved organic carbon, DIC is dissolved inorganic carbon and POC is particulate organic carbon. As a convention positive values of fluxes represent a net loss of C from the ecosystem. In the cited equation positive values of fluxes represent a net loss of C from the peat to the atmosphere (Strack et al., 2008). However, in the present study the greenhouse gas (GHG) emissions to the atmosphere are considered as negative values.

Previous studies of net ecosystem exchange of CO_2 in northern peatlands report values ranging from uptake of over 220 g CO_2 m^{-2} yr^{-1} (60 g C m^{-2} yr^{-1}) to release of 310 g CO_2 m^{-2} yr^{-1} (84 g C m^{-2} yr^{-1}) (Strack et al., 2008). However, drained peatlands globally release more than 2 Gt CO_2-eq yr^{-1} of carbon to the atmosphere (Joosten, 2011). The latest studies of cutover bare peat in Alberta report the rate of CO_2 release between 126 - 680 g C m^{-2} (Strack et al., 2014). In eastern Canada, annual emissions of over 300 g C m^{-2} have been reported from cutover peatlands (Waddington et al., 2002).

In order to study the C balance of the forest plantation it is important to describe the controlling variables that drive gross ecosystem photosynthesis (GEP) of the planted species, *P. mariana* and the colonizer species, *B. papyrifera*, and ecosystem respiration (ER).

1.1.2.2. Carbon balance and controls on Gross Ecosystem Photosynthesis (GEP) and Ecosystem Respiration (ER)

In the past, peatlands have stored large amounts of organic C owing to positive net ecosystem exchange (NEE), as ecosystem C uptake exceeded ecosystem C release (Vasander and Kettunen, 2006). In fact, in peatlands net primary production (NPP) is lower than in other ecosystems (Frolking et al. 1998; Vasander and Kettunen, 2006), but descomposition is slower. Among the most important factors controlling rates of photosynthesis are photosynthetically active radiation (PAR) (Davidson and Janssens, 2006; Groendahl et al., 2007), air temperature (Illeris et al., 2004; Groendahl et al., 2007), volumetric water content (Davidson and Janssens, 2006; Groendahl et al., 2007), nutrient availability in the soil (Mikan et al., 2002; Marchand et al., 2004; Groendahl et al., 2007), and growing-season length (Luo, 2007; Girardin et al., 2008; Groendahl et al., 2007). Atmospheric CO_2 is fixed by plants via photosynthesis during the growing season and subsequently is deposited as litter both on and in the soil (Vasander and Kettunen, 2006). In boreal peatlands, the remaining fixed C is converted into plant structures, particularly into the belowground biomass (as reviewed by Vasander and Kettunen, 2006).

Soil respiration depends mostly on temperature and water table variation (Updegraff et al., 2001; Moore et al., 2002; Chimner and Cooper, 2003). Organic matter in peatlands is also decomposed anaerobically, often leading to CH_4 production and release. Pore water CH_4 concentrations increased from unvegetated to vegetated surfaces (Whiting and Chanton, 1991) suggesting that newly introduced organic matter by plant root growth and death within the substrate are important for CH_4 production. Once produced, CH_4 is emitted from peat via: diffusion through the peat, ebullition, and passage through plants (Conrad, 1989; Chanton et al., 1992b; Joabsson et al., 1999). In peatlands, the dominant processes to produce methane are diffusion though the peat and ebullition (Popp et al., 1999; Keller and Bridgham, 2007). Methane can be oxidized to CO_2 and the oxidation rate depends on CH_4 concentration and oxygen availability, which are related to moisture conditions, temperature, and the activity of CH_4 oxidizing bacteria in the peat matrix (Vasander and Kettunen, 2006). CH_4 oxidation, or methanotrophy, occurs in oxic environments as anaerobically produced methane is oxidized by methanotrophic bacteria to form CO_2. CH_4 flux might be driven by temperature, as Dunfield et al. (1993) suggest that production might increase more rapidly than oxidation with temperature increase. Since saturated conditions are the principal controls on CH_4 flux, there is a strong temperature relationship when the water table is close to the surface. Strack et al. (2006a) reported that higher temperature and lowered water table could increase GEP, providing fresh organic matter for methanogens even in drier peat due to shifting root zone size. Gorham (1991) estimated the mean annual release of CH_4 from northern peatlands as 5 g C m^{-2}. Nevertheless, the dry conditions present in drained sites result in a substantial reduction in CH_4 emissions. Often, at bare non-restored peatlands where the water level remains deep, sites may actually act as small CH_4 sinks (Waddington and Price, 2000).

Another component of the peatland C cycle is dissolved organic carbon (DOC) export, which is derived from plant growth and decomposition processes (Thurman, 1985). The export of C as DOC is also an important component in peatland carbon balance (Moore, 1998). DOC is formed in saturated conditions in peatlands due to partial and slow decomposition (Strack et al., 2008). Hydrology is the major control on DOC production, distribution and export from disturbed peatlands (Waddington et al., 2007).

1.1.3. Peatland restoration and reclamation

Horticultural peat extraction requires drainage of the peatland, opening ditches to accommodate machinery and facilitate drying of peat prior to extraction. The peat body is partially removed by a vaccum-milling technique and afterwards the extraction ditches often remain open, which does not allow rewetting of the area. The loss of organic layers, year after year, alters the hydrology and physicochemical conditions of substrate available for plant recolonization (Cooper et al., 2000). Previous studies, reported that low nutrient levels, the lack of seed bank and full sun exposure limit the natural recolonization of cutover peatlands (e.g. Salonen (1987, 1992); Cooper et al., 2000). Following peat field preparation for extraction, these sites have a high water level fluctuaction, due to the grid of open ditches (Price et al., 2003) and present unstable surfaces to colonize due to frost heaving (Groeneveld and Rochefort, 2002). Earlier research on cutover peatlands, (e.g. Renou-Wilson et al. 2011; Bussieres et al. 2008; Hugron et al. 2011), concludes that fertilization is required to promote tree seedling growth and survival. Moreover, the peat profile in post-extractive peatlands has different soil structure and proprieties, hydraulic conductivity, and water flow (water content and water potential) than undisturbed sites (Baird et al., 2008). Thus, cutover peatlands also require redevelopment of hydrological conditions similar to undisturbed peatland during restoration, where the water table is more stable and fluctuates less (Yu et al., 2010). Water table distribution and fluctuation should be returned to a range that provides appropriate water potential, tension, capillary rise and resistance to allow evapotranspiration and avoid water stress (Price et al., 2010). Furthermore, summer rainfall has a greater influence then hydrology on post-restoration success (Cooper et al., 1998). Due to low precipitation amounts in western Canada, there is often an annual water deficit and water stress may occur and impact the reintroduced vegetation community (Graf et al., 2008; Strong and Leggat, 1981). Water stress is one of the fundamental factors to consider for vegetation stress following cutover peatland restoration. For ecological restoration, understanding the interaction between vegetation establishment and soil properties is important to rehabilitate the ecohydrological conditions of cutover peatlands (Gorham et al., 2003).

Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (SER, 2004). A peatland is formally reclaimed when it recovers most of its ecosystem services (SER, 2004). Peatland restoration requires an understanding of vegetation regeneration and the effects of soil proprieties on disturbance areas. Land-use changes in peatlands, such as drainage for peat extraction, alter the local hydroclimatology and affects greenhouse gas exchange (e.g., Waddington and Price, 2000). As described above, peatlands that have been drained and extracted do not easily restore their original ecological function (Lavoie and Rochefort, 1996).

In Alberta, undisturbed peatlands have more tree cover than in eastern Canada; for that reason it is important to reintroduce conifer trees in dry cutover peatlands. To recover a peatland's ecological function, hydrological restoration, as described above, first must occur. Though, rewetting the cutover peatland after planting could also compromise the tree reintroduction. If the disturbed area remains with open ditches, *Betula sp*. and other invasive species (e.g. *Typha sp*., *Eriophorum sp*., and *Salix sp*.) are able to colonize cutover peatlands due to the dry post-drainage surface, and the establishment of trees may increase with time and by feedback evaporate more water (Lavoie et al., 1998).

Invasive species are plants, animals or other organisms introduced by human and non-native to the ecosystem, where they become established and disperse, generating a negative impact on the local ecosystem and species (IUCN, 2005). *Betula papyrifera* (March) is considered invasive on cutover peatlands when occurring at a high density (Renou et al., 2007), because of they result in large precipitation interception and lower the water table though evapotranpiration (Price et al., 2003). Its colonization on cutover peat may also be encouraged with nutrient availability (Graf et al., 2012). *B. papyrifera* (paper birch) grows on a variety of soils following the northern limit of tree growth in North America with a very plastic gene pool and common hybridization (Safford et al., 1990). It is adapted to cold climate and short cool summer. *B. papyrifera* tolerates variation in amount of precipitation from annual precipitation average of about 300 to 1520 mm and can grow on almost any soil and topographic range, but they are a nutrient sensitive species (Safford et al., 1990). According to Safford et al (1990), *B. papyrifera* tends to be more abundant on dry sites, where they grow faster, than wet or poorly drained soils. Generally, seedlings develop well in full sunlight, as often occurs following a disturbance. Their roots develop mainly in the top 60 cm; however, rooting depth depends on soil depth and nutrient availability.

The restoration plan at the study site aimed to recover the target species canopy, *P. mariana*, and have it develop before invasion by non-targeted species (e.g., *B. papyrifera*). An appropiate dose of fertilizer and the establishment of a *P. mariana* canopy would then provide a shade cover to allow for reintroduction of shade-loving moss communities as the second step of ecological restoration towards increasing biodiversity. Despite this goal, *B.* papyrifera colonization occurred within the plantation.

According to the new Alberta Wetland Policy (Alberta Government, 2013), wetland management decisions will be linked to ecosystem services, of which climate regulation through C storage as an important service provided by peatlands. Very little data exists on the C balance on forest plantation on cutover peat (e.g. Renou and Farrell, 2005, Black et al., 2008) and thus there is a need to quantify sources and sinks of C in these ecosystems. There is also a need to understand the impact of *B. papyrifera* colonization on microclimatic conditions and C accumulation. Although, *B. papyrifera* colonization will contribute to fix C into biomass, it also could have an effect on successional pathway of the restoration methods and other services provided by the restored ecosystem (e.g., water regulation and biodiversity).

1.1.3.1. Peatland restoration techniques

Since the 1990s, research on North American peatland restoration has resulted in the development of an ecosystem-scale technique named the “moss layer transfer technique”, which consists of collecting a thin layer of vegetation from nearby undisturbed peatland and spreading plant fragments (diaspores) over a ten times larger area of cutover peatland (Rochefort et al., 2003). Straw mulch is applied to maintain moist surface conditions and ditches are filled or blocked (Quinty and Rochefort, 2003). For ombrotrophic peatlands (bogs), the primary purpose of this technique is the re-establishment of *Sphagnum* moss cover and successful rewetting of the site in order to restore the carbon accumulation processes (Gorham and Rochefort, 2003). However, typical peatland plant diversity is also expected to re-establish using the moss layer transfer technique as all types of plant propagules (rhizomes, roots, seeds) are transferred along with moss fragments, or can be directly planted (Rochefort, 2000; Poulin et al., 2012).

While the moss layer transfer technique is the most common in Canada, other techniques include rewetting along with spontaneous revegetation (Lavoie et al., 2003), or hay-transfer for fens (Graf et al., 2012). However, rewetting alone might not be sufficient to restore severely degraded peatlands (Zak et al., 2010), as there is a need to recover other aspects of the hydrology of the site. There is also direct planting of seedlings (e.g. Cooper et al., 1998), which would also be the case in forest plantation (i.e., tree seedlings planted).

1.1.3.2. Forest plantation on cutover peatlands

As we propose to actively reintroduce trees as a restoration action to create a shady habitat where forest moss community could be reintroduced afterwards, we review what is know on the plantation of trees in cutover peatlands.

Several previous studies in northern Europe have examined the introduction of saplings to cutover peatlands (Pikk and Valk, 1996; Renou and Farrell, 2005), but the species utilised (*Betula pendula* Roth, B*etula pubescens* Ehrh. and *Pinus sylvestris* L.) (Kaunisto and Aro, 1996) are not native to North America. In order to define the appropriate selection of native species for the forest plantations, *P. mariana* (black spruce) is one of the most abundant tree species occurring naturally on Canadian peatlands and has performed well in various plantations on cutover peatland sites (Bussières et al., 2008). Thus, this native species is potentially useful for management situations where high productivity and use of naturally occurring species are prime concerns.

Northern continental climate with very cold winters and short growing season where ground freezes for a large part of the year is the native range of *P. mariana* (Lavoie and Payette, 1992). In this range, annual precipitation averages between 330 and 570 mm with 35-55% of falling as snow. Natural habitat for *P. mariana* is usually wet organic soils, which are nutrient poor, on gently sloping terrain (Zoltai et al., 1974). *P. mariana* has shallow rooting habit within the active zone of 40 cm depth, mostly spread laterally (Steven, 2000).It is tolerant of shade; their seedlings will develop in 10% of full light intensity, but survival and growth are better in open areas (Steven, 2000). Mature stands are associated with *Vaccinium vitis-ideae* and brown mosses including

Pleurozium schreberi, *Hylocomium splendens* and *Ptilium crista-castrensis*, *Aulacomnium palustre* and *Sphagnum spp* (DeLong et al., 1990). Bogs are one of the most common habitats for *P. mariana* in the Alberta Plateau portion of its range (DeLong et al., 1990). *P. mariana* grows more slowly than others associated species (Viereck et al., 1990). Under unmanaged optimum conditions, *P. mariana* can reach a mature average of 12 to 20 m tall and about 23 cm in diameter at breast height (DBH), and in poor sites, 8 to 12 m tall and about 13 cm in DBH (Viereck et al., 1990).

Cutover peatlands have an unstable surface and are deficient in plant nutrients with low phosphorus and potassium contents, and relatively low nitrogen content (Wind-Mulder et al., 1996). Consequently, the application of all three minerals (N, P, and K) is essential for a successful tree plantation (Hugron et al., 2011). Considering these constraints, various methods for forest plantation on cutover peatlands have been reviewed by Hugron et al. (2011). One method suggests planting seedlings of the dominant species, *P. mariana*, in 2 x 2 m spacing with localized fertilizer applied as "tea bags" buried beneath the tree seedling, with the recommendation to use 10 g tablets made of 20-10-15 (N-P_2O_5-K_2O) (Hugron et al., 2011). Although forest plantations on cutover peatlands have been established in eastern Canada (e.g. Bussières et al., 2008), trials in western Canada are lacking and fertilizer dose and methods could vary.

1.1.3.3. Impacts of restoration on C and greenhouse gas fluxes

Peatland restoration is growing in importance in Europe and North America, and is likely to remain important (Strack et al., 2008). Peatland management in Europe has been mainly aimed at restoring global biodiversity, but it is now released that it can also play an important role in reducing GHG emissions (Wilson et al., 2013). Dry conditions in cutover peatlands facilitate peat oxidation, increasing CO_2 emissions (Waddington and Price, 2000). Due to the conditions on non-vegetated cutover peatland there is no carbon fixation into the ecosystem, but increased aeration in the surface peat significantly enhances organic matter oxidation and CO_2 emission (Tuittila et al., 1999). Precise considerations will have to be given to water management, when working on adapting the moss layer transfer methods to the restoration of treed bog in drier climate. Indeed, an appropriate water management is important in order to minimize greenhouse gas (GHG) emissions on peatlands (Strack et al., 2008) and can result in a return of carbon sequestration (Waddington and Price, 2000).

In Finnish cutover peatlands, Tuittila et al. (1999) indicated that high water level can lower respiration derived from plants by decreasing the oxidation rate of root exudates and dead plant material. Rewetting a cutover peatland reduces CO_2 emissions (Waddington et al., 2010; Strack and Zuback, 2013; Strack et al., 2014) and increases CH_4 flux (Waddington and Day, 2007; Strack at al., 2014). Moreover, Strack and Zuback (2013) suggest that vegetation recovery can also significantly increased gross ecosystem photosynthesis (GEP) and decreased ecosystem respiration on restored cutover peat fields compared to unrestored areas and that after 10 years post restoration; this resulted in a carbon balance more similar to the natural peatland. However, restoration (at least in the short term) does not return the net carbon sink function of a natural bog (Waddington and Price, 2000). In contrast, Tuittila et al., (1999) found that after successful rewetting, there was a rapid restoration of the carbon sink function. Although it remains unclear how long it will take for restored peatlands to become carbon sinks, restoration greatly reduces CO_2 emissions compared to unrestored cutover peatlands (Strack et al., 2014).

Forest plantation on cutover peatlands can be another potential land use change to offset GHG emissions (Joosten and Clarke, 2002). Due to forest plantation, gradual changes in the soil structure and biology may change the rate of peat decomposition, atmospheric CO_2 will be sequestered into the growing tree biomass, and heterotrophic respiration (microbial activity) may increase in the peat soil (Makiranta et al., 2007). During the growing season, net primary production (NPP) increases as vegetation biomass grows, while litter production adds carbon storage in the ecosystem (Höper et al., 2008). Combining these effects, forest plantation on peat soils has been found to reduce their net C source, although its range is greatly dependent on assumptions regarding the rate of peat C loss (Byrne et al., 2006). Many factors, such as biomass production, should be considered to estimate the impact on C stock. However, there is little data on C and GHG exchange for forest plantation on cutover peat and no studies exist in North America.

1.2. Objectives and Hypotheses

Previous studies demonstrate the need for fertilizer in forest plantation on cutover peatlands. However, the adequate dose of fertilizer to apply for cutover peatland restoration in western Canada remains unclear. It is also unclear how the fertilizer dose impacts the colonization by non-target species and their effect on local conditions that could influence *P. mariana* growth. There are also no studies on GHG exchange in tree plantation on cutover peatlands in North America.

Therefore, the specific objectives of this study were to:

1) determine the effect of fertilizer dose on *P. mariana* and *B. papyrifera* growth, including C stored in biomass, within the forest plantation,

2) evaluate the impact of removal of *B. papyrifera* on *P. mariana* growth and microclimatic conditions (volumetric water content (ϴ), relative humidity (RH) and insolation (photosynthetically active radiation (PAR)) and,

3) estimate the carbon balance of a forest plantation on a cutover peatland.

1.2.1. Hypotheses

Three main hypotheses were developed to guide this study. Specific hypothesis are listed below for each specific objective.

1) Adding fertilizer will improve *P. mariana* and *B. papyrifera* growth and C accumulation in the biomass.

2) It is also hypothesized that removal of the competitor species, *B. papyrifera*, will promote basal diameter and annual elongation of leader stem of *P. mariana* by improving microclimatic conditions such as VWC (ϴ), RH and insolation (PAR) availability.

3) It is hypothesized that forest plantation will result in reduced carbon emission compared to unrestored cutover peatland.

1.3. Study Site

The study area, Paxson Bog (Figure 1.1) is located in the Athabasca Region (54°40'3.28"N; 113°7'24.57"W) in the east-central part of Alberta, Canada. This peatland lies entirely within the Dry Mixedwood Subregion of the Boreal Forest natural region of Alberta (Natural Regions Committee, 2006). This zone is sub-humid, meaning evaporation exceeds precipitation (Devito and Mendoza, 2007). Climatic moisture deficits in the boreal mixedwood zone are high with an annual water deficit between 0 and 200 mm (Strong and Leggat, 1981, Graf et al., 2008). The climate is characterized by dry autumns and winters and wet summers, where July is usually the wettest month (Strong and Leggat, 1981). The subhumid subregion has daily summer mean temperatures that range from 8.4 to 19.6°C and daily winter mean temperatures from -19.9 to -4.4°C. The annual precipitation average is 503.7 mm with 24 % falling as snow (Environment Canada, 2013).

The study site is dominated by organic soils underlain by a mixture of till and alluvial deposits. The property, operated by Premier Tech, is primarily a peat bog on a clay mineral soil with a total area of approximately 254 ha bordered to the north by agricultural land, to the south by a crown land (forest) and agricultural land, to the east by a forest and agricultural private land, and to the west by crown land (forest). The restored site covers over 5 ha, where the forest plantation was tested as an experimental restoration phase (Premier Tech, 2012). The ombrotrophic peatland was originally ditched around its perimeter, with additional minor ditches within the fields at 25-30 m spacing, as required for extraction using the vacuum technique (Daigle and Gautreau-Daigle, 2001, Premier Tech, 2012). The project map of Paxson Bog (Figure 1.1) shows the restoration plan design and proposed restoration techniques for recovering the vegetation and hydrology at the Paxson cutover peatland. The regional topography is characterized by rolling and gently rolling landscape, but the overall site topography of Paxson Bog was flat (Premier Tech, 2012). The total depth of peat was about 2 m before the extraction, while the average peat depth after the extraction is 0.6 m (Premier Tech, 2012).

The typical plant communities of peatlands in this region consist of specialized shrub and herbs growing on acidic peat substrates. Tree strata are dominated by black spruce (*Picea mariana* (Mill.) B.S.P) and tamarack (*Larix laricina* (Du Roi) Koch) forming open canopy stands.

Shrubs and forbs are predominantly species of Ericaceae (e.g., *Rhododendron groenlandicum* Oeder, *Vaccinium vits-idaea* minus and *Vaccinium oxycoccus* L.) and sedges from Cyperaceae, especially *Carex* spp (Premier Tech, 2012). Bryophytes including brown mosses and *Sphagnum* mosses are also very important (e.g., Vitt, 2000).

The study area for the proposed research is at the extreme south end of the cutover peatland (Figure 1.1). In 2005, the company (Premier Terch) and the Peatland Ecology Research Group (PERG) designed a restoration plan with a *P. mariana* plantation, where four levels of fertilizer (control, low, moderate and high doses) were randomly applied (Figure 1.2 and 1.3). The wet condition at that time, due to precipitation, brought the buried “tea bag” released fertilizer to the surface facilitating a spontaneous invasion of *B. papyrifera*, right around the planted tree seedlings. The main colonizer species has been identified as *Betula papyrifera* (March). Likewise, *Betula populifolia* (March) has been found also to be a good pioneer specie in post-production peatland to a characteristic invasive level (Lavoie et al., 1998). In the present study, *B. papyrifera* was a non-target species to the restoration plant, for this reason not all the individuals present on the site have been identified, but the majority looks similar to *B. papyrifera*. The water table was consistently below the remnant peat (i.e., within the underlying mineral substrate) and thus was not monitored in the present study. More details of the specific study design are given in the following chapters.

1.4. Thesis outline

This thesis is divided into two main parts and presented in manuscript format. Chapter 2 presents results related to the fertilization trial and *B. papyrifera* invasion effects on *P. mariana* growth within the plantation (Objective 1 and 2). Chapter 3 presents an investigation of carbon balance on a forested cutover peatland, seven years post-plantation (Objective 3). Chapter 4 summarizes the main findings of the thesis, suggests areas of future research and evaluates the contribution of the study to improving peatland management in Alberta and Canada.

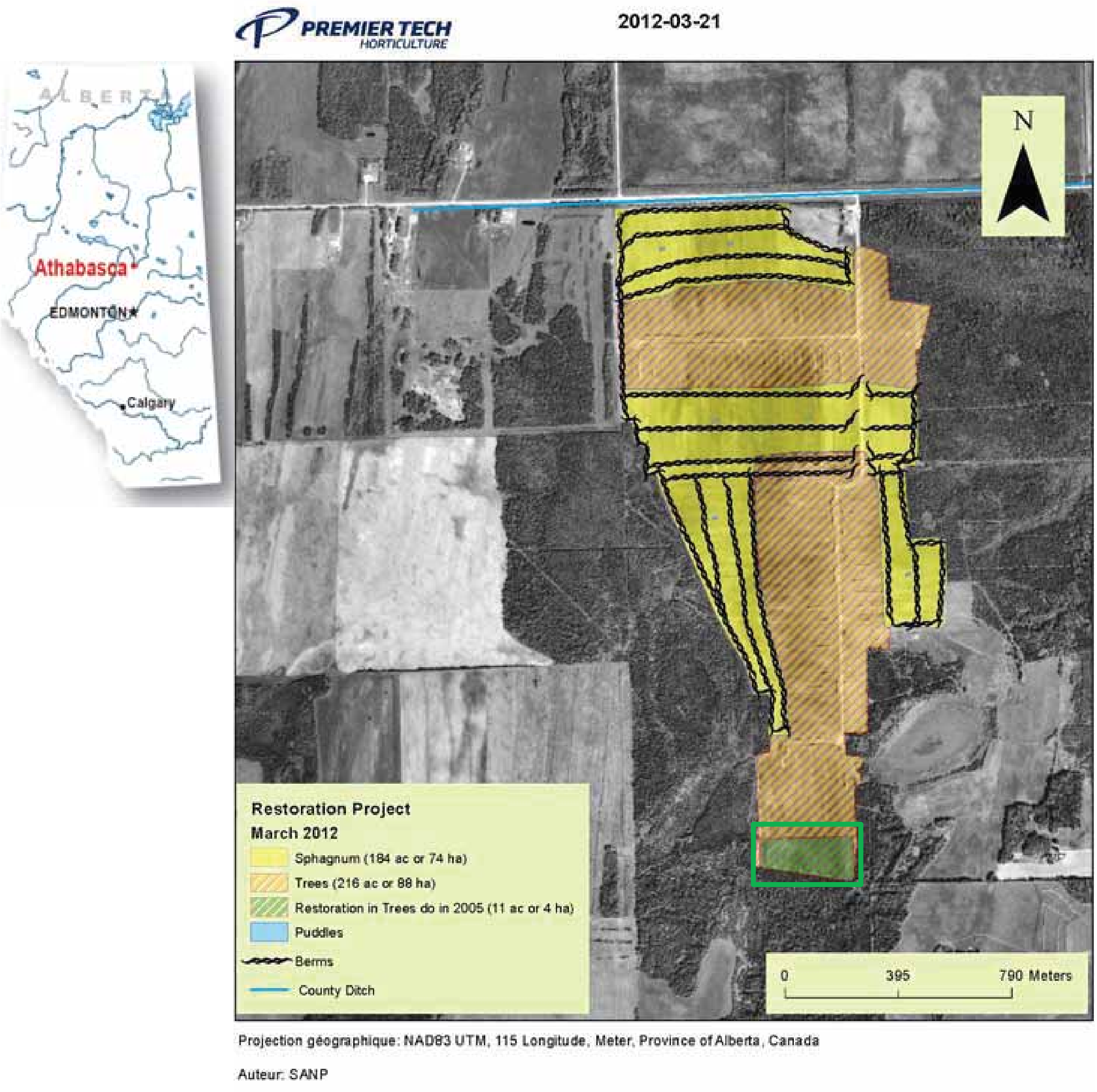


Figure 1.1. The study area, Paxson Bog, is located near the town of Athabasca in the east-central part of Alberta. Seven years prior to the study (2005), the experimental restoration plan started (green quadrant) with a forest plantation. The restoration projects for the remainder of the cutover area have been defined, but only the green area has been implemented (236 ha). Source: Premier Tech Horticulture.

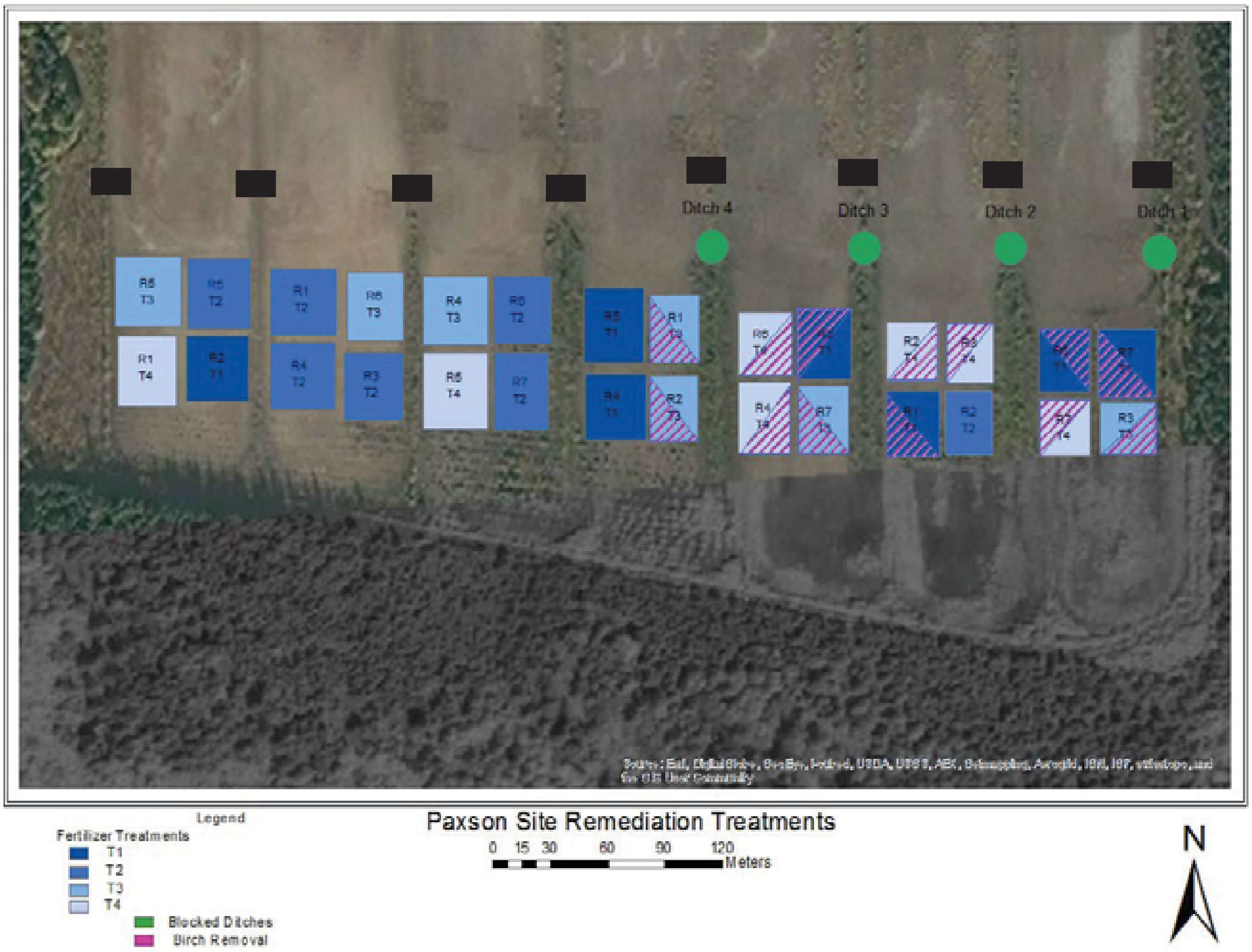


Figure 1.2. Field representation of fertilization treatments within the *P. mariana* plantation organized in a complete randomized experimental design with each dose repeated seven times. In 2005, 100 *P. mariana* seedlings were planted (10x10) within each experimental unit and four doses of fertilizer were tested (high, medium, low and no additions). Seven years later, invasive *B. papyrifera* surrounding the planted tree were removed over half diagonal of each experimental unit marked with pink hatch-lines. Ditches (indicate with black rectangles) were blocked 21 m from the plantation in August 2012. Methane fluxes were measured on the four ditches indicated in the figure with green dots.

Figure 1.3. a) Current landscape at the study site, bare peat (foreground) and *B. papyrifera* colonization (in the distance). **b)** Image of the forest plantation. Picture of plot R2T1 with high dose of fertilizer. Note the presence of *B. papyrifera* surrounding each planted *P. mariana* seedling.

1.5. References

Aerts, R., van Logtestijn, R.S.P., Karlsson, P.S., 2006. Nitrogen supply differentially affects litter decomposition rates and nitrogen dynamics of sub-arctic bog species. Global Change Biol. 146, 652–658.

Alberta Environmental, 2002. Alberta Agriculture, Food and Rural Development. Liming Acid Soils, Agdex 534-1. http://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/agdex3435

Alberta Government, 2013. Alberta Wetland Policy, Alberta Environment and Sustainable Resource Development, Edmonton, AB, Canada, p. 25.

Baird, A.J., Belyea, L.R., Morris, P, J., 2009. Carbon cycling in northern peatlands: upscaling of peatland-atmosphere fluxes of methane: small scale heterogeneity in process rates and the pitfalls of ''Bucket-and-slab'' models. Geophys Union Geophys Monogr Ser 184.

Black, K., O'Brien, P., Redmond, J., 2008. The extent of recent peatland afforestation in Ireland. Irish Forestry 65(1&2): 71-81.

Bridgham, S.D., Pastor, J., Updegraff, K., Malterer, T.J., Johnson, K., Harth, C., Chen, J., 1999. Ecosystem control over temperature and energy flux in Northern Peatlands Ecol Appl 9, 1345-1358.

Bussières, J., Boudreau, S., and Rochefort, L., 2008. Establish trees on cut-over peatlands in Eastern Canada. Mires and Peat, Vol. 3, Article 10, http://www.mires-and-peat.net/, ISSN 1819-754X © 2008 International Mire Conservation Group and International Peat Society.

Byrne, K.A., Cabral, R., Pöllänen, M. and Farrell, E.P., 2007. Natural regeneration. In: Wilson, D. & Farrell, E.P. (eds.) CARBAL. Carbon Gas Balances in Industrial Cutaway Peatlands in Ireland. University College Dublin, 15–17.

Cooper, D. J., MacDonald, L. E., 2000. Restoring the vegetation of mined peatlands in the southern Rocky Mountains of Colorado, USA. *Restoration Ecology.* 8, 103-111.

Caisse, G., Rochefort, L., Boudreau, S., and Munson, A.D., 2006. The importance of fertilization in the afforestation of cutover peatlands in eastern Canada. 5th European Conference on Ecological Restoration, Greifswald, Germany, 21–25 August 2006. p. 1.

Canadian Sphagnum Peat Moss Association (CSPMA). Available at: http://www.peatmoss.com/blog/environment/ (Last accessed on April 2015)

Chanton, J.P., Martens, C.S., Kelley, C.A., Crill, P.M., Showers, W.J., 1992. Methane transport mechanisms and isotopic fractionation in emergent macrophytes of an Alaskan tundra lake. Journal of Geophysical Research 97(D15), 16681–16688.

Charman, D., 2002. Peatlands and Environmental Change. John Wiley & Sons Ltd., Chichester.

Chimner, R.A., Cooper, D.J., 2003. Influence of water table levels on CO_2 emissions in a Colorado subalpine fen: an in situ microcosm study. Soil Biology & Biochemistry 35, 435 –451.

Clymo, R.S., 1983. Peat. In: Gore, A.J.P. (Ed.), Ecosystems of the World, 4A. Mires: swamp, bog, fen and moor, General Studies, Elsevier, Amsterdam, p. 159–224.

Conrad, R., 1989. Control of methane production in terrestrial ecosystems. In: Andreae, M.O., Schimel, D.S., (eds.) Exchange of trace gases between terrestrial ecosystems and the atmosphere. Wiley, New York, 39–58.

Cooper, D.J., MacDonald, L.H., Wenger, S.K., Woods, S.W., 1998. Hydrologic restoration of a fen in Rocky Mountain National Park, Colorado, USA. Wetlands 18, 335–345.

Cooper D.J., MacDonal L.H., 2003. Restoring the vegetation of mined peatlands in the Southern Rock Mountains of Colorado, U.S.A. Restoration Ecology Vol.8, No. 2, p. 103-111.

DeLong, C., Annas, R.M., Stewart, A.C., 1990. Boreal White and Black Spruce Zone. Location and Distribution. Available at: https://www.for.gov.bc.ca/hfd/pubs/docs/srs/Srs06/chap16.pdf (Last accessed on April 2015)

Devito, K.J., Mendoza, C., 2007. Maintenance and dynamics of natural wetlands in western boreal forests: synthesis of current understanding from the Utikuma research study area. Pages C1-62 in CEMA, editors. Appendices to the guideline for wetland establishment on reclaimed oil sands leases revised (2007) edition. Available online at: http://www.cemaonline.ca/

Dunfield, P., Knowles, R., Dumont, R., Moore, T.R., 1993. Methane production and consumption in temperate and subarctic peat soils: response to temperature and pH. Soil Biology and Biochemistry 25, 321–326.

Environment Canada, 2010. National Inventory Report 1990-2008: Greenhouse Gas Sources and Sinks in Canada. Government of Canada.

Environmental Site Assessment Paxson Bog, 2011. Premier Tech.

FAO, 2012. Joosten, H., Tapio-Biström M.L., Tol S. Peatlands-guiance for climate change mitigation by conservation, rehabilitation and sustainable use. Available at: http://www.aseanpeat.net/index.cfm?&menuid=176 (Last accessed on September 2014).

Fay, E., Lavoie C., 2009. The impact of birch seedlings on evapotranspiration from a mined peatland: an experimental study in southern Quebec, Canada. Mires and Peat, Vol. 5, Article 03, 1-7.

Foote, L. 2012. Threshold considerations and wetland reclamation in Alberta's mineable oil sands. Ecology and Society 17(1): 35.

Frolking, S., Talbot, J., Jones, M.C., Treat, C.C, Kauffman, J. B., Tuittila, Eeva-Stiin, Roulet, N., 2011. Peatlands in the Earth's 21st century climate system. Environmental Reviews, Vol. 19, No. NA: p. 371-396.

Glaser, P.H., Jasssen, S.J.A., 1992. Raised bog in eastern North America: transition in landforms and gross stratigraphy. Can. J. Bot. 64: 395-415.

González, E., Rochefort, L., Boudreau, S., Hugron, S., Poulin, M., 2013. Can indicator species predict restoration outcomes early in the monitoring process? A case study with peatlands Ecol. Ind. 32, 232–238.

González, E., Rochefort, L., 2014. Drivers of success in 53 cutover bogs restored by a moss layer transfer technique. Ecol. Eng. 68, 279–290.

Gorham, E., 1991. Northern peatlands: role in the carbon cycle and probable response to climatic warming. Ecological Applications 1, 182–195.

Gorham, E., Rochefort, L., 2003. Peatland restoration: A brief assessment with special reference to Sphagnum bogs. Wetlands Ecology and Management 11, 109-119.

Graf, M.D., Rochefort, L., Poulin, M., 2008. Spontaneous revegetation of cutaway peatlands of North America. Wetlands 28, 28-39.

Graf, M., Bérubé, V., Rochefort, L., 2012. Restoration of peatlands after peat extraction. In: Vitt, D., Bhatti, J. (Eds.), Restoration and Reclamation of Boreal Ecosystems. Cambridge University Press, p. 259–280

Groeneveld, E.V.G., Masse, A., Rochefort, L., 2007. Polytrichum strictum as a nurse-plant to facilitate Sphagnum and boreal vascular plant establishment. Restoration Ecology 15, 709–719.

Groeneveld, E.V.G, Rochefort, L., 2002. Nursing plants in peatland restoration: on their potential use to alleviate frost heaving problems. Suo 53, 73-85.

Hånell, B., 1991. Peatland forestry in Sweden. in Jeglum, J.K. and Overend, R.P. (eds). Symposium '89, Peat and Peatlands: Diversification and Innovation, Vol I Peatland Forestry, Quebec City, 7-11, 1989. Can. Soc. For Peat and Peatlands, Can. Natl. Comm of Internalt. Peat Soc, p.19-25.

Höper, H., Augustin, J., Cagampan, J.P., Drösler, M., Lundin, L., Moors, E., Vasander, H., Waddington, J.M., and Wilson, D., 2008. Restoration of peatlands and greenhouse gas balances. In: Strack, M., (ed.) Peatlands and Climate Change. International Peat Society, Finland, p. 182-210.

Hugron, S., Bussières, J., Rochefort, L., 2011. Plantation d'essences forestières dans le contexte de la restauration écologique des tourbières: un guide pratique, Groupe de recherche en écologie des tourbières, Université Laval, Québec, p 88.

Hytönen, J., Kaunisto S., 1999. Effect of fertilization on the biomass production of coppiced mixed birch and willow stands on a cut-away peatland. Biomass and Bioenergy 17 (1999) 455-469

IUCN, International Union for Conservation of Nature, 2005. Declaration of Méze. Invasive species definition. Available online at: http://www.iucn.org/about/union/secretariat/offices/iucnmed/iucn_med_programme/species/invasive_species/ (Last accessed on January 2015)

IPCC, 2000. Robert T. Watson, Ian R. Noble, Bert Bolin, N. H. Ravindranath, David J. Verardo and David J. Dokken. Cambridge University Press, UK. Chap 2. Available at: http://www.ipcc.ch/ipccreports/sres/land_use/index.php?idp=47 (Last accessed on July 2014) International Peat Society, 2001. Peatlands and peat. http://www.peatsociety.org/

Joabsson, A., Christensen, T.R., Wallen, B., 1999. Influence of vascular plant photosynthetic rate on CH_4 emission from peat monoliths from southern boreal Sweden. Polar Research 18, 215-220.

Joosten, H., 2011. The global peatland CO_2 picture. In: Tanneberger, F. & Wichtmann, W. (eds.) Carbon Credits From Peatland Rewetting. Climate - Biodiversity - Land Use. Schweizerbart Science Publishers, Stuttgart, 20 and 29–30.

Joosten, H., Clarke, D., 2002. Wise Use of Mires and Peatlands. International Mire Conservation Group and International Peat Society, Saarijärven Offset Oy, Saarijärvi, Finland.p. 504.

Kaunisto, S., Aro, L., 1996. Forestry use of cutaway peatlands. In: Vasander, H. (ed.) Peatland in Finland, Finnish Peatland Society, Helsinki, Finland, 130−134.

Kaunisto S., 1981 Natural regeneration of Betula pendula and B. pubescens on peat cut-away area. Suo32 (3):53-60.

Keller, J.K., Bridgham, S.D., 2007. Pathways of anaerobic carbon cycling across an ombrotrophic-minerotrophic peatland gradient. Limnol Oceanogr 52:96–107.

Kuhry, P., Nicholson, B.J., Gignac, L.D., Vitt, D.H., Bayley, S.E. 1993. Development of Sphagnum-dominated peatlands in boreal continental Canada. Canadian Journal of Botany 71:10-22.

Lachance, D., Lavoie, C., Desrochers, A., 2005. The impact of peatland afforestation on plant and bird diversity in southeastern Québec. Ecoscience 12, 161-171.

Lapalainen, E., 1996. Global Peat Resources. International Peat Society, Jyska, Finland.

Lavoie, C. & Payette, S., 1992. Black spruce growth forms as a record of a changing winter environment at treeline, Quebec, Canada. Arctic and Alpine Research, 24, 40– 49.

Lavoie, C., Rochefort, L., 1996. The natural revegetation of a harvested peatland in southern Québec: a spatial and dendroecological analysis. Écoscience 3, 101–111.

Lavoie, C., Saint-Loui, A., 1998. The spread of gray birch (Betula populifolia) in eastern Quebec: landscape and historical considerations. Can. J. Bot. 77: 859–868.

Locky, D., 2011. A. Wetlands: Alberta's Keystone Ecosystem at a Crossroads. Green Paper Prepared for the Alberta Institute of Agrologists. Annual Conference of the Alberta Institute of Agrologists Banff, Alberta.

Limpens, J., Berendse, F., Blodau, C., Canadell, J.G., Freeman, C., Holden, J., Roulet, N., Rydin, H., Schaepman-S, G. 2008. Peatlands and the carbon cycle: from local processes to global implications – a synthesis. Biogeosciences. 5, 1475-1491.

Land use, land-use change and forestry (LULUCF), 2005. Definitions, modalities, rules and guidelines relating to land use, land-use change and forestry activities under the Kyoto Protocol. Decision 16/CMP.1. FCCC/KP/CMP/2005/8/Add.3. Available online at: http://www.redd-monitor.org/wp-content/uploads/2009/09/Kyoto_COP001_016.pdf (Last accessed on March 2015)

Makiranta, P., Hytonen, J., Aro, L., Maljanen, M., Pihlatie, M., Potila, H., Shurpali, N. J., Laine, J., Lohila, A., Martikainene, P.J., Minkkinene, K., 2007. Soil greenhouse gas emissions from afforested organic soil croplands and cutaway peatlands. Boreal Env. Res. 12: 159-175.

McCarter, C. P., & Price, J. S., 2013. The hydrology of the Bois-des-Bel bog peatland restoration: 10 years post-restoration. Ecological Engineering, 55, 73-81.

McCarter, C.P.R., Price, J., 2014. The hydrology of the Bois-des-Bel peatland restoration: hydrophysical properties limiting connectivity between regenerated Sphagnum and remnant vacuum harvested peat deposit. Ecohydrology. Doi: 10.1002/eco.1498

Meteorological Service of Canada, Environnement Canada, 2013. Environment Canada: http://climate.weatheroffice.gc.ca/ climateData (Last accessed on September 2014)

Moore, P.D., 2002. The future of cool temperate bogs. Environmental conservation 29, 3 –20.

Moore, T. R., Roulet, N. T., Waddington, J. M., 1998. Uncertainty in predicting the effect of climatic change on the carbon cycling of Canadian peatlands. Climatic Change 40: 229-245.

Oikarinen, M, Pyykkoénen, J., 1981. The efect of thinning and fertilization on the growth of pubescent birch (Betula pubescent) on drained Myrtillus spruce swamp in Ostrobothnia. Folia Forestalia 1981; 486:1-15.

Parish, F., Sirin, A., Charman, D., Joosten, H., Minayeva, T., Silvius, M., 2008. Assessment on Peatlands, Biodiversity and Climate Change: Main Report. Global. Stringer.

Paxson Restoration Report, Premier Tech, 2012.

Popp, T.J., Chanton, J.P., Whiting, G.J., Grant, N., 1999. Methane stable isotope distribution at a *Carex* dominated fen in north central Alberta. Global Biogeochemical Cycles 1, 1063-1077.

Poulin, M., Rochefort, L., Quinty, F., Lavoie, C., 2005. Spontaneous revegetation of mined peatlands in eastern Canada. Can. J. Bot. 83: 539–557

Price, J.S., Heathwaite, A.L., Baird, A.J., 2003. Hydrological processes in abandoned and restored peatlands: An overview of management approaches. Wetlands Ecology and Management 11: 65-83.

Price, J.S., McLaren, R.G., Rudolph, D.L., 2010. Landscape restoration after oil sands mining: conceptual design and hydrological modelling for fen reconstruction. International Journal of Mining, Reclamation and Environment 24(2), 109-123.

Pikk, J., Valk, U., 1996. Results of afforestation experiments of cut-over peatlands in Estonia. In: Lüttig, W. (ed.) Proceedings of the 10th International Peat Congress, Volume 2, International Peat Society, Stuttgart, Germany, 219−224.

Quinty, F., Rochefort. L., 2000. Bare peat substrate instability in peatlands restoration: problems and solutions. In: Rochefort, L., Daigle, J.-Y., (eds) 2000. Sustaining our peatlands, Proceedings of the 11th International Peat Congress, vol. II. Quebec, Canada, 6–12 August 2000. International Peat Society, Edmonton, Alberta, Canada, p. 751–756

Quinty, F., Rochefort. L., 2003. Peatland restoration guide, 2nd ed. Canadian Sphagnum Peat Moss Association at New Brunswick Department of Natural Resources and Energy. Québec, Québec. 106 p. http://www.gret-perg.ulaval.ca/habitats-gret.html.

Poulin M., Andersen R., Rochefort L., 2012. A new approach for tracking vegetation change after restoration: A case study with Peatlands. Society for Ecological Restoration doi: 10.1111/j.1526-100X.2012.00889.x

Renou, F., Farrell, E. P., 2005. Reclaiming peatlands for forestry: the Irish experience. In: Madsen, P. A. (ed.), Restoration of boreal and temperate forests. CRC Press, Boca Raton, p. 541–557.

Renou, F., Scallan, Ú., Keane, M. & Farrell, E.P. 2007. Early performance of native birch (Betula spp.) planted on cutaway peatlands: influence of species, stock types and seedlings size. European Journal of Forest Research, 126, 545–554.

Renou-Wilson, F., 2011. Optimal pratices in the afforestation of cutaway peatlands. Lambert Academic Publishing, Saarbrücken, Germany. p 254.

Rochefort, L., 2000. Sphagnum A Keystone Genus in Habitat Restoration. The Bryologist 103, 503-508.

Rochefort, L., Quinty, F., Campeau, S., Johnson, K, Malterer, T., 2003. North American approach to the restoration of Sphagnum dominated peatlands. Wetlands Ecology and Management 11, 3–20.

Rochefort L, Strack M, Poulin M, Price JS, Graf M, Desrochers A, Lavoie C, Lapointe L. 2012. Northern peatlands, In Wetland Habitats of North America: Ecology and Conservation Concerns, D Batzer, A Baldwin (eds.), University of California Press, Berkeley, California, USA, pp. 119-134.

Russi D., Brink, P. T., Farmer, A., Badura, T., Coates, D., Förster, J., Kumar R., Davidson, N., 2013. The Economics of Ecosystems and Biodiversity for Water and Wetlands. IEEP, London and Brussels; Ramsar Secretariat, Gland.

Safford, L. O.; Bjorkbom, J. C.; Zasada, J. C. 1990. Betula papyrifera Marsh, paper birch. Pages 158-171 In: Burns, Russell M.; Honkala, Barbara H., editors. Silvics of North America: Volume 2. Hardwoods. Agriculture Handbook 654. Washington, DC: USDA Forest Service. Available: http://www.na.fs.fed.us/pubs/silvics_manual/volume_2/betula/papyrifera.htm (Last accessed April 2015)

Salonen, V., 1987. Relationship between the seed rain and the establishment of vegetation in two areas abandoned after peat harvesting. Ecography 10, 171-174

Saarinen, T., 1996. Biomass and production of two vascular plants in a boreal mesotrophic fen. Can. J. Bot.74:934-938.

Society for Ecological Restoration International Science & Policy Working Group (SERIS & PWG), 2004. The SER International Primer on Ecological Restoration. Tucson: Society for Ecological

Restoration International. Available at http://www.ser.org/resources/resources-detail-view/ser-international-primer-on-ecological-restoration (Last accessed on February 2015).

Schumann, M., Joosten, H., 2008. Global Peatland Restoration Manual. Available at: http://www.imcg.net/docum/prm/gprm_01.pdf. (Last accessed on September 2014).

Silvola, J., Alm, J., Ahlholm, U., Nykanen, H., Martikainen, P.J., 1996. CO_2 fluxes from peat in boreal mires under varying temperatures and moisture conditions. Journal of Ecology 84, 219-228.

Steven C.G., 2000. Ecophysiology of Northern Spruce Species. The performance of planted seedlings. NRC Research Press Canada, doi: 97806601847089780660179599

Strack, M., Waller, M.F., Waddington, J.M., 2006. Sedge Succession and Peatland Methane Dynamics: A Potential Feedback to Climate Change. Ecosystems 9, 278-287.

Strack, M., Waddington, J.M., Turetsky, M., Roulet, N.T., Byrne, K.A. 2008. Northern peatlands, greenhouse gas exchange and climate change. In: Strack, M. (Ed.), Peatlands and Climate Change, International Peat Society and Saarijärven Offset Oy, Saarijärvi, Finland, p. 44-69.

Strack, M., Zuback, Y., 2013. Annual carbon balance of a peatland 10yr following restoration, Biogeosciences, 10, 2885-2896, doi: 10.5194/bg-10-2885-2013.

Strack, M., Keith, A.M., Xu, B., 2014. Growing season carbon dioxide and methane exchange at ta restored peatland on the Western Boreal Plain. Ecological Engineering 64, 231-239.

Strong, W.L., K.R. Leggat., 1981. Ecoregions of Alberta. ENR Technical Report (T/4) from the Alberta Energy and Natural Resources, Edmonton, Alberta.

The Canadian System of Soil Classification, 1998. 3rd ed., NRC research press. Canada.

Ten Brink P., Russi D., Farmer A., Badura T., Coates D., Förster J., Kumar R. and Davidson N. 2013 The Economics of Ecosystems and Biodiversity for Water and Wetlands. Executive Summary.

Thurman, E. M., 1985. Humic Substances in Soil, Sediment, and Water: Geochemistry, Isolation, and Characterization. John Wiley and Sons, New York NY, 87-103.

Tuittila, E. S., Komulainen, V-M, Vasander, H., Laine, J., 1999. Restored cut-away peatlands as a sink of atmoshpheric CO_2. Oecologia, 120, 563-574.

Updegraff, K. Bridgham, S.D., Pastor, J., Weishampel, P., Harth, C., 2001. Response of CO_2 and CH_4 emissions from peatlands to warming and water table manipulation. Ecological Applications 11(2), 311-326.

Vasander, H., Kettunen, A., 2006. Carbon in Boreal Peatlands. Ecological Studies (R.K. Wieder and D.H. Vitt (eds.), 188, 165-194.

Viereck, L. A., Johnston, .F, 1990. Picea mariana (Mill.) B.S.P. black spruce. In: Burns, Russell M.; Honkala, Barbara H., technical coordinators. Silvics of North America. Volume 1. Conifers. Agric. Handb. 654. Washington, DC: U.S. Department of Agriculture, Forest Service: 227-237. [13386].
Available at: http://www.na.fs.fed.us/pubs/silvics_manual/Volume_1/picea/mariana.htm (Last accessed on April 2015)

Vitt, D.H., Halsey, L.A., Bauer, I.E., Campbell, C., 2000. Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. Canadian Journal of Earth Sciences 37, 683-693.

Vitt, D.H., 2006. Functional characteristics and indicator of Boreal Peatlands. In R. Weider & D.Vitt, Boreal Peatland Ecosystem Springer, p. 9-24.

Waddington, J.M., Strack, M., Greenwood M.J., 2010. Toward restoring the net carbon sink function of degraded peatlands: Short-term response in CO_2 exchange to ecosystem-scale restoration. Journal of geophysical research Vol. 115 G01008

Waddington, J.M., Day, S.M., 2007. Methane emissions from a peatland following restoration. Journal of Geophysical Research 112. G03018, doi: 10.1029/2007JG000400.

Waddington, J.M., McNeil, P., 2002. Peat oxidation in an abandoned cutover peatland. Can. J. Soil Sci. 82, 279–286.

Waddington, J.M., Warner K.D., Kennedy, G.W., 2002. Cutover peatlands: A persistent source of atmospheric CO_2. Global biogeochemical cycles, Vol. 16, NO. 1, 1002, 10.129/2001GB001398

Waddington, J.M., Price, J.S., 2000. Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. Physical Geography 21(5), 433-451

Wetlands International, 2008. The Global Peatland fund. The Netherlands. www.wetlands.org.

Whiting, G.J., Chanton, J.P., Bartlett, D.S., Happell, J.D., 1991. Relationships between CH_4 emission, biomass, and CO_2 exchange in a subtropical grassland. Journal of Geophysical Research-Atmospheres 96, 13067-13071.

Wilson, D., Farrell, C., Mueller, C., Hepp, S., Resou-Wilson, F., 2013. Rewetted industrial cutaway peatlands in western Ireland: a prime location for climate change mitigation? Mires and Peat, Volume 11 (2013), Article 01, 1–22, http://www.mires-and-peat.net/, ISSN 1819-754X © 2013 International Mire Conservation Group and International Peat Society

Wilson, S., Griffiths, M., Anielski, M., 2001. The Alberta GPI Accounts: Wetlands and Peatlands. Report 23. Pembina Institute for Appropriate Development, http://www.pembina.org/, ISBN 0-921719-68-X © 2001 The Pembina Institute

Wind-Mulder, H., 1998. Towards the restoration of peatlands: Comparisons of harvested and natural peatlands and examination of revegetation techniques. Ph.D. Thesis, p. 211.

Yli-Petäys, M., Laine, J., Vasander, H., Tuittila, E-S., 2007. Carbon gas exchange of a re-vegetated cut-away peatland five decades after abandonment. Boreal Environment Research 12, 177-190.

Yu, Z.C., 2012. Northern peatland carbon stocks and dynamics: a review. Biogeosciences, 9, 4071–4085, 2012

Yu, Z.C., Loisel, J, Brosseau, D.P., Beilman, DW, Hunt, S.J., 2010. Global peatland dynamics since the Last Glacial Maximum. Geophys. Res. Lett. 37(13): L13402.

Zak, D., Gelbrecht, J., Wagner, C., Payer, B., Augustin, J., 2010 Phosphorus mobilization in rewetted fens: the effect of altered peat properties and implications for their restoration. Ecol Appl 20:1336–1349.

Zoltai, S.C., Vitt, D.H., 1990. Holocene climatic change and the distribution of peatlands in western interior Canada. Quat. Res. 33: 231–240.

Zoltai, S. C., and W. W. Pettipiece. 1974. Tree distribution on perennially frozen earth hummocks. Arctic and Alpine Research 6(4):403-411

CHAPTER 2: Effect of fertilizer dose and *Betula papyrifera* colonization on success of a *Picea mariana* plantation on a cutover peatland

Abstract

Forest plantation on cutover peatlands may be considered a viable restoration technique in western Canada, where natural bogs have a high density of *Picea mariana* trees. Fertilizer is needed to promote *P. mariana* establishment; however, it also encourages spontaneous colonization by non-peatland species such as *Betula papyrifera* when fertilizer is on the peat surface. This study assessed the fertilizer dose most appropriate for *P. mariana* establishment and growth on a cutover peatland and monitored the impact of *B. papyrifera* colonization on *P. mariana* growth through a removal experiment. Four levels of fertilizer dose were applied to a cutover peatland at Paxson, Alberta, Canada. Below ground fertilizer additions improved tree establishment and growth, but due to inundation of the site following plantation, the higher dose treatments leached fertilizer to the surface and favoured the colonization of *B. papyrifera*. Seven years post-plantation, fertilizer promoted 84% of *P. mariana* survival and the highest fertilizer dose improved *P. mariana* and *B. papyrifera* (birch) growth. A birch removal experiment showed that removal of *B. papyrifera* had a significant effect on the increase of annual growth of *P. mariana.* There were differences in microclimatic conditions (including soil water content, relative humidity and photosynthetically active radiation) between birch removal and intact plots, resulting in a substantial impact on *P. mariana* growth. Avoiding *B. papyrifera* colonization on site is more effective than cutting them down due to their ability to rapidly recolonize from basal stumps.

2.1. Introduction

To extract peat for horticultural use, the land needs to be drained and surface vegetation removed (Strack and Waddington, 2012), which consequently changes the entire ecosystem (Joosten et al., 2011). Drainage of peatlands can degrade these wetland ecosystems to a state of reduced habitat diversity (Raunio et al. 2008; Tarvainen et al., 2013), and reduces the presence of endangered native peatland species (Tarvainen et al., 2013). The regeneration process in cutover peatlands is slow; however, human intervention can facilitate adequate environmental conditions to promote recolonization (Quinty and Rochefort, 2003). In western Canada, undisturbed peatlands have forest cover (Vitt, 2006) suggesting that restoring peatlands in western Canada should consider this tree dominance. This study was a first attempt to restore cutover bog with the approach of tree plantation. Previous research has been carried out to describe the optimal techniques to restore peatlands, but to date most has focused on the more humid climate of eastern Canadian provinces (Rochefort et al., 2003; Strack et al., 2014). When considering species for Alberta cutover peatland forest plantation, *P. mariana* is a strong choice, as it is one of the dominant tree species occurring naturally on Canadian bogs, and Bussières et al. (2008) demonstrated that it grows well in various plantations on cutover sites.

However, in cutover peatlands *P. mariana* growth is difficult because residual peat is deficient in plant nutrients with low phosphorus (P) and potassium (K) contents, and relatively low nitrogen (N) contents (Wind-Mulder et al., 1996). Therefore, to stimulate *P. mariana* seedlings the addition of NPK fertilizer is essential (Caisse et al., 2006; Hugron et al., 2011). Therefore, a trial was initiated in Alberta in 2005 to determine the best fertilizer application dose. Following the plantation at the study site, inundation occurred due to unusual precipitation leading to the site inundation and consequently the leaching of the below-ground inserted fertilizer treatments. Thus, seven years post-plantation, the problem of *B. papyrifera* invasion needed to be addressed as fertilization may also have encouraged spontaneous colonization by *B. papyrifera* (Graf et al., 2009).

The resulting dense *B. papyrifera* colony may influence the site hydrology through transpiration (Fay and Lavoie, 2009), further lowering the water table and limiting peatland recovery. The dry post-drainage surface on cutover peatlands presents difficult environmental conditions for recovery of the bog plant community and the ecosystem hydrology (Gorham, 2003) resulting in conditions that often favor invasive species establishment, e.g., *Betula papyrifera* (March) (paper birch) (Quinty and Rochefort, 2003), which could be an obstacle to the rehabilitation of long term ecological peatland functions (Quinty and Rochefort, 2003). In addition, aeration of bare peat facilitates species invasion (Laine et al. 1995; Pellerin et al. 2009: Laine et al, 2011: Graf et al., 2012). *B. papyrifera* colonization has also been identified as a potential ecological problem for peatland restoration (Fay and Lavoie, 2009). *B. papyrifera* can tolerate a wide range of environmental conditions (Fay and Lavoie, 2009), have easy seed dispersion over a large distance by wind (Campbell et al., 2000) and plants have a high nutrient absorption rate allowing quick growth in open areas (Fay and Lavoie, 2009). Potential consequences of *B. papyrifera* colonization could be a control of hydrology, mulching and shading of the ground, and competition for nutrients with *P. mariana*, delaying their growth. Thus, establishment of a dense *B. papyrifera* forest could lower the water table, limit *P. mariana* growth and make the site very dry, and then mosses are unlikely to establish in future. The main goal for peatland restoration is to rehabilitate a wetland system that is able of accumulating organic matter in the form of peat (Hugron et al., 2011) and *B. papyrifera* colonization may make it difficult to achieve this goal.

This paper investigates the appropriate fertilization dose for *P. mariana* forest plantation on cutover peat and determines the impact of *B. papyrifera* colonization on *P. mariana* growth on cutover peatlands. This study aims to improve peatland restoration measures in western Canada by evaluating forest plantation focused on *P. mariana*; therefore, we tested what would be the best the fertilizer dose to promote optimised *P. mariana* survival and growth. Since *B. papyrifera* colonization may occur within the plantation if below-ground fertilizer leaches to the peat surface, this study also assessed the effect of fertilizer dose on *B. papyrifera* growth, and the effect of *B. papyrifera* invasion on *P. mariana* growth via a birch removal experiment. It is hypothesized that a high dose of fertilizer during *P. mariana* plantation increases the availability of nutrients and supports tree establishment and better growth. The second hypothesis is that presence of *B. papyrifera* will negatively impact *P. mariana* growth. The third hypothesis is that the removal of the competitor species, *B. papyrifera*, will increase *P. mariana* annual elongation of leader stem by improving microclimatic conditions, such as peat volumetric water content (ϴ), relative humidity (RH) and insolation (photosynthetically active radiation (PAR)).

2.2. Methods

2.2.1. Study Site

The study area, Paxson Bog, is located near Athabasca (54°40’3.28”N; 113°7’24.57”W), in the east-central part of Alberta, Canada. The study area is a cutover peat bog on a clay mineral soil with a total area of around 5 ha, where a *P. mariana* plantation was tested as an experimental restoration phase. Weather conditions during planting were collected from Alberta AgroClimatic Information Service (Table 2.1). In 2005, the company (Premier Tech) and the Peatland Ecology Research Group (PERG) designed a restoration plan with a *P. mariana* plantation, where four levels of fertilizer (control, low, moderate and high doses) were randomly applied (Figure 1.2 and 1.3).

In 2013 (May to October), two meteorological stations recorded the environmental conditions (temperature and precipitation; HOBOware sensors) every 30 minutes on site (Table 2.1). These results were corroborated with the data from Alberta AgroClimatic Information Service (Athabasca, ACGM, http://agriculture.alberta.ca/acis/alberta-weather-data-viewer.jsp). For the 2013 growing season at the study site, total annual precipitation was 264.4 mm (Paxson on-site meteorological station). The site received the most of precipitation (95 mm) in July. The mean temperature during the study period was 15.5 °C.

In 2013, the mean peat pH was 4.06 ± 0.044, mean corrected conductivity was 933.3 ± 139.3 µS/cm (contributions from H^+ subtracted from specific conductivities, Sjörs, 1950). Peat depth was 0.6 ± 0.2 m from the mineral soil and it varies across the site describing a gradient with shallower peat in the middle area of the north plots (appendix Figure A.2.1). The residual peat was very weakly decomposed (von Post H3) and mean bulk density was 0.28 ± 0.04 g cm^{-3}.

In fall 2012, the ditches were blocked 21 m from the experimental plot in an attempt to re-establish the water table and hydrological conditions in the restored area. The ditches were filled in just north of the restored area using excess peat pushed into a ridge using equipment including a leveller and a front-end loader (Figure 1.2). The annual mean ϴ for 2005 measured by

Premier Tech was 25.92 ± 0.76% and for 2012 the mean was 23.52 ± 0.4%. The variability of ϴ was high throughout the growing season. However, in 2013 after blocking the ditches, mean ϴ was 35.13 ± 0.76%.

2.2.2. The effect of fertilisation on *P. mariana* tree establishment

The effect of nutrient additions on *P. mariana* establishment in a cutover bog was carried out within a completely randomised design. The experiment was established by PERG in 2005. *P.mariana* seedlings that were 2 years old were planted in plugs. Previous studies have shown differences in tree growth between rates of fertilizer application on cutover peatland in eastern Canada (e.g. Caisse et al., 2006; Bussières et al., 2008). For the present study, the effect of fertilization was assessed seven years after *P. mariana* plantation. Four levels of fertilizer application of 20-10-15 (N-P_2O_5-K_2O) NPK fertilizer were tested: 1) control (non-fertilized), 2) low dose (8.9 g/bag), 3) medium dose (17.9g/bag) and 4) high dose (26.8 g/bag). Each dose was replicated randomly seven times resulting in a forest plantation that includes 28 experimental units (Figure 1.2). Each unit consists of a 400 m^2 plantation of 100 (10 x 10) *P. mariana* trees, spaced 2 m apart. During planting in 2005, each dose of fertilizer was buried beneath each seedling as a “tea bag”.

To determine the effect of fertilizer dose on *P. mariana* and *B. papyrifera* growth, every *P. mariana* planted was surveyed. The survey was conducted on the central 6x6 planted *P. mariana* of each plot to avoid edge effects, particularly near remnant ditches due to dense *B. papyrifera* colonization in these areas. In September 2012, survival, basal diameter and total height of each planted *P. mariana* was measured within this inner 6x6 planted trees.

All statistical analysis in this study was performed using IBM SPSS Statistic (v.21). The tree survey database was used to evaluate the effect of fertilizer doses (Normality Shapiro-Wilk test, $p>0.05$) on tree growth and tested if fertilizer improved *P. mariana* and *B. papyrifera* growth. Analysis of variance (ANOVA) were defined with a significance level of 0.05 to analyze the differences in group means between fertilizer doses for dependent variables, including survival, basal diameter, and height for *P. mariana* and *B. papyrifera*.

2.2.3. Environmental variables

Peat volumetric water content (ϴ) at the growing surface of each experimental unit was measured using a portable WET-Sensor™ (Delta-T Devices, HH2, Cambridge, UK) time-domain reflectometry (TDR) device during the growing season from August to October in 2012 (pre-cutting) and from May to October in 2013 (post-cutting). During each measurement, ϴ was recorded monthly and systematically (Figure 2.1) at seven locations within each subplot, in the middle of four trees, and averaged across the plot to obtain a plot-scale ϴ value for 0-6 cm upper soil layer. The depth of the peat deposit was measured at an average of three random spots around each plot. A threaded telescopic rod was pushed vertically into the peat, until it reached the mineral soil contact.

To determine peat bulk density in each experimental unit a sample of known volume was collected and weighed when dry. A tin (880 cm^3) was pressed into the surface peat, and using a knife the soil was cut and the full tin of soil was removed, taking care not to compress the soil during sampling. In the laboratory, samples were dried at 105°C in aluminum plates for 24 hours and then weighed. Bulk density was determined as the dry weight divided by the sampled volume. Peat humification is a measure of the decomposition and structure of the peat. Higher degree of humification indicates a more well-decomposed peat (Bonnett et al., 2009). The von Post scale was used to assess humification of surface peat samples prior to drying (Von Post and Granlund, 1926).

2.2.3. The unexpected effect of fertilizer and remediation trial

Wet conditions due to precipitation following planting brought the fertilizer to the surface, leading to spontaneous colonization by *B. papyrifera*, particularly in the eastern side of the study site. *B. papyrifera* grew around each planted *P. mariana* and in high density on both sides of remnant ditches. The main colonizer species has been identify as *Betula papyrifera* (March) (Paper birch). Although, western Canada is not a normal distribution of *Betula populifolia* (March) occasional seedlings have been identified on site, and *B. populifolia* has been also described as a good pioneer species in extracted peatlands (Lavoie et al., 1998). In the present study, not all the birch individuals that colonized the site have been identified, but the majority are likely *B. papyrifera* and will be referred to as this throughout the paper.

In order to assess the impact of removal of *B. papyrifera* on *P. mariana* growth and microclimatic conditions (volumetric water content (ϴ), relative humidity (RH) and insolation (photosynthetically active radiation (PAR)) seven years post-plantation a *B. papyrifera* removal experiment was designed. In August 2012, a split plot experiment in the eastern part of the study site was applied with random selection of half of each experimental unit, cutting down the birches around the planted black spruce. The *B. papyrifera* survey measured height, basal diameter, and number of branches growing from the same spot of each planted *P. mariana* within a circle of radius of 50 cm. Basal diameter and total height of every branch from the main stem was measured prior to removal. All *B. papyrifera* trees were removed around planted *P. mariana* from half of the diagonal within the plots in the wetter portion of the site (eastern side) in three fertilizer treatments: high dose, low dose and control (Figure 1.2). This *B. papyrifera* removal experiment was replicated five times for high dose, and four times for low dose and control.

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

In July 2013, the impact of *B. papyrifera* aboveground removal was evaluated by measuring as independent variables photosynthetically active radiation (PAR; µmol m^{-2} s^{-1}) and relative humidity (RH; %) on both birch removal and non-removal areas measured at ground level and 1.30 m height each 50 cm along the diagonal of the plot running perpendicular to the diagonal that divided the plot into removal treatment classes. Therefore, multiple measurements were made within each treatment from the edge of the removal through to the centre. Measurements were made using a portable infrared gas analyzer (IRGA: PP systems EGM 4). Volumetric Water Content (Ɵ) was measured at this time using the portable WET-Sensor™ at the growing surface of each plot systematically at seven specific locations in the plot (Figure 2.1) as described above (i.e., 3-4 measurements in each treatment within the plot). In September 2013, basal diameter, height and annual height growth (elongation of the leader stem) of all *P. mariana* within the central 6x6 planted trees of each plot was measured. 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 and Payette, 2004).

A semi-parametric method for longitudinal data analysis, general estimating equation model (GEE), was used to analyze the impact of birch removal and each fertilizer treatment (high, low and no fertilizer dose) on *P. mariana* growth (basal diameter and elongation of the leader stem) and microclimatic conditions including volumetric water content (Ɵ), relative humidity (RH) and insolation (PAR).

Table 2.1. Mean values for weather condition for the 2005 year of planting (Data from AgroClimatic Information Service (ACIS) Government of Alberta: Agriculture and Rural Development). For 2013, data was collected from our own meteorological station at the study site.

Year	**2005**			**2013**				
Month	**Temp (°C)**	**RH (%)**	**Pp. (mm)**	**Temp at 2 m (°C)**	**RH (%)**	**Pp. (mm)**	**Ɵ (0-6) (%)**	**Temp. 5 cm (°C)**
April	6.08	57.25	6.34	-4.23	79.44	0	-	-
May	9.96	59.83	25.76	12.31	61.10	33.20	-	-
June	13.46	76.70	61.82	14.39	82.82	75.25	32.7	15.31
July	15.39	75.90	100.6	15.41	82.70	95.45	21.17	20.14
August	13.19	75.87	48.92	15.55	85.27	43.55	37.25	16.04
September	8.42	75.32	26.52	11.21	80.02	6.75	45.32	19.47
October	-	-	21.68	5.39	90.16	10.20	44.94	10.76
Growing Season	**11.08**	**70.34**	**291.62**	**10.00**	**80.22**	**264.40**	**35.13**	**16.34**

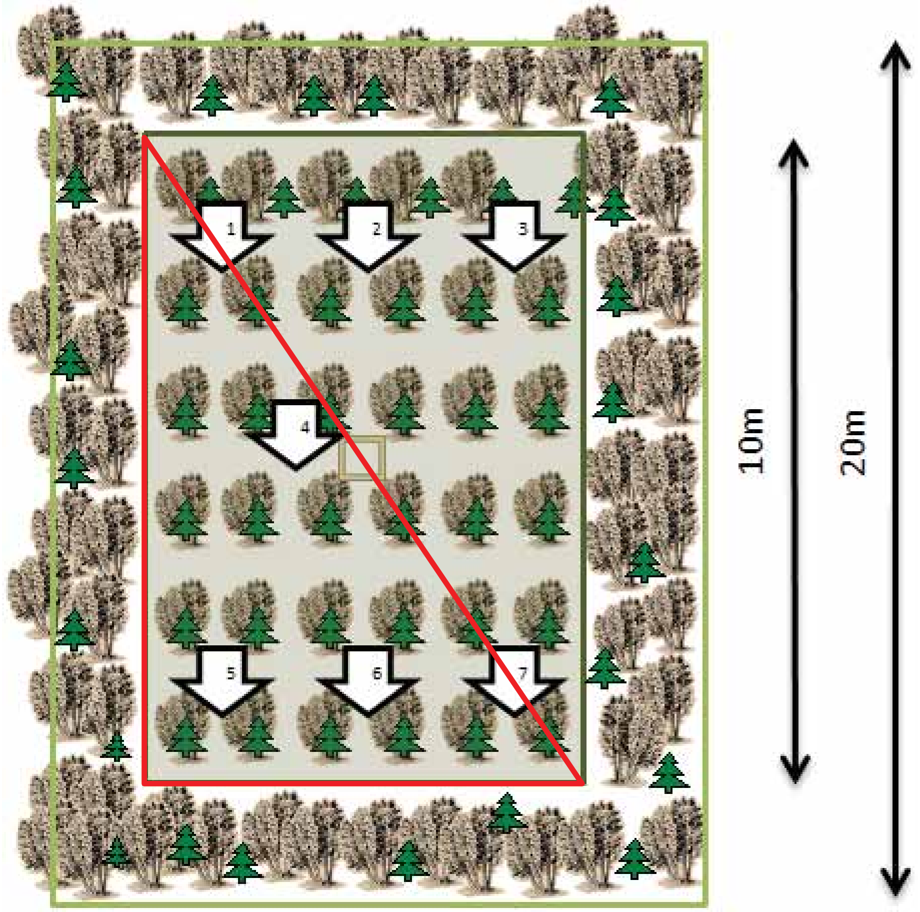


Figure 2.1. Location of tree and soil measurements within the experimental unit (only within the 6 by 6 inner trees) to avoid edge effect. *B. papyrifera* main stems present within a radius of 50 cm of the main planted *P. mariana* stem were assessed. Arrows show the spot for systematic volumetric water content (ϴ) measurements and chemistry samples (see Appendix). The red area outlines the random selection of birch removal experiment where the aboveground *B. papyrifera* were cut down around the planted *P. mariana*.

2.3. Results

2.3.1. Effect of fertilizer dose on forest plantation on cutover peatland after 7 years

Seven years after *P. mariana* seedlings were planted on the cutover peat field, 845 of the 1008 (84 ± 12%) surveyed trees survived. When fertilized 90% of the trees survived compared to 65% when non-fertilized (ANOVA, $F_{3,\ 1007}$ = 32.673, p<0.001) (Figure 2.2). Across the entire plantation mean basal diameter for *P. mariana* was 1.65 ± 0.02 cm and height was 100.16 ± 1.6 cm (Table 2.3). Fertilizer dose promoted *P. mariana* growth indicated by both basal diameter (ANOVA, $F_{3,\ 960}$ =56.74, p<0.001) and height (ANOVA, $F_{3,\ 960}$ =226.72, p<0.001; Table 2.3).

The mean basal diameter for *B. papyrifera* was 1.96 ± 0.03 cm and the mean height was 138.1 ± 0.03 cm. Fertilizer dose also had a significant effect on *B. papyrifera* basal diameter (ANOVA, $F_{2,940}$=6.45, p=0.002) and, height (ANOVA, $F_{2,940}$=41.905, p<0.001; Table 2.3).

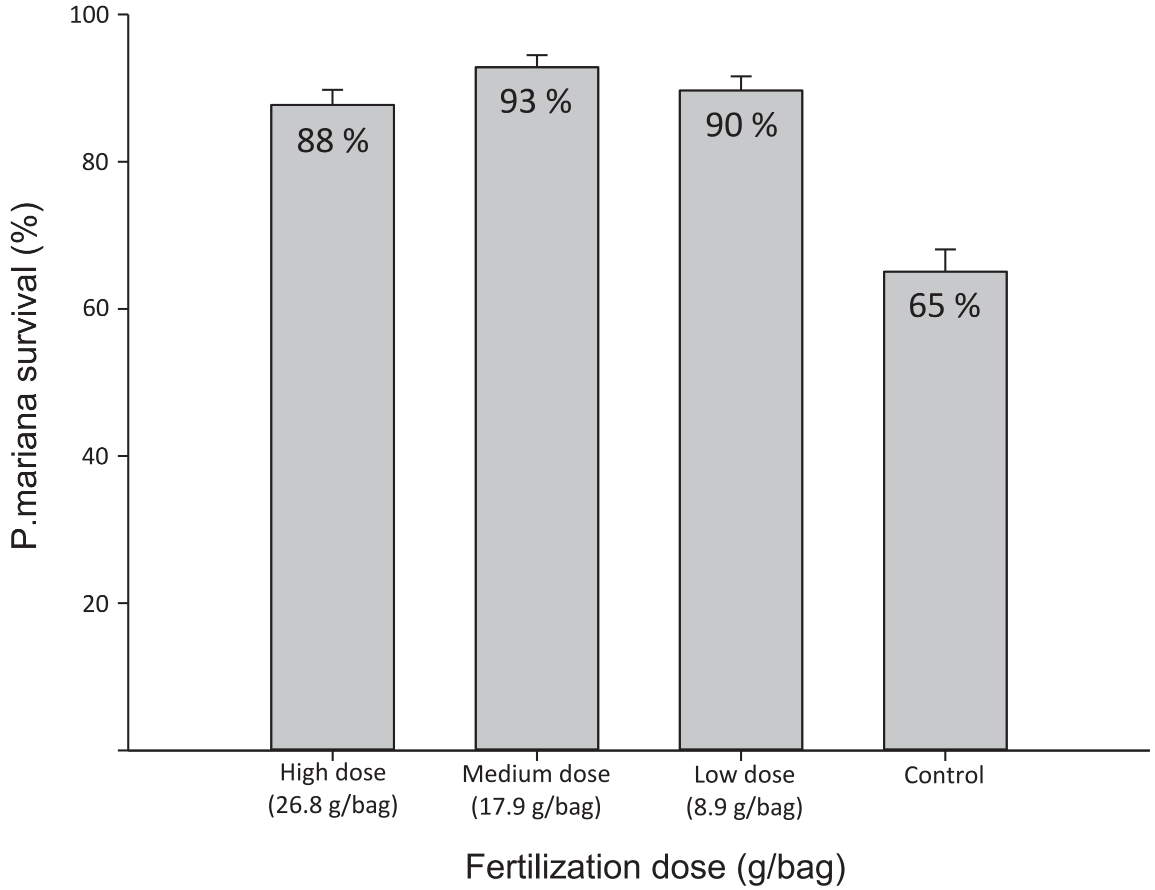


Figure 2.2. Means ± standard error of *P. mariana* survival by fertilizer dose after seven years (ANOVA, $F_{3,\ 1007}$ =32.673, p<0.001). The survival tree graphic proof the importants to add nutrients to the tree plantation, but the quality of survival tree is more influence by other conditions further that dose of fertilizer.

Table 2.2. *P. mariana* and *B. papyrifera* tree survey, seven years post *P. mariana* plantation in relation to their fertilization treatment and standard error of mean of basal diameter, height mean by fertilizer treatment. Doses are significantly different for a given parameter if they do not share a letter in common, statistics values are described in below, Table 2.3.

Species	**Fertilizer dose**	**Height (cm)**	**Basal Diameter (cm)**
P. mariana	High (26.8 g/bag)	136.2 ± 2.4 ^{a}	1.9 ± 0.04 ^{a}
	Medium (17.9 g/bag)	112.8 ± 2.4 ^{b}	1.67 ± 0.04 ^{ab}
	Low (8.9g/bag)	103.2 ± 2.7 ^{c}	1.7 ± 0.04 ^{b}
	Control (Non fertilizer)	51.7 ± 1.8 ^{d}	1.24 ± 0.04 ^{c}
	Total Average	**100.16 ± 1.6**	**1.65 ± 0.02**
B. papyrifera	High dose (26.8 g/bag)	156.3 ± 0.03 ^{x}	2.05 ± 0.4 ^{x}
	Medium dose (17.9 g/bag)	176.6± 0.06 ^{xy}	1.93 ± 0.3 ^{xy}
	Low dose (8.9g/bag)	119.8 ± 0.06 ^{y}	1.81 ± 0.1 ^{y}
	Control (Non fertilizer)	79 ± 0.1 ^{z}	1.84 ± 0.7 ^{xy}
	Total Average	**138.1 ± 0.03**	**1.96 ± 0.03**

Table 2.3. *P. mariana* and *B. papyrifera* relation between survival, basal diameter and height to the fertilization treatment. One-way ANOVA statistic values ($p<0.05$).

	Fertilizer Treatment	**F**	**p-value**	**df**
P.mariana	Survival	32.673	0.000	3(1007)
	Basal Diameter	56.738	0.000	3(960)
	Height	226.724	0.000	3(960)
B. papyrifera	Basal Diameter	6.453	0.002	2(940)
	Height	41.905	0.000	2 (940)

2.3.2. The impact of *B. papyrifera* invasion on microclimate and removal experiment around the reintroduced *P. mariana*

Removal of *B. papyrifera* significantly increased VWC (Ɵ) in the birch removal plots (GEE, Wald Chi-square=60.51, Std. Error=4.86, df=1 (26), p<0.001; Table 2.4). However, Ɵ was actually reduced by 2.6, and increased by 3.4 and 2.9%, respectively to high, low and non-fertilizer doses (GEE, Wald Chi-square=0.07, Std. Error=1.43, df=1 (26), p=0.790.001). The presence of invasive *B. papyrifera* around the planted *P. mariana* significantly reduce photosynthetically active radiation (PAR) at ground level at soil level (GEE, Wald Chi-square=37.5, Std. Error=186.88, df=1 (26), p<0.001), where PAR at soil level increased around 200 µmol m^{-2} s^{-1} within the removal plots (Figure 2.4). Birch removal experiment results also showed an impact on microclimate conditions by reducing relative humidity (RH) at soil level by 2 % (from 42.6 to 40.4 % in general). Relative humidity varied significantly with fertilizer dose (GEE, Wald Chi-square=7.91, Std. Error=0.82, df=1(26), p=0.005) and there was a significant interaction between birch removal and fertilizer dose (GEE, Wald Chi-square=304.6, Std. Error=2.91, df= 1(26), p<0.001) (Figure 2.5).

The cutting of the invasive *B. papyrifera* has a significant effect on the growth of the basal diameter of *P. mariana* (GEE, Wald Chi-square=36.72, Std. Error=0.37, df= 1 (26), p<0.001). After one year of birch removal experiment, plots with high and low doses of fertilizer and control (non-fertilizer) had basal diameter increase by 0.66 ± 0.06, 0.73 ± 0.07 and 0.83 ± 0.07 cm respectively in birch removal plots (Table 2.4), compared from 0.26 cm ± 0.07 and 0.28 ± 0.07 and 1.7 ± 0.07 cm in non-removal plots. Seven years post-tree reintroduction, the cutting of the invasive birch around the planted *P. mariana* induced different responses of the annual elongation of leader stem as a function of the fertilizer dose; there was a significant interaction between annual growth and fertilizer treatments (GEE, Wald Chi-square=23.16, Std. Error=3.68, df=1 (26), p<0.001). High dose of fertilizer and control leader elongation was greater within areas with *B. papyrifera* intact than where they were removed (Figure 2.3). *P. mariana* trees within intact areas increased their annual elongation of leader stem by 1.14 ± 2.61 cm in high dose of fertilizer, while in control plots annual growth was 4.93 ± 2.91 cm greater than in removal areas (Figure 2.3). At plots with low dose of fertilizer elongation of the leader stem was greater in plots where *B. papyrifera* had been removed.

Table 2.4. Mean and standard error of VWC (ϴ), basal diameter of *P. mariana* (cm) in 2012 (before applying the birch removal experiment) and 2103 (one growing season post-birch removal), and annual elongation of leader stem of *P. mariana* (cm) as a function of doses of fertilizer within plots where *B. papyrifera* were removed and intact (non-removal).

Treatment		**ϴ**	**Basal Diameter (cm)**		**Annual elongation**
Fertilizer	**Birch impact**	**(%)**	**2012**	**2013**	**of leader stem (cm)**
High dose	Removal	35.03 ± 3.18	1.96 ± 0.16	2.62 ± 0.22	17.52 ± 2.61
	Intact	37.61 ± 3.18	2.05 ± 0.16	2.4 ± 0.24	18.66 ± 2.61
Low dose	Removal	35.77 ± 3.56	1.87 ± 0.17	2.6 ± 0.24	17.05 ± 2.91
	Intact	32.34 ± 3.56	1.74 ± 0.17	2.0 ± 0.24	14.61± 2.91
Control	Removal	37.08 ± 3.56	1.3 ± 0.17	2.13 ± 0.24	11.44 ± 2.91
	Intact	34.2 ± 3.56	1.45 ± 0.17	1.73 ± 0.24	16.37 ± 2.91

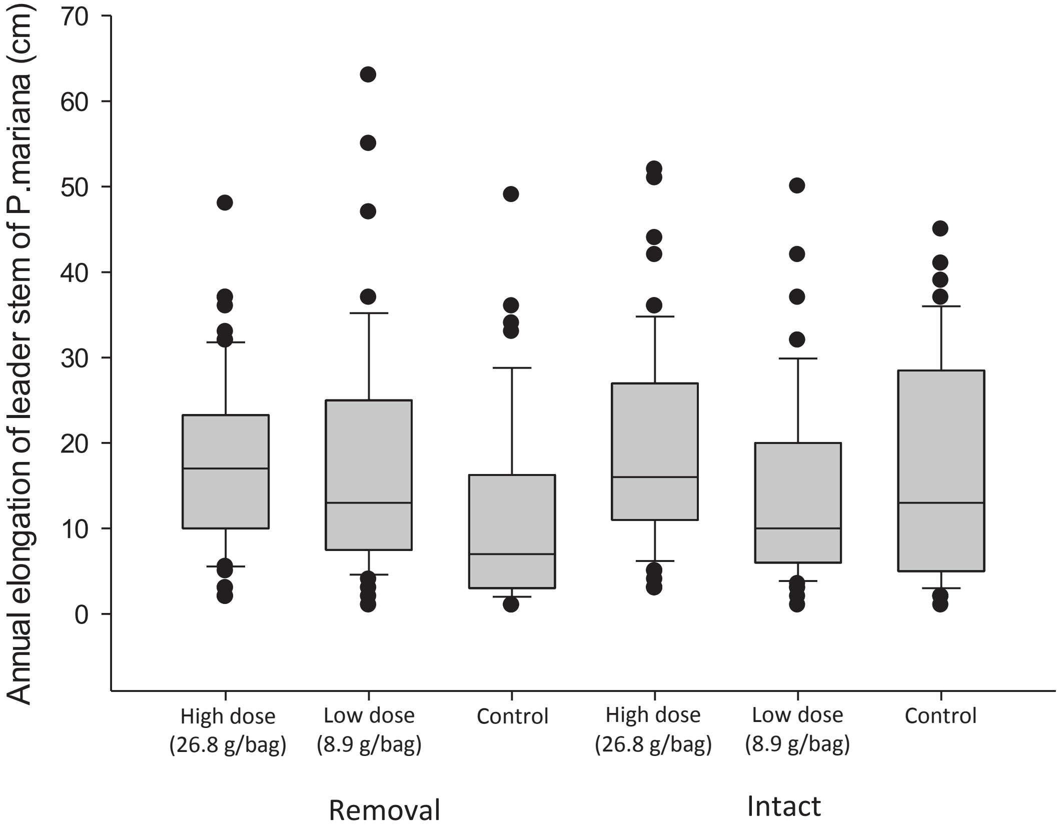


Figure 2.3. Annual elongation of leader stem of *P. mariana* (cm) as a function of doses of fertilizer within plots where *B. papyrifera* were removed and intact (non-removal). The line in the middle of the box represents the median, the edges of the box the 25 and 75^{th} percentiles and the error bars 95% of the data set, outlier are values more and less than 3/2 times of upper and lower quartiles. There was interaction effect between *P. mariana* annual elongation of leader stem with fertilizer treatment and birch removal (GEE, Wald Chi-square=23.16, Std. Error=3.68, df= 1 (26), p<0.001).

.

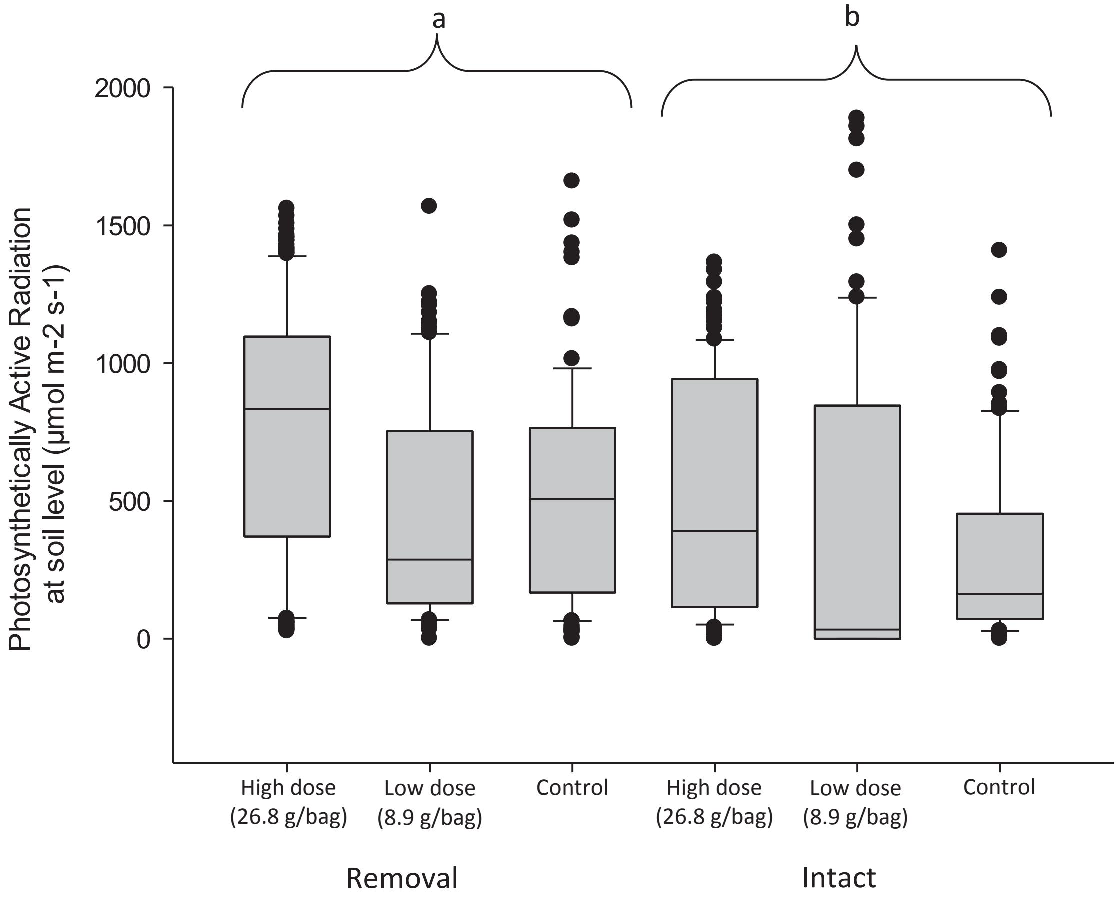


Figure 2.4. Photosynthetically Active Radiation (PAR) at soil level (µmol m^{-2} s^{-1}) with plots where *B. papyrifera* were removed and intact (non-removal). The line in the middle of the box represents the median, the edges of the box the 25 and 75th percentiles and the error bars 95% of the data set, outlier are values more and less than 3/2 times of upper and lower quartiles. PAR was significantly higher following birch removal (GEE, Wald Chi-square=13.89 Std. Error=77.61, df= 1(26), p=0.000) and there was a significant interaction between birch removal and fertilizer doses (GEE, Wald Chi-square=37.5 Std. Error=186.9, df= 1(26), p=0.000).

.

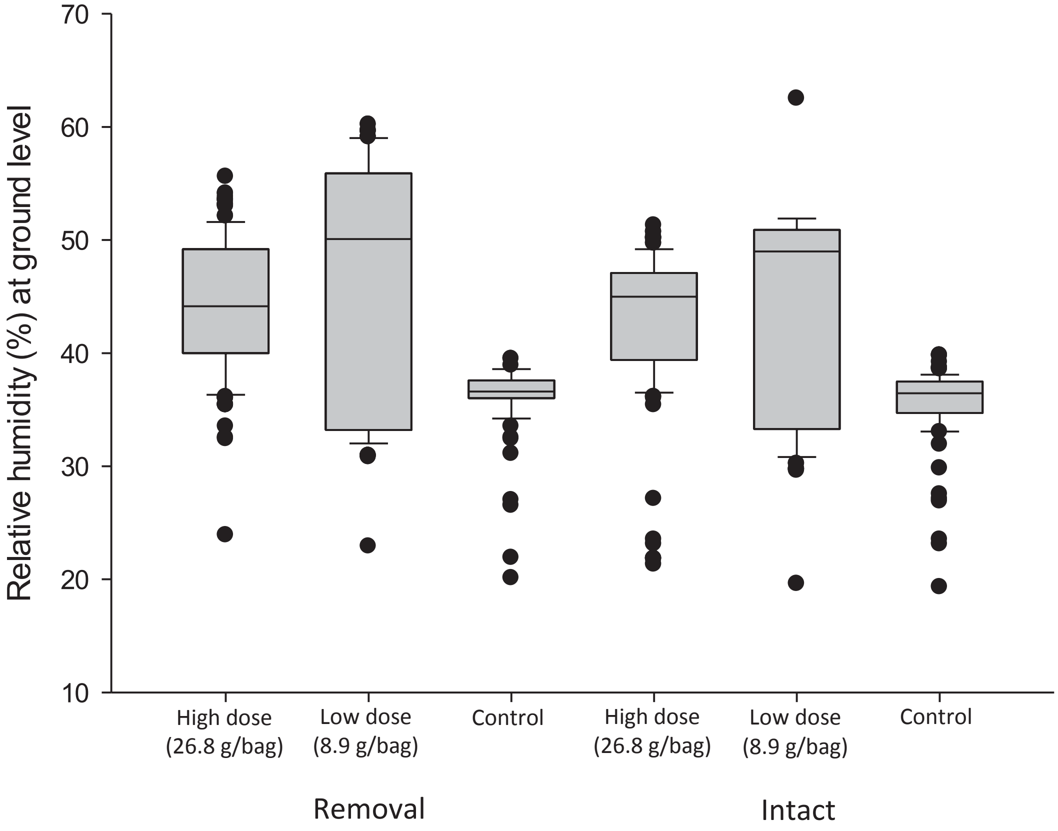


Figure 2.5. Relative humidity (%) at ground level within plots where *B. papyrifera* were removed and intact (non-removal). The line in the middle of the box represents the mean, the edges of the box the 25 and 75th percentiles and the error bars 95% of the data set. Relative humidity varied significantly with fertilizer dose (GEE, Wald Chi-square=7.91, Std. Error=0.82, df= 1(26), p=0.005) and there was a significant interaction between birch removal and fertilizer dose (GEE, Wald Chi-square=304.6, Std. Error=2.91, df= 1(26), p<0.001).

2.4. Discussion

This study demonstrated that fertilizer application improved *P. mariana* survival, establishment and subsequent growth, but the resulting leaching of this fertilizer, as caused by flooding in this case, had the unfortunate effect to favour *B. papyrifera* colonization around the planted trees. These results support the pattern of previous afforestation studies that have defined fertilization as required on cutover peatlands to promote the growth and survival of tree seedlings (e.g. Renou-Wilson et al., 2011; Bussières et al., 2008; Hugron et al., 2011). After seven years post-plantation, the effect of fertilizer doses on *P. mariana* and *B. papyrifera* growth within the forest plantation was evaluated in this study. Results show that adding fertilizer improved *P. mariana* and *B. papyrifera* growth. The fertilization application on the forest plantation in this drier climate has the same effect as previous studies done in eastern Canadian provinces. For example, Bussières et al., (2008), showed a need of fertilizer for tree growth due to the nutrient poor condition of cutover peatland, although high dose of fertilizer was not required for *P. mariana* plantation. For the present study, located in western Canada, the results supported the same conclusion that growth of *P. mariana* trees with a low dose of fertilizer (8.9 g/bag) is not significantly different that higher doses (26.9 g/bag). In addition, adding too much fertilizer can pollute ground water (Hugron et al., 2011) and increases mineralization of the residual peat.

A potential side effect of fertilization is *B. papyrifera* colonization, which appears to be controlled by the dose of fertilizer. Seven years post-plantation, the impact of removal of *B. papyrifera* on *P. mariana* growth and microclimatic conditions (volumetric water content (Θ), relative humidity (RH) and insolation (PAR)) has been tested. The removal of the competitor species, *B. papyrifera*, improved basal diameter and, in some cases, annual elongation of leader stem of *P. mariana* by improving microclimatic conditions such as Θ, relative humidity (RH) and insolation (PAR) availability. Although it was beyond on the scope of the present study, we also found peat depth was negatively correlated with bulk density (Pearson coefficient= -0.751**, n=26, p=0.000) and volumetric water content (Pearson coefficient= 0.534**, n=26, p=0.005) and in addition, peat depth was negative correlate with *B. papyrifera* height (Pearson coefficient= -0.748**, n=11, p=0.008) and diameter (Pearson coefficient= -0.707*, n=11, p=0.015) (Appendix, Table A.2.2). *B. papyrifera* trees do not usually establish on sites that are very wet. A high water table can interfere with root respiration in vascular species. *B. papyrifera* trees are not tolerant of very wet soil, and this can prevent their establishment or cause their death (Fay and Lavoie, 2009).

Although fertilization is important to achieve the desired habitat structure, the resulting *B. papyrifera* colonization directly affected the *P. mariana* growth through its impact on completion and microclimate conditions (Ɵ, PAR and RH). In 2013 after birch removal and blocking the ditches, mean Ɵ was 35.13 ± 0.76%, compared to 23.5 ± 0.4% in 2012. Ɵ also had a positive effect on *P. mariana* annual elongation of leader stem. High density of *B. papyrifera* invasion not only raises evapotranspiration in the site (Makiranta et al., 2007) and may change Ɵ in the soil, but litter accumulating on the ground also could inhibit the establishment of other peatland understory species (e.g., mosses). It is worth noting that if the restoration goal is to recover a forest wetland habitat, the high evapotranspiration of *B. papyrifera* should be taken into consideration. For instance, 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 becomes exhausted (Price et al. 2003; Fay and Lavoie, 2009). Finally, although some impact of birch removal was noted in this study removing birch already established may also not be the most appropriate method to evaluate their impact on *P. mariana* growth. The *B. papyrifera* regrew quickly from stumps and likely started to impact local conditions even within the first year post-removal.

2.4.1. General management recommendations

In this study, the influence of *B. papyrifera* invasive colonization on the *P. mariana* plantation has been quantified for a year by removing *B. papyrifera* around the planted tree. In practice, the cutting of birch branches down to a stem will not lead to long term changes in microclimate as this practice increases the vigor of regeneration (WDNR, 2014). Thus, during the next year following birch removal the transpiration will increase again, along with negative impact of shading the ground. Therefore, it is more desirable to prevent *B. papyrifera* colonization in the first place than attempt to manage them once on site. Low dose of fertilizer (8.9 g/bag) was enough to help the *P. mariana* growth and survival, and avoid high density of *B. papyrifera* colonization, suggesting this may be the most desirable fertilizer dose to use when reintroducting *P. mariana* trees in cutover peatlands. Moreover, peat depth and Ɵ had a negative impact on *B. papyrifera* volume (Appendix Table A2.2). Similarly, Hugron et al., (2011) suggested that peat depth greater than 40 cm had less *B. papyrifera* colonization. This suggests that maintaining a thicker residual peat column post-extraction and keeping the site wetter by attempting to restore hydrology could help to prevent *B. papyrifera* colonization. Thus, to restore early and effectively rewet, and fertilize with a minimal dose should result in better outcomes for a forest plantation on a cutover peatland.

2.5. Conclusions

The high dose of fertilizer resulted in the greatest tree growth, but, aside from the unfertilized controls plots, did not significantly improve *P. mariana* survival compared to the lower fertilizer doses. Therfore, the high dose tested in this study (26.9 g/bag) is not required for success of *P. mariana* plantation on cutover peatland in western Canada. Low fertilizer doses of 8.9 g/bag were enough to ensure 84 ± 12% survival of *P. mariana* seedlings and enhance their growth relative to the unfertilized control while having a lower level of *B. papyrifera* colonization than higher doses.

After one year of birch removal, these plots show a greater growth of *P. mariana* suggested that removal of the competitor species, *B. papyrifera*, improved basal diameter and annual elongation of leader stem of *P. mariana* by improving microclimatic conditions VWC (Ɵ), RH and insolation (PAR) availability. Higher relative humidity and soil volumetric water content (ϴ) within birch removal plots may be due to a large transpiration draw from the *B. papyrifera*, suggesting their presence probable lowers water table and could reduce the chance of successful restoration to a peatland ecosystem. Avoiding *B. papyrifera* colonization on site is likely more effective that their removal due to their ability to rapidly recolonize from stumps. Thus, when creating a forest plantation on cutover peat, planting soon after extraction ceases in an area that has been effectively rewetted and using minimal fertilization is recommended.

2.6. References

Alberta AgroClimatic Information Service (Athabasca, ACGM, http://agriculture.alberta.ca/acis/alberta-weather-data-viewer.jsp), (Last accessed on December 2014)

Alberta Government, 2013. Alberta Wetland Policy, Alberta Environment and Sustainable Resource Development, Edmonton, AB, Canada. p 25.

Andersen, R., Rochefort, L., Landry, L., 2011. La chimie des tourbières du Québec: une synthèse de 30 années de données. Le Naturaliste Canadien, 135: 5-14.

Andersen, R., Rochefort, L., Poulin, M., 2010. Peat, water and plant tissue chemistry monitoring: A seven-year case-study in a restored peatland. Wetlands, 30: 159-170.

Bates, T. E., 1993. Soil handling and preparation. P. 19-24 dans Soil sampling and methods of analysis, M. R. Carter (éd.). Canadian Society of Soil Science. Lewis Publishers, Boca Raton.

Bonnett, S.A.F., Ross, S., Linstead, C., Maltby, E., 2009. A review of techniques for monitoring the success of peatland restoration. University of Liverpool. Natural England. Commissioned Reports, num. 86.

Bussières, J., Boudreau, S., Rochefort, L., 2008. Establish trees on cut-over peatlands in Eastern Canada. Mires and Peat, Vol. 3, Article 10, http://www.mires-and-peat.net/, ISSN 1819-754X © 2008 International Mire Conservation Group and International Peat Society.

Caisse, G., Rochefort, L., Boudreau, S., Munson, A.D., 2006. The importance of fertilization in the afforestation of cutover peatlands in eastern Canada. 5th European Conference on Ecological Restoration, Greifswald, Germany, 21–25 August 2006. p. 1.

Campbell, D.R., Rochefort, L., Lavoie, C., 2000. The colonisation potential of peatland plants recolonising post-vacuum-extracted bogs. In: Rochefort L, Daigle JY (eds) Sustaining our peatlands. Proceedings of the 11th international peat congress, vol. II. Canadian Society of Peat and Peatlands, International Peat Society, Quebec City, p. 670–674

Delta-T Devices. 2005. WET-sensor user manual v1.3. Cambridge, U.K.: Delta-T Devices.

Gamache and Payette, 2004. Height growth response of tree line black spruce to recent climate warming across the forest-tundra of eastern Canada .Journal of Ecology 2004 92, 835–845

Gorham, E., Rochefort, L., 2003. Peatland restoration: A brief assessment with special reference to Sphagnum bogs. Wetlands Ecology and Management 11, 109-119.

Fay, E., Lavoie C., 2009. The impact of birch seedlings on evapotranspiration from a mined peatland: an experimental study in southern Quebec, Canada. Mires and Peat, Vol. 5, Article 03, 1-7.

GRET, 2011. Peatland Ecology Research Group. Chemistry analysis report.

Graf, M.D., Berube V., Rochefort, L., 2012. Restoration of peatlands after extraction. Chapter 12. Restoration and Reclamation of Boreal Ecosystem, ed. Dale Vitt and Jagtar Bhattti. Cambridge University Press.

Graf, M.D., Rochefort, L., 2009. Examining the peat-accumulating potential of fen vegetation in the context of fen restoration of harvested peatlands. Ecoscience 16(2), 158-166.

Groeneveld, E.V.G., Masse, A., Rochefort, L., 2007. Polytrichum strictum as a nurse-plant to facilitate Sphagnum and boreal vascular plant establishment. Restoration Ecology 15, 709–719.

Hugron, S., Bussières, J., Rochefort, L., 2011. Plantation d'essences forestières dans le contexte de la restauration écologique des tourbières : un guide pratique, Groupe de recherche en écologie des tourbières, Université Laval, Québec, p 88.

Joosten, H., 2011. The global peatland CO_2 picture. In: Tanneberger, F. & Wichtmann, W. (eds.) Carbon Credits From Peatland Rewetting. Climate-Biodiversity-Land Use. Schweizerbart Science Publishers, Stuttgart, 20 and 29–30.

IPCC (Intergovernmental Panel on Climate Change), (1990). Climate Change 2007: The Physical Science Basis. Intergovernmental Panel on Climate Change 2001, New York. http://www.ipcc.ch

Kaunisto, S., Aro, L., 1996. Forestry use of cutaway peatlands. In: Vasander, H. (ed.) Peatland in Finland, Finnish Peatland Society, Helsinki, Finland, 130−134.

Laine, A. M., Leppälä, M., Tarvainen, O., Päätalo, M.-L., Seppänen, R., Tolvanen, A., 2011. Restoration of managed pine fens: effect on hydrology and vegetation. Applied Vegetation Science 14:340–349.

Lavoie, C., Saint-Loui, A., 1998. The spread of gray birch (Betula populifolia) in eastern Quebec: landscape and historical considerations. Can. J. Bot. 77: 859–868.

Makiranta, P., Hytönene, J., Aro, L., Maljanen, M., Pihlatie, M., Potila, H., Shurpali, N.J., Laine, J., Lohila, A., Martikainen, P.J., Minkinen, K., 2007. Soil greenhouse gas emissions from afforested organic soil croplands and cutaway peatlands. Boreal environment research, 12: 159-175.

Paxson Restoration Report, Premier Tech, 2012.

Price, J.S., Heathwaite, A.L., Baird, A.J., 2003. Hydrological processes in abandoned and restored peatlands: An overview of management approaches. Wetlands Ecology and Management 11: 65-83.

Price, J.S., Rochefort, L., Quinty, F., 1998. Energy and moisture considerations on cutover peatlands: surface microtopography, mulch cover and Sphagnum regeneration. Ecological Engineering (10):293-312.

Quinty, F., Rochefort, L., 2003. Peatland restoration guide, second ed. Canadian Sphagnum Peat Moss Association and New Brunswick Department of Natural Resources and Energy. Québec.

Raunio, A., Schulman, A., Kontula, T., 2008. Suomen luontotyyppien uhanalaisuus. Osa 1: Tulokset ja arvioinnin perusteet. [Assessment of threatened habitat types in Finland - Part 1: Results and basis for assessment]. The Finnish Environment 8/2008, Helsinki, Finland.

Renou F, Farrell EP., 2005. Reclaiming peatlands for forestry: the Irish experience. In: Stanturf JA, Madsen PA (eds) Restoration of boreal and temperate forests. CRC Press, Boca Raton, p 541–557.

Renou, F., Scallan U., Keane, M., Farrell E. P., 2007. Reclaiming peatlands for forestry: the Irish experience. 1-56670-635-1/05/$0.00+$1.50 © 2005 by CRC Press LLC.

Renou-Wilson, F., 2011. Optimal pratices in the afforestation of cutaway peatlands. Lambert Academic Publishing, Saarbrücken, Germany. p 254.

Rochefort, L., 2000. Sphagnum A Keystone Genus in Habitat Restoration. The Bryologist 103, 503-508.

Rochefort, L., Quinty, F., Campeau, S., Johnson, K, Malterer, T., 2003. North American approach to the restoration of Sphagnum dominated peatlands. Wetlands Ecology and Management 11, 3–20.

Salonen, V., 1992. Effects of artificial plant cover on plant colonization of a bare surface. Journal of Vegetation Science3:109-12.

Sjörs, H., 1950. On the relation between vegetation and electrolytes in northern Swedish mire water. Oikos 2:241-258.

SPSS, Statistic v.21. SYSTAT 21.0 for Windows. IBM, SPSS, Chicago, Illinois, USA.

Strack, M., Waddington, J.M., Turetsky, M., Roulet, N.T., Byrne, K.A. 2008. Northern peatlands, greenhouse gas exchange and climate change. In: Strack, M. (Ed.), Peatlands and Climate Change, International Peat Society and Saarijärven Offset Oy, Saarijärvi, Finland, p. 44-69.

Strack, M, Waddington, J.M., 2012. Effects of peat extraction and restoration on greenhouse gas exchange from Canadian peatlands, In Restoration and Reclamation of Boreal Ecosystems, DH Vitt, J Bhatti (eds.), Cambridge University Press, p. 386-403.

Strack, M., Keith, A.M., Xu, B., 2014. Growing season carbon dioxide and methane exchange at ta restored peatland on the western Boreal Plain. Ecological Engineering 64, 231-239.

Tarvainen, O., Laine, A. M., Peltonen, M., Tolvanen, A., 2013. Mineralization and Decomposition Rates in Restored Pine Fens. Restoration Ecology Vol. 21, No. 5, p. 592–599.

Vitt, D.H., 2006. Functional characteristics and indicator of Boreal Peatlands. In R. Weider & D.Vitt, Boreal Peatland Ecosystem. Springer. p. 9-24.

Von Post, L., Granlund, E., 1926. Södra Sveriges Torvtillgångar I. Sveriges Geologiska Undersökning Serie C 335, 1–127.

WDNR (Winconsin Department of Natural Resources), 2014. Silviculture Handbook 24315.44, Chapter 44.

Wind-Mulder, H., 1998. Towards the restoration of peatlands: Comparisons of harvested and natural peatlands and examination of revegetation techniques. Ph.D. Thesis, p. 211.

Zak, D., Gelbrecht, J., Wagner, C., Steinberg, C.E.W., 2008. Evaluation of phosphorus mobilisation potential in rewetted fens by an improved sequential chemical extraction procedure. European Journal of Soil Science 59:1191–1201.

APPENDIX

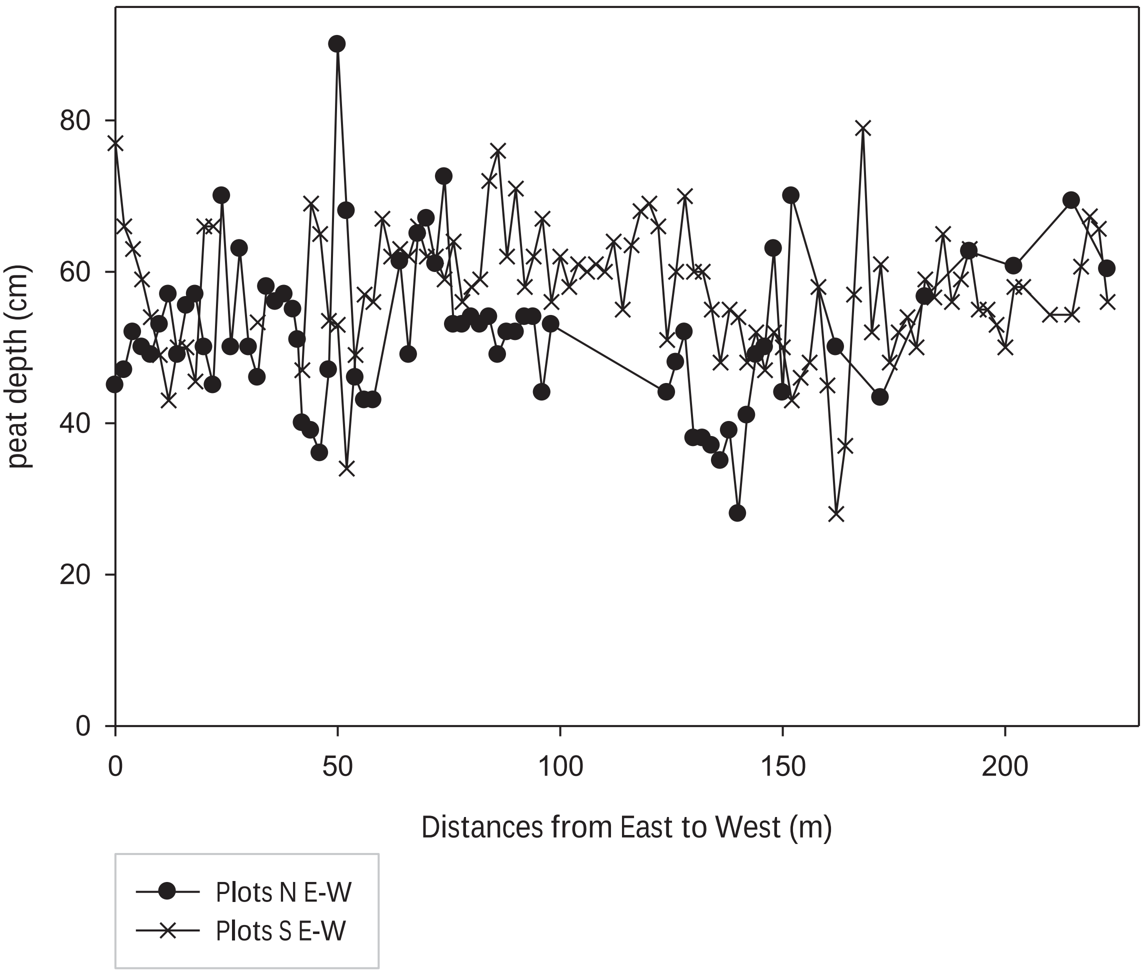


Figure A.2.1. Peat depth across the experimental site distances from east to west. Plots N E-W are located on the North (first line closed to the non- restored cutover peatland) and Plots S E-W are located on the South (second line closed to the forest) of the restoration site (See Figure 1.2).

Table A.2.1. Mean and standard error of peat (0-5 cm) chemistry variables between doses of fertilizer: high (26.8 g/bag), low (8.9g/bag) and control (Non fertilizer)[a]. Soil chemistry analysis included pH of peat, conductivity (Sμ cm^{-1}, contributions from H^+ subtracted from specific conductivities, Sjörs, 1950),P BrayII (ppm)[b], exchangeable (in $NH_4Cl/BaCl_2$)[c]: Ca, Mg, Fe, Mn, K, Na (ppm) and, N/NO_3, N/NH_4 and Cl (mg/l).

Fertilizer dose	**High(26.8 g/bag)**	**Low (8.9g/bag)**	**Control (Non fertilizer)**
pH	4.1 ± 0.1	3.9 ± 0.1	3.8 ± 0.1
EC (μS cm^{-1})	749.9 ± 213.8	966.9 ± 455.4	1434.4 ± 402.1
P-PO_4 BrayII (ppm)	152.9 ± 43.2	295.5 ± 98.9	554.7 ± 323.8
Na (ppm)	86.7 ± 14.6	90.2 ± 29.7	177 ± 29
K (ppm)	47 ± 15.5	65.7 ± 20.8	51.5 ± 50.5
Mg (ppm)	1631.7 ± 340.9	1968.5 ± 649.8	3734.5 ± 494.5
Fe (ppm)	760.9 ± 226.1	1399.8 ± 74.8	1263.9 ± 52.2
Cu (ppm)	-	4.4 ± 2.5	14.3 ± 14.2
Zn (ppm)	11.3 ± 2.23	25.7 ± 6.1	35.1 ± 18.5
Mn (ppm)	164 ± 40	418.9 ± 173.2	547.1 ± 34.8
Ca (ppm)	17015.7 ± 2486.8	15514.5 ± 2447.5	26182 ± 6983
Concentration Cl (mg/l)	3.3 ± 0.2	4.1 ± 0.9	4.3 ± 0.03
Concentration N-NH_4 (mg/l)	7.2 ± 4.9	5.2 ± 0.7	19 ± 4.4
Concentration N-NO_3 (mg/l)	15.7 ± 11.1	6 ± 3.7	29.5 ± 27.5

a. Medium dose of fertilizer was not measured for this analysis.

b. ppm: part per million by EMS method (Extraction media saturated) organic in soil by extraction with a solvent. The peat pH was measured in a 0.1M solution of $CaCl_2$. Conductivity was measured on samples saturated with distillate water (ratio 1:10) and then corrected according to Sjörs (1950).

c. mg/l: Exchangeable in $NH_4Cl/BaCl_2$. Total elements were determined using standard methods (ICP spectroscopy for P, K, Na, Ca, Mg, Fe and Mn, FIA Quickchem methods for N–NH_4^+ and N–NO_3^-).

Table A.2.2. Pearson Correlation coefficient (N=28) between ϴ (%), peat depth, bulk density and basal diameter and height for *P. mariana* and *B. papyrifera*.

	P. mariana		*B. papyrifera*	
	Basal diameter	**Height**	**Basal diameter**	**Height**
ϴ (%)	-0.490**(28)	0.657**(28)	-0.335(28)	-0.439 (28)
Peat Depth (cm)	0.375(26)	-0.271(26))	-0.707*(11)	-0.748** (11)
Bulk Density (g cm^3)	-0.021(26)	-0.512**(26)	0.646*(26)	0.685*(26)

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Table A.2.3. General estimating equation model (GEE) of birch removal and fertilizer treatment on *P.mariana* growth (annual elongation of leader stem and basal diameter) and microclimatic conditions (Insolation (PAR), relative humidity (RH), volumetric water content (ϴ)).

Dependent Variable		Treatment	Wald Chi-square	Std. Error	p-value	df
P.mariana	**Annual elongation of leader stem**	Interaction	23.16	3.68	0.000	1(26)
		Fertilizer	2.09	0.93	0.148	1(26)
		Removal	0.58	1.58	0.445	1(26)
	Basal Diamater 2013	Interaction	184.97	0.24	0.000	1(25)
		Fertilizer	10.71	0.05	0.001	1(25)
		Removal	5.78	0.17	0.016	1(25)
Microclimatic conditions	**PAR**	Interaction	37.5	186.88	0.000	1(26)
		Fertilizer	5.54	34.32	0.019	1(26)
		Removal	13.89	77.61	0.000	1(26)
	RH	Interaction	304.6	2.91	0.000	1(26)
		Fertilizer	7.91	0.82	0.005	1(26)
		Removal	5.83	0.96	0.16	1(26)
	ϴ	Interaction	60.51	4.86	0.000	1(26)
		Fertilizer	0.07	1.43	0.788	1(26)
		Removal	0.52	1.32	0.47	1(26)

CHAPTER 3: The Impact of Forest Plantation on Carbon Exchange on Cutover Peatlands in Western Canada

Abstract

Peatland ecosystems play an important role in the global carbon cycle, storing up to 30% of the global soil carbon (C) stock. The C storage function in this type of wetland is damaged by the extraction of peat, and could be restored by forest plantation post-extraction. Due to a dry local climate, undisturbed bog peatlands in western Canada often have more tree cover of *Picea mariana* (Mill.) B.S.P. Thus, forest plantation may be an appropriate land-use for cutover peatlands. This study determined the effect of forest plantation on a cutover peatland's C balance.

Four levels of fertilizer dose, each replicated seven times, were applied to improve tree growth in a cutover peatland in Alberta, Canada (54°40'3.28"N; 113°7'24.57"W). Seven years following *P. mariana* plantation, the impact of the forest plantation on C balance was estimated considering C stored in *P. mariana* biomass due to net primary production and carbon dioxide (CO_2) and methane (CH_4) fluxes from bare peat. Carbon stored in biomass of *Betula papyrifera* (March.) that had spontaneously colonized the site was also determined. Given that the water table remained very deep and that the original peat-accumulating vegetation was not present, the site remained a source of C, primarily in the form of CO_2 emission by soil respiration. However, C released to the atmosphere was partially offset by C fixed in forest biomass, which increased at higher fertilization doses. This study provides information on C exchange and will be useful in land-management decisions on peatland restoration techniques where C stocks and greenhouse gas fluxes are considered.

3.1. Introduction

Alberta's land area is made up of approximately 16% peatlands (Locky, 2011). These wetland ecosystems are disturbed by the extraction of peat involving vegetation removal and drainage. Drainage and extraction of peatlands leads to large carbon dioxide (CO_2) emissions while greatly reducing methane (CH_4) fluxes (Waddington and Price, 2000). The increased aeration of the remaining surface peat significantly enhances organic matter oxidation and increases CO_2 emission (Tuittila et al., 1999). Previous research documents large carbon (C) emissions that remain after peat extraction (e.g., Strack at al., 2014; Waddington et al., 2002). The residual peat is often too poor to allow for adequate plant community growth, because cutover peatlands are low in nutrients and devoid of seed banks. Therefore, to partly remediate these greenhouse gas (GHG) emissions, restoration techniques have been tested in western Canada (Strack et al., 2014). In addition to restoration, forest plantation may be a suitable technique to consider to partially return cutover peatlands' C storage function by C fixation in forest biomass, and may be appropriate as undisturbed peatlands are largely treed in western Canada (Vitt, 2006). This project assesses the C balance of a forest plantation on a cutover peatland in Alberta, Canada.

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 (Bussières et al., 2008). *Betula papyrifera* (March.) (Paper birch), a deciduous tree commonly colonizing cutover peatlands, is considered an invasive species when it occurs at a high density (Renou et al., 2007), and its colonization may also be encouraged at high fertilization doses (Chapter 2). *B. papyrifera* colonization may also affect the hydrology of the 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). Furthermore, *B. papyrifera* invasion may also reduce the long-term resilience of peatlands (Fay and Lavoie, 2009). However, its rapid growth on cutover peatlands should also provide a C sink. Fertilization might also impact the C balance due to changes in organic matter quantity (FAO, 2005) and quality and changes in soil moisture due to evapotranspiration when there is high density of *B. papyrifera* colonization (Fay and Lavoie, 2009).

Restoration goals aim to recover the ecological functions of the ecosystem within landscapes by mixing habitat conservation and sustainables land use (Bonnet et al., 2009). Restoration should provide the capability of resilience of the ecosystem, so it can recuperate from natural impacts (e.g. pollution, climatic variation, fragmentation, invasive species, and disturbance) (Keith et al., 2013). Furthermore, cutover peatland management and restoration focus on recovering ecological and hydrological functions (Rochefort, 2000). The aim of restoration is to return a self-regulating and naturally functioning ecosystem; in peatlands this implicates secondary succession processes that have been driven by drainage (Laine et al., 2011). Rewetting of the soil helps slow organic matter decomposition, and revegetation allows for C uptake through photosynthesis and thus, the restoration of peatland ecosystems can also reduce ecosystem GHG flux (Couwenberg et al., 2008). The altered plant species composition in restored sites also affects C accumulation via the rate of biomass production and decomposability of the litter produced (Laiho et al., 1996; Laine et al., 2011). According to the new Alberta Wetland Policy (Alberta Government, 2013), wetland management decisions will be linked to ecosystem services, of which climate regulation through C storage is an important service provided by peatlands (IPCC, 2007). Very little data exists on the C balance of forest plantation on cutover peat (Strack et al., 2008), and thus there is a need to quantify sources and sinks of C in these ecosystems to help inform land management decisions.

The net accumulation of C in forest ecosystems is the outcome between inputs via photosynthesis and soil characteristics, and losses via organic matter decomposition (Aertz et al., 2006). Ecosystem respiration (ER) includes both autotrophic (plant) and heterotrophic respiration (largely microbial). The balance of photosynthesis and autotrophic respiration is assimilated to plant structures. The above and belowground C cycling is also driven by hydrology, which is expected to be affected by drainage in cutover sites; consequently, the drier conditions tend to increase CO_2 emission (e.g., Waddington and Price, 2000). An understanding of the controls (e.g., fertilizer application) on rates of photosynthesis (plant productivity) and soil respiration within a forest plantation on cutover peatland is required to describe forest plantation scale C cycling, in particular the productivity, accumulation of biomass, and peat soil C fluxes.

The balance between CO_2 uptake by photosynthesis and release by ecosystem respiration (ER) is called net ecosystem exchange (NEE). Previous studies of NEE in northern peatlands provide values ranging from uptake of over 220 g CO_2 m^{-2} yr^{-1} (60 g C m^{-2} yr^{-1}) to release of 310 g CO_2 m^{-2} yr^{-1} (84 g C m^{-2} yr^{-1}) (Strack et al., 2008). On the other hand, an analysis of peat cores suggests a mean long-term peat C accumulation rate of 23 g C m^{-2} yr^{-1} (Loisel et al., 2014). In Alberta, the latest studies on cutover bare peat report a rate of CO_2 release between 126 - 680 g C m^{-2} over the growing season (Strack et al., 2014). Similarly in eastern Canada, annual releases of over 300 g C m^{-2} have been described from cutover peatlands (Waddington et al., 2002). On the other hand, the dry conditions result in a substantial reduction in CH_4 emissions, and often, abandoned peatlands may actually act as small CH_4 sinks (Waddington and Price, 2000). In Europe, previous studies estimate the values of C balances for afforested stands after 10 years as 9 t C $ha^{-1}yr^{-1}$ (Black et al., 2009). In afforested peatlands in Scotland, 4-8 years after the ground vegetation had recolonized, the peatland became a sink absorbing 3 t C ha^{-1} yr^{-1} (Hargreaves et al., 2003). However, no C exchange studies have been completed in a forest plantation on cutover peatland in Canada.

Therefore, the objectives of this study were to: 1) determine the C stock in biomass of *P. mariana* and *B. papyrifera* trees growing in a seven-year old forest plantation on cutover peat, 2) quantify growing season soil CO_2 and CH_4 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.

3.2. Methods

3.2.1. Study Site

The study area, Paxson Bog, is located near the town of Athabasca, in the east-central part of Alberta, Canada. In 2005, the restoration plan for Paxson bog (54°40’3.28”N; 113°7’24.57”W) was designed including a *P. mariana* plantation with four levels of fertilizer application of 20-10-15 (N-P_2O_5-K_2O) NPK fertilizer: 1) high dose (26.8 g/bag), 2) medium dose (17.9g/bag), 3) low dose (8.9 g/bag), and 4) control (non-fertilized). Each does was replicated randomly seven times resulting in a forest plantation that included 28 experimental units. Each unit consisted of a 400 m^2 plantation of 100 (10 x 10) *P. mariana* trees. During planting in 2005, each dose of fertilizer was buried beneath each seedling as a “tea bag”. Wet conditions due to precipitation brought the fertilizer to the surface, leading to spontaneous colonization by *B. papyrifera*. Tree surveys were conducted on the central 6x6 planted trees of each plot to avoid edge effects near remnant ditches. The main colonizer species has been identified as *Betula papyrifera* (March). 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 et al., 1998). 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.

At the end of the growing season in 2012, ditches were filled with peat material around 20 m north of the plantation to block the runoff and attempt to keep the site wetter. In 2012 and 2013, the annual mean for peat volumetric water content (ϴ) was 25.92 ± 0.85% and 35.13 ± 0.76%. Water content had high variability both over the growing season and between plots. In 2013, the mean peat pH was 4.06 ± 0.04, mean specific conductivity was 933.3 ± 139.3 µS/cm (contributions from H^+ subtracted from specific conductivities, Sjörs, 1950), and peat depth was 0.6 ± 0.2 m. The residual peat was very weakly decomposed (von Post H3) and mean bulk density was 0.28 ± 0.044 g/cm^3.

3.2.2. Environmental variables

During the growing season, May to October 2013, two meteorological stations recorded the environmental conditions (temperature and precipitation; HOBOware sensors) every 30 minutes. These results were corroborated with the data from Alberta AgroClimatic Information Service (Athabasca, ACGM, http://agriculture.alberta.ca/acis/alberta-weather-data-viewer.jsp) (Table 2.1). During the field period from July to October 2012 and May to October in 2013, peat ϴ was measured systematically seven times in each plot every month with a WET sensor (Delta-T devices, HH2). The WET sensor detects the dielectric properties of the soil and outputs ϴ (%), temperature (°C) and conductivity (µS cm^{-1}) (Figure 1.2).

3.2.3. 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 CO_2 and CH_4. 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) biomass, and the soil respiration, including 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%. Carbon balance was determined for each dose of fertilizer.

$$\Delta C = (PM_{AG} + PM_{BG}) + (BP_{AG} + BP_{BG}) - (CO_2 \text{ flux} + CH_4 \text{ flux}) \qquad (1)$$

This equation was developed from three components where, the first two components involved biomass estimation for the tree species, while the last involved soil C fluxes. We used a convention that positive values for net C exchange indicate accumulation of C in the ecosystem (tree + soils). The unit was g C m^{-2} yr^{-1}.

3.2.3.1. 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 described height, basal diameter, and number of branches growing from the same spot as *P. mariana* within a circle of radius of 50 cm.

During the field season in 2012, aboveground biomass allometric relationships were based on 134 trees harvested for both species, 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 each component (stem, branch, and leaves and twigs). Wood and bark were not separated. Some root samples were collected, but due to the difficulty of the collection and low sample numbers, a previous model to estimate belowground biomass based on aboveground biomass from Li et al. (2003) was used applying hardwood and softwood equations for *B. papyrifera* and *P. mariana*, respectively.

Allometric equations based on Lambert et al. (2005) set nonlinear regression equations for each biomass compartment. While many researchers have reported that diameter at breast height (DBH) is an adequate biomass predictor for mature boreal tree species, the small size of the trees at our research site suggested that the stem diameter at soil surface (basal diameter) would be more appropriate for small trees especially for the slow growing species in the boreal forest (Bond-Lamberty et al., 2002). There was heteroscedasticity of residuals of the relationship between diameter and height for *P. mariana* and *B. papyrifera* with fertilizer as an additional fixed effect and this often occurs in biomass data and is caused by an increase of residual variance as basal diameter increases (Lambert et al., 2005). The heteroscedasticity was addressed by log transformation. Since the difference between different doses of fertilizer was not significant for total biomass (ANOVA, $F_{2, 940}$=59.7, p<0.001), the biomass models were defined for fertilizer and no fertilizer plots effects and interaction with basal diameter were performed with a 5% significance level (Lambert et al., 2005). Generalized linear model (GLM) with repeated measures was used to build a model with log transformed total biomass as dependent and continuous variable with log transformed basal diameter, indicator continuous variable, considering the categorical and repeated independent variable, fertilization (control vs. all fertilizer treatments grouped together) as a fixed factor. Similar allometric equations were evaluated for each component (i.e. stems, branches, twigs).

These equations were developed using the trees harvested for biomass and used to estimate the total biomass of all the surveyed trees. Once developed, the models were applied for each tree measured in the survey to estimate the total biomass of the forest plantation. To calculate the total *B. papyrifera* biomass a stem survey measured every branch in the main stem (basal diameter and height) in the representative area for every plot (100 m^2).

To estimate C stored in the tree biomass, C content in dry biomass was analysed by combustion in a pure oxygen environment using a Perkin Elmer model 2400 series II CNH analyzer (Chemistry Analytical Facility, University of Calgary). It was determined that each gram of wood was equivalent to 0.59 gram of C for both tree species. The biomass models were used to estimate the total tree aboveground biomass, and then biomass for each plot was summarized and divided by the plot surface area (g biomass m^{-2}) and represents forest plantation C uptake in g C m^{-2} $(7\ yr)^{-1}$. These values were converted to an annual flux assuming a constant growth of the trees every year and therefore it represents the average annual net primary productivity (NPP) over this time period.

3.2.3.2. Carbon dioxide (CO_2) flux

Soil C 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. A collar (60 cm x 60 cm) was installed into the ground and a transparent plastic chamber (60cm x 60 cm x 30 cm), equipped with a battery-powered fan to mix the headspace and covered with an opaque tarp was placed on the collar to simulate night soil respiration to avoid overestimation of CO_2 measurements by sun warming the chamber over the bare peat. To ensure an airtight seal between the chamber and the collar, a groove in the collar was filled with water. Carbon dioxide concentration was measured in the chamber headspace using a portable infrared gas analyzer (IRGA: PP systems EGM 4). The CO_2

concentration and temperature in the headspace were recorded every 15 seconds with the IRGA for a period of 2 minutes. Soil respiration was determined from the linear change in CO_2 concentration over time after correcting the volume of the gas in the chamber to account for height of the collar above the peat surface and headspace temperature. Temperature of the peat profile at depths 2, 5, 10, 15 and 20 cm was also recorded using a thermocouple thermometer.

Soil respiration data followed a non-normal distribution (Shapiro-Wilk test, $p<0.005$) and the residual analysis describes two slopes of data (Figure 3.1). Residual versus predicted values also showed correlation. Although a statistically significant regression between air temperature and soil respiration was observed, it did not describe the data well, overestimating CO_2 concentration for low temperatures and underestimating for high temperatures. The model could not be validated and the residual analysis between measurements and estimated values using air temperature were not representative. Instead, monthly averages for fertilized and unfertilized plots were used to estimate the CO_2 soil losses during the growing season based on instantaneous chamber measurements.

To analyze the effect of fertilizer dose and month on the soil respiration seven years post-application, a generalized linear mixed model (LMM) analysis was used. To meet the assumptions of the test, soil respiration was log transformed and was the dependent variable. Month and fertilizer dose and the interaction between them were factors in the model considering differences between month (cold months (May, September and October) and warm months (June, July and August) and fertilizer dose (randomly repeated in the experimental design: High, Medium, Low and control) with plot as a random factor to account for repeated measures. All statistical analysis in this study was performed using IBM SPSS Statistic (v.21).

3.2.3.3. Methane flux

Each month during the growing season, methane flux was measured using the closed chamber method at 10 random plots in the same locations described above and at four remnant ditches over bare peat. All random plots were at locations coincident with CO_2 flux measurements and represented a range of fertilizer treatments. An opaque plastic chamber (60 cm x 60 cm x 30 cm), equipped with a battery-powered fan to mix the headspace, and was placed on top of collars on the ground, with water in the groove to create an air tight 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., UK). Samples were analyzed to the Department of Geography, University of Calgary using a Varian Gas Chromatograph 3800 (GC) 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 thermometer (VWR Int., USA). 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). Soil temperature in the peat profile at 2, 5, 10, 15, 20, 25, and 30 cm depths were monitored during CH_4 flux measurement using thermocouple thermometers.

Two CH_4 flux values have been estimated: 1) CH_4 flux from the middle of each plot and 2) CH_4 flux from the ditches where there were different environmental conditions due to a strong edge effect (e.g., high density of *B. papyrifera*) and lower elevation. Monthly mean for CH_4 flux has been used to estimate seasonal CH_4 flux from the site. Ditches have been estimated as 2% proportion of the field for each site.

CH_4 data followed a normal distribution (test of Normality Shapiro-Wilk, $p > 0.05$). In order to evaluate the effect of fertilizer on CH_4 flux, a generalized linear mixed model (LMM) analysis was used with CH_4 flux as the dependent variable and month and fertilizer dose and the interaction between month and fertilizer doses, including ditches as fixed factors. Plot was included as a random factor to account for repeated measures.

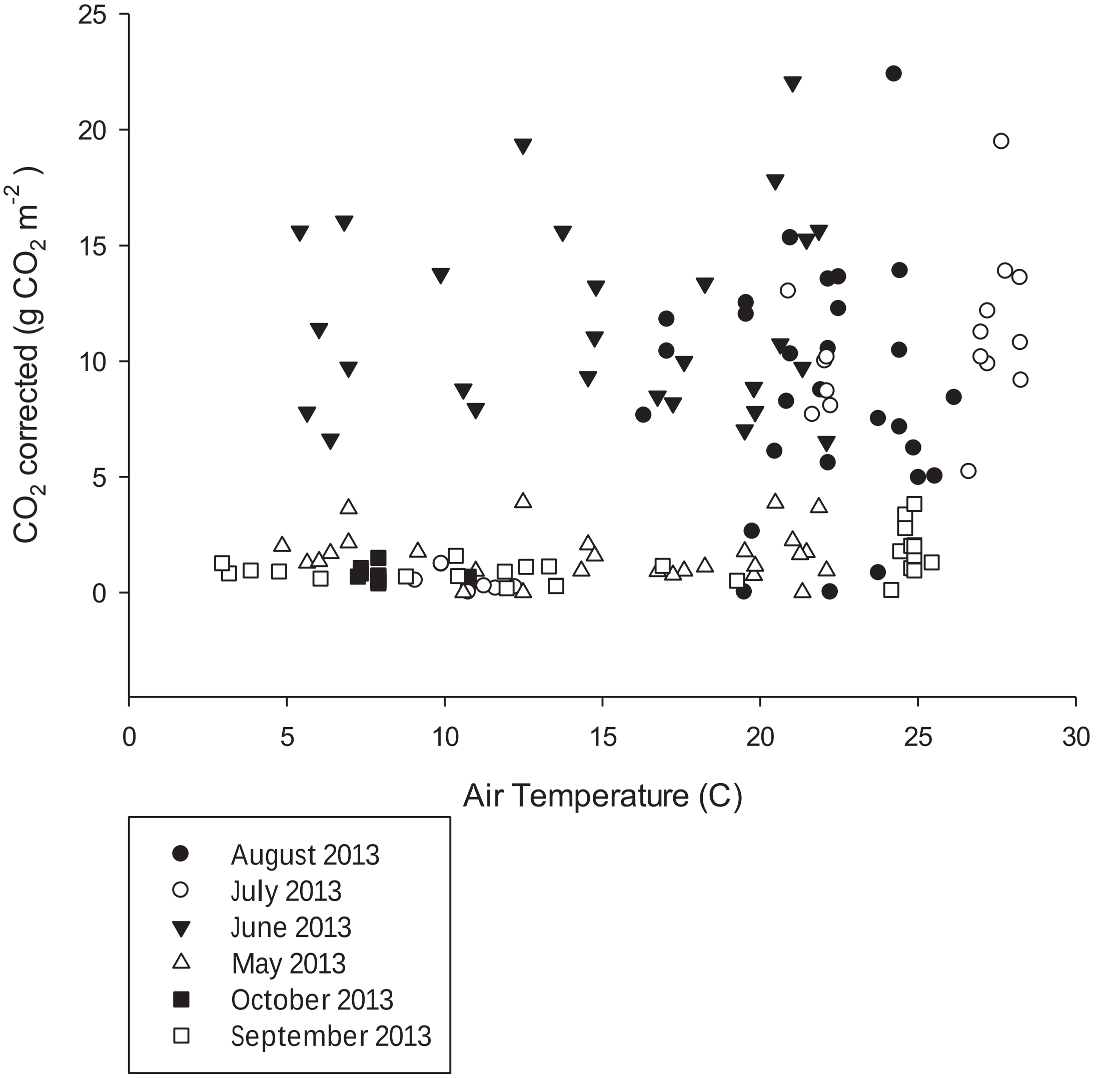


Figure 3.1. Scatter plot between air temperature and total soil respiration, correcting the volume of the gas in the chamber to account for height of the collar above the peat surface and headspace temperature (g CO_2/m^2/day) by month.

3.3. Results

3.3.1. Environmental conditions

Total precipitation for May to October 2013 was 264.4 mm (Paxson Meteorological station). The site received the most of precipitation (95 mm) in July. The mean temperature during the study period was 15.5 °C. The two meteorological stations showed slight differences within the study area. Meteorological station 1 (M1) was located in the area where there was more tree biomass. On average meteorological station 2 (M2) was 0.6 °C warmer, had relative humidity lower by 2.2% and received 8 mm more precipitation than M1.

3.3.2. Effect of fertilizer dose on tree growth

A descriptive analysis of the *P. mariana* survival showed a higher percentage of survival after the addition of nutrients to the tree plantation (ANOVA, $F_{3,\ 1007}$=32.673, p<0.001; see also Chapter 2). However, there was not a statistically significant difference between the doses. On the other hand, non-fertilized areas had a significantly lower *P. mariana* survival of 65%. Seven years after *P. mariana* plantation on a cutover peatland, 84 ± 12 % of the trees survived. Of the 84% alive, 90% of the trees had been fertilized.

Seven years post-plantation the *P. mariana* stand had a mean basal diameter of 1.6 ± 0.1 cm and height of 100.1 ± 3.4 cm. *B. papyrifera* basal diameter was on average 2.0 ± 0.05 cm, while average height was 138.1 ± 0.05 cm (Table 3.1). Both tree species responded to fertilizer with an increase in biomass at fertilized compared to non-fertilized plots (Table 3.1). Aboveground biomass equations exhibited significant fits with basal diameter (Figure 3.2). 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 3.2). Fertilization was also significant in the equations for some, but not all biomass components (Table 3.2).

Table 3.1. Mean and standard error by tree of basal diameter, height, number of branches from the main stem, above biomass divided by compartments (Table **3.2**) and belowground biomass estimated Li et al. (2003) equations for *P. mariana* and *B. papyrifera* survey seven years after plantation by fertilizer treatment.

Specie		*P. mariana*		*B. papyrifera*	
Treatment		**No Fertilizer**	**Fertilizer**	**No Fertilizer**	**Fertilizer**
Number of branches		.	.	3.92 ± 0.3	12.1 ± 0.3
Height (cm)		51.7 ± 1.8	117± 1.5	79 ± 0.1	143.6 ± 0.03
Basal diameter (cm)		1.24 ± 0.1	1.8 ±0.1	1.8 ± 0.1	1.97 ± 0.03
Aboveground biomass (g)	**Total tree**	131 ± 10	343.2 ± 8.9	89.3 ± 8.8	222.6 ± 13.4
	Twigs + leaves	70 ± 5.2	113.2 ± 3.1	28.1 ± 2.4	38.6 ± 1.9
	Branches	40 ± 2.4	62.1 ± 1.4	41.6 ± 3.8	60.4 ± 3.4
	Stem	14.2 ± 1.2	69.2 ± 1.9	32.2 ± 2.5	94.1 ± 4.2
Belowground biomass (g)		29.1 ± 2.2	76.2 ± 2.2	23.2 ± 1.3	36.8 ± 1.1
Total biomass (g)		160.1 ± 12.4	419.4 ± 10.9	112.5 ± 10.1	259.4 ± 14.5

3.3.3. Biomass at the plantation

Using the parameters from Table 3.2, biomass was estimated for both control (un-fertilized) and fertilized plots. The mean equilibrium storage of the *P. mariana* aboveground biomass for fertilized plots was 343.2 ± 8.9 g of which 19% was stem biomass, 21% was branch biomass and 33% was twig and leaf biomass, and for the non-fertilized plots, was 131 ± 10 g of which 11.4% was stem biomass, 17.8% was branch biomass and 33.1% was twig and leaf biomass. The mean of below ground biomass was 76.2 ± 2.0 g for the fertilized plots and 29.1 ± 2.2 g for non-fertilized plots. The calculated estimate for below ground biomass corresponds with 47% of the total biomass for fertilized plots and 18% of the total biomass for unfertilized plots. The total average biomass accumulation (net primary production, NPP) for *P. mariana* for fertilized plots was 12.7 ± 0.9 g C m^{-2} yr^{-1} and 4.9 ± 0.9 g C m^{-2} yr^{-1} for non-fertilized plots.

The total equilibrium aboveground biomass for the colonizer species, *B. papyrifera*, for fertilized plots was 222.6 ± 13.4 g, of which 27.7% was stem biomass, 15.5% was branch biomass, and 11.8% was leaf biomass and for the non-fertilized plots was 89.3 ± 8.8 g of which 39% was stem biomass, 27.5% was branch biomass and 19.5% was twig and leaf biomass. The *B. papyrifera* colonization on the edge of the plots 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 below ground biomass was 36.8 ± 1.1 g for the fertilized plots and 23.2 ± 1.3 g for non-fertilized plots. The below ground biomass corresponds with 14% of the total biomass for fertilized plots and 20% of the total biomass for unfertilized plots. The mean annual NPP for *B. papyrifera* for non-fertilized plots was 7.1 ± 3.9 g C m^{-2} yr^{-1} and was 236.3 ± 52.8 g C m^{-2} yr^{-1} for fertilized plots.

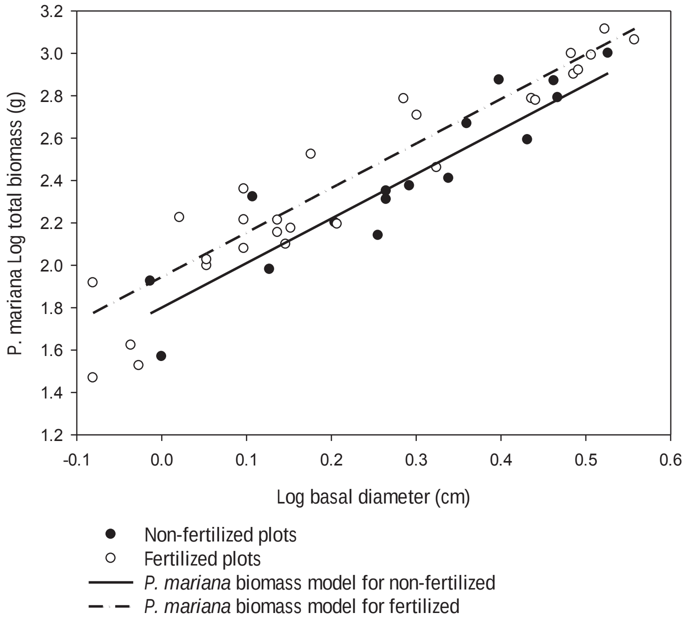
Table 3.2. Allometric biomass models. Parameters and statistical information for allometric equations[a,b]

Species/component	**a**	**b**	**c**	**Std. Error**
P. mariana/ total biomass	1.656	2.102	0.144	0.066
P. mariana / leaves	1.160	0.446	n.s.[c]	0.072
P. mariana / branches	1.035	0.384	n.s.	0.054
P. mariana / stem	0.387	2.276	0.402	0.076
B. papyrifera / total biomass	0.989	2.492	0.218	0.118
B. papyrifera / leave	0.807	2.196	n.s.	0.024
B. papyrifera / branches	0.918	2.371	n.s.	0.072
B. papyrifera / stem	0.565	2.06	0.346	0.176

a. Total biomass and stem biomass equations for *P. mariana* and *B. papyrifera* were of the form: Log(biomass component (g biomass/tree)) = a + b*log(basal diameter (cm)) + c(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.

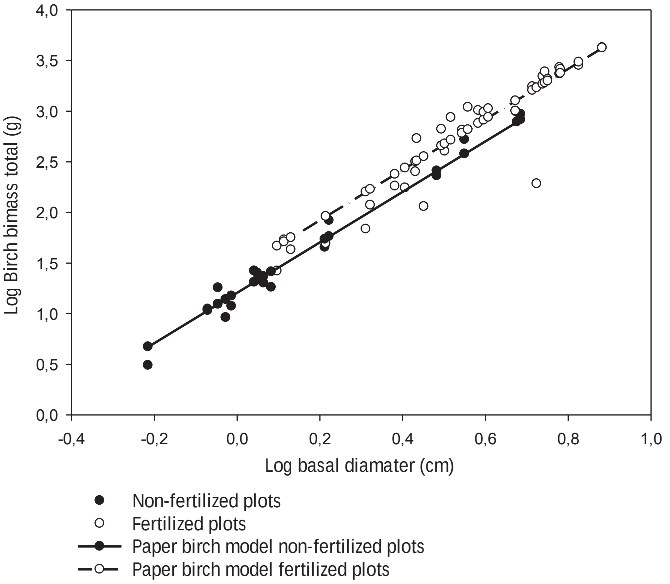
b. Leaves and branches biomass equations for *P.mariana* and *B. papyrifera* were of the form: Log(biomass component (g biomass/tree)) = a + b*(basal diameter(cm)) + c(fertilization treatment), where fertilization treatment was a non-significant categorical variable.

c. n.s. = not significant



***P. mariana* Log (total biomass) = 1.656 + 2.102*Log $\varnothing_b$ (cm) + 0.1444*Fertilizer**

(GLM, Std. Error=.0661, Wald Chi-Square=627.122, df =1 (150), p-value=.000)



***B. papyrifera* Log (total biomass) = 0.989+ 2.492*Log $\varnothing_b$ (cm) + 0.218*Fertilizer**

(GLM, Std. Error=.1178, Wald Chi-Square=70.510, df =1 (150), p-value=.000)

Figure 3.2. 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.

3.3.4. Soil carbon fluxes

3.3.4.1. Carbon dioxide (CO_2) flux

Seven years post-restoration, there was an interaction between seasons and fertilizer treatment (LMM, $F_{1, 76}$=802.6, p-value=0.00). Fertilizer dose significantly affected soil respiration (LMM, $F_{3, 64}$=5.55, p-value=0.002), particularly in May, September and October (LMM, $F_{1, 76}$=535.227, p-value=0.000) (Figure 3.3). Negative values indicate C losses from the soil. Daily average of CO_2 emission for non-fertilized plots was -4.31 ± 0.62 g CO_2 m^{-2} and for fertilized plots was -4.97 ± 0.9, -6.1 ± 1.4, -5 ± 1.1 g CO_2 m^{-2} d^{-1} for high, medium and low dose of fertilizer, respectively (Table 3.3). The highest soil respiration was -14.7 ± 1.4 g C m^{-2} d^{-1} for medium dose plots in June. The lowest soil respiration was -0.7 ± 0.2 g C m^{-2} d^{-1} for plots with low dose of fertilizer in October (Figure 3.3). Estimated annual CO_2 emissions for non-fertilized plots were -236.5 ± 30 g C m^{-2} yr^{-1} and -306.4 ± 56.7 g C m^{-2} yr^{-1} for fertilized plots.

3.3.4.2. Methane flux

CH_4 flux on average was 0.9 ± 3.8 mg CH_4 m^{-2} d^{-1}. The CH_4 emission varied though the growing season having the highest emission during July 2013 at -8.4 ± 3.4 mg CH_4 m^{-2} d^{-1}. In August, the lowest value was 8.9 ± 4.7 mg CH_4 m^{-2} d^{-1}. Annual field CH_4 emissions were -0.7 ± 3.9 and 1.4 ± 3.5 g C m^{-2} yr^{-1} for fertilized and unfertilized plots respectively.

One year after blocking the ditches close to the restored site, there was no significant difference between fertilizer doses on fields and ditches for CH_4 flux (ANOVA, $F_{4,65}$=1.077, p=0.376). The distribution of the CH_4 flux was not significantly related with fertilizer dose and month (LMM, $F_{4, 30}$=0.713, p-value=0.590). The annual emission from ditches was 0.94 ± 6.5 g C m^{-2} yr^{-1}. Overall, following previous studies (e.g. Munir et al., 2014), dry conditions during the growing season and the lack of water table close to the surface resulted in very low CH_4 fluxes in general.

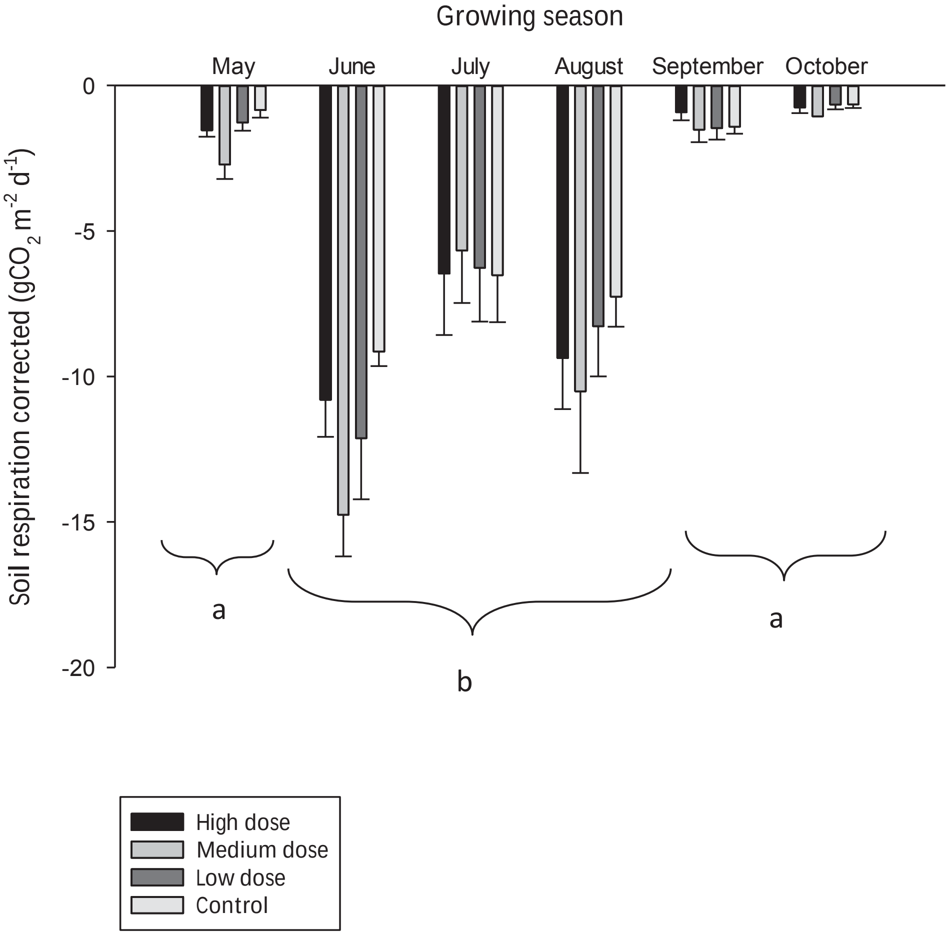


Figure 3.3. The effect of fertilizer treatments on soil respiration (CO_2 total corrected). Monthly means and standard error for fertilizer doses has been used to estimate the CO_2 losses during the growing season based on instantaneous chamber measurements. Negative values indicate C losses from the soil. Letters indicate significant difference between warm and cold months. Months within each group were not tested for significant differences within the warm and and cold months.

Table 3.3. Monthly means and standard errors of CH_4 (mg $CH_4/m^2/d$) flux by each dose of fertilizer. Methane flux also presented as average values for fields and ditches. Negative values indicate C losses from the soil.

Fluxes	Fertilizer doses	June	July	August	September	October	Year 2013
CH_4 (mgCH_4 $m^{-2}d^{-1}$)	**High**	-3.9 ±3.8	-1.2 ±3.7	-5.8 ±4.1	-5.8 ±2.1	-1.5 ±2.7	-3.4 ±3.3
	Medium	8 ±4.5	-2.5 ±5.1	-	-5.4±3.9	1.4 ±4.5	0.3 ±4.7
	Low	-1.2 ±3.7	-	6.6 ±5.1	-2.6±3.1	1.8±3.1	0.8 ±3.9
	Control	3.3±3.3	-8.4±3.4	8.9±4.7	4.34±2.7	2.9 ± 3.3	1.4 ±3.5
	Field	*-2.3±3.1*	*-1.6±5.1*	*1 ±5.9*	*-1.5±1.9*	*1.9 ± 3.1*	*0.9 ±3.8*
	Ditches	-	*6.3 ±15*	*6.3±3.6*	*-0.6±4.1*	*-1.4±3.4*	*0.94 ±6.5*

3.3.5. 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 biomass and the total soil respiration by non-fertilized and fertilized plots for the site were summmarized (Table 3.4). The highest dose of fertilizer improved tree growth for both species resulting in the greatest reduction in C emission. Particularly, *B. papyrifera* colonization increased with fertilizer dose and greatly increased C accumulation in biomass. 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 -230.2 ± 25.6 g C m^{-2} yr^{-1} and -294.4 ± 59.6 g C m^{-2} yr^{-1} for unfertilized and fertilized plots, respectively. Considering the biomass of the *B. papyrifera* colonization, the total net C balance for non-fertilized plots was -223.1 ± 38.3 g C m^{-2} yr^{-1} and while fertilized plots had a mean C balance of -58 ± 6.8 g C m^{-2} yr^{-1} (Table 3.4).

Table 3.4. Mean and standard error for net primary production for *P. mariana* and *B. papyrifera* above and belowground biomass and annual soil losses of CO_2 and CH_4 by fertilized and non-fertilized plots. Negative values indicate C losses from the soil/ecosystem.

Treatment		**Non fertilized**	**Fertilized**
P. mariana **(g C m^{-2}yr^{-1})**	Aboveground	4 ± 0.7	10.4±0.8
	Belowground	0.9 ± 0.2	2.3±0.2
	Total biomass	**4.9 ± 0.9**	**12.7 ± 1**
B. papyrifera **(g C m^{-2}yr^{-1})**	Aboveground	5.6 ± 3.1	201.7 ± 44.7
	Belowground	1.5 ± 0.8	34.6 ± 8.1
	Total biomass	**7.1 ± 3.9**	**236.4 ± 52.8**
CO_2 (g C m^{-2} yr^{-1})		-236.5 ± 30	-306.4 ± 56.7
CH_4 (g C m^{-2} yr^{-1})		1.4 ± 3.5	-0.7 ± 3.9
ΔC both species (g C m^{-2} yr^{-1})		**-223.1 ± 21.7**	**-58 ± 6.8**
ΔC *P. mariana* **only (g C m^{-2} yr^{-1})**		**-230.2 ± 25.6**	**-294.4 ±59.6**

3.4. Discussion

During the first seven years following *P. mariana* seedling plantation, fertilization has had an effect on ecosystem C balance by supporting biomass production and therefore, offers the largest C storage capacity. The rate of fertilizer applied was the principal variable that determined the *P. mariana* survival after seven years and its biomass production. Net primary production (NPP) of *P. mariana* was estimated to be on average 12.7 ± 0.9 g C m^{-2} yr^{-1} for fertilized plots and 4.9 ± 0.9 g C m^{-2} yr^{-1} for un-fertilized plots. Previous researchers report much higher tree biomass growth for *P. mariana* wood production in plantations on mineral soil of 136 ± 19 g C m^{-2} yr^{-1} (Hermle et al., 2010) or between 80 to 350 g C m^{-2} yr^{-1} (Hunt et al., 2010). Stand age and soil quality likely negatively impacted the *P. mariana* biomass growth for this plantation on bare peat after extraction. In Alberta, the annual *P .mariana* aboveground production on a drained peatland is 66 and 60 g C m^{-2} and was 38 and 33 g C m^{-2} for undisturbed peatland (Munir et al., 2014). Across bogs in Alberta, Wieder et al. (2006) report that the rate of C accumulation in aboveground *P. mariana* biomass peaked at 74 years after fire at a value of 8.2 ± 13 mol C m^{-2} yr^{1}. While the highest fertilization treatment (26.8 g/bag) had better nutrient conditions for *P. mariana* growth and helped increase total plantation biomass, it also helped support colonizing *B. papyrifera*.

The biomass of *B. papyrifera* was also influenced by the dose of fertilizer, resulting in increased *B. papyrifera* density at high doses. Dense *B. papyrifera* colonization had a direct effect on C fixation through increasing tree biomass. In fact, in fertilized plots, *B. papyrifera* biomass was much greater than *P. mariana* biomass (Table 3.1). A dense population of *B. papyrifera* 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 soil respiration (Makiranta 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 (Makiranta et al., 2007). In fact, respiration rate was higher at fertilized plots in this study. *B. papyrifera* leaf biomass that has been included in C stock estimates is not permanent since *B. papyrifera* is deciduous species. This likely overestimates the total biomass in the area, but has a smaller impact on C balance estimates as this litter is deposited in the soil system.

Soil respiration at Paxson was estimated on average as 306.3 ± 27.7 g C m^{-2} yr^{-1} and 236.5 ± 30 g C m^{-2} yr^{-1} for fertilized and non-fertilized plots, respectively over bare peat. Comparing this value with previous research, the soil respiration at Paxson was similar to cutover bare peat in Quebec with reported growing season soil respiration of 126-280.5 g C m^{-2} yr^{-1} (Waddington et al., 2010) and it is also in the range of emission 126 to 680 g C m^{-2} yr^{-1} on cutover bare peat in Alberta (Strack et al., 2014).

Although many previous studies have modelled annual soil respiration from peatlands using soil temperature (e.g. Waddington et al., 2010; Riutta et al., 2007; Strack at al., 2014), no valid relationship between soil respiration and air temperature was found in the current study. On the other hand, respiration was significantly higher during the warm months (June-August) compared to cold months (May, September, October; Figure 3.3). Soil respiration was measured on bare peat at ground level and related with air temperature from the meteorological station, which is located at 2 m height. Differences in temperature between ground and 2 m height could be an explanation for the lack of correlation. It was also clear that during May, September and October, fertilizer dose and air temperature had direct effect on soil respiration as all measured values were very low during this period. On the other hand, during the June, July and August, soil respiration ranged from -5.7 ± 1.8 to -14.7 ±1.4 g C m^{-2} d^{-1}, although the actual rate was not well correlated to temperature. Possibly additional limitations such as substrate quality (e.g. Basiliko et al., 2007) or soil moisture (e.g. Greenwood, 2005) were likely more important than temperature for controlling soil respiration during these months. Soil moisture was monitored during soil respiration measurements. It was highly variable across each plot and also correlated to soil respiration (ANOVA, $F_{6, 64}$= 4.055, $p<0.0001$). However, due to the lack of continuous data during the growing season, soil moisture could not be used as a variable to model soil respiration.

CH_4 flux at this site did not make an important contribution to the net C balance. Other sites on abandoned cutover peatlands also report very low CH_4 flux and in some cases CH_4 consumption (e.g., Waddington and Day, 2007; Strack and Zuback, 2013). Waddington and Day (2007) reported that CH_4 flux from remnant drainage ditches can be orders of magnitude higher than those from cutover peat fields and thus must be characterized to determine site level CH_4 flux. However, in our study, CH_4 flux from remnant drainage ditches was not higher than neighbouring fields likely due to dry soil conditions that existed also in the ditches.

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.

The carbon balance of a forest plantation on a cutover peatland resulted in reduced carbon emission compared to unrestored cutover peatland. Forest plantation on cutover peatlands is an alternative after-use technique to reduce GHG emissions though C storage in tree biomass. Increasing aboveground biomass may balance part of the C loss 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., Minkkinen et al., 2002). This cutover peatland remains a source of C as the growing *P. mariana* and *B. papyrifera* are unable to capture the entire C released through oxidation of the residual peat. Nonetheless, the fertilized plots were most effective in supporting biomass production through forest growth, and therefore offer the largest reduction in net C emissions. The estimated C balance at Paxson seven years post plantation was lower than cutover bare peat at -58 ± 6.8 g C m^{-2} yr^{-1} due to the effect of fertilizer and consequently *B. papyrifera* colonization. The C balance may be positive in some sections (i.e. a net sink of C) if the dense *B. papyrifera* colonization near ditches had been quantified. On the other hand, the majority of the C stored on fertilized plots was present in the colonizing *B. papyrifera* and this has potential implications for other ecosystem services (e.g., biodiversity, habitat for wetland species).

The net release of C to the atmosphere from cutover peatlands may decrease using forest plantation as a restoration technique, compared to bare peat in similar areas, especially when the increased sequestration of C into the growing stand is considered. However, the study site continued to release C through the oxidation of residual peat likely due to dry conditions remaining on site, and this occurs in many peat restoration techniques when the oxidation of residual peat releases more C than can be captured through biomass production (e.g., Petrone et al., 2001; Hargreaves et al., 2003; Makiranta et al., 2012). Rewetting organic soils reduces peat oxidation (IPCC, 2013). 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, Strack et al., 2014). Nevertheless, rewetting may also lead to increased CH_4 emissions (Joosten et al., 2011), particularly since, input of C from root exudates and *B. papyrifera* litter can increase rates of CH_4 production and emission (Trinder et al., 2008), and consequently increase decomposition of peat following restoration (Basiliko et al., 2007).

To increase the C fixation, the reintroduction of understory vegetation and rewetting the areas are the key factors to increase the photosynthesis and reduce soil respiration. Previous research (e.g. Rochefort, 2000; Poulin et al., 2012; Graf et al., 2009; Strack et al., 2014) demonstrated the effectiveness of "moss layer transfer" techniques on cutover peatland to improve ecosystem services, including C uptake. Introducing forest floor vegetation along with the forest plantation would help to improve C uptaken and also avoid colonization by undesirable species (Hugron et al., 2011).

3.4.1. General management recommendations

Fertilization is needed for tree establishment and growth on cutover peat in Canada (this study, Bussières et al., 2008). The dose of fertilizer, volumetric water content and peat depth could determine the density of *B. papyrifera* colonization (see also Chapter 2). Straw mulch could reduce the high density of *B. papyrifera* colonization on edges (Graf et al., 2009), but was not tested in the present study. Rewetting is also important for limiting soil respiration and may also limit *B. papyrifera* colonization (Chapter 2). 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 plantation could determine the plant survival and colonization by non-target species. While the present study site was too dry 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.

Since there is no understory in the restored area, C losses by soil respiration are not balanced by ground layer photosynthesis. Vegetation cover should be introduced to establish the original plant community and structure of the understory to avoid soil erosion and frost heaving (Rochefort, 2003). Following "moss layer transfer" technique, introducing peatland plant propagules (any part of a plant that can regenerate a new individual) and moss fragments, and covering with straw mulch during the *P. mariana* plantation should assist plant community establishment (Graf et al., 2009), to improve future resilience in the ecosystem (Rochefort, 2000; Poulin et al., 2012).

Overall, more traditional peatland restoration may be more desirable than forest plantation from a C balance point of view; however, on some dry areas within cutover peatland, 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.

3.5. Conclusions

This study found that seven years after *P. mariana* seedlings were planted, forest plantation on a cutover peatland reduced the net loss of carbon from the cutover peatland through carbon fixation in tree biomass compared to unrestored cutover peatland. Although a higher fertilizer dose resulted in greater biomass accumulation, all sites remained carbon sources on average over the seven years since the trees were planted. Fertilization was also linked to *B. papyrifera* colonization, which may have an impact on additional ecosystem services and ability to achieve restoration goals (e.g., preventing return to wetland system, limiting biodiversity). Future plantation projects on cutover peatlands should include rewetting and introduction of understory to further reduce C emissions.

3.6. References

Aerts, R., van Logtestijn, R.S.P., Karlsson, P.S., 2006. Nitrogen supply differentially affects litter decomposition rates and nitrogen dynamics of sub-arctic bog species. Global Change Biol. 146, 652–658.

Alm, J., Shurpali, N.J., Tuittila, E.S., Laurila, T., Maljanen, M., Saarnio, S., 2007. Methods for determining emission factors for the use of peat and peatlands---flux measurement and modeling. Boreal Environment Research, (12): 85-100.

Alberta AgroClimatic Information Service (Athabasca, ACGM, http://agriculture.alberta.ca/acis/alberta-weather-data-viewer.jsp). (Last accessed on December 2014).

Alberta Government, 2013. Alberta Wetland Policy, Alberta Environment and Sustainable Resource Development, Edmonton, AB, Canada, p. 25.

Basiliko, N., Blodau, C. P., Bengtson, P. C., Roehm, C., Moore, T. R., 2007. Regulation of Decomposition and Methane Dynamics across Natural, Commercially Mined, and Restored Northern Peatlands, Ecosystems, 10, 7, 1148–1165, doi:10.1007/s10021-007-9083-2, 2007.

Bhatti, J.S, Errington, R.C., Bauer, I.E., Hurdle, P.A., 2006. Carbon stock trends along forested peatland margins in central Saskatchewan. Canadian Journal of Soil Science.

Black, K., Byrne, K.A., Mencuccini, M., Tobin, B., Nieuwenhuis, M., Reidy, B., Bolger, T., Saiz, G., Green, C., Farrell, E.P., Osborne, B., 2009. Carbon stocks and stock changes across a Sitka spruce chronosequence on surface water gley soils. Forestry. 82(3):255-272.

Bond-Lamberty, B., Wang, C., Gower, S.T., 2002. Aboveground and belowground biomass and sapwood area alllometric equations for six boreal tree species of northern Manitoba. Canadian Journal of Forest Research; Aug 2002; 32, 8; CBCA Complete. 1441.

Bonnett, S.A.F., Ross, S., Linstead, C. and Maltby, E., 2009. A review of techniques for monitoring the success of peatland restoration. University of Liverpool. Natural England. Commissioned Reports, Number 086.

Bussières, J., Boudreau, S., and Rochefort, L., 2008. Establish trees on cut-over peatlands in Eastern Canada. Mires and Peat, Vol. 3, Article 10, http://www.mires-and-peat.net/, ISSN 1819-754X © 2008 International Mire Conservation Group and International Peat Society.

Byrne, K.A., Cabral, R., Pöllänen, M. and Farrell, E.P., 2007. Natural regeneration. In: Wilson, D. & Farrell, E.P. (eds.) CARBAL. Carbon Gas Balances in Industrial Cutaway Peatlands in Ireland. University College Dublin, 15–17.

Couwenberg, J., Fritz, C., 2012. Towards developing IPCC methane "emission factors" for peatlands (organic soils). Mires and Peat, Volumen 10. Article 03, 1–17, http://www.mires-and-peat.net/, ISSN 1819-754X

Delta-T Devices. 2005. WET-sensor user manual v1.3. Cambridge, U.K.: Delta-T Devices.

FAO, 2005. The importance of soil organic matter Key to drought-resistant soil and sustained food and production. Chapter 4 – Practices that influence the amount of organic matter. ISBN 92-5-105366-9 http://www.fao.org/docrep/009/a0100e/a0100e.pdf

Fay, E., Lavoie C., 2009. The impact of birch seedlings on evapotranspiration from a mined peatland: an experimental study in southern Quebec, Canada. Mires and Peat, Vol. 5, Article 03, 1-7.

Gorham, E., 1991. Northern peatlands: role in the carbon cycle and probable response to climatic warming. Ecological Applications 1, 182–195.

Gorham, E., Rochefort, L., 2003. Peatland restoration: A brief assessment with special reference to *Sphagnum* bogs. Wetlands Ecology and Management 11, 109-119.

Graf, M.D., Rochefort, L., 2009. Examining the peat-accumulating potential of fen vegetation in the context of fen restoration of harvested peatlands. Ecoscience 16(2), 158-166.

Greenwood, M., 2005. The effect of Restoration on CO_2 exchange in a cutover peatland. Master of Science at McMaster University.

Grigal, D.F, Kernik, L.K., 1984. Generality of P. mariana biomass equations. Canadian Journal of Forest Research; 14:468-70.

Hargreaves, K.J., Milne, R, Cannell, M.G.R, 2003. Carbon balance of afforested peatland in Scotland. Forestry, Vol. 76, No.3.

Hermle, S., Lavigne, M.B., Bernier, P.Y., Bergeron, O., Paré, D., 2010. Component respiration, ecosystem respiration and net primary production of a mature P. mariana forest in northern Quebec. Tree Physiology 30, 527-540.

Hugron, S., Bussières, J., Rochefort, L., 2011. Plantation d'essences forestières dans le contexte de la restauration écologique des tourbières : un guide pratique, Groupe de recherche en écologie des tourbières, Université Laval, Québec, p. 88.

Hytönen, J., Kaunisto, S., 1999. Effect of fertilization on the biomass production of coppiced mixed birch and willow stands on a cut-away peatland. Biomass and Bioenergy 17. 455-469.

Hunt, S.L., Gordon, A.M., Morris, D.M., 2010. Carbon stocks in managed conifer forests in northern Ontario, Canada. Silva Fennica 44(4): 563–582.

Keith, D.A., Rodríguez, J.P., Rodríguez-Clark, K.M., Nicholson, E., Aapala, K., 2013. Scientific Foundations for an IUCN Red List of Ecosystems. PLoS ONE 8(5):e62111. doi:10.1371/journal.pone.0062111

Joosten, H., 2011. The global peatland CO_2 picture. In: Tanneberger, F. & Wichtmann, W. (eds.) Carbon Credits From Peatland Rewetting. Climate-Biodiversity-Land Use. Schweizerbart Science Publishers, Stuttgart, 20 and 29–30.

Joosten, H. and Clarke, D., 2002. Wise Use of Mires and Peatlands. International Mire Conservation Group and International Peat Society, Saarijärven Offset Oy, Saarijärvi, Finland, p. 504.

IPCC (Intergovernmental Panel on Climate Change), 2007. Impacts, adaptation and vulnerability: contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson, Eds. Cambridge: Cambridge University Press. p 976

IPCC (Intergovernmental Panel on Climate Change), 2013. Supplements to the 2006 IPCC Guidelines for national greenhouse gas inventories. Wetlands, 2013. http://www.ipcc.ch.

Lambert, M.C., Ung, C.H., Raulier, F., 2005. Canadian national tree aboveground biomass equations. Can. J. For. Res. 35: 1996–2018 doi: 10.1139/X05-112. Web site at http://cjfr.nrc.ca.

Laine, A. M., Leppälä, M., Tarvainen, O., Päätalo, M.-L., Seppänen, R., Tolvanen, A., 2011. Restoration of managed pine fens: effect on hydrology and vegetation. Applied Vegetation Science 14:340–349.

Laiho, R., Finér, L., 1996. Changes in root biomass after water level drawdown on pine mires in southern Finland. Scandinavian Journal of Forest Research 11, 251 – 260.

Lavoie, C., Saint-Loui, A., 1998. The spread of gray birch (Betula populifolia) in eastern Quebec: landscape and historical considerations. Can. J. Bot. 77: 859–868.

Li, Z., Kurz, W.A., Apps, M.J., Beukema, S.J., 2003. Belowground biomass dynamics in the Carbon Budget Model of the Canadian Forest Sector: recent improvements and implications for the estimation of NPP and NEP. Canadian Journal of Forest Research 33: 126-136.

Limpens, J., Berendse, F., Blodau, C., Canadell, J.G., Freeman, C., Holden, J., Roulet, N., Rydin, H., Schaepman-S, G. 2008. Peatlands and the carbon cycle: from local processes to global implications a synthesis. Biogeosciences. 5, 1475-1491.

Locky, D., 2011. A. Wetlands: Alberta's Keystone Ecosystem at a Crossroads. Green Paper Prepared for the Alberta Institute of Agrologists. Annual Conference of the Alberta Institute of Agrologists Banff, Alberta.

Loisel, J., Yu, Z., Beilman, D. W., Camill, P., Alm, J., Amesbury, M. J., Anderson, D., Andersson, S., Bochicchio, C., Barber, K., Belyea, L. R., Bunbury, J., Chambers, F. M., Charman, D. J., De Vleeschouwer, F., Fiałkiewicz-Kozieł, B., Finkelstein, S. A., Gałka, M., Garneau, M., Hammarlund, D., Hinchcliffe, W., Holmquist, J., Hughes, P., Jones, M. C., Klein, E. S., Kokfelt, U., Korhola, A., Kuhry, P., Lamarre, A., Lamentowicz, M., Large, D., Lavoie, M., MacDonald, G., Magnan, G., Makila, M., Mallon, G., Mathijssen, P., Mauquoy, D., McCarroll, J., Moore, T. R., Nichols, J., O'Reilly, B., Oksanen, P., Packalen, M., Peteet, D., Richard, P. J. H., Robinson, S., Ronkainen, T., Rundgren, M., Britta, A., Sannel, K., Tarnocai, C., Thom, T., Tuittila, E.-S., Turetsky, M., Valiranta, M., van der Linden, M., van Geel, B., van Bellen, S., Vitt, D., Zhao, Y., and Zhou, W. 2014. A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation, The Holocene, in press, 2014.

Makiranta, P., Hytönene, J., Aro, L., Maljanen, M., Pihlatie, M., Potila, H., Shurpali, N.J., Laine, J., Lohila, A., Martikainen, P.J., Minkinen, K., 2007. Soil greenhouse gas emissions from afforested organic soil croplands and cutaway peatlands. Boreal environment research, 12: 159-175.

Makiranta, P., Laiho, R., Penttila, T., Minkkinen, K., 2012. The impact of logging residue on soil GHG fluxes in a drained peatland forest. Soil Biology & Biochemistry 48, 1-9.

Minkkinen, K., korhonene, R., Savolainene, I., Laine, J., 2002. Carbon balance and radiative forcing of Finnish peatlands 1900-2100- the impact of forestry drainage. Global Change Biology 8, 785-799.

Munir, T.M, Xu, B., Perkins, M., Strack, M., 2014. Responses of carbon dioxide flux and plant biomass to water table drawdown in a treed peatland in northern Alberta: a climate change perspective. Biogeosciences 11, 807-820.

Paxson Restoration Report, Premier Tech, 2012.

Petrone, R.M., Waddington, J.M., Price, J.S., 2001. Ecosystem scale evapotranspiration and net CO_2 exchange from a restored peatland. Hydrology. Proc. 15: 2839–2845.

Poulin, M., Andersen, R., Rochefort, L., 2012. A new approach for tracking vegetation change after restoration: A case study with Peatlands. Society for Ecological Restoration. doi: 10.1111/j.1526-100X.2012.00889.x.

Price, J.S., Heathwaite, A.L., Baird, A.J., 2003. Hydrological processes in abandoned and restored peatlands: An overview of management approaches. Wetlands Ecology and Management 11: 65-83.

Quinty, F., Rochefort, L., 2003. Peatland restoration guide, second ed. Canadian Sphagnum Peat Moss Association and New Brunswick Department of Natural Resources and Energy. Québec.

Renou, F., Scallan, U., Keane, M.,·Farrell, E. P., 2007. Reclaiming peatlands for forestry: the Irish experience. 1-56670-635-1/05 © 2005 by CRC Press LLC.

Rochefort, L., 2000. Sphagnum A Keystone Genus in Habitat Restoration. The Bryologist 103, 503-508.

Rochefort, L., Quinty, F., Campeau, S., Johnson, K, Malterer, T., 2003. North American approach to the restoration of Sphagnum dominated peatlands. Wetlands Ecology and Management 11, 3–20.

Saarnio, S., Moreno, M., Shurpali, N.J., Tuitila, E. S., Makila, M., Alm, J., 2007. Annual CO_2 and CH_4 fluxes of pristine boreal mires as a background for the life cycle analyses of peat energy.

Silvola, J., Alm, J., Ahlholm, U., Nykanen, H., Martikainen, P.J., 1996. CO_2 fluxes from peat in boreal mires under varying temperatures and moisture conditions. Journal of Ecology 84, 219-228.

SPSS, Statistic v.21. SYSTAT 21.0 for Windows. IBM, SPSS, Chicago, Illinois, USA.

Strack, M., Waller, M.F., Waddington, J.M., 2006. Sedge Succession and Peatland Methane Dynamics: Potential Feedback to Climate Change. Ecosystems 9, 278-287.

Strack, M., Waddington, J.M., Turetsky, M., Roulet, N.T., Byrne, K.A. 2008. Northern peatlands, greenhouse gas exchange and climate change. In: Strack, M. (Ed.), Peatlands and Climate Change, International Peat Society and Saarijärven Offset Oy, Saarijärvi, Finland, p. 44-69.

Strack, M., Keith, A.M., Xu, B., 2014. Growing season carbon dioxide and methane exchange at ta restored peatland on the western Boreal Plain. Ecological Engineering 64, 231-239.

Strong, W.L. and K.R. Leggat., 1981. Ecoregions of Alberta. ENR Technical Report (T/4) from the Alberta Energy and Natural Resources, Edmonton, Alberta.

Ter-Mikaelian, M.T., Korzukhin, M.D., 1997. Biomass equations for sixty-five North American tree species. For. Ecol. Manage.97: 1–24.

Tuittila, E. S., Komulainen, V-M, Vasander, H., Laine, J., 1999. Restored cut-away peatlands as a sink of atmoshpheric CO_2. Oecologia, 120, 563-574.

Trinder, C.J, Artz, R.R.E, Johnson, D., 2008. Contribution of plant photosynthetic to soil respiration and dissolved organic carbon in a naturally recolonizing cutover peatland. Soil Biology & Biochemistry 40, 1622–1628.

Vitt, D.H., 2006. Functional characteristics and indicator of Boreal Peatlands. In R. Weider & D.Vitt, Boreal Peatland Ecosystem. Springer, p.9-24.

Vitt, D.H., L.A., Halsey, I.E., Bauer, Campbell, C., 2000. Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. Canadian Journal of Earth Sciences 37, 683-693.

Waddington, J.M., Strack, M., Greenwood M.J., 2010. Toward restoring the net carbon sink function of degraded peatlands: Short-term response in CO_2 exchange to ecosystem-scale restoration. Journal of geophysical research Vol. 115 G01008.

Waddington, J.M., Day, S.M., 2007. Methane emissions from a peatland following restoration. Journal of Geophysical Research 112. G03018, doi: 10.1029/2007JG000400.

Waddington, J.M., Warner, K.D., Kennedy, G.W., 2002. Cutover peatlands: A persistent source of atmospheric CO_2. Global biogeochemical cycles, Vol. 16, NO. 1, 1002, 10.129/2001GB001398.

Waddington, J.M., Price, J.S., 2000. Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. Physical Geography 21(5), 433-451.

Wieder, R. K., Vitt, D. H., Benscoter, B. W., 2006. Peatlands and the Boreal Forest, in R. K. Wieder, D. H. Vitt (eds.): Boreal Peatland Ecosystems. Ecological Studies 188, Springer, Heidelberg, Germany, p. 1–8.

Wieder, R. K., Scott, K. D., Kamminga, K., Vile, M. A., Vitt, D. H., Bone, T., Xu, B., Benscoter, B. W., and Bhatti, J. S.: Postfire carbon balance in boreal bogs of Alberta, Canada, Glob. Change Biol., 15, 63–81, 200

Yli-Petäys, M., Laine, J., Vasander, H., Tuittila, E-S., 2007. Carbon gas exchange of a re-vegetated cut-away peatland five decades after abandonment. Boreal Environment Research 12, 177-190.

CHAPTER 4: Conclusion and Recommendations

4.1. Summary

This research project evaluated the fertilizer dose that promotes *P. mariana* survival and growth and survival in a plantation on a cutover peatland and the C balance of this plantation. The hypotheses were that adding fertilizer would improve *P. mariana* and *B. papyrifera* growth and C accumulation in the biomass and this has been supported with the results. The high dose of fertilizer resulted in the largest trees and most biomass accumulation. However, the high dose of fertilizer tested in this study (26.9 g/bag) may not be required for success of *P. mariana* plantation on cutover peatland. The low fertilizer dose of 8.9 g/bag was enough to ensure 84 ± 12 % of *P. mariana* survival and enhance its growth while having a lower level of effect on the invasion by *B. papyrifera*.

The impact of *B. papyrifera* colonization has been quantified over a year by cutting birch stem around planted trees for three of the fertilization treatment over half of the experiment unit. The hypothesis about the cutting of the competitor species enhancing *P. mariana* growth was supported to a small degree by this study. Microclimatic conditions, such as RH and insolation availability were changed by birch removal. A low density of *B. papyrifera* invasion can help decreasing the evapotranspiration, favour better microclimate condition (higher Ɵ, RH and PAR) in the soil during the growing season, having a direct positive effect on *P. mariana* growth. For instance, lower Ɵ and RH following birch removal may be due to removal of a large transpiration draw from *B. papyrifera*, suggesting their presence likely lowers water table and could reduce the chance of successful restoration to a peatland ecosystem. At the study site, the water table was not monitored due to the fact that it was regularly below the remnant peat.

To estimate the C balance of a forest plantation on a cutover peatland, C stock in biomass of *P. mariana* and *B. papyrifera* trees growing in a seven-year old forest plantation on cutover peat was determined and subtracted from soil carbon losses. Higher fertilizer dose resulted in greater biomass accumulation. The total average biomass for *P. mariana* for fertilized plots was 12.7 ± 0.9 g C m^{-2} yr^{-1} and 4.9 ± 0.9 g C m^{-2} yr^{-1} for non-fertilized plots. The total average biomass for *B. papyrifera* for fertilized plots was 236.4 ± 52.8 g C m^{-2} yr^{-1} and 7.1 ± 3.9 g C m^{-2} yr^{-1} for non-fertilized plots (Table 3.4).

Annual CO_2 emissions were 306.4 ± 56.7 g C m^{-2} yr^{-1} and 236.5 ± 30 g C m^{-2} yr^{-1} for fertilized and non-fertilized plots, respectively. Annual field CH_4 emissions were (-0.7 ± 3.9) and 1.4 ± 3.5 g C m^{-2} yr^{-1} for fertilized and unfertilized plots respectively. In addition, the annual CH_4 emission from ditches was 0.94 ± 6.5 g C m^{-2}. Combining soil C losses with biomass accumulation, the total net carbon balance for the *P. mariana* plantation alone was -294.4 ± 59.6 g C m^{-2} yr^{-1} and -230.2 ± 25.6 g C m^{-2} yr^{-1} for fertilized and unfertilized plots, respectively where negative values indicate loss of carbon to the atmosphere. Considering the biomass of the *B. papyrifera* colonization, the total net C balance for fertilized plots was -58 ± 6.8 g C m^{-2} yr^{-1} and for non-fertilized plots was -230.2 ± 25.6 g C m^{-2} yr^{-1}.

This cutover peatland remains a source of C as the growing *P. mariana* and *B. papyrifera* are unable to capture the entire C released through oxidation of the residual peat. Nonetheless, the fertilized plots were most effective in supporting biomass production through growth of the *P. mariana* plantation and associated birch invasion, and therefore offer the largest reduction in net C emissions. To increase the C fixation in the area, understory vegetation could be introduced and may also help meet the aim to improve the overall ecosystem services provided on site. Previous studies (e.g. Rochefort, 2000; Poulin et al., 2012, Graf et al., 2009, Strack et al., 2014) demonstrated the effectiveness of “moss layer transfer” techniques on cutover peatland in terms of ecosystems services - e.g. biodiversity, C accumulation, and peat accumulation. Understory vegetation at the study site will increase the C fixation though photosynthesis, the species richness in the area will increase biodiversity and biochemical cycling, which will provide soil structure and habitat for invertebrates and amphibians (Mazerolle et al., 2006).

This study is a contribution to science literature by providing information to improve restoration techniques on cutover peatlands in Canada and to optimize the resources to rehabilitate peatland C accumulation function and habitat, and ecosystem resilience in the longer term.

4.2. Implications for practice

The contribution of the study to improving peatland management in Alberta and Canada are evaluated in this section. The success of restoration is affected by many factors, especially by the state of degradation and type of peatland (Schumann and Joosten, 2008). Restoration goals and the preferred habitat structure must be clearly defined for cutover peatland restoration in order to determine the most effective restoration plan to recover the main ecosystem functions and services.

Fertilization is needed for tree establishment and growth on cutover peat. The dose of fertilizer could determine the density of *B. papyrifera* colonization, although the fertilizer effect is also related to the water level, inundation and peat depth. Results from this study are specific to the historic conditions encountered at the Paxson bog study site. Recommendations from Paxson bog could be compared with other research about fertilizer dose in eastern Canada and may be more useful in defining the appropriate dose to apply in similar conditions in western Canada and elsewhere. With this in mind, results from the present study suggest that 9 g/bag (32.4 kg/ha) of 20-10-15 ($N-P_2O_5-K_2O$) is sufficient. This is similar to the 10 g/bag of 20-10-15 ($N-P_2O_5-K_2O$) related to the forest plantation guide (Hugron et al., 2011) recommendations.

Restoring water table around 40 cm depth below the surface is essential, because the initial water supply after plantation could determine plant survival (Hugron et al., 2011). *P. mariana* growth was positively correlated to soil moisture (Appendix, Table A2.2) and following the Peatland Restoration Guide Second Edition (Quinty and Rochefort, 2003), the best choice at Paxson was filling ditches close to the restored area by pushing and compacting peat collected on nearby surfaces using different equipment such as a leveller and a front end loader. All ditches were blocked 20 m north from the edge of the plot with 5 m wide dams. However, the site remained very dry, likely because only a small area was restored and the remaining ditch network still largely controlled hydrology. These dry conditions helped *B. papyrifera* trees thrive and enhanced soil C losses. Therefore, it is important to plan restoration activities within the context of other activities going on at the site.

Peat depth and Θ had a negative impact on *B. papyrifera* volume (Appendix, Table A2.2.). Hugron et al. (2011) suggest that peat depth greater than 40 cm had lower density of *B.*

papyrifera colonization. Rewetting the site is one of the key factor to restore hydrological conditions. Thus, to restore early and effectively rewet while using a low dose of fertilizer may be optimal management activities for a forest plantation on a cutover peatland and help prevent *B. papyrifera* establishment.

Forest expansion has been associated with habitat loss for *Sphagnum* and other moss species (Pellerin and Lavoie, 2000). Since there is no understory in the restored area, vegetation cover should be introduced to restore the natural composition and structure of the understory and prevent soil erosion and frost heaving (Rochefort, 2003). Introducing plant diaspores and covering these with straw mulch before the *P. mariana* plantation, when machinery could be used, should facilitate the vegetation establishment (Graf et al., 2009). Following "moss layer transfer" technique, all types of peatland plant propagules (rhizomes, roots, seeds) and moss fragments should be transferred, to increase the future resilience in the ecosystem (Rochefort, 2000; Poulin et al., 2012).

4.3. Future Research in Forest Plantation on Cutover Peat

Direct measurement of *B. papyrifera* and *P. mariana* transpiration and soil water tension would help to better understand the role of *B. papyrifera* on the site's hydrology and *P. mariana* water use. In addition, more research is needed to study the spatial variability of nutrient availability and water flow in each experimental units post plantation and their influence on tree growth and C balance.

During the first year after fertilization, N_2O fluxes should be considered to estimate GHG emission for the forest plantation as they could result from N addition to the soil (Ojanen et al., 2010). If the water table conditions change and more water is lost as discharge, dissolved organic carbon measurement should be taken in account to estimate the C balance in the site.

The current study provided an average value over the first seven years for how a tree plantation improves C fixation though biomass. However, C flux measurements from first year post-restoration, along with changes in the plant community over time should be completed. More research is also needed on the impact of establishing a full plant carpet dominated by peatland species including *Sphagnum* and shade tolerant mosses and stabilizing the water table closer to the surface (e.g. Quinty and Rochefort, 2003) on the C balance of the plantation.

Finally, previous studies estimate that between 15 to 30 years or longer is needed to restore a peatland's ecosystem services (Kusler and Kentula, 1990; Samaritani et al., 2009; Lucchese et al., 2010). Therefore, long-term evaluation is important following wetland restoration (Kusler and Kentula, 1990; Lucchese et al., 2010), suggesting that one to two years (in the case of birch removal) or seven years (for the plantation growth) is too short for monitoring, and between 10 to 20 years of monitoring is desirable.

4.4. References

Cooper, D. J., MacDonald, L. E., 2000. Restoring the vegetation of mined peatlands in the southern Rocky Mountains of Colorado, USA. *Restoration Ecology.* 8, 103-111.

Gorham, E., Rochefort, L., 2003. Peatland restoration: A brief assessment with special reference to Sphagnum bogs. Wetlands Ecology and Management 11, 109-119.

Graf, M.D., Rochefort, L., Poulin, M., 2008. Spontaneous revegetation of cutaway peatlands of North America. Wetlands 28, 28-39.

Graf, M.D., Rochefort, L., 2009. Examining the peat-accumulating potential of fen vegetation in the context of fen restoration of harvested peatlands. Ecoscience 16(2), 158-166.

Hugron, S., Bussières, J., Rochefort, L., 2011. Plantation d'essences forestières dans le contexte de la restauration écologique des tourbières : un guide pratique, Groupe de recherche en écologie des tourbières, Université Laval, Québec, p. 88.

Hytönen, J., Kaunisto, S., 1999. Effect of fertilization on the biomass production of coppiced mixed birch and willow stands on a cut-away peatland. Biomass and Bioenergy 17. 455-469.

Lucchese, M., Waddington, J.M., Poulin, M., Pouliot, R., Rochefort L., Strack, M., 2010. Organic matter accumulation in a restored peatland: Evaluating restoration success. Ecol. Eng. 36, 482-488.

Mazerolle, M., Poulin, M., Lavoie, C., Rochefort, L., Desrochers, A., Drolet, B., 2006. Animal and vegetation patterns in natural and man-made bog pools: implications for restoration. Freshwater Biology 51, 333–350.

Ojanen, P., Minkkinen, K., Alm, J., Penttilä, T., 2010. Soil–atmosphere CO_2, CH_4 and N_2O fluxes in boreal forestry-drained peatlands. Forest Ecology and Management 260 (2010) 411–421

Paxson Restoration Report, Premier Tech, 2012.

Pellerin, S., Lavoie, C., 2000. Peatland fragments of southern Quebec: recent evolution of their vegetation structure. Can. J. Bot. 78, 255-265.

Poulin, M., Andersen, R., Rochefort, L., 2012. A new approach for tracking vegetation change after restoration: A case study with Peatlands. Society for Ecological Restoration. doi: 10.1111/j.1526-100X.2012.00889.x.

Pikk, J., Valk, U., 1996. Results of afforestation experiments of cut-over peatlands in Estonia. In: Lüttig, W. (ed.) Proceedings of the 10th International Peat Congress, Volume 2, International Peat Society, Stuttgart, Germany, 219−224.

Quinty, F., Rochefort, L., 2003. Peatland restoration guide, 2nd ed. Canadian Sphagnum Peat Moss Association at New Brunswick Department of Natural Resources and Energy. Québec, Québec, p.106. http://www.gret-perg.ulaval.ca/habitats-gret.html.

Rochefort, L., 2000. Sphagnum A Keystone Genus in Habitat Restoration. The Bryologist 103, 503-508.

Rochefort, L., Quinty, F., Campeau, S., Johnson, K, Malterer, T., 2003. North American approach to the restoration of Sphagnum dominated peatlands. Wetlands Ecology and Management 11, 3–20.

Schumann, M., Joosten, H., 2008. Global Peatland Restoration Manual. Available at: http://www.imcg.net/docum/prm/gprm_01.pdf (Last accessed on September 2013)

PHOTOGRAPHIC APPENDIX

Figure A.1. Photos of the study site. Upper left shows the forest plantation in May 2013, upper right unrestored area in June 2014. The bottom provides a contrasting image of a nearby undisturbed bog.

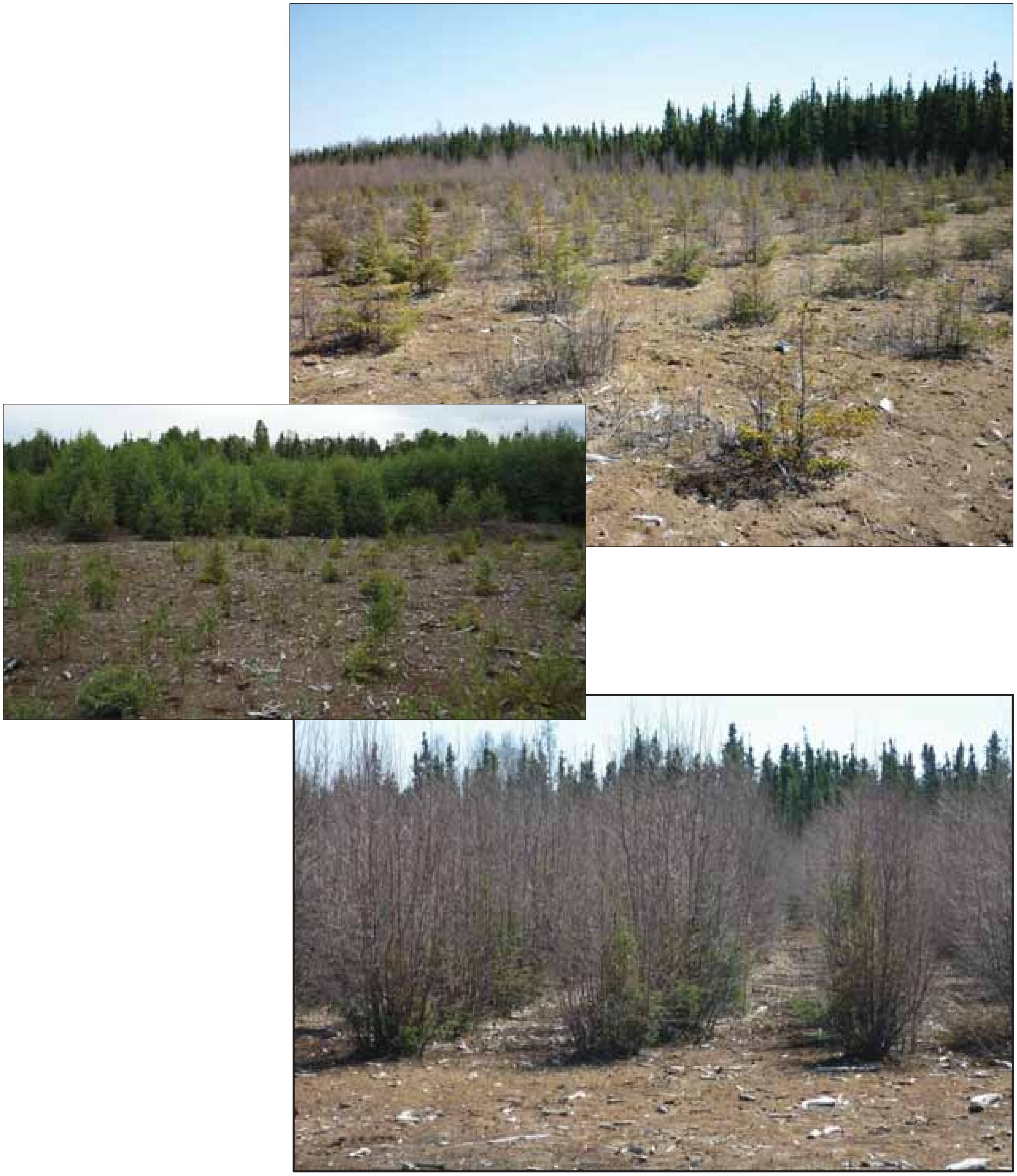


Figure A.2. Pictures of different doses of fertilizer at the experimental site in Paxson (October 2013). Top picture show plot R4T2 (Medium dose of fertilizer). The middle picture show two plots, in the front plot R2T4 (Control) and at the back of the picture R4T3 (Low dose of fertilizer). On the bottom is plot R3T1 (High dose of fertilizer).

Figure A.3. Picture of the ditches at the site. First on the left is blocked ditch in August 2012. In the middle, year after blocked the ditches, ditch full of water in May 2013. On the right the picture is a blocked ditch and density of *B. papyrifera* colonization in the ditches, edge effect, in September 2013.

Figure A.4. Pictures of *B. papyrifera* colonization around the planted *P. mariana*. The fertilizer doses were buried beneath the seedling and it promoted the *B. papyrifera* seeds to colonize the same spot.

Figure A.5. Picture of *P. mariana* plantation at the beginning of the growing season (May 2013) after birch removal.

Figure A.6. Annual elongation of leader stem of *P. mariana* (cm) after first growing season of birch removal. It was recorded by measuring the distance between successive terminal buds scars (internode) downwards from the sampling year (2013) until secondary growth of stems (thick bark).

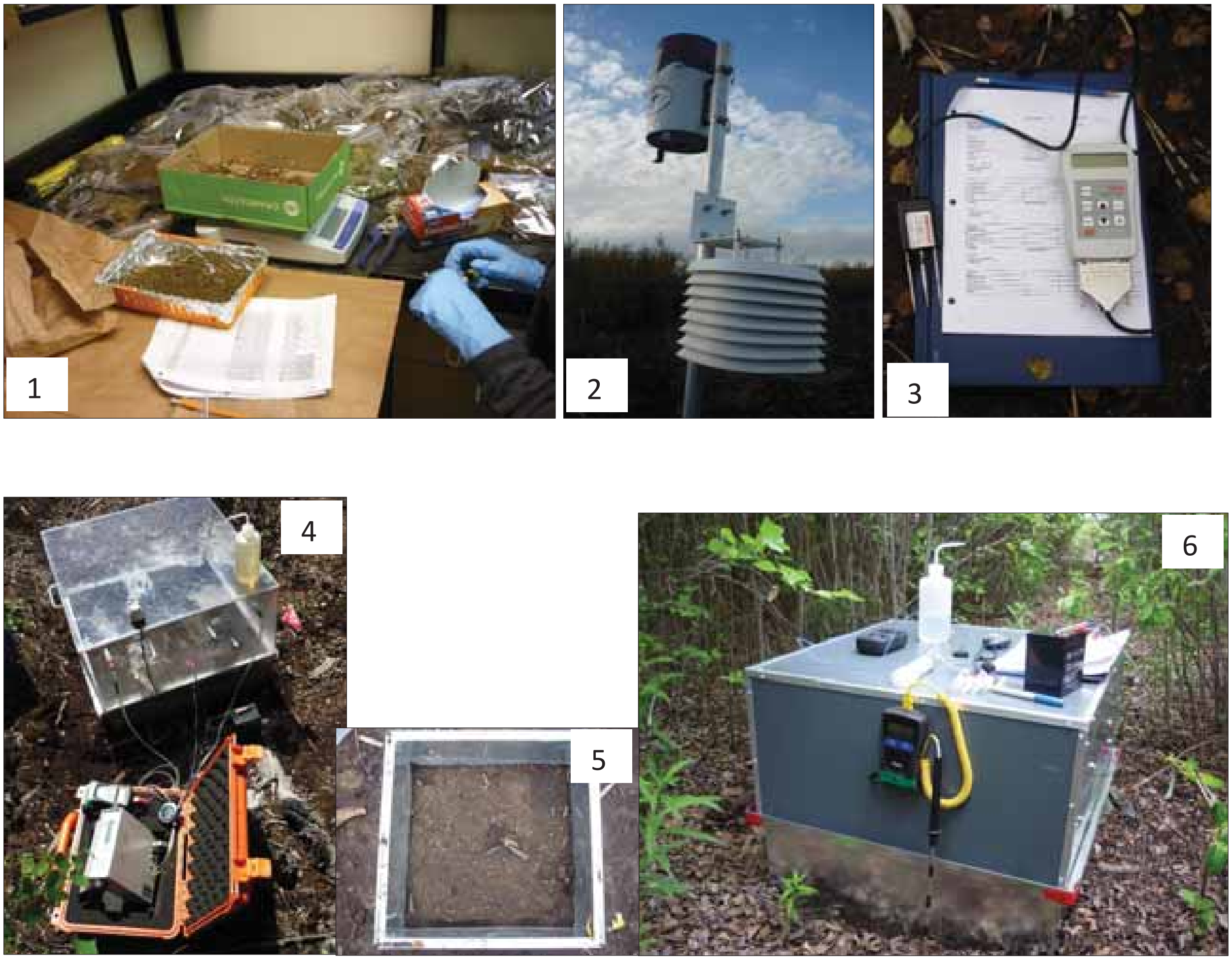


Figure A.7. Picture of the process to estimate C balance. From top left to bottom right. **1)** Dry biomass samples for *P.mariana* and *B. papyrifera*. Separate and weight by compartiments (stem, branches, leave). Material to mesure soil C losses from the bare peat at the forest plantation. **2)** Meteorological stations record temperature and precipitation (HOBOware sensors) every 30 minutes. **3)** Portable WET-Sensor™ **4)** Portable infrared gas analyzer (IRGA: PP systems EGM 4) and transparent plastic chamber (60cm x 60 cm x 30 cm), equipped with a battery-powered fan to mix the headspace and covered with an opaque tarp was placed on the collar. **5)** Collar (60 cm x 60 cm) was installed into the bare peat. **6)** 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 collars on the bare peat, with water in the groove to create an air tight seal. Thermocouple thermometer to record peat profile at different depths (2, 5, 10, 15, 20 cm).