Revegetation of Fen Peatlands Following Oil and Gas Extraction in Northern Alberta

by

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ABSTRACT

A field experiment from 2012 to 2013 at two locations in northeastern Alberta examined the short-term success of different fen revegetation strategies following the removal of infrastructure (road and well-pad) associated with oil extraction. Although all treatments resulted in limited overall success in achieving revegetation relative to the adjacent intact fens, transplanting with sedge and cotton grass was more effective than that of other treatments. While composted (dead) peat had little to no effect on revegetation, live peat modified the plant community slightly, as did a rough surface treatment. Transplants of woody species were more successful at the top and middle micro-topographic positions on the well-pad, and generally enhanced species richness and diversity. Water availability was important in regulating species recovery at all locations. After two years all treatments remain highly dissimilar to that of the adjacent undisturbed fens.

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Chapter 1. INTRODUCTION

Fen revegetation is widely recognized as a key component of the management of disturbed peatlands. However, to achieve revegetation new methods are required for reclaiming affected areas. Oil and gas industry development can alter or destroy natural surface cover, including peatlands, which cover up to 65% of the landscape in the relatively dry Western Boreal Plains in Northern Alberta (Price et al. 2010). The ability to revegetate fen peatlands in the post-mine landscape is a topic of significant research and practical investigation in Northern Alberta (Robert et al. 1999; Riggsbee et al. 2011). Optimum approaches for fen revegetation have been modeled (Cooper and MacDonald 2000). However, little data exist on the role of different management practices and methods in regulating subsequent conditions within peatlands that might facilitate ecosystem restoration after infrastructure removal (Doyle et al. 2008). The fundamental problem is to design a revegetation strategy that can support the fen ecosystem required to sustain the hydrological and ecological processes and functions of a fen peatland (Price et al. 2010).

Recent surveys of peatlands in northeastern Alberta have revealed that most peatlands, including fens, initiated since the last glaciation were the product of paludification, or swamping of upland soils (Vitt et al. 2010). Bauer et al. (2003) noted that long-term rates of peat accumulation with plant community change are highest in fens of Alberta. As proposed by Kulczynski (1949), it appears that fen communities can successfully track gradual increases in local water tables. Although the importance of paludification is recognized as a significant natural process, this knowledge has not been transferred to peatland revegetation strategies (Vitt et al. 2010). The current study attempted to enhance the paludification process. Terrestrialization (or infilling of water bodies) was rarely, if ever, involved in the initiation of peatlands across the mid-boreal region of Canada (Kuhry et al. 1993).

Construction techniques and removal of fill material during the reclamation of well pads and roads is problematic. Considerations include whether to remove all the fill or to just lower the fill elevation to a depth near the water table, whether geotextile liners should be removed, how fill material chemistry might affect fen water chemistry, depth of underlying peat, whether natural recovery is possible, and whether and which amendments are necessary for reclaiming well pads and roads (Osko 2010). Understanding how survival of transplanted species depends on soil hydrology, chemistry and the surrounding plant community, are all important in the development of planned wetland management strategies. Water, soil and planting techniques might be particularly important to determine the best strategy to maintain fen vegetation and prevent fen deterioration (Jonson and Valppu 2003). Therefore, it is essential that fundamental research be done to quantify the effects of different revegetation treatments, including transplanting native plant species from adjacent fens, adding a peat amendment, and the role of variation in micro-topography in determining revegetation success. Also important is an understanding of the hydrologic and soil conditions that support a desirable plant community. Manipulation of transplanted vegetation and understanding its response to peat addition, micro-topographical and hydrological changes, and natural recovery provide a key means of managing for the long-term sustainability of revegetated fens.

This study is concerned with the restoration of a fen ecosystem on two sites: one on a peat-mineral fen substrate following removal of a well pad in the Cold Lake region of Alberta; and a second on an access road within a fen in Northern Alberta near Fort McMurray. Both are poor treed fens within the boreal region where abundant energy extraction is occurring. The main challenge in this process is to identify a revegetation strategy that can support the key ecological and hydrological processes necessary to support a plant community consistent with management objectives (Kremer et al. 1998).

1.1 Purpose and Objectives

The management of fen revegetation following the removal of infrastructure associated with oil and gas extraction depends heavily on a reliable understanding of what revegetation technique should be applied and how this process can efficiently restore peatlands. In the case of fen revegetation in Northern Alberta, limited information is available regarding what species of transplants and natural vegetation combinations, together with soil, ground water, and amendment applications, can help to restore fens.

This thesis reports on an original study involving a partnership between the University of Alberta, Circle T Consulting Inc., Canadian Natural Resources Ltd, Cenovus Energy, ConocoPhillips Canada Resources Ltd., Devon Canada Corp., Husky Energy, Imperial Oil Resources Ltd., Japan Canada Oil Sands Ltd., Meg Energy Corp., Nexen Energy ULC, Statoil Canada Ltd., Suncor Energy, and Alberta-Pacific Forest Industries Inc. It attempts to address questions relating best practices for fen revegetation and potential mechanisms for their application. This thesis was created with the intent of increasing scientific knowledge of the specific response of transplanted species and natural plant communities to the different treatments and environmental conditions on disturbed fens. This knowledge should assist land managers to understand the plant, soil, and ground water relationships significant to revegetation success. This information will help land management staff develop more sustainable land management practices applicable across different companies. Finally, this thesis will identify some gaps relating to revegetation strategies and indicate future research direction.

The specific objectives of this research are as follows:

(1) Evaluate the success of transplants (survival and/or growth) installed under different treatments;

(2) Quantify natural vegetation recovery in areas exposed to different application of treatments, and

(3) Characterize the composition of propagules present in live and stockpiled peat.

1.2 Thesis Overview

In Chapter 3, I examine responses of transplanted native plant species and natural vegetation recovery in response to variable surface roughness, topographical position and peat inoculation treatments on a peat-mineral substrate established after removal of clay fill from an oil well pad constructed within a treed fen. Vegetation responses to additional environmental conditions (water level, water and soil temperature, nutrient and hydrocarbon content) were also studied. In Chapter 4, I assess responses of transplanted native plant species and natural vegetation performance on a mineral substrate established by partial removal of fill material from a road constructed within a fen. I again studied water level, water and soil temperature, nutrient and hydrocarbon content to interpret vegetation responses. In Chapter 5, I provide a synthesis of results from both studies, identify implications for the revegetation of disturbed areas, and highlight additional research needs.

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Chapter 2. UNDERSTANDING PEATLAND REVEGETATION IN THE OIL SANDS REGION OF NORTHERN ALBERTA: A LITERATURE REVIEW

2.1 Canada's Boreal Ecosystem

Canada's boreal region is one of the largest ecosystems on the planet. The boreal forest stretches from the Yukon and northeastern British Columbia across the northern Prairie Provinces and much of Quebec and Ontario, through Labrador and Newfoundland. The boreal forms a north-south band more than 1000 kilometers wide (Locky and Bayley 2006).

Peatlands are an important element of the global carbon cycle that store about one-third of the world's total carbon (Gorham 1991). Conventional oil, gas and oil sands development has impacted Northern Alberta's peatlands through the construction of roads, pipelines and well pads. This infrastructure could seriously violate the integrity of ecosystems (Rooney et al. 2012). However, the footprint of these disturbances could be greatly reduced by appropriate management practices and revegetation of affected sites after infrastructure removal (Cooper and MacDonald 2000).

This chapter reviews the impact from major disturbances on peatlands, including their response to energy sector disturbances and identifies the best management practices for revegetation in boreal fen areas. First, information pertaining to natural peatlands will be reviewed in order to better understand the development of these ecosystems, as well as identify the environmental and biological conditions that support them. Next, the effectiveness of different revegetation strategies will be addressed, including transplanting species, top-dressing with surface amendment and topographical positions. Finally, monitoring and success of current revegetation approaches and techniques for restoring peatlands will be considered.

2.2 Peatlands

Peatlands occupy a large part of the boreal landscape and are valued for a variety of ecosystem services, including water storage, stream flow regulation, and water quality (Hanson et. al. 2008). Peatlands cover 103,200 km^2 of Alberta (16.3% of the land base) and are most widespread in the north of the province (Vitt et al. 1996). Peatlands account for 25 to 50% of the landscape in Alberta's Boreal Plain Ecosystem. Peat consists of dead organic material that has been accumulating due to greater rates of accumulation than decomposition, and which has not been translocated after its formation. A peatland may or may not have surface vegetation, but always has a naturally accumulated peat layer at the land surface (Rydin at al. 2006). In Canada minerotrophic fens account for approximately one-third of the peatland area (Tarnocai and Stolbovoy 2006). Fens cover a wide

for approximately one-third of the peatland area (Tarnocai and Stolbovoy 2006). Fens cover a wide
minerotrophic spectrum from rich (pH values greater than 6.5), where mineral and groundwater input from neighboring uplands and peat substratum is high, to poor (pH values between 4.5 and 5.5), where mineral and groundwater inputs contributing circum-neutral water are low (Webster et al. 2013).

A key aspect of peatlands is that plants, water, and the organic matter in the peat substrate are tightly connected and interdependent. Plants define what type of peat will be formed and its hydraulic properties. Hydrology defines whether and what type of plants will grow, as well as peat properties, including its decomposition (Vitt et al. 1996). Peat structure and relief further refine how water will move and fluctuate through the substrate over time.

2.2.1 Types and Functions of Peatlands

Peatlands are usually classified as bogs when situated higher up in the landscape within recharge areas (high mires) where water moves away, while fens are situated in landscape depressions where water accumulates (low mires). Contemporary peatland classifications indicate ombrogenous mires are fed only by precipitation such as rain or snow, and geogenous mires are fed by water from mineral soils or bedrocks (Schumann and Joosten 2008). Bogs and fens switch to mire due to the peat accumulation.

Different ecological mire types result from receipt of different qualities of water, including acidity, nutrient availability, and characteristic plant species. Ultimately, chemical buffering defines pH trajectories and results in the following accepted method of classification (Schumann and Joosten 2008), which is based on hydrogenetic typology. Hydrogenetic typology distinguishes two groups of mires: horizontal mires when water levels form a horizontal plane in a closed basin, and sloping mires when water levels form an inclining plane indicative of slow water movement (Macrae et al. 2013).

Finally, wetland classification also recognizes water rise mires, flood mires, percolation mires, surface flow mires and acrotelm mires. Water rise mires develop when the water level in the catchment rises so slowly that a previously dry depression becomes wet, but no open water is evident. Flood mires are periodically flooded by rivers, lakes or seas (Schumann and Joosten 2008). Percolation mires occur where the water supply is large and evenly spread out during the year.

Surface flow mires are detected where an ample water supply regularly occurs, but is exceeded by water losses during short periods (i.e. peak summer evaporation).

Peatland functions in boreal ecosystems have developed over millennia. Progressive accumulation of peat resulted in a dynamic system in which the hydrological, ecological, and carbon storage functions are intimately interwoven. When peatland systems develop with hydrology and ecology leading to peat accumulation, these systems are in tune with the fluxes and stores of water, matter and energy (Price et al. 2010).

2.2.2 Hydrology of Peatlands

Peatlands depend on a constant long-term water supply. The origin of water supply influences the type of vegetation and nutrient availability. Geogenous waters are minerotrophic, meaning they contain dissolved cations and anions extracted from mineral soils. Minerotrophic waters supply nutrients favorable for plant growth and lead to 'fen' development (Hilden 2005). Geogenous waters are divided into three types depending on water flow and source (Wieder and Vitt 2006):

1. Stagnant water – soil water and stagnant bodies of water (topogenous),
2. Flowing – groundwater including seepages and springs (soligenous);
3. Flood water – from water courses that result in lateral flow away from the direction of stream flow (limnogenous).

Peatlands also receive water from precipitation. Surface water can be lost quickly through runoff or evaporation. However, the deeper the drying zone, the slower water is lost through capillary action and evaporation. Even in dry or burned surface peat layers there is a damp layer just beneath. As free water is lost, what remains is bound or held water that is very hard to remove by plants or by regular solar energy in a shaded environment (Quinty and Rochefort 2003).

Peatland complexes occur across the boreal and ultimately vary in hydrology with climate, specifically gradients of precipitation and temperature. Climate varies in the boreal from comparatively cool and moist in the south to cold and dry in the north. In cool and moist climates, soligenous blanket fens and ombrogenous plateau bogs dominate (Wieder and Vitt 2006). As the climate becomes dryer and more continental, trees and shrubs become more common and patterned bogs decrease due to a reduction in water availability at the peatland surface (Gong et al. 2012).

2.2.3 Water Quality of Peatlands

The chemistry of peatland water and amount of water entering a peatland affect its properties. Concentrations of nitrogen and phosphorus in peatland waters are low (Vitt et al. 1995). Greater water flows in fens may cause greater nutrient inputs. Fens become oligotrophic when incoming water flows through nutrient-poor substrates. Fens in these conditions usually have similar vegetation to that found in bogs. Fens that receive more nutrient rich inputs and higher flow rates cause mesotrophic conditions and are called rich fens (Vitt and Chee 1990). Peat formation, and associated bog and fen differentiation, take place along the mineral gradient, with pH varying from 3 to 9, and base cation concentration from nearly zero to 1,000 mg/L, respectively (Hajek et al. 2006).

Alkalinity is a function of pH since as hydrogen ions decrease, base cations increase. The complete absence of bicarbonate alkalinity below pH 5.5 is a main threshold setting habitat limits of many peatland species (Wieder and Vitt 2006). Fens that have little alkalinity and a pH below 5.5 are dominated by oligotrophic species of *Sphagnum*. Fens with pH above 5.5 and the presence of alkalinity have little *Sphagnum*, but mosses still dominate the ground layer (Wieder and Vitt 2006).

Surface water in fens is consistently linked to groundwater. The surrounding bedrock and groundwater determines the chemistry of fen water flow. In western Canada, proximity to carbonate-rich sedimentary bedrock ensures inputs rich in calcium, magnesium, and carbonates. Thus brown-moss dominated fens occupy carbonate-rich areas, but poor fens are dominant in areas with acidic substrates (Wieder and Vitt 2006).

2.2.4 Vegetation

Vegetation types differ among peatlands and depend on chemical and hydrological gradients. In general, rich fens lack a significant cover of *Sphagnum* and are dominated by other mosses (Bauer et al. 2003). Communities of *Poaceae* (grasses) and *Cyperaceae* (sedges) are common in fens. Vascular plant production increases with nutrient availability and cation concentrations along the fen gradient. Fen species include: black spruce (*Picea mariana*), Labrador tea (*Ledum groenlandicum*), marsh reed grass (*Calamagrostis canadensis*), spotted water hemlock (*Cicuta maculata*), fireweed (*Epilobium angustifolium*), American willowherb (*Epilobium ciliatum*), common horsetail (*Equisetum arvense*), wild strawberry (*Fragaria virginiana*), reed canarygrass (*Phalaris arundinacea*), common rivergrass (*Scolochloa festucacaea*), bulrushes (*Scirpus spp.*), sea arrowgrass (*Triglochin maritima*), Kentucky bluegrass (*Poa pratensis*), cattail (*Typha latifolia*), white clover (*Trifolium repens*), Canada goldenrod (*Solidago canadensis*) and slough grass (*Beckmannia syzigachne*). Differentiation between vegetation found in fens may depend on the underlying substrate and hydrology (Rezanezhad et al. 2012). The combination of hydrology, climate, chemistry, substrate and vegetation ultimately defines peatland type. Environmental gradients also affect types of vegetation and the diversity of fauna (Trites and Bayley 2009).

2.3 Oil Sands in Alberta

The oil sands in Alberta are the third largest oil resource in the world. The three main regions, Athabasca, Peace River and Cold Lake – occupy a surface area of roughly 142,200 km^2. It is estimated that with present technology, roughly 170 billion barrels of oil are extractable (RSC 2010). Of this oil reserve, 80% is found at a depth greater than 75 m under the earth's surface. In such cases the oil is extracted by *in-situ* methods. Only 20% is recoverable by traditional open-pit mining (Isaacs 2005).

2.3.1 Effect of Oil Sand Infrastructure and Removal on the Environment

Oil and gas exploration, production and processing represent major disturbances to peatland ecosystems (Schneider and Dyer 2006). During traditional oil/gas exploration and production in peatland regions, roads must be built to construct and access production pads on which oil/gas (or steam injection) wells are developed. In Canada, these roads and pads are constructed by the placement of clay and/or gravel fill directly onto the peatland surface. Peatlands are characterized by thick deposits (up to several meters) of water-saturated peat, with very gently sloping water tables positioned at or near the peat surface. When roads transect peatlands and have minimal installation of culverts, as is typically the case in Alberta, upslope flooding and downslope water table drawdown can extend to considerable distances away from the road (Vitt et al. 2011).

Natural resources development, including exploration and transportation activities, alters the local land surface of well pads and roads (Zhang et al. 2014). Hydrological regime, fen soil and water chemistry, and consequently vegetation, are often altered at various spatial scales. Fen revegetation might help measure a plant community's tolerance to environmental stress (Matthew et al. 2013).

2.3.2 Chemical Composition and Toxicity of Organic Compounds

BTEX (benzene, toluene, ethylbenzene, xylene) are volatile, mono-aromatic, organic compounds found in petroleum and oil sands. BTEX compounds are usually released as a mixture and not as a single compound, thereby increasing its toxicity (Hagen 2013). Petroleum hydrocarbons released to the soil may move into the groundwater. Due to their relatively higher water solubility, BTEX compounds always migrate from soil to groundwater systems and contaminate it (Pawlak et al. 2007). Some of these compounds will evaporate into the air and others will dissolve into groundwater and move away from the release area. Some compounds will attach to soil particles and may remain in the groundwater (Junfeng et al. 2007).

2.4 Disturbance of Peatlands

Peatlands have strong relationships between plants, water and organic substrate composition; when one component is affected, ultimately all components change (Lavoie et al. 2009). However, these components do not react in a consistent way. Generally, plant species are more easily affected by harvest and other disturbance than changes to hydrology (e.g. by ditching and pumping). Although peatlands are quite stable typically, once they begin to undergo vegetation change, it is difficult to stop these transformations and preserve current conditions.

Disturbance involves a sudden change, to which the system attempts to adapt. If disturbance is accute, the original state may never again be achieved, and a different equilibrium may develop. For example, soil profiles and spatial patterning, cannot be recreated due to the chemical transformations of available nutrients (Price et al. 2010). Undisturbed and revegetated sites tend to act as nutrient sinks until an equilibrium is established because of the availability of sorption sites in the soil. As the soil sorption sites become saturated, biochemical and biological processes continue to remove nutrients from the water column. Moreover, peatlands may have little to no vegetation growth 40 years after disturbance (Graf and Rochefort 2009). During the disturbance fens may have been filled with consolidated tailings, fine clay particles left from bitumen extraction, or from the addition of gypsum intended to remove water. Soil stored from when the fen was excavated and sand that used to be sticky with bitumen is placed over the clay (Graf and Rochefort 2009). Finally, the effect of this industrial activity can alter fen systems that are difficult to restore.

Consequently, it is necessary to manage fen hydrology and ecology after disturbances (Price et al. 2010). A good understanding of vegetation and hydrology in undisturbed and disturbed peatlands can help to make a best choice for reclamation, restoration, and management of peatlands disturbed by oil and gas development in Alberta.

2.5 Restoration of Boreal Peatlands

Degraded systems can be recovered by such activities as reclamation, restoration and revegetation (Price et al. 2010). They can also recover passively through self-regeneration (Bhatti and Vitt 2012). Restoration is the act of restoring converted land to a former condition. Ecological restoration is the process of rescuing an ecosystem from an undesirable state, including reassembling composition, structure and function of a community after disturbance. Reclamation is the process of converting disturbed or damaged land to its former or other productive uses. Revegetation provides denuded land with vegetation cover, stabilizes and protects the soil, and is considered part of the reclamation or restoration process (Mason 2010).

Restoration is simplest when only the vegetation has been altered, but hydrology remains the same (Bauer et al. 2003). The next stage of restoration is more complex. This phase represents peatlands (especially percolation and acrotelm mires) where disturbance has changed soil hydraulic properties but peat accumulation has continued (Wieder and Vitt 2006). Restoration of the water regime in the original peatland is tedious and requires difficult and expensive approaches to remove any compact peat layers (Wind-Mulder et al. 1996). Severe peatland disturbance can lead to irreversible degradation by altering long-term drainage or decomposition. The hydrology of percolation and acrotelm mires changes with modification in the hydraulic properties of slightly humified peats (Devito et al. 2005). As peat development is slow, it takes tens to hundreds of years to re-establish new peat deposits with the original properties. The last stage of disturbance includes peatlands that have lost so much peat due to different disturbances such as mining, erosion or oxidation, that the peatland body has lost its hydrological balance. While some ecosystem functions can be improved, complete restoration of a self-regulating mire is impossible (Devito et al. 2005). Peatland restoration should begin with restoring the most difficult components, because they determine the weaker component conditions (Johnson and Miyanishi 2010).

2.5.1 Planning Restoration Operations

Restoration planning is a key factor for success because it allows integrating restoration into peatland management (Cobbaert et al. 2004). Successful vegetation establishment relies on a series of procedures, which if done incorrectly, can lead to restoration failure. For example, using too little straw may reduce the cost of restoration in the short term, but inadequate straw mulch may not provide enough protection to plant fragments, and in turn, can seriously compromise vegetation establishment. However, recent surveys of peatland in northeastern Alberta have revealed that straw might be added as an efficient amendment. Straw application improves soil structure, porosity, water holding capacity and bulk density; increases peatland infiltration and permeability; reduces water loss and leaching; and adds significant quantities of organic matter and produces a more natural soil pH. Introducing suitable species together with straw may be necessary to promote the development of a fen plant community (Wheeler and Shaw 1995).

Using peat amendment can have positive and harmful effects on the vegetation development during restoration. In some cases peat amendment can establish aggressive, fast growing plants that persist for a long time after invasion (Rewers et al. 2012). In contrast, peat amendment may help recolonization in severe environments. In the case of fen revegetation, the amendment of peat has been shown to increase the cover of sedge species, which facilitates the establishment of woody and herbaceous species by stabilizing the microclimate and substrate (Rewers et al. 2012).

Analysis of these elements, together with data for different vegetation transplanting and hydrological regimes, can indicate the main factors for success or failure during restoration. Timing of restoration is also important. Restoration should be done as soon as possible after the disturbance, and delays can cause additional operational treatments, costs, and decrease the likelihood of success (Schumann and Joosten 2008).

2.6 Natural Recovery

Natural recovery is the natural re-establishment of plants within disturbed wetlands. In other words, it is a progression along a successional pathway to reach a stable state. There are many benefits of natural recovery. Native propagules in the seed bank are better adapted to local conditions, whereas seeded species may be less suitable having been imported from other areas (Cooper 2004). Natural recovery allows the plant community to develop through succession in a way that might improve ecosystem functions. However, there are some disadvantages of this process. It is slow, often taking many decades to return to the pre-disturbance community. A return to pre-disturbance conditions might also not occur, because many factors can influence the trajectory of community development such as disturbance, anthropogenic interference, and invasion of undesirable species from adjacent areas. Based on this, active revegetation may be required as a preferred solution for land restoration.

2.7 Revegetation

Ecological peat functions depend on plant species composition and performance. In rare cases, wetland restoration can occur naturally without implementing methods of plant reintroduction (Bhatti and Vitt 2012). However, in most cases, species should be actively re-established to promptly restore ecosystem function.

Recent peatland surveys (Wheeler and Shaw 1995) showed that fen ecosystems require revegetation after peat mining. Moreover, some cases of successful revegetation of wetlands, including revegetation with *Sphagnum* cover, have been reported in the literature (Lavoie and Rochefort 1996, Soro et al. 1999). Some plants might colonize peat deposits and help stabilize the soil surface and facilitate establishment of other species (Grosvernier et al. 1995, Tuttila et al. 2000). Understanding the revegetation processes is key to reclamation success.

There are several techniques that can be used to aid vegetation establishment, including seeding, transplants, or the use of donor seed banks (or equivalent with vegetative propagules). Seeding of individual plants is one option for restoring many wetland species (Cronk and Fennessy 2001; Cooper and MacDonald 2000). Direct seeding involves sowing seed directly into prepared ground. Direct seeding generally is more efficient in terms of time, cost and labour. It also allows for a more diverse seed mix, leading to greater plant diversity. The main limitation with direct seeding is usually the availability of seed. Establishment of plants from direct seeding can be patchy and can take several years, especially for hard-seeded species. Planting mature plants circumvents germination and establishment (Mallik and Karim 2008). Planting can complement reseeding and increase the chances of revegetation success by leading to more rapid plant establishment. Sometimes planting is the only feasible method of establishing certain plants. Seeds of many shrubs, for instance, may germinate only occasionally, establish poorly, or grow slowly under natural or stressed conditions. Species transplanting can increase revegetation success by allowing plants to by-pass the sensitive life stages of seed germination, seedling emergence and early survival (Mallik and Karim 2008).

Another strategy to achieve revegetation is to draw on the natural seed bank (Shaughnessy 2010), which may require stimuli to break seed dormancy. Disturbances to the soil such as tillage, excavation, tree throw, and soil faunal activity can bring seeds to the surface exposing them to favorable conditions that promote germination, or conversely, prevent them from germinating due to unfavorable conditions (Shaughnessy 2010).

Alternatively, natural revegetation in wetlands might happen without seed bank assistance by vegetative propagules under certain conditions (Mackenzie 2004). Parts of plants able to provide asexual reproduction include rhizomes, stolons, stems, branches, bulbs, tubers, and root suckers (Luken 1990). Clonal propagation is an important means of achieving population increases (Wijesinghe and Wigham 1997).

2.7.1 Transplant Species Biology

Black spruce (*Picea mariana* (Miller) B.S.P.), cotton grass (*Eriophorum vaginatum* L.), Labrador tea (*Ledum groenlandicum*) and sedge (*Carex* spp.) are common plant species found in wetlands of northern Alberta, and thus are candidate species for fen revegetation. These species can survive in cold, nutrient-poor, or contaminated soils (Lahring 2004). Moreover, they are highly adaptable to a broad range of environmental conditions and are widely distributed in acidic and nutrient-poor sites (Kummerow and Krause 1982).

Black spruce is one of the most important species of the Canadian boreal forest and is indigenous to the United States and Canada. Black spruce occurs throughout the boreal forest and is associated with muskegs and sphagnum bogs. To the north, the proportion of black spruce increases because of a harsher climate (Fralish and Franklin 2002). Black spruce is recommended for re-vegetating disturbed sites in boreal regions (Black and Bliss 1980; Fedkenheuer et al. 1980). It is useful for revegetating seismic lines, borrow pits, abandoned roads, and well sites. In Western Canada, black spruce naturally invades well-drained raised surfaces in disturbed and abandoned peatlands. This species can be established on disturbed sites by direct seeding or by transplanting nursery-grown seedlings (Uchytil 1991). In northeastern Alberta, overwinter survival of container-grown and transplanted black spruce seedlings was satisfactory on amended oil sand tailings. Bare root transplants show good growth and survival when planted directly into organic layers of fen peatlands (Uchytil 1991). Black spruce transplant survival and growth are generally better following summer than spring out-planting (Uchytil 1991).

Cotton grass is dominant in many boreal landscapes. The thin, flat, 2-7 mm wide leaves of cotton grass are basal and grass-like (Gartner et al. 1986). Cotton grass produces abundant seeds (Chapin et al. 1979; Bogart et al. 2010) and might stabilize fen soils. The presence of cotton grass encourages additional revegetation because it improves habitat for the initiation and growth of other vascular plants and mosses. CO_2 emission rates are also larger with the presence of cotton grass (Mariener et al. 2004).

Labrador tea is an *Ericaceous* evergreen shrub of acidic, wet areas common to northern moist coniferous forests in northern and central Alberta (Glenn 2001). Communities of Labrador tea occupy areas with mesic to subhygric moisture, and submesotrophic to mesotrophic nutrient regimes. Labrador tea has stems up to 1.2 m height (Royer and Dickinson 1996). Labrador tea has potential for revegetating disturbed sites. These species can tolerate and resprout readily after different types of disturbance (Famous and Spencer 1989). It likely colonizes disturbed sites and is part of mid- successional communities within fens (Gucker 2006). Labrador tea may be an indicator of soil environmental contamination in the vicinity of oil and gas mines (Pugh et al. 2002).

Wetland sedges (*Carex spp.*) are widely distributed in northern Alberta, and are one of the most common vegetation groups found in nutrient poor fens (List and Reisch 2012). Sedges are perennial herbs, generally with 3-sided stems. In general, sedges tend to be densely tufted perennial plants with long root-stock stolons (Hallworth and Chinnappa 1997). Sedges (*Carex* spp.) are well-adapted to such processes as flood attenuation, water storage and purification, fen nutrient cycling, forage production. These species play a key role in maintaining fen integrity (Winward 1986). Sedges have extensive root systems that bind streambank soils (Manning et al. 1989; Kleinfelder et al. 1992).

2.7.2 Water Table Depth Influence on Plant Establishment

Water table depth is one of the factors controlling vegetation establishment in fens (Cooper and Foote 2003). Peatland ecologists have long known the importance of the paludification process, but it has not been moved to peatland revegetation methodologies. Vegetative composition and density of peatland are influenced by altering wetland water level. To maximize habitat availability, depth and timing of flooding should be manipulated according to the plant requirements (Fredrickson and Taylor 1982). Peatland plant communities develop in response to this environmental gradient based primarily on their individual abilities to tolerate flooding and anaerobic soils but also in response to biotic interactions with other species. Establishment of plant species along an environmental gradient can contribute to sharp plant zonation patterns where species separate out along an elevation gradient in response to differences in flooding and salinity

(Miao et al. 2013). Over the precise control of hydrology and manipulation of plant succession, ecologists can achieve successful revegetation.

2.7.3 Plant Competition

Competition from plants that are invaders of revegetation sites might influence the establishment of the revegetated and desired plant species (Toshihiko 1994). Natural succession in revegetated fens might cultivate monocultures of *Typha latifolia.* This can occur due to high seed dispersal rates of the latter species (Ekstam and Forseby. 1999). Such highly productive plants can also limit the establishment of other desired plant species. Revegetated fen sites are often vulnerable to plant invasions that can hinder revegetation success. Invasive plants typically reduce biodiversity and alter important ecosystem functions and services (Osland 2009).

In revegetated peatlands, establishment of peat forming vegetation must be the primary goal for revegetation. The rhizome network of fen species, together with an existing peat mat and the die-off of species belowground production, generates new peat. Moreover, water regime together with peat forming vegetation might discourage non-peatland invasives and support saturated soil conditions that allow other peatland plants to prosper (Cooper 2004).

Plants often respond both quickly and visibly to environmental stressors such as an alteration in hydrology, land use, high nutrient input, or invasive plants and competition. A fen's ability to support certain plant species can serve as an indicator of its capability to sustain specific functions and biological processes (Lopez and Fennessy 2002; Cronk and Fennessy2001; Fennessy et al. 2001).

2.7.4 Landscape and Microtopography

A variety of landscape structure designs have been suggested for wetland hydrologic management. Each type of structure has advantages and disadvantages based on the cost of installation, maintenance requirements, and desired water levels. Ideally, such structures should control water elevations, dewatering of the wetland as well as the raising of water levels to the maximum safely allowed by the design (Hammer 1997). Elevation, topography, drainage patterns and aspect influence plant growth and revegetation success (Grismer and Hogan 2004).

Roughness creates variation in microsite, which is likely to lead to some topographical conditions that favor plant establishment, either from seed, transplants, or plant propagules. Creating topographical diversity, combined with strategic plant placement, allows incorporation of woody, shrub and sedge plantings to applicable elevations, where plants are protected within microsites and can become better established (Moser et al. 2007). Diverse micro-topography is intended to reduce competition from invasive species, which thrive in flooded fields. In addition, adding roughness to peatland surfaces might increase the survival of transplanted and naturally colonizing species on peatland. Surface roughness maximizes hydrological (maximizing infiltration and minimizing runoff) and biological (develop and support of vegetation succession) functions in the soil. Micro-topography modifies overland flows, affects water storage in surface depressions, modifies the fraction of soil covered by water, and controls hydraulic resistance which controls the flow velocity (Rodriguez-Caballero et al. 2012).

2.7.5 Monitoring and Success

Monitoring is a crucial and required step for revegetation processes (Nassauer 2004) and should be conducted over an extended period. Monitoring of hydrologic parameters is also important, because it influences vegetation performance (Nassauer 2004). The main goal of monitoring is a precise estimation of revegetation success (Boyd and Davies 2012). Usually revegetation efforts may not be monitored until the second growing season due to the slow development of vegetation. However, some disturbed peatlands re-establish within one growing season. Monitoring may be conducted for 30-50 years to record establishment of a new plant community developing on a heavily disturbed peat community (Nassauer 2004). It helps to assess vegetation across the site. At the beginning, the vegetation cover, dominant vegetation and presence of non-peatland species are described at the site level. Next, permanent plots should be applied by specific sizes and established in areas representative of the entire site. Finally, percent cover of all species, peat, water table, and pH measures should be monitored until revegetation success is achieved.

2.8 Summary

The importance of restoration after disturbance for proper function of peatlands is well known and knowledge regarding appropriate restoration methods is increasing. However, few studies have addressed practices to facilitate revegetation of fens disturbed by oil and gas exploration in Northern Alberta. Hydrology, water quality, and soil chemistry can also be affected by such disturbances, such that a number of soil amendments and/or site preparation techniques might be applied to aid in revegetation success. Interactions among these practices and specific revegetation treatments require study to identify which combinations of treatments are likely to be successful under given site conditions. A better understanding of fen revegetation strategies, including transplanted species survival and natural community performance under different treatments and ecological variables will provide important information for developing prospective management strategies for reducing disturbance effects after reclamation of oil and gas industry disturbances.

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Chapter 3. SURFACE REVEGETATION ON A PEAT-MINERAL FEN SUBSTRATE FOLLOWING WELL PAD REMOVAL

3.1. Introduction

Northern peatlands are wetland ecosystems commonly found in Canadian boreal regions. In Canada's prairie provinces (Alberta, Saskatchewan, and Manitoba) peatlands cover 365,157 km^2 - approximately 20% of the land area (Vitt et al. 2001). Peatlands are important ecosystems due to their ability to provide biodiversity, sequester and store carbon, and regulate the water cycle. Peatlands supply important ecological functions through peat decomposition, vegetation succession and water movement and filtration, all of which can be impacted by disturbances, including infrastructure (e.g. roads, well pads) associated with oil and gas extraction. These functions are particularly vital for fens due to their tendency to be more productive and accumulate more carbon than bogs of the same age (Yu 2006).

Revegetation of natural fens following the removal of oil and gas infrastructure associated with previous energy extraction is an important topic for study in Northern Alberta. The objective of revegetation is to establish a self-sustaining plant community that is consistent with adjacent fen conditions (Carrera-Hernández et al. 2012), a process that ideally should take place at the landscape scale for areas such as the Cold Lake region of NE Alberta (Johnson and Miyanishi 2008). Disturbances associated with energy infrastructure often cause marked alteration to the ecosystem, including widespread physical disturbance of the original plant community, altered hydrology of both surface and groundwater, and pronounced changes to the physical and chemical properties of soils (Elshorbagy et al. 2005).

To develop appropriate revegetation strategies, an analysis of natural vegetation colonization, survival of any assisted plant revegetation treatments, and ongoing soil and water dynamics, is necessary, particularly where concerns arise due to the lack of satisfactory revegetation methods and guidelines (Hammersmark et al. 2010). As few revegetation strategies have been applied to fens undergoing revegetation following the removal of oil and gas infrastructure, the present study explores relationships between transplanted species survival, natural community recovery, and environmental conditions, with different treatments intended to facilitate revegetation. These strategies are required to develop specific recommendations for sustaining long-term wetland (fen) condition and function, including the development of best management practices for fen revegetation.

Select metrics have been developed over time to evaluate the structure and function of revegetated wetlands. These metrics include soil properties (Bishel-Machung et al. 1996; Stolt et al. 2000; Nair et al. 2001) and vegetation development (Edwards and Proffitt 2003; Leck 2003; Seabloom and van der Valk 2003). A recent study by Raab and Bayley (2013) recommended early intervention using planting of *C. aquatilis* (known to be tolerant of oil sands contaminants) on wet meadow habit following oil sands mining. The presence of *Carex*-dominated communities shows promise for future revegetation success. Similarly, Aronson and Galatowitsch (2008) showed that biotic barriers, mainly the difference in colonization efficiency between invasive and native plants, and abiotic barriers such as unfavorable hydrology, can prevent vegetation within restored wetlands from eventually resembling that of natural wetlands. Addressing both biotic and abiotic barriers to revegetation is necessary for planning, designing, and implementing treatments to revegetate fens. Mechanisms responsible for observed differences in revegetation efficacy (e.g. plant performance and survival, soil and water quality, groundwater level, pollutants) remain poorly understood.

Fen revegetation has become a priority issue for Northern Alberta given the abundance of oil and gas development. Achieving revegetation requires appropriate site preparation and strategies for plant reintroduction. Species transplanting is often hampered by invasive species, insufficient native species for planting, and a lack of information on the methods needed to establish certain key species (D'Antonio and Chambers 2006). The most limiting factor in revegetation efforts can be the cost and availability of obtaining planting material of native fen species (Booth and Jones 2001). Screening and identifying ecotypes of native wetland species for transplanting is required, much like what has been done elsewhere on uplands (e.g. Best and Bork 2003).

The question remains as to how can revegetation success of disturbed fens be improved? Information on beneficial practices would assist land managers with deciding which plant species and treatments to use in order to maximize fen revegetation, as well as understand the limitations associated with this process. Here I report on the results of a controlled field experiment conducted on a well pad undergoing revegetation. This study was intended to meet the following specific objectives:

(1) Evaluate the success of transplants (survival and/or growth) installed under contrasting live peat inoculation and micro-topographical conditions;

(2) Quantify natural vegetation recovery in areas exposed to different peat application and micro-topography treatments;
(3) Characterize the composition of propagules present in live peat.

3.2. Materials and Methods

3.2.1. Study Site

The study site is situated approximately 20 km north of La Corey in NE Alberta, just south of the Canadian Forces Base Primrose Air Weapons Range (54°24′18″ N; 110°16′46″ W). This area is in the Eastern Alberta Plains physiographic region, near the border between the Dry and Central Mixedwood Natural Subregions (Natural Regions 2006). Long-term average precipitation at the nearest weather station in Cold Lake, Alberta (85 km to the east), averages 427 mm annually, with 323.8 mm (80%) falling from April to September inclusive (Environment Canada website), and peaking in June and July with convectional storm activity. Mean long-term average temperature is 1.7°C, ranging seasonally from -16.6°C in January to +16.9°C in July (Environment Canada). This particular region has relatively warm summers and high growing degree-day accumulations relative to other Boreal regions.

Wet, poorly drained sites support a variety of bog and fen communities. The composition and structure of these communities depends on water levels and nutrient status. Treed and shrubby fens are most common, while sedge fens and bogs are minor components. Dominant plant species include black spruce, dwarf willow and bog birch, common Labrador tea, a variety of forbs, as well as feather mosses and peat mosses. Soils are either Gleysols, or more commonly Organics within peatlands. Organic soils underlying wetlands are usually Terric Mesisols, while Fibric Mesisols are associated with poor fens and bogs.

The study site used in this project was a conventional drilling pad situated within a treed poor fen that has now been removed and is undergoing revegetation. During initial construction in 1997, the 140 x 130 m pad was built using fill from a borrow pit approximately 100 m west of the study site. The area was cleared of woody vegetation by logging larger trees and pushing the smaller trees down with a dozer. The pad consisted of a layer of approximately 1.5 m of clay-loam fill with moderate salinity deposited over the wood corduroy. The latter was constructed from on-site woody debris placed directly on the fen surface. Fill was removed in November 2010 across the study site with a track-hoe, and used to refill the borrow pit. Although the track-hoe was able to remove most of the mineral material, a layer of fill (up to 10 cm thick, but variable in presence and thickness) remained across the site. In addition, to bring buried peat to the surface and incorporate the remaining fill, a track-hoe was used to mechanically invert the surface of the site. The result was a very rough (up to 1 m relief) mounded surface consisting of variation in patches of exposed peat and thin fill veneer across the study site.

3.2.2 Experimental Design and Treatments

To assess the effectiveness of both surface roughness (i.e. site preparation) and vegetation re-establishment techniques, we used a split-plot design, with 4 blocks. Each block was 40 by 40 m in size (Fig. 3.1). Blocks were separated by working alleys up to 10 m in width to allow travel by equipment while conducting treatments. In addition, a minimum buffer width of 3 m was maintained between the edge of each block and the outside of the well pad. Within each block, 4 macroplots were established, each 10 m wide by 40 m long. Two of the 4 macroplots were randomly assigned to be mechanically smoothed with a bulldozer, track-hoe, or combination, while the other two were left rough. Several equipment passes during semi-frozen conditions in late March 2012 resulted in minimal relief (i.e. < 15 cm) within smoothed macroplots, while rough macroplots had relief up to 1 m.

Each macroplot in turn, was divided into 2, 10 x 20 m mesoplots, with one mesoplot within each macroplot randomly assigned to either natural recovery (i.e. no live peat inoculation), or live peat inoculation (Fig. 3.1). Live peat was collected in late March of 2012 from an area 20 km north of the study area in the Primrose Air Weapons Range, from a fen undergoing new development. The peat material was skimmed off of the soil surface with a tracked excavator (hoe) and piled for loading onto trucks. Material was loaded into trucks with an excavator. Then approximately 4 m^3 of material was transferred to each of the assigned treatment plots by loading it into a detached gravel-truck box with an excavator, transferring the peat to the plot, where it was finally spread out over the plot with the excavator. The live peat was removed to 10-15 cm depth, trucked to the well pad undergoing revegetation, and temporarily stockpiled. Extraction, transport, and stockpiling resulted in thorough mixing of peat. Application of live peat was done within 7 days using a track hoe. Live material was sprinkled over the plots with the hoe bucket to achieve approximately 1-2 cm of peat application throughout. Traffic from the track hoe was applied to all macroplots (those with and without peat) to ensure consistent traffic and compaction effects. To avoid desiccation of soils and/or associated inoculant in all macroplots, a thin layer of wheat straw (1-2 cm) was spread over the top of all plots using a procedure similar to that used to apply the peat. Straw was applied from bales that were made 9 months previously during the harvest of cropland the previous fall.

Finally, within each mesoplot, a second set of microplots (10 x 10 m in size) were established in a split-split plot design to compare natural recovery (either with or without peat inoculation) to the recovery achieved with the addition of live transplants of vegetation from the adjacent fen wetland. All sampling was confined inside a 1 m buffer from the edge of the microplot (leaving an area 8 x 8 m in size for sampling). Within each microplot, 2 permanently marked quadrats, 1 x 1 m in size were established (Fig. 3.2). Within the natural recovery microplots, these quadrats were assessed with no other treatments present. Within the transplant treatments, these quadrats were planted with black spruce (*Picea mariana*), Labrador tea (*Ledum groenlandicum*), and sedge, all of which were removed from the adjacent fen. While different sedge species were problematic to identify during transplanting, subsequent monitoring of sedge revealed a mixture of *Carex aquatilis* (about 30%) and *Carex utriculata* (about 70%).

Transplants were installed in late May of 2012. Within quadrats of microplots located in smoothed mesoplots, plants of each species were established in groupings of 3 per quadrat, but at only 1 micro-topographic location - approximately mesic conditions (N= 96 plants/species in all smoothed plots: 16 microplots x 2 quadrats x 3 plants). However, within rough microplots, each of the 2 quadrats were planted with each species at 3 micro-topographic locations, including 1) elevated (i.e. xeric) peaks, 2) mesic mid slopes, and 3) hydric depressions about 1 cm above water, with 3 plants at each location in each quadrat (N=288 plants/species in all rough treatments: 16 microplots x 2 quadrats x 3 positions x 3 plants). This stratification of species allowed testing of 3 elevational positions (mound-top, middle and bottom), as well as comparison with the adjacent smoothed treatment (particularly in relation to the middle position of rough plots). In total 384 transplants were installed of each species. Species were collected within 10-20 meters off site. Collection of transplants was done to a depth of 5-10 cm using small shovels. Planting was conducted over two weeks in early June.

3.2.3 Transplanted Species and Natural Vegetation Assessments

The fate of all transplants was evaluated in each of 2012 and 2013 during early August. Survival was evaluated as the number of each species alive in every quadrat (Appendix 1.1). In addition, growth of all live transplanted black spruce was estimated in 2013. Spruce height was measured using a ruler from the top of the soil to the top of the longest leaf with or without peat inoculation on both smooth and rough macroplots. Height measures were taken prior to (early May) and after growth (late August) that year on all live trees.

Composition of vegetation in all quadrats, both within those undergoing natural recovery, and those augmented with transplants, was completed August 4-11, 2013. Each naturally vegetated quadrat was visually assessed for percent cover by species. Unknown species that occurred only once in the quadrats were not included in statistical analyses (Shaughnessy 2010). Species difficult to identify were brought to the lab. These species were identified using a microscope, in combination with a working knowledge of taxonomic terminology and concise images of leaf, bud, stem, flower and fruit morphology. All nomenclature for vascular plants followed Moss (1983), while mosses followed Jonson (1995).

Finally, two control transects to characterize natural fen composition were installed in the surrounding fen. Two transects were placed 20 m out from the edge of the CNRL well pad (1 on the north side, 1 on the west side). The purpose of control transects was to estimate undisturbed conditions in the adjacent fen, and thereby provide a benchmark condition to determine how different the original fen was from the experimental treatments within the study site. Quadrat frames were placed every 2 m over each of the 2 transects, which were 22 and 14 m long, for a total of 12 and 8 plots observed at the west and north transects, respectively. Quadrats sampled on the control transects included 1 x 1 quadrats to assess small trees and shrubs, while nested 0.5 x 0.5 quadrats were used for measuring herbaceous vegetation (including sedges), mosses and lichens.

3.2.4 Environmental Measures

Environmental data such as soil physical and chemical characteristics, hydrocarbon values, and moisture content, soil and water temperature, and water level (both below ground level and relative to a standardized elevation) were assessed.

In August 2012, soil samples were randomly taken from each block at the CNRL site and the surrounding fen, and analyzed for Na^+, K^+, Mg^{2+}, Ca^{2+}, PO_4^{3-}, SO_4^{2-}, pH, electrical conductivity,

Mn^{3+}, Fe^{3+}, OM, TP and TKN. Within each block we collected four soil cores (5 cm diameter x 5 cm deep) from randomly chosen quadrats of natural recovery treatments without peat inoculation. Sub-samples were bulked after first removing litter and any shoots. Additionally, four soil cores from each of the adjacent fen transects (NW and SE) off the well pad were extracted and combined within transect for analysis. Samples were stored in plastic bags and kept in a cooler until sent for analysis to the Natural Resources Analytical Laboratory (NRAL) of the University of Alberta. In total, six bulked samples were analyzed from the CNRL site.

In August and October 2013, soil samples were taken again at random points from every smoothed mesoplot, both with and without live peat application. We limited soil sampling within blocks to smoothed macroplots to reduce cost of the analysis. To sample the peat and non-peat mesoplots separately, we took two cores in each mesoplot, which were then bulked by block to a total of eight samples: eight in peat added, and eight in non-peat. To sample soil in the surrounding fen, eight soil cores per transect (two on each side) were removed and bulked for analysis.

For each soil sample removed in 2013, hydrocarbon content was assessed on the well pad and adjacent fen. For this assessment four cores were bulked for each of the eight soil samples for every mesoplot (with or without peat) within smooth macroplots for every block, as well as the controls (northwest and southeast). In total, ten soil samples were stored in bottles until analyzed.

Metal concentrations (Ca^{2+}, Fe^{3+}, K^{+}, Mg^{2+}, Mn^{3+}, Na^{+}) in soils were analyzed using a Spectra AA 880 Atomic Absorption Spectrometer (Varian Australia Pty Ltd, Mulgrave, Victoria, Australia). The anion SO_4^{2-} was analyzed with a DX600 ion chromatogram (Westco Scientific Limited, Sunnyvale, California, USA). The anion PO_4^{3-}, total phosphorus (TP), total nitrogen (TN) and potassium (TK), were evaluated using a 200 Smartchem discrete wet chemistry analyzer (Westco Scientific Limited, Sunnyvale, CA, USA). We determined organic C content using the loss on ignition method (Dean 1974). Electrical conductivity and pH were measured using an AR20 pH/conductivity meter (Fisher Scientific, Sunnyvale, CA, USA). Gravimetric moisture content was analyzed by weighing before and after drying (Carter 2001). These soil parameters are the most important for fen characteristcs.

Concentrations of benzene, toluene, ethylbenzene, and xylene were determined using a HP5890 Series II Gas Chromatograph (GMI Inc., Ramsey, MN, USA), while polyaromatic hydrocarbon was determined using an Agilent 7890A Gas Chromatograph (GMI Inc., Ramsey, MN, USA), consistent with the petroleum hydrocarbons method (Canadian Council of Ministers of the

Environment 2001). All soil preparation and analyses were done by technicians at the University of Alberta Natural Resources Analytical Lab (NRAL) and the Kaizen Lab in Calgary, AB.

Groundwater monitoring pipes were installed at the CNRL study site in June 2012. Four shallow groundwater pipes were placed within the former well pad area (one per block). In addition, two wells were placed 100 m and 150 m to the NW of the well pad in the adjacent fen, and another two were placed 150 m and 180 m to the SE, also in the fen, but downstream of the highway (Fig. 3.3). Pipes were constructed of perforated PVC 6.5 cm in diameter and capped at the end. A screening sock was placed over the perforated end to allow water to enter the well but prevent sediment and debris from entering.

Water level data were collected over the summer of 2012 and 2013 to determine the height of the water table at the pad site and in the surrounding fen. Fen ground water samples were collected in August 2012 from the monitoring pipes, placed in 200 ml plastic bottles, and transported to the NRAL facility for analysis. Four water samples were taken from the well pad (one per block), and four off: two NW of the well pad, and two SE of the well pad. Water samples were tested for major anions and cations, as well as other key physical and chemical properties (Na^+, K^+, Mg^{2+}, Ca^{2+}, PO_4^{3-}, SO_4^{2-}, pH, electrical conductivity, Mn^{3+}, Fe^{3+}, NPOC and TN). The laboratory equipment used on water samples was the same as for soil samples.

Soil temperature was assessed at one location in each block with HOBO PROv2 data loggers (Onset Corporation, Bourne, MA, USA). Sensors were installed in June of 2012, and used to track temperatures through October of 2013. Soil digital temperature sensors monitored temperature every 1 hour at 5 cm depth within each of the top, middle and bottom positions of a randomly chosen rough microplot, and within a random location of an adjacent smooth microplot. Soil temperature probes were removed at the end of the growing season each year. Finally, HOBO data loggers in block 2 also measured water temperature to 0.2°C precision. Measures of water depth were made in each well monthly throughout the growing season.

3.2.5. Examination of Live Peat Composition

Live peat used in the treatments was tested for living propagules to determine regeneration potential by vegetation development. Samples of live peat were randomly taken during the collection period from the site of live peat harvest, located approximately 35 km north-east of the well pad (54.899 ^{o}N; 110.524 ^{o}W). Peat was promptly transported to Vegreville, Alberta, and grown out in a greenhouse at the Alberta Innovates Technology Futures research station.

Peat material was spread over 40 trays in May 2012 and examined every two weeks for four consecutive months. Peat volume per tray was 1953 cm^3, and all trays were watered weekly, without special temperature and light-controlled conditions. During assessment, species richness and composition were determined of each vascular plant emerging. In addition, monthly cover estimates were made of mosses and lichens.

3.3. Data Analysis

Prior to analysis, all data were checked for normality and homogeneity of variances using Proc UNIVARIATE in Statistical Analysis Software v9.3 (SAS 9.3 Inc. 2012). Survival data were found to be non-normal for transplants using a Shapiro Wilks test (P<0.05), and subsequently arcsine transformed. For these and all other data exposed to a transformation, original data (means and SEs) are presented for ease of interpretation. Additionally, survival data were analyzed separately by year to assess immediate and longer-term responses to treatments.

Survival data were subsequently analyzed with mixed models in SAS 9.3, using a similar approach for each of the three species (black spruce, Labrator tea and sedge). A multi-staged process was used to test the fixed effects of surface treatment and peat addition, and within the rough treatment, the additional effect of planting position. To evaluate overall effects of surface treatment, survival data were averaged by macroplot and run using block, block*surface and plot (block*surface) as random. To evaluate the separate impact of roughness on survival of plants at the mid position, survival data from the smooth treatments were compared only to those from the middle planting position of rough plots.

To assess peat effects on survival, data for each species were summarized to the mesoplot level and run in mixed models using peat and peat x surface as fixed effects. Block and all interactions of block with the fixed effects, and plots nested therein, were treated as random. Similar to the roughness assessment, this process was repeated for 1) data averaged over all positions in the rough plots, and 2) data from the mid position only for comparison to the smooth treatment. To assess specific effects of planting position on survival within the rough treatment, data from rough macroplots were analyzed using peat, position and peat*position as fixed effects, with block and all interactions of block (and plots therein) with the fixed effects as random.

Prior to analysis, final black spruce height was relativized to initial tree height in May of 2013 to adjust for variation in initial tree size, resulting in relative height ratios (RHR) for each tree. Calculation of the relative height ratio (RHR) for each tree (Garnier and Navas 2012) used Equation 1:

$$\text{RHR} = \text{final height/initial height} \quad (1)$$

To subsequently evaluate height growth in transplanted spruce, two analyses were used. Fixed effects of surface treatment and peat addition, and within the rough treatment, the additional effect of planting position on the growth of spruce RHR, were tested using a mixed model ANOVA. A similar procedure was done for Labrador tea and sedge cover. To assess peat effects on spruce RHR and the cover of transplanted species, data were run in mixed models using peat and peat *surface as fixed effects. To evaluate position effects within the rough treatment, data were run using peat and peat * position as fixed effects.

To evaluate environmental conditions and total richness (i.e. vascular plant species plus bryophytes) within the transplanted and natural plots, fixed effects of surface treatment and peat addition on the cover of water, rock, exposed mineral soil, woody debris, litter and total species richness were tested separately for transplanted and natural plots using a mixed model ANOVA. Ground cover and species richness between the natural recovery and transplanted quadrats was also directly compared using a one-way ANOVA. Additionally, relationships between environmental variables (observed water levels, soil moisture and temperature) and the survival of each transplanted species, as well as overall richness, were evaluated using Pearson correlations calculated with Proc CORR in SAS 9.3. Pearson correlations were performed for each of black spruce, Labrador tea, and sedge survival, as well as species richness in natural recovery plots where environmental measurements were made. Survival data and species richness used for this analysis were limited to those taken directly from quadrats corresponding to those locations where water levels, soil temperatures and soil moisture were measured. Environmental and vegetation data were correlated separately for each of 2012 and 2013 using independent data, except soil moisture, which was only assessed in 2012. Due to the limited sample sizes, significance of correlations was set at $P<0.10$. In addition, landscape variables of soil temperature were correlated with transplant survival within the top, middle, and bottom position (separately) of rough plots.

Treatment effects on detailed plant community composition during natural recovery of vegetation were examined using multivariate analytical techniques. To assess specific effects of treatment impacts on August composition in natural recovery plots, a permutation-based MANOVA (PerMANOVA) was used to determine whether composition differed among the fixed effects of surface roughness and peat application (Anderson 2001). Position could not be tested because species composition was taken at a spatial resolution (1 m^2 quadrats) larger than that of the individual positions. PerMANOVA was performed using the Sorensen distance measure, with all analyses conducted in PC-ORD v5 (McCune and Grace 2002). Significance was based on the proportion of randomized trials with an indicator cover greater than or equal to the observed cover value (McCune and Grace 2002) based on Equation 2:

$$P = (1\text{+number of runs} \geq \text{observed}) / (1\text{+number of randomized runs}) \quad (2)$$

This was supplemented with an indicator species analysis (ISA), which allows direct testing of correlation between individual plant species and fixed treatment classes (surface and peat treatments) using 4999 permutations (McCune and Grace 2002).

Finally, to assess patterns in compositional responses across all mesoplots, nonmetric multi-dimensional scaling (NMDS) ordination was performed on all species data from August 2013 using a Sorensen distance measure in PC-ORD (McCune and Grace 2002). This process facilitates visual separation among treatment classes, and can be followed up with correlations of these patterns (and resulting explanatory axes) with external environmental variables. Real data were run 250 times, as were the randomized data for the Monte Carlo test. A total of 500 iterations were used to obtain the final stable solution. Axes scores were interpreted based on Pearson correlations with all species found on the site, with $|r| > 0.30$ considered significant.

A multi-staged process was used to evaluate the extent to which plant community composition on the experimental plots had progressed towards the original fen condition, including in relation to the fixed effects of surface treatment and peat addition. As a first step, the similarity and dissimilarity between each of the 128 microplots (64 natural and 64 transplanted) was compared to the composition in the original fen. This assessment used only the cover of all herb and bryophyte species, and averaged cover data across the 0.5 x 0.5 m quadrats within each experimental unit (i.e. 2, 1m^2 quadrats in each microplot, and 8, 0.5 x 0.5 m quadrats across the 2 control transects – 4 each). The latter was done to ensure equal sample areas were being compared between the microplots and control transects. Similarity based on species richness was subsequently calculated using Jaccard's similarity coefficient (Jaccard 1912) using Equation 3:

$$S_J = a/(a + b + c), \text{ where} \quad (3)$$

a = number of species common to (shared by) quadrats,

b = number of species unique to the first quadrat,

c = number of species unique to the second quadrat.

In addition, dissimilarity was calculated using a Bray-Curtis index (Bray and Curtis 1957), which includes metrics of species abundance. This was done using Equation 4:

$$D_{ij}=\Sigma \, |X_{ij} - X_{ik}| \, / \Sigma(X_{ij} + X_{ik}), \tag{4}$$

j, *k* = individuals in each of the comparing sample,

Xij and Xik are the number of quadrats containing species i at site j or k,

|Xij - Xik|=absolute difference,

(Xij + Xik)=sum.

Similarity and dissimilarity data were then analyzed with mixed models in SAS 9.3 to evaluate effects of surface treatment, peat addition, transplanting, and all possible interactions. To assess specific effects of transplanting and peat addition on species similarity within the rough and smooth treatments, data from these plots were analyzed using peat, transplanting, surface, peat*surface, surface*transplanting, transplanting*peat, transplanting*peat*surface as fixed effects, with block and all interactions of block (and plots therein) with the fixed effects as random.

Finally, the number of establishing vascular plants and cover of moss and lichens, emerging from the live peat, were recorded in samples grown in the greeenhouse at Vegreville. All plant emergence data, together with live moss and lichen cover, were summarized for each of the 40 trays. Mean density of all vascular plants per tray, and percent cover of bryophytes, along with standard deviations showing variance among trays, are reported. In addition, the frequency of species occurrence across trays is reported, similar to the method used by Cohen-Fernández et al. (2013).

3.4. Results

3.4.1 Transplanted Species

Overall survival of transplants by the end of the study in 2013, including that of black spruce (rough = 11.5%; smooth =13.6%), Labrador tea (rough = 13.2%; smooth = 16.7%) and sedges (rough = 86.1%; smooth = 84.4%), were not affected by surface roughness overall, nor when examined solely within the middle planting position (Table 3.1). Similarly, peat application had no effect on the survival of spruce (with peat = 12.1%; without peat = 11.9%), Labrador tea (with peat = 12.5%; without peat = 16.6%), and sedges (with peat = 82.8%; without peat = 85.9%).

Both black spruce and Labrador tea survival were affected by position*peat interactions during 2012 (Table 3.1). Closer examination of these interactions indicated that the greatest spruce survival in rough plots occurred at the top position of the peat-treated plots, which differed from the bottom position of the same peat-treated plots (Fig. 3.4A). Spruce survival did not differ across positions in the absence of peat addition. In the case of Labrador tea, survival on plots without peat once again did not differ across positions (Fig. 3.4B). However, Labrador tea survival was greater at the middle and bottom position on plots lacking peat, as well as on plots at the top position receiving peat, but only relative to the bottom position within peat treated plots (Fig. 3.4B). Sedge survival was uniformly high in 2012 at 98.17%.

One year later in 2013, comparative spruce and Labrador tea survival were much lower than the year prior, declining from more than 50% typically, to less than 20% for both species. Additionally, position effects, but not peat effects, remained evident on both these species (Table 3.1). Spruce survival was lower (P <0.05) at the bottom position (1.04%±4.6) compared to the top (17.73%±4.56) and middle (15.62%±4.56) micro-topographic locations. Survival of Labrador tea followed a similar trend, being lower (P <0.05) at the bottom position (2.08% ±6.05) compared to the top (18.75%±6.05) and middle (18.74%±6.05) positions. Sedge survival was not affected by any of the treatments (P>0.10), and remained uniformly high, ranging from 84.4% to 87.5% across the 3 positions in 2013. Finally, transplant survival was not correlated with soil temperature within any of the micro-topographic positions (Table 3.2).

Black spruce RHR ranged from 0.97 to 1.146 across plots. Black spruce RHR was effected by planting position, but not surface or peat treatment (Table 3.3). Plots at the bottom position of rough plots had lower (P<0.05) spruce RHR compared to those trees alive within the middle and top locations (Fig. 3.5), with the latter up to 7% greater in height.

At the end of the first and second establishment years, 2012 and 2013 respectively, cover of the shrub (Labrador tea) and herb (sedge) transplants were affected by planting position (Table 3.4). In addition, Labrador tea cover in 2012 responded to the interaction of peat by position (Table 3.4). In the absence of peat application, the greatest Labrador tea cover occurred at the middle planting position, which differed from bottom and top positions within plots lacking peat (Figure 3.6). Additionally, Labrador tea cover was particularly low in the bottom position of plots receiving peat that year (Fig. 3.6). Transplant sedge cover in 2012 was lower (*P* <0.05) at the top position (2.78% ±0.29) compared to the bottom (3.53% ±0.29) and middle (3.88% ±0.29) positions. One year later in 2013, the cover of planted Labrador tea was lower (*P* <0.05) at the bottom position compared to the top and middle positions (Fig. 3.7A). Finally, cover of sedge remained lower within the top position compared to the other positions in 2013 (Fig. 3.7B).

3.4.2. Plant Community Responses

Surprisingly, species richness was not affected at the end of the study in 2013 within the transplanted plots, nor the naturally regenerating plots, in response to peat application and surface roughness (Table 3.5). Richness within transplanted mesoplots ranged from 1 species plot^{-1} to 31 species plot^{-1}. Richness within naturally re-vegetating mesoplots ranged from 1 species plot^{-1} to 29 species plot^{-1}. Species richness within naturally revegetated microplots (17.32 ± 6.74 species plot^{-1}) was lower (F=11.57; *P*=0.04) compared to that in microplots containing transplants (18.41 ± 6.75 species plot^{-1}). Finally, species richness was not correlated with soil moisture, temperature or water level (*P*>0.10) (Table 3.6).

Species diversity within naturally regenerating plots was affected at the end of the study in 2013 by peat treatment (*P*<0.05) (Table 3.7). Diversity was lower on plots receiving peat amendment (1.991 ±0.19) compared with those not receiving peat (2.201 ±0.19). Shannon's diversity within transplanted plots ranged from 0 to 2.820. Diversity within naturally revegetated plots ranged from 0 on the smooth plots (both those with and without peat treatment) to 2.844 on the smooth plots with peat addition. Species diversity within naturally revegetated plots (2.095 ± 0.64) was similar (F=0.59; *P*=0.50) to that in plots containing transplants (2.126 ± 0.56). Finally, species diversity was not correlated with soil moisture, temperature and water level (*P*>0.10) (Table 3.6).

PerMANOVA tests, and comparisons of species composition among the fixed effects of surface roughness and peat application, showed significant differences in species composition for roughness but not peat (Table 3.8). The associated indicator species analysis revealed that perennial trees, shrubs, and mosses were positively associated (*P*<0.05) with the rough surface treatment. In contrast, sedges and short-lived (annual and biennial) forbs were positively related to the smooth surface treatment. Finally, several trees, shrubs, and bryophytes were positively associated (*P*<0.05) with plots lacking live peat inoculation (Table 3.9). No species were associated with areas receiving peat application.

The NMDS analysis of plant community data at CNRL resulted in a three dimensional solution with a final stress of 12.41. Axis 1 in the ordination represented 49.5% of species variance, while axes 2 and 3 represented 22.5 and 10.6%, respectively (Fig. 3.8). Correlation of the environmental attributes and plant community characteristics with the ordination axes indicated that the amount of rock, open water, soil, and woody debris, together with the cover of perennial trees, shrubs, forbs, horsetails and mosses, were correlated with axes 1 and 2 (Table 3.10). In addition, sedges were correlated with axes 2 and 3. Shrubs were correlated with axes 1 and 3 (Table 3.10).

Jaccard's similarity and Bray-Curtis species dissimilarity between the original fen and plots exposed to the different treatments did not vary in relation to any of the revegetation strategies tested, including surface roughness and peat application (Table 3.11).

3.4.3. Environmental Conditions

Ground cover components did not differ within transplanted plots exposed to different peat treatments (Table 3.12). However, the cover of rock differed between rough and smooth plots (Table 3.12). Rock was lower ($P<0.10$) within the smooth treatment compared to the rough areas, regardless of transplanting treatment (Fig. 3.9). Bare soil (26.23%), open water (65.41%), litter (2.48%) and woody debris (4.12%) cover were not affected by the surface treatments in 2013.

Similar to the transplanted plots, ground cover conditions did not differ for the peat application and its interaction with surface treatment within the natural recovery plots (Table 3.12). However, the area of rock was again affected by surface roughness ($P<0.05$) within naturally regenerating plots during 2013 (Table 3.12). Rock was greater within the rough treatment compared to the smooth areas (Fig. 3.9).

Bare soil, open water, litter and woody debris cover were again not affected by the surface treatments. Finally, the amount of exposed rock ($F= 5.44$; $P=0.10$), litter ($F=2.62$; $P=0.15$), open water ($F=0.06$; $P=0.81$), bare mineral soil ($F=1.28$; $P=0.28$) and woody debris ($F=0.18$; $P=0.68$) within naturally revegetated plots remained similar to that in transplanted areas.

Soil samples assessed were comprised of a mix of slightly decomposed peat and mineral soil. In general, compared to the undisturbed fen in 2012, the CNRL pad well had elevated levels of Ca^{2+}, Mg^{2+}, $SO4^{2-}$, and Na^{+}, and lower levels of K^{+}. Levels of Fe^{3+} and Mn^{3+} did not differ. Trace amounts of PO_4^{3-} were detected in soils on the CNRL well pad in 2012 (Table 3.13). Soil pH values ranged from 7.94 to 8.36, and from 7.10 to 8.15, among sampling locations in 2012 and 2013, respectively (Table 3.13; Table 3.14). Soil pH values were also greater at sampling locations on the well pad compared with the adjacent undisturbed fen over the two years (Table 3.13; Table 3.14). Electrical conductivity of soil within the well site and undisturbed fen were close to intermediate levels over the 2 years (conductivity = 134-754 µS cm^{-1} in August 2012, and 164-500 µS cm^{-1} in August 2013) and do not differ in relation to peat application (P=0.65).

Soil pH (F=1.54; P=0.26) and electrical conductivity (F=0.08; P=0.79) values, levels of Ca^{2+}(F=0.07; P= 0.80), Fe^{3+}(F=0.13 ; P=0.74), K^{+}(F=0.09; P= 0.78), Mg^{2+}(F=0.05; P= 0.83), Mn^{3+}(F=0.14; P= 0.71), Na^{+}(F=3.90; P=0.10), SO_4^{2-}(F=0.28; P=0.65), soil OM content (F=0.69; P= 0.17), total nitrogen (F=0.04; P= 0.84) and total phosphorus (F=3.0; P= 0.14), within the plots without peat were similar to those with peat addition. In contrast, levels of soil Cl^{-} in the absence of peat (25.02 ± 19.10) were lower (F=4.75; P= 0.05) compared to those with peat addition (59.53 ± 19.10).

Hydrochemical properties of the ground water differed between disturbed and undisturbed areas (Table 3.13). Water content of phosphate and nitrogen were greatest in block four (103.2 mg L^{-1} and 1.2 mg L^{-1}, respectively). Trace amounts of PO_4^{3-} and Fe^{3+} were detected in the disturbed and undisturbed fen (Table 3.13). Water pH values were greater within the well pad in comparison with the undisturbed fen over the two years. Electrical conductivity ranged from fresh water (EC<100 µS cm^{-1}) to saline (EC>1000 µS cm^{-1}) within the well pad and surrounding fen.

Limited hydrocarbons were found within the soil samples (Table 3.15). Polyaromatic hydrocarbon F3 (C_{16}-C_{34}) values within plots not receiving peat (361 ± 0.0 mg/kg) were similar (F=0.00; P=0.99) compared to those with peat addition (470.7± 142.3 mg/kg). Similar results were observed (F=0.00; P=0.99) for hydrocarbon F4 (C_{34}-C_{50}) values within plots lacking peat (346 ± 0.0 mg kg^{-1}) and those with peat (391.3± 99.02 mg kg^{-1}) (Table 3.14).

Elevational water levels indicate a generalized direction of water flow from the NW to the SE across the study site (Table 3.16). The lowest water levels occurred downstream (i.e. SE) across the highway. In contrast, block four situated immediately upstream of the culvert had the highest water table relative to the ground surface in 2012 (Table 3.17). Block one on the well pad further upstream of the highway had water levels lower in elevation and deeper from the soil surface over two years (Tables 3.17). However, the adjacent natural fen had elevation water levels even lower than the well pad study site. Water levels also did not change significantly at the site over the two years, but decreased slightly in elevation over time within the adjacent intact fen (Table 3.17).

Average soil temperatures were 12.4 (± 4.1) ^{o}C and 14.2 (± 3.6) ^{o}C during 2012 and 2013, respectively. Average water temperature was 12.8 (± 1.9) ^{o}C. Results are outlined in Table 3.18.

3.4.4. Live Peat Composition

Plant densities and bryophyte cover grown from live peat in the greenhouse increased over the first 8 weeks (Table 3.19), and then remained relatively constant to the end of week 10 (July 2012). Small cranberries, mosses and sedges were the most common species that appeared over the study period, leading to the greatest plant densities and frequency (Fig. 3.10). In addition, trees (*Populus tremuloides*) had a high plant density in peat samples despite a low frequency of occurrence among trays. Grasses such as *Beckmannia syzigachne* reached abundant levels, both in density and frequency, after only 4 weeks (Table 3.19).

3.5. Discussion

3.5.1. Transplant Performance

Black spruce survival was greatest at the top micro-topographic position within peat treated plots, and survival was generally low at the bottom position, particularly in 2013. High overwinter mortality led to only 1% of black spruce trees remaining alive at the latter position. Unlike the current study, poorer black spruce survival has previously been demonstrated on uplands relative to lowland locations (Wang 1991). Several mechanisms exist that could account for the reduction in spruce survival at the bottom of artificial peat 'mounds'. Black spruce planted within the lower position was generally planted near the water table (e.g. 5-10 cm above). Increased exposure to saturated water conditions in the rooting zone is known to reduce black spruce survival (Kozlowski 1997), in part due to anaerobic conditions and associated reductions in root respiration (Jeglum 1974). However, lower positions may also suffer from cooler soil temperatures, which can reduce survival of black spruce (Kozlowski and Pallardy 1997). Our results suggest planting at least half way up the mounds in rough topography, which equated to at least 30 cm above the water table, encouraged spruce survival.

While the purpose of applying the live peat material was to introduce plant propagules that could potentially colonize the site, increases in spruce survival during the first year where peat was applied may reflect the benefit of added organic matter in insulating the soil (Lambers et al. 1998), in turn conserving soil moisture (Caisse et al. 2008). Although no relationship was found in this study (see Table 3.6) between spruce survival and soil moisture, a limited availability of data may have prevented proper testing of this possibility. The live peat application could have also increased nutrient supply (Mugasha et al. 1999), but this is less likely considering that the primary planting medium examined here consisted of peat. Although difficult to identify for certain, the benefits of peat appeared to aid spruce survival shortly after planting (Locky et al. 2005). Viereck and Johnston (1990) noted that black spruce does well on heavy peat underlain by considerable amounts of decayed woody material. In the present study, about 40% of the ground consisted of mineral soil, which could result in warmer temperatures and lower soil moisture, conditions that peat addition could help overcome (Wolken et al. 2011).

Unfortunately, peat application did not have lasting benefits on spruce survival (or RHR) into 2013, suggesting the long-term benefits of peat application for spruce were lacking. This finding is not surprising given that the peat layer applied just prior to planting was relatively thin (1-2 cm), and thus, could have disappeared from the site prior to the second establishment year. Such a thin layer of peat may be prone to being eroded away by wind or water. It also raises the possibility that had more peat been initially applied to plots prior to planting, greater, longer-term benefits in spruce survival may have occurred. Alternatively, in the absence of longer-term benefits, my results suggest the cost of peat application do not appear to be justified, at least not specifically as a soil amendment.

Not surprisingly, black spruce RHR was greater in 2013 for spruce trees planted at the top and middle positions, and is consistent with the trends in survival data discussed earlier. Excess moisture and reduced soil aeration at the lower position therefore not only reduced survival, but also likely impeded growth of those trees that did survive, and is consistent with other investigations examining abiotic constraints on the growth of young black spruce (Jeglum 1974). Reduced growth at this location within the 'micro-topography' also increases the likelihood of further black spruce mortality in subsequent years.

Despite the increased survival and growth of black spruce on the upper portions of mounds in rough surface treatments, no differences in overall spruce survival and growth were found between trees planted in rough and smooth plots. Consequently, the benefits of creating and maintaining a rough surface for the purpose of enhancing spruce establishment does not seem to be warranted, at least based on the 2-year establishment data collected here. Further examination of soil

– vegetation relations in response to planting position and peat application would be useful over the long-term for evaluating and predicting the survival of spruce transplants.

Labrador tea survival followed a pattern similar to that of spruce, with little overall benefit of planting this species into a rough surface. Within rough plots, survival was again greater within the top and middle positions, and likely reflects the increased susceptibility of this species to excess moisture (Levitt 1972) and anaerobic conditions (Akhtar and Nazir 2013) at this location, particularly with ongoing seasonal changes in inundation with rainfall and spring runoff. Again, benefits of the live peat to Labrador tea were limited to the first year, when peat appeared to enhance survival of this species at the top of mounds within rough plots. Peat application may have reduced moisture loss or mitigated air and/or soil temperature extremes, factors known to impact Labrador tea survival (Nellessen 2004), thereby improving shrub survival. As with spruce, these effects disappeared one year later, and may reflect the need for greater initial peat applications to ensure longer term benefits if applied as a soil amendment.

Unlike the two woody transplant species, sedge had the most favorable survival of all 3 species in both establishment years, with survival remaining more than 80%. Sedge survival was not effected by surface roughness, peat application, or planting position, although sedge cover responses suggested the most favorable growth of sedge occurred on the mid and bottom micro-topographic positions. Sedge has an inherent ability to withstand flooded conditions (Koncalova et al. 1998), but also tolerates dry conditions, suggesting it has the greatest phenotypic plasticity or niche tolerance of all three species planted. Other research has shown that proximity to the water table is an important consideration when using *C. aquatilis* for revegetating peatlands (Vitt et al. 2011), and indicates that the greatest overall success can be attained by planting sedges into microsites with optimal hydrology. In the current study, this appeared to be associated with all planting locations other than the upper portions of rough plots. This has the added benefit of minimizing susceptibility to excessive moisture associated with unexpected increases in flooding, such as may occur during heavy rains or years of heavy spring runoff.

Changes in water depth across the well site also appeared to be strongly impacted by the adjacent highway, which increases water depth (by impeding water flow). This effect could well be responsible for reducing spruce, Lab tea, and sedge performance in the lowest micro-topographic position of rough treatments. Moreover, long-term monitoring of transplants should be conducted to fully evaluate the benefit of transplants for achieving fen revegetation.

3.5.2. Plant Community

Total species richness did not respond to the surface roughness or peat treatments, and factors other than soil temperature, soil moisture or water depth appeared to be responsible for variation in richness among plots based on the limited environmental data available for correlation with the vegetation data. While overall richness did not change in response to surface roughness, plots nevertheless changed in species composition. However, offsetting effects of smooth and rough treatments in favoring a different suite a species appeared to result in no net difference in richness relative to the type of surface treatment.

Rough and smooth surface treatments resulted in divergence in community composition, as represented by specific indicator species. Smooth plots were associated with aquatic sedges and ruderal (disturbance-adapted) forbs. Forbs such as *Senecio congestus* represent early seral species that are likely colonizing the smooth plots because of the added mechanical disturbance associated with smoothing itself (McEvoy et al. 1993), a process that also reduced the area of exposed rock, likely by burying them. A similar situation exists for *Potentilla palustris*, which is another early to mid seral forb adept at colonizing disturbed areas (Bastl et al. 2009). Finally, the mechanism for the increase in water sedge, *Carex aquatilis*, on smooth plots is unknown, but could reflect the potential that this species may be ideally adapted to colonize the 'moderate' moisture conditions associated with this 'mid slope' position throughout these areas (Deng et al. 2013).

In contrast, rough plots were closely associated with both mid to late seral woody species (trees and shrubs), as well as mosses. The increased association with moss (*Ceratodon* spp. and *Polytrichum* spp.) may reflect the increased likelihood of a portion of the plot area having increased access to the water table, as water is critical for moss survival (Kangas et al. 2014), particularly during drier periods. The association of trees and shrubs with rough plots may reflect either the extended reduction in disturbance on these areas (i.e. they were last disturbed 1 year prior to the smooth plots), or alternatively, the increased heterogeneity in microsite conditions could have favored shrub and tree development. Aspen (*Populus tremuloides*) and balsam poplar (*Populus balsamifera*) colonization from seed, and possibly that of the willows (*Salix* spp.) as well, is typically a slow process reliant on seed entry, and subsequent seedling germination and survival, a process that occurs relatively infrequently for small seeded species like these (Yarie 1993). Preferential establishment of these species on rough plots may also be more likely with a rough (i.e.

uneven) topographic surface, which could improve airborne seed capture (Blood and Titus 2010), and potentially provide the small scale microsite heterogeneity effective for seed entry and survival (Janousek and Folger 2014). Microsite variability in turn, is likely to translate into a greater variety of niches for the establishment of different species. Ultimately, more research is needed to understand the complete array of factors responsible for preferential establishment of woody species on rough treatments in this study.

Surprisingly, species diversity was lower in plots receiving live peat application, which is in sharp contrast to our expectation that live peat addition would enhance recovery, as several previous studies have shown (Hope et al. 2005). Moreover, contrary to expectations, the indicator analysis revealed that no species were associated with the peat addition treatment, and instead, peat addition decreased the abundance of many species during revegetation, including both *Populus* trees, several bryophytes (mosses and lichen), and two shrubs (Table 3.20). This finding is particularly perplexing given that the live peat used had an abundance of vascular plant and bryophyte propagules present, as evidenced by results of the greenhouse growth test.

The lack of diversity and plant abundance responses within the peat addition treatments indicates peat (and live propagule) addition alone failed to translate into widespread establishment of additional species. Given the relatively thin nature of the live peat layer (less than 2 cm) applied, this layer may have promptly dried out despite application of straw to prevent this, which in turn, could have reduced the viability of living root fragments (Bowman et al. 1986), and also inhibit the germination and eventual viability of vascular seeds and bryophyte spores (Salonen and Laaksonen 1994).

Ultimately, the cause of the poor establishment of additional species within the peat addition treatments remains unknown. One possibility is that the addition of peat inhibited seed entry for wind born seeds (likely to be the case for the species spread by wind), and which would be particularly important for those species that need mineral soil for establishment. This is known to be the case for species such as *Senecio congestus*, *Typha latifolia*, and *Taraxacum officinale* (Cronk and Fenneessy 2001). Peat addition may also have reduced mineral soil temperature, which could pose a disadvantage for species requiring warmer soils such as *Picea mariana* and *Populus tremuloides* (Cronk and Fenneessy 2001). Similarly, willows and Labrador tea also develop better in warmer soils (Nichols 1998; Pajunen et al. 2009). Another consideration is that any naturally regenerating plants below the added peat may not have survived, particularly if unable to emerge through the peat layer. Additionally, the added peat would also reduce the detection and visibility of those species comprising low ground cover, particularly if the latter regenerate from previously dormant spores on the ground surface. This alone could account for the reduction in moss and lichen cover observed on plots with peat addition.

Overall, species richness and diversity were generally greater in transplanted areas rather than those undergoing natural recovery. The marginal increase in both these responses appeared to be the direct result of the additional species installed during the transplantation process. These results confirm that transplantation is an effective strategy to increase revegetation and facilitate succession towards the end goal of restoring a fen community. Several species were also found that were not endemic to fens of the boreal forest however, including *Agropyron cristatum* (L.) Gaertn. (crested wheatgrass), and *Sonchus arvensis* L. (perennial sow thistle), a non-native plant provincially designated as a noxious weed in Alberta. These species are non-natives associated with anthropogenic disturbances, and should be monitored to ensure they do not become more widespread over time.

3.5.3. Environment

No, or minimal hydrocarbon contamination was detected at the study site and surrounding undisturbed fen. This suggests that minimal contamination occurred during drilling and reclamation, and would not limit fen revegetation attempts. In contrast, hydrologic conditions varied substantially across the pad, largely due to the adjacent highway. This transport corridor is acting like a dam (Fig. 3.3), and by impeding water flow to the SE, is creating greater flooding in blocks 3 and 4 against the highway. Increased floodwater levels, coupled with more uncertainty in water levels, may make it harder to restore vegetation within those 2 blocks of the disturbed fen on the well pad (Smith and Medeiros 2013). To remedy this, improved drainage is needed under the highway to allow water to flow more continuously from above the highway to below.

The well pad also had greater minerals, such as calcium (Ca), magnesium (Mg), and sulfate (SO_4) in the soil, as well as sodium (Na) in the fen water. In general, grasses and shrubs are more sensitive to variation in minerology, with salinity influencing species composition (González-Alcaraz et al. 2014). For example, *Typha latifolia* is tolerant of high salt levels (Jesus et al. 2013). High salts impose both ionic and osmotic stresses on plants, resulting in an excess accumulation of sodium (Na) in plant tissues (Hasegawa et al. 2011). Additionally, if Na levels are high or not balanced with Ca and Mg, fen soil can be negatively impacted. The positively charged Na cations attach to the negatively charged particles in the soil, causing the soil to be sticky when wet, and hard and impermeable when dry, both of which reduce rooting opportunities for vegetation (Ahmad and Sharma 2008). Finally, the CNRL well-pad also had a greater soil pH (i.e. more basic) known to favor herbs rather than mosses (Bragazza and Gerdol 1996).

3.6. Conclusion

Revegetation was affected by both the surface roughness treatments, and to a lesser extent, peat application. Transplanting also met with considerable success, and led to a small increase in species richness. Black spruce and Lab tea survival were particularly favorable on the upper and mid topographic positions of rough plots, while sedges were effective in establishing at all micro-topographic positions. No relationships were found between soil conditions and transplant survival or ensuing species richness or diversity, although limited data collection may have reduced our ability to test these factors.

Despite the positive signs of species establishment within the revegetation treatments, all treatments remain a long-ways from recovery (with Jaccard similarity values < 10%, and in the case of Bray-Curtis similarity, less than 5%). Thus, significantly more time is required in order for these communities undergoing revegetation to become even 50% similar to the undisturbed fen. Future comparisons of disturbed and undisturbed areas should be conducted. Peatland revegetation guidelines should be revised to reflect these results, although long-term monitoring is likely necessary to fully assess the effectiveness of these revegetation treatments. Further studies are also needed to examine why live peat was not effective for improving community recovery, and was perhaps detrimental to species recovery.

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Table 3.1. Summary F-test results from the mixed model ANOVA of black spruce, Labrador tea and sedge transplant survival at the CNRL site during the first (2012) and second (2013) years of establishment.

	Black Spruce		Labrador Tea		*Carex* spp.	
Treatment	2012	2013	2012	2013	2012	2013
Surface (all plots)[1]	$1.37_{1,14}$ [4]	$0.12_{1,3}$	$0.42_{1,13}$	$0.42_{1,11}$	$0.75_{1,22}$	$0.12_{1,11}$
Peat (all plots)[1]	$1.96_{1,14}$	$0.06_{1,14}$	$0.51_{1,10.8}$	$2.01_{1,14}$	$0.75_{1,22}$	$0.35_{1,14}$
Peat*Surface (all plots)[1]	$2.01_{1,14}$	$0.13_{1,14}$	$0.33_{1,14}$	$0.01_{1,14}$	$1.25_{1,22}$	$0.04_{1,14}$
Surface (middle only)[2]	$1.74_{1,14}$	$0.02_{1,3}$	$0.14_{1,13.3}$	$0.09_{1,11}$	$1.00_{1,8}$	$0.26_{1,11}$
Peat (middle only)[2]	$0.71_{1,14}$	$0.18_{1,22}$	$0.78_{1,3.98}$	$3.2_{1,14}$	$1.00_{1,8}$	$0.17_{1,14}$
Peat*Surface (middle only)[2]	$1.88_{1,14}$	$0.02_{1,22}$	$0.75_{1,3.18}$	$0.24_{1,14}$	$1.00_{1,8}$	$017_{1,14}$
Position[3]	$2.17_{2,6}$	$7.83^{***}_{2,15.8}$	$0.71_{2,14}$	$5.01_{2,6}$*	$1.00_{2,14}$	$1.05_{2,28}$
Position*Peat[3]	$3.84_{2,21}$**	$2.03_{2,13.6}$	$3.97^{**}_{2,14}$	$0.33_{2,22}$	$1.00_{2,14}$	$0.18_{2,28}$

***,**,* Significance indicated at $P<0.01$, $P<0.05$, and $P<0.10$, respectively.

[1] Data from rough treatments were averaged across all micro-topographic positions prior to analysis.

[2] Data from rough treatments were assessed using only the middle position, for comparison to smooth plots.

[3] Data examined using rough plots only.

[4] Subscripts indicate numerator and denominator degrees of freedom for each F-test, respectively.

Table 3.2. Pearson correlation coefficients (*r*) and associated significance for the relationships between survival of spruce, Labrador tea and sedge, and soil temperature (°C) within different micro-topographical positions. No correlations were significant at *P*<0.10. For this analysis, data were grouped by position (analysed separetly by position).

	Black Spruce		Labrador tea		Sedge[1]	
Position	*R*	*P*	*r*	*P*	*r*	*P*
			2012			
Top	0.06	0.94	-0.43	0.57	N/A	N/A
Middle	0.22	0.78	-0.03	0.97	N/A	N/A
Bottom	-0.76	0.24	-0.4	0.6	N/A	N/A
			2013			
Top	-0.72	0.28	-0.45	0.55	-0.67	0.33
Middle	-0.88	0.12	-0.89	0.11	N/A	N/A
Bottom	-0.12	0.88	-0.12	0.88	N/A	N/A

[1] Sedge survival was 100% in 2012, then declined in 2013 allowing assessment in the 2nd year.

Table 3.3. Summary of ANOVA F-test results from the mixed model ANOVA of black spruce relative height ratio (RHR) responses to peat and surface treatments, as well as the peat and position treatments, across the CNRL site during the growing season of 2013. Significance at *P*<0.05 is in bold.

Treatment	df[2]	F-test (RHR)
Peat	1,7.84	0.58
Surface	2,2.75	1.73
Peat*Surface	1,2.68	0.04
Peat[1]	1,7.46	0.07
Position[1]	2,11.4	**5.31**
Peat*Position[1]	2,11.4	0.61

[1] Position effect could only be tested within the rough treatments.
[2] df was calculated using a Kenward-Roger adjustment for small sample sizes.

Table 3.4. Summary of ANOVA F-test results from the mixed model ANOVA of planted Labrador tea and sedge cover at the CNRL site during each of the 2 study years.

Source	Labrador Tea		Sedge.	
	2012	2013	2012	2013
Surface (all plots)[1]	$0.60_{1,11}$	$0.01_{1,3}$	$1.45_{1,3}$	$2.44_{1,3}$
Peat (all plots)[1]	$0.18_{1,3}$	$0.01_{1,3}$	$0.52_{1,14}$	$0.06_{1,3}$
Peat*Surface (all plots)[1]	$0.48_{1,11}$	$0.32_{1,3}$	$0.28_{1,14}$	$0.01_{1,3}$
Surface (middle only)[2]	$0.03_{1,11}$	$1.61_{1,3}$	$0.23_{1,11}$	$0.95_{1,3}$
Peat (middle only)[2]	$0.68_{1,3}$	$0.14_{1,3}$	$0.75_{1,14}$	$0.10_{1,3}$
Peat*Surface (middle only)[2]	$1.06_{1,11}$	$0.53_{1,3}$	$0.75_{1,14}$	$0.00_{1,19}$
Position[3]	$7.49*_{2,14}$	$9.1*_{2,6.47}$	$7.45*_{2,6}$	$7.68**_{2,14}$
Position*Peat[3]	$4.11*_{2,14}$	$1.18_{2,29.1}$	$0.97_{2,14}$	$0.16_{2,14}$

**,* Significance indicated at $P<0.01$ and $P<0.05$, respectively.

[1] Data from rough treatments were averaged across positions prior to analysis.
[2] Data from rough treatments used only the middle position for comparison to smooth plots.
[3] Data examined using rough plots only.

Table 3.5. Summary of ANOVA F-test results from the mixed model ANOVA evaluating plant community richness in response to the peat application and surface roughness treatments at the CNRL site during 2013. No factors were significant ($P>0.10$).

Source	Transplanted Quadrats	Natural Recovery Quadrats
Surface	$1.81_{1,9.98}$	$0.80_{1,9.57}$
Peat	$0.08_{1,6.7}$	$0.92_{1,3}$
Peat*Surface	$0.01_{1,6.7}$	$0.01_{1,3.69}$

Table 3.6. Pearson correlation coefficients (*r*) and associated significance for the relationship between various vegetation attributes (spruce, Labrador tea and sedge survival, as well as total richness), and the environmental variables of depth to water, surface soil moisture, and soil temperature. No factors were significant (P>0.10). For water level, soil moisture and soil temperature, response data were grouped by those specific plots within which environmental measures were taken.

	Black Spruce		Labrador tea		Sedge[1]		Richness		Diversity	
Environmental Factor	*R*	*P-value*	*r*	*P-value*	*r*	*P-value*	*r*	*P-value*	*r*	*P-value*
					-------------------- *2012* --------------------					
Water Level Depth[2] (cm)	-0.26	0.74	-0.13	0.87	N/A	N/A	-0.73	0.27	-0.82	0.20
Soil Moisture (%)	-0.52	0.48	-0.29	0.71	N/A	N/A	-0.80	0.20	-0.89	0.11
Soil Temperature[2] (°C)	-0.12	0.88	-0.18	0.88	N/A	N/A	-0.89	0.12	-0.76	0.24
					-------------------- *2013* --------------------					
Water Level Depth[2] (cm)	-0.03	0.97	-0.19	0.81	-0.45	0.55	-0.48	0.52	-0.77	0.23
Soil Moisture (%)	0.56	0.44	0.32	0.71	0.64	0.35	-0.46	0.55	0.73	0.27
Soil Temperature[2] (°C)	-0.67	0.33	-0.53	0.47	-0.27	0.73	-0.44	0.56	-0.88	0.12

[1] Sedge survival was 100% in 2012 (and thus, not analyzed formally), then declined in 2013 allowing assessment in the 2nd year.
[2] Environmental data were grouped over those microplots containing temperature sensors, water pipes for depth sampling, and those plots where soil moisture was measured.

Table 3.7. Summary of ANOVA F-test results from the mixed model ANOVA evaluating plant community diversity in response to the peat application and surface roughness treatments at the CNRL site during 2013. Significance at *P*<0.05 is in bold.

Source	Transplanted Plots	Natural Recovery Plots
Surface	$1.02_{1,11}$	$0.75_{1,11}$
Peat	$2.14_{1,14}$	$\mathbf{4.75_{1,14}}$
Peat*Surface	$0.31_{1,14}$	$0.09_{1,14}$

Table 3.8 Summary of PerMANOVA analysis of fixed treatment effects on community composition in response to surface roughness and peat addition at the CNRL site during 2013. Significance at *P*≤0.05 is in bold.

Treatment	*P*-value	F-test
Rough	**0.05**	**1.85**
Peat	0.50	0.94
Rough*Peat	0.91	0.51

Table 3.9. Summary of Indicator Species Analysis of local plant species on the naturally recovering plots in the second establishment year (2013) at the CNRL site. Only species with significant indicator values (IV) are listed (minimum *P*<0.10).

			Roughness Treatment			Peat Inoculation Treatment		
Growth Habit	Duration	Plant Species	Preferred Class	IV	*P*-value	Preferred Class	IV	*P*-value
Sedge	Perennial	*Carex aquatilis*	Smooth	41.9	0.017			
Forb	Annual/Biennial	*Senecio congestus*	Smooth	63.1	0.038			
Forb	Perennial	*Potentilla palustris*	Smooth	30.1	0.058			
Shrub	Perennial	*Salix candida*	Rough	65.5	0.01			
Shrub	Perennial	*Salix lucida*	Rough	46.3	0.042			
Tree	Perennial	*Populus tremuloides*	Rough	63.9	0.01	No peat	58.2	0.032
Tree	Perennial	*Populus balsamifera*	Rough	43	0.022	No peat	40.5	0.044
Moss		*Ceratodon purpureus*	Rough	72.9	0.002			
Moss		*Polytrichum juniperinum*	Rough	56.9	0.005	No peat	47.1	0.064
Shrub	Perennial	*Ledum groenlandicum*				No peat	31.5	0.053
Liverwort		*Marchantia polymorpha*				No peat	69.4	0.001
Shrub	Perennial	*Salix exigua*				No peat	35.7	0.071

Table 3.10. Summary correlations between treatments, environmental factors, and key species, with each of the 3 axes arising from the NMDS ordination of 2013 vegetation responses and treatments. Species shown include provincially important species and those with *P*<0.10 based on the indicator species analysis.

		2013 Ordination Axes (% Variance Represented)		
Factors and Descriptions		1 (49.5%)	2 (22.5%)	3 (10.6%)
Treatment Vectors[1]				
R	Rock	0.555	0.453	
OW	Open Water	-0.730	-0.342	
S	Soil	0.690	0.322	
WD	Woody Debris	0.374	0.394	
Indicator species[2]				
Caraqu	*Carex aquatilis*			0.410
Cerpur	*Ceratodon purpureus*	0.411	0.450	
Ledgro	*Ledum groenlandicum*	0.322		
Marpol	*Marchantia polymorpha*	0.526	0.300	
Poljun	*Polytrichum juniperinum*	0.383		
Popbal	*Populus balsamifera*	0.450		
Poptre	*Populus tremuloides*	0.481	0.319	
Salcan	*Salix candida*	0.416	0.428	
Salluc	*Salix lucida*	0.470		0.306
Sencon	*Senecio congestus*		-0.431	
Orther Correlated Species[2]				
Carath	*Carex atherodes*		-0.374	-0.419
Carutr	*Carex utriculata*		0.324	0.691
Equflu	*Equisetum fluviatile*	0.519	0.363	
Salbeb	*Salix bebbiana*	0.325		-0.305
Taroff	*Taraxacum officinale*	0.344	0.310	

[1] Treatment vectors show trends in overlays of the ordinations at a cutoff *r* value > |0.30|.
[2] Key species show trends in overlays of the ordinations at a cutoff *r* value > |0.30|.

Table 3.11. Summary of ANOVA F-test results from the mixed model ANOVA evaluating plant community similarity and dissimilarity in response to the peat application, surface roughness and transplanting treatments at the CNRL site during 2013. No factors were significant (*P*>0.10).

Treatment	Similarity	Dissimilarity
Peat	$0.80_{1,7.73}$	$2.39_{1,8.5}$
Surface	$1.71_{1,9.69}$	$0.06_{1,3}$
Transplanting	$0.03_{1,11.2}$	$2.18_{1,3}$
Peat*Surface	$0.01_{1,7.73}$	$0.24_{1,13.5}$
Surface*Transplanting	$1.34_{1,11.2}$	$0.93_{1,3}$
Peat*Transplanting	$0.65_{1,10.2}$	$0.39_{1,4.41}$
Peat*Surface*Transplanting	$2.96_{1,10.2}$	$1.12_{1,10.1}$

Table 3.12. Summary of ANOVA F-test results from the mixed model ANOVA evaluating ground cover conditions against the peat and surface treatments. Data were assessed separately for transplanted and natural recovery plots at the CNRL site in 2013.

Treatment	Rock	Water	Soil	Debris	Litter
		--------------- Transplanted Plots ---------------			
Surface	$3.96^{*}_{1,9.12}$	$2.77_{1,13.7}$	$3.34_{1,3}$	$0.47_{1,11}$	$3.19_{1,10.5}$
Peat	$0.03_{1,3}$	$1.9_{1,7.73}$	$2.98_{1,6}$	$0.39_{1,3}$	$0.26_{1,12.8}$
Peat*Surface	$0.01_{1,5.08}$	$0.02_{1,7.73}$	$0.08_{1,6}$	$2.16_{1,11}$	$2.05_{1,12.8}$
		--------------- Natural Recovery Plots -------------			
Surface	$8.51^{**}_{1,4.01}$	$2.22_{1,11.4}$	$1.81_{1,9}$	$2.54_{1,22}$	$0.02_{1,3}$
Peat	$0.02_{1,3}$	$0.43_{1,8.4}$	$0.56_{1,9}$	$0.30_{1,3}$	$0.05_{1,3}$
Peat*Surface	$0.76_{1,5.26}$	$0.03_{1,8.4}$	$0.10_{1,9}$	$4.32_{1,22}$	$1.66_{1,3}$

**,* Significance indicated at $P<0.05$, and $P<0.10$, respectively.

Table 3.13. Chemistry of soil and water samples collected across the CNRL site and surrounding undisturbed fen in the first establishment year (August 2012).

Location	Na mg/L	K mg/L	Mg mg/L	Ca mg/L	PO_4 mg/L	SO_4 mg/L	pH	EC µS/cm	Mn mg/L	Fe mg/L	OM %	TP mg/L	TN mg/L	OC mg/L
Block 1	16.40	6.66	38.10	91.27	n.a.[1]	1.70	8.01	754	0.42	<DL[2]	2.29	0.56	5.77	
Block 2	12.49	7.99	12.54	32.00	n.a.	2.67	7.99	306	0.03	0.45	6.41	0.16	11.77	
Block 3	12.08	4.20	34.07	91.71	n.a.	1.52	8.31	714	0.39	<DL	2.55	0.54	4.73	
Block 4	22.04	3.22	26.28	64.29	n.a.	1.33	8.10	603	0.28	<DL	6.23	0.45	29.59	
NW Control	1.75	22.40	8.79	4.84	n.a.	0.89	6.27	134	0.13	0.49	1.51	0.46	10.27	
SE Control	20.78	10.98	31.39	66.05	n.a.	0.30	7.65	654	0.25	0.45	4.86	0.74	18.46	
Block 1	11.54	0.79	9.91	23.18	n.a.	5.56	7.09	281	0.66	<DL			0.93	35.81
Block 2	13.29	1.21	37.11	57.78	n.a.	6.82	7.59	575	0.52	<DL			0.94	31.63
Block 3	16.59	1.32	56.46	140.30	n.a.	77.46	7.51	1080	1.72	<DL			1.07	33.38
Block 4	1.94	0.63	1.40	5.93	0.42	0.43	4.08	86	0.12	0.66			2.13	103.20
NW Control	5.00	0.57	1.13	3.24	0.43	1.02	4.23	90	0.10	0.67			1.32	72.76
SE Control	4.78	1.86	39.42	62.76	n.a.	0.53	7.03	547	1.19	<DL			1.79	26.54

[1] Indicates not available.

[2] Indicates levels of Fe^{3+} below detection levels.

Table 3.14. Chemistry of soil samples at the CNRL site and surrounding undisturbed fen under various peat treatments in the second establishment year (August 2013).

Location	Treatment	pH	EC µS/cm	Ca mg/L	Fe mg/L	K mg/L	Mg mg/L	Mn mg/L	Na mg/L	Cl mg/L	PO_4 mg/L	SO_4 mg/L	OM %	TN %	TP %
Block 1	No peat	8.15	473	66.56	0.21	2.74	23.94	0.88	13.04	19.09	n.a.[1]	0.89	1.44	0.04	0.03
Block 1	Peat	7.27	421	41.37	0.42	4.47	21.35	0.03	42.92	83.07	n.a.	n.a.	80.74	1.85	0.04
Block 2	No peat	7.74	364	39.71	0.71	11.56	15.59	0.26	18.24	53.5	n.a.	0.46	36.76	0.9	0.05
Block 2	Peat	8.15	423	70.24	0.17	5.96	23.08	0.74	17.32	44.42	n.a.	0.46	7.82	0.19	0.03
Block 3	No peat	7.58	329	49.47	3.10	6.55	22.55	0.11	11.29	13.71	n.a.	0.61	52.55	1.36	0.05
Block 3	Peat	7.11	254	27.2	17.34	9.10	18.39	0.17	14.67	27.59	n.a.	n.a.	33.84	0.84	0.03
Block 4	No peat	7.66	299	36.48	7.80	5.34	20.24	0.10	12.5	13.76	n.a.	n.a.	73.22	1.96	0.05
Block 4	Peat	7.27	421	41.37	0.42	4.47	21.35	0.03	42.92	83.07	n.a.	n.a.	80.74	1.85	0.04
Northwest	Control	6.73	296	26.12	0.18	35.66	18.53	0.03	11.65	25.66	8.76	2.37	88.2	1.22	0.08
Southeast	Control	6.24	308	28.30	0.15	28.07	18.29	0.62	5.33	15.21	8.60	2.38	87.02	1.17	0.07

[1] n.a. indicates not available.

Table 3.15. Hydrocarbon chemistry of soil samples collected at the CNRL site and surrounding undisturbed fen in the second establishment year (October 2013).

Location	Treatment	Benzene	Toluene	Ethyl-benzene	Xylenes	F1 (C_{6-10})	F2 (C_{10}-C_{16})	F3 (C_{16}-C_{34})	F4 (C_{34}-C_{50})
Block 1	No Peat	<0.01	<0.01	<0.01	<0.02	<5	<10	<10	<10
Block 1	Peat	<0.01	<0.01	<0.01	<0.02	<5	<10	628	484
Block 2	No Peat	<0.01	<0.01	<0.01	<0.02	<5	<10	361	346
Block 2	Peat	<0.01	<0.01	<0.01	<0.02	<5	<10	<10	<10
Block 3	No Peat	<0.01	<0.01	<0.01	<0.02	<5	<10	<10	<10
Block 3	Peat	<0.01	<0.01	<0.01	<0.02	<5	<10	433	403
Block 4	No Peat	<0.01	<0.01	<0.01	<0.02	<5	<10	<10	<10
Block 4	Peat	<0.01	<0.01	<0.01	<0.02	<5	<10	351	287
Northwest	Control	<0.01	0.194	<0.01	<0.02	<5	<10	803	484
Southeast	Control	<0.01	<0.01	<0.01	<0.02	<5	<10	704	549

Table 3.16. Water level values showing relative height above sea level for various blocks across the CNRL site and within the surrounding undisturbed fen over two establishment years.

Location	June	July	August	September	October
			------------------------ 2012 ------------------------		
Block 1	639.63	639.62	639.85	639.87	639.93
Block 2	639.68	639.67	640.08	640.11	640.14
Block 3	639.79	639.76	639.81	639.82	639.86
Block 4	640.10	640.05	639.88	639.90	639.94
			-------- Northwest (upstream) --------		
100 m	639.89	639.82	639.61	639.63	639.65
150 m	639.93	639.86	639.63	639.65	639.67
			------- Southeast (downstream) -------		
150 m[1]	N/A	N/A	638.88	638.91	638.93
180 m[1]	N/A	N/A	638.64	638.65	638.67
			------------------------ 2013 ------------------------		
Block 1	639.92	639.87	639.91	639.92	640.00
Block 2	640.13	640.06	640.11	640.14	640.23
Block 3	639.91	639.84	639.85	639.92	639.99
Block 4	640.00	639.89	639.96	639.96	640.04
			-------- Northwest (upstream) --------		
100 m	639.63	639.56	639.59	639.65	639.67
150 m	639.63	639.59	639.62	639.65	639.71
			------- Southeast (downstream) -------		
150 m	638.91	638.87	638.90	638.98	639.01
180 m	638.68	638.59	638.65	638.68	638.71

[1] Water level pipes were installed in August 2012.

Table 3.17. Water depth values (cm below the soil surface) at various locations across the CNRL study site and within the surrounding undisturbed fen during each of the two study years.

	June	July	August	September	October
			------------------------- 2012 -------------------------		
Block 1	46.0	47.0	24.0	22.0	16.0
Block 2	45.0	46.0	5.0	2.0	-1.0
Block 3	23.0	26.0	21.0	20.0	16.0
Block 4	1.0	6.0	23.0	21.0	17.0
			-------- Northwest (upstream) --------		
100 m	17.0	24.0	45.0	43.0	41.0
150 m	15.0	22.0	45.0	43.0	41.0
			-------- Southeast (downstream) --------		
150 m[1]	N/A	N/A	24.0	21.0	19.0
180 m[1]	N/A	N/A	29.0	28.0	26.0
			------------------------- 2013 -------------------------		
Block 1	17.5	22.4	18.0	16.9	9.5
Block 2	0.0	7.4	1.8	-0.5	-10.0
Block 3	11.3	18.3	16.8	9.9	3.5
Block 4	11.3	21.6	15.0	15.3	7.0
			-------- Northwest (upstream) --------		
100 m	43.4	49.9	47.0	40.9	39.5
150 m	45.3	49.0	46.0	42.7	37.5
			-------- Southeast (downstream) --------		
150 m	21.5	24.9	22.0	14.4	11.0
180 m	25.0	34.0	28.0	25.3	22.0

[1] Water level pipes were installed in August 2012.

Table 3.18. Soil and water temperatures at the CNRL site over two establishment years.

Response	Block	June	July	August	September	October
		---------------------------- 2012	----------------------------			
Soil Temperature (^{0}C)	1	12.7	17.7	17.2	11.8	3.1
Soil Temperature (^{0}C)	2	10.5	16.8	17.0	10.9	3.0
Soil Temperature (^{0}C)	3	12.7	17.7	17.3	11.7	4.3
Soil Temperature (^{0}C)	4	12.8	17.9	17.2	11.9	3.0
		---------------------------- 2013	----------------------------			
Soil Temperature(^{0}C)	1	15.8	18.3	17.9	13.6	6.4
Soil Temperature (^{0}C)	2	15.4	16.9	16.4	11.9	5.5
Soil Temperature (^{0}C)	3	16.8	18.8	18.4	13.8	6.3
Soil Temperature (^{0}C)	4	16.2	18.1	17.5	13.4	6.3
Water Temperature (^{0}C)[1]	2	12.9	15.2	14.8	13.1	8.2

[1] Water temperature was examined in the second establishment year 2013.

Table 3.19. Vascular and non-vascular plant characteristics emerging from live peat grown within trays after 12 weeks.

Growth Form	Species	Mean Density (plants $tray^{-1}$)	Mean Cover (% $tray^{-1}$)	Total Frequency (% of trays)
Trees	*Picea mariana*	0.4 (±0.5)		15.0
	Populus tremuloides	2.5 (±5.3)		52.5
Shrubs	*Betula pumila*	0.8 (±0.3)		20.0
	Ledum groenlandicum	0.5 (±1.3)		17.5
	Vaccinium myrtilloides	2.3 (±4.7)		55.0
	Vaccinium oxycoccos	8.6 (±7.9)		92.5
Forbs	*Fragaria vesca*	0.6 (±2.5)		5.0
	Equisetum arvense	0.2 (±0.9)		25.0
Sedge	*Carex utriculata*	9.5 (±5.2)		100.0
Grass	*Beckmannia syzigachne*	1.1 (±2.5)		27.5
Mosses	*Polytrichum strictum*		6.8 (±14.4)	70.0
	Sphagnum girgensohnii		65.5 (±23.7)	100.0
Lichen	*Cladina rangiferina*		0.9 (±6.3)	27.5

Table 3.20. Summary of mean (±SD) indicator species plant cover (%) values at the CNRL site during the second establishment year in relation to roughness and peat treatment combinations.

Indicator Species		Smooth		Rough	
		No Peat	Peat	No Peat	Peat
Common Labrador tea	Ledgro	3.2(±1.1)	2.8(±1.8)	8.2(±1.2)	5.3(±0.8)
Water sedge	Caraqu	5.0(±4.2)	11.4(±1.4)	11.7(3.7)	7.9(±2.1)
Green-tongue liverwort	Marpol	6.4(±0.8)	3.5(±1.2)	18(±2.6)	7.7(±2.1)
Marsh ragwort	Sencon	6.1(±1.8)	7.1(±1.1)	4.7(±0.3)	1.7(±0.1)
Marsh cinquefoil	Potpal	0.3(±0.1)	2.0(±0.6)	0.0	0.4(±0.1)
Hoary willow	Salcan	1.6(±0.1)	2.0(±0.1)	11.7(±2.4)	4.9(±0.7)
Shining willow	Salluc	1.9(±1.1)	0.9(±0.6)	4.2(±2.8)	4.5(±1.6)
Narrow-leaved willow	Salexi	0.5(±0.7)	0.8(±0.2)	1.5(±0.1)	0.2(±0.1)
Trembling aspen	Poptre	1.7(±0.1)	0.5(±0.1)	4.9(±1.1)	2.9(±0.5)
Balsam poplar	Popbal	0.7(±0.1)	0.0	1.6(±0.5)	0.7(±0.1)
Fire moss	Cerpur	6.3(±0.3)	3.7(±1.1)	12(±2.3)	8.6(±2.6)
Juniper moss	Poljun	0.5(±0.1)	0.4(±0.1)	2.6(±1.3)	0.3(±0.1)

List of Figure

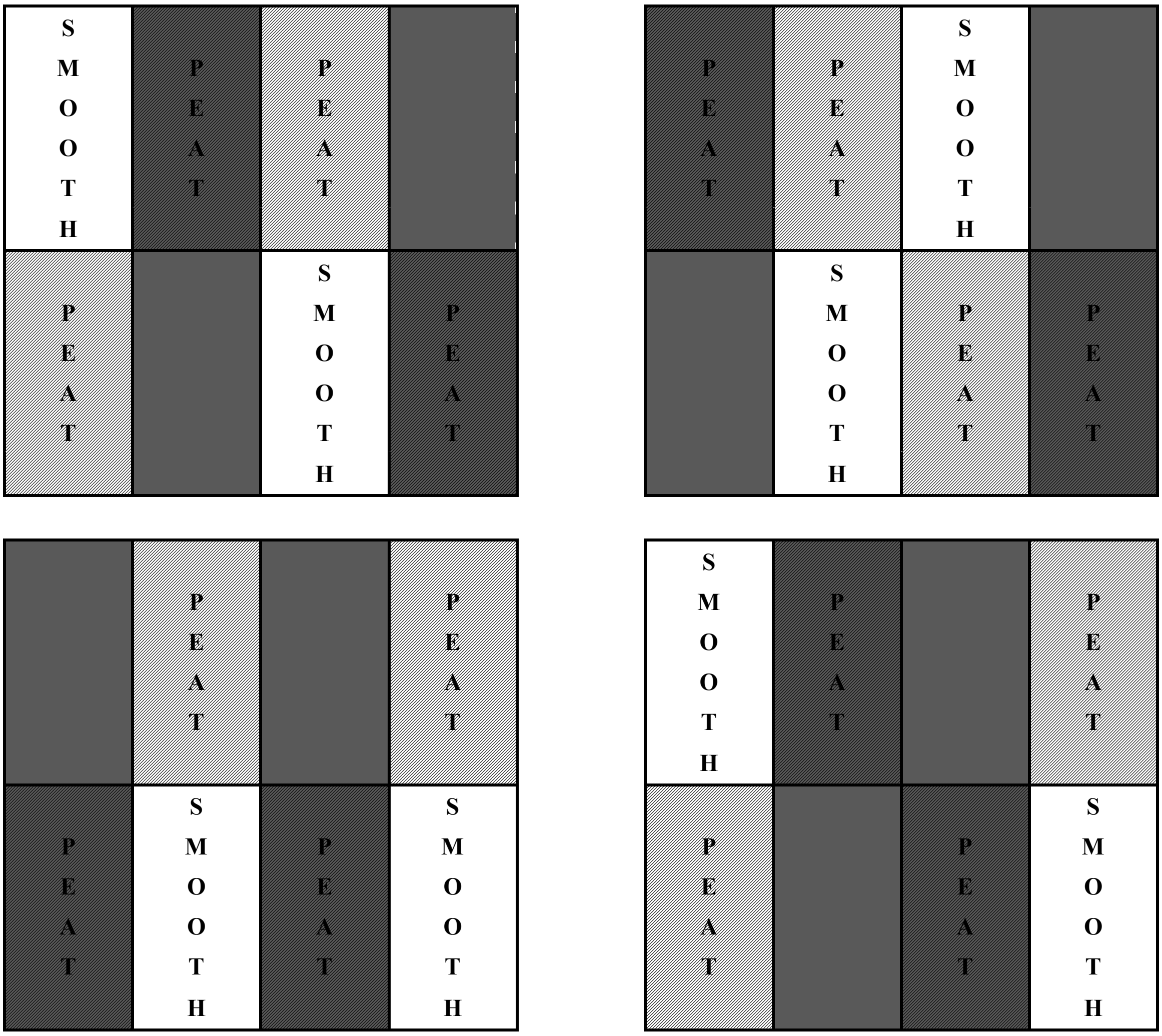


Figure 3.1. Layout of of mesoplot subplots (10 x 20 m) receiving application of peat amendment within macroplots (10 x 40 m) of 4 blocks at the CNRL study site near La Corey, Alberta.

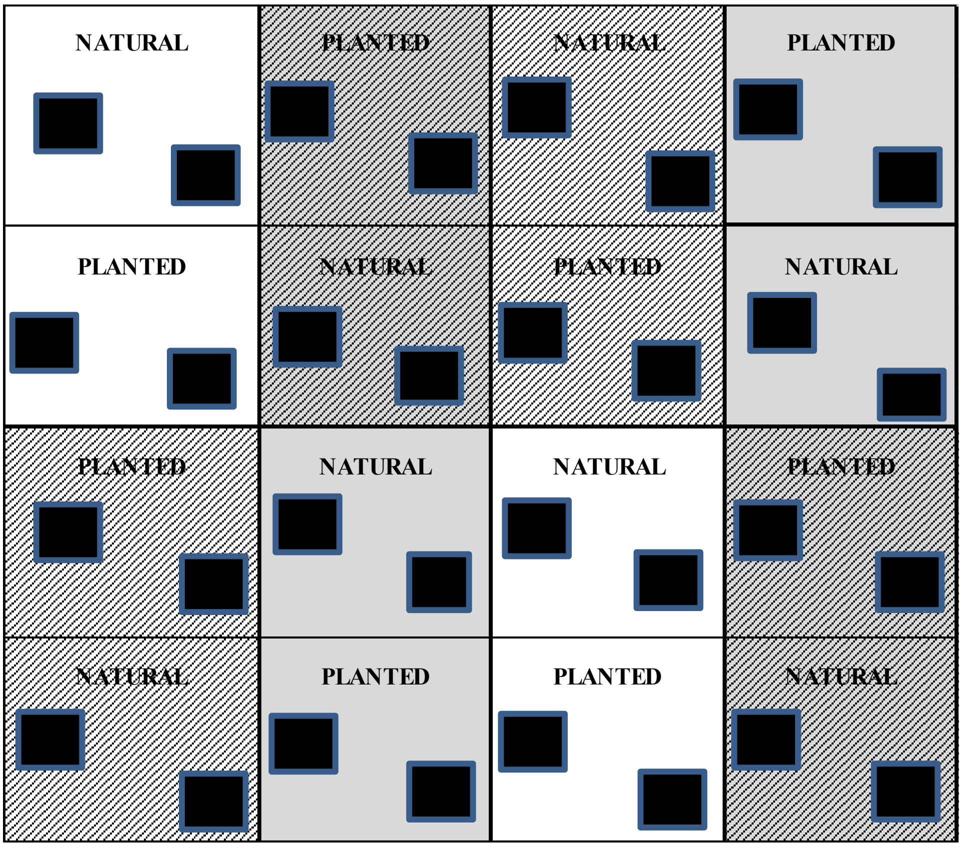
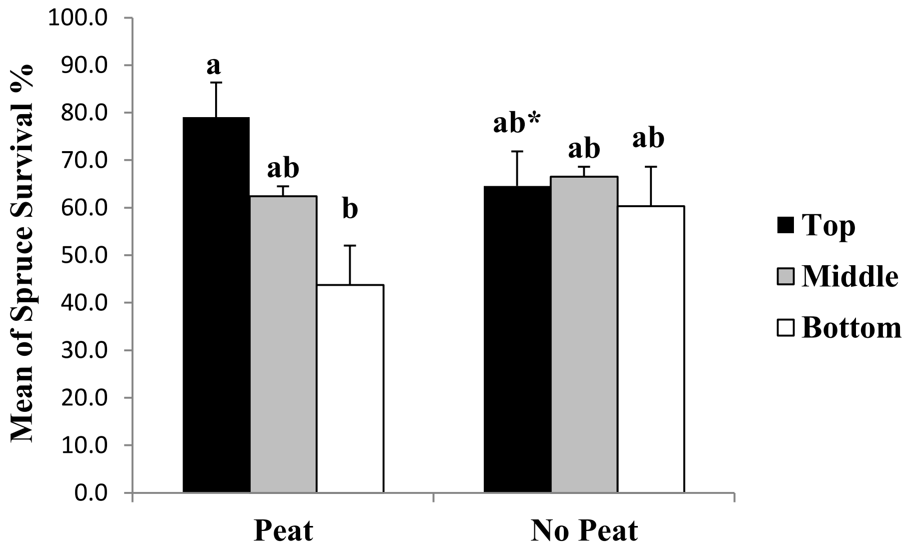


Figure 3. 2. Layout of two subsampling quadrats (1 x 1 m) within planted and natural microplots (10 x 10 m) at the CNRL study site near La Corey, Alberta.

Figure 3.3. Aerial photo of the CNRL study site illustrating the locations of water level measurement in the surrounding undisturbed fen.

A)



Mean of Spruce Survival %
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
a
ab
b
ab*
ab
ab
Peat
No Peat
Top
Middle
Bottom

B)

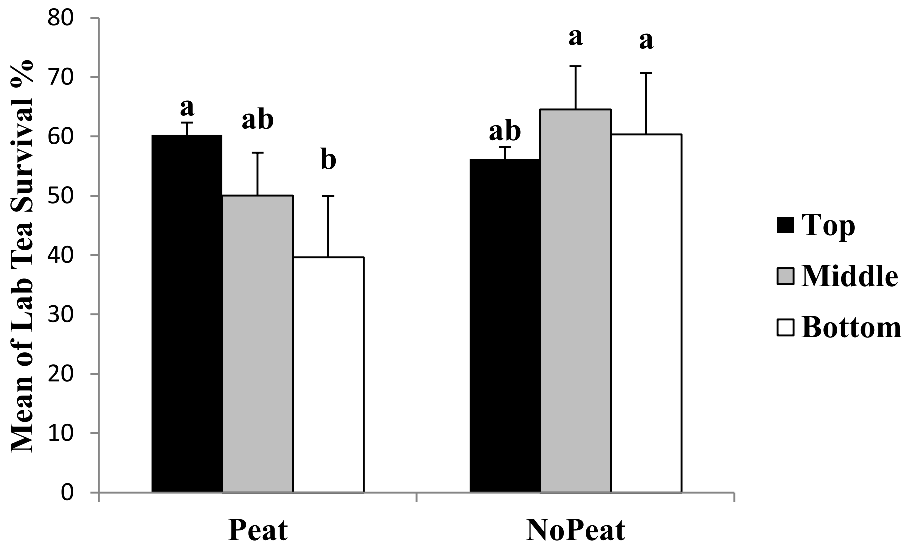


Figure 3.4. Comparison of A) black spruce survival, and B) Labrador tea survival, among micro-topographic positions within the rough treatments during 2012 at the CNRL site. Within a response, means with different letters differs, *P*<0.05. Treatment shown with a * differs from the top position of peat treated plots (*P*= 0.056). Data analysis performed on transformed data, but original means shown for clarity.

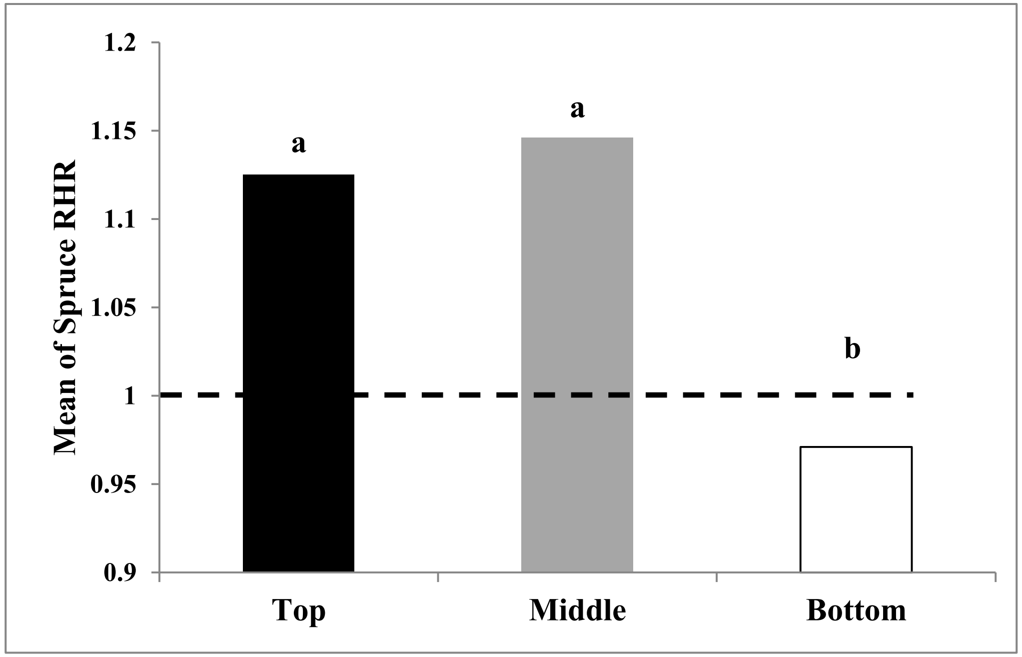


Figure 3.5. Comparison of black spruce relative height ratio (RHR) among various planting positions during the 2013 growing season at the CNRL site. Means with different letters differ, $P<0.05$. Data analysis performed on transformed data, but original means shown for clarity.

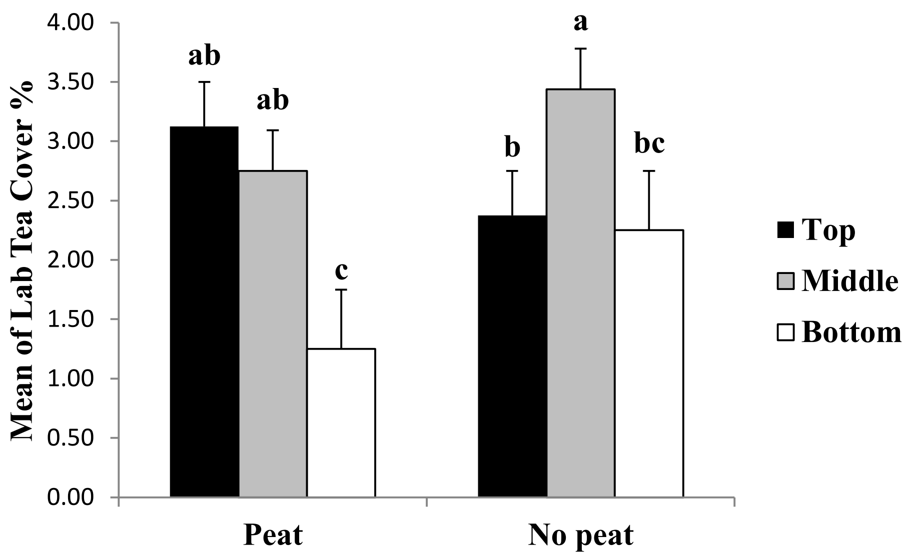
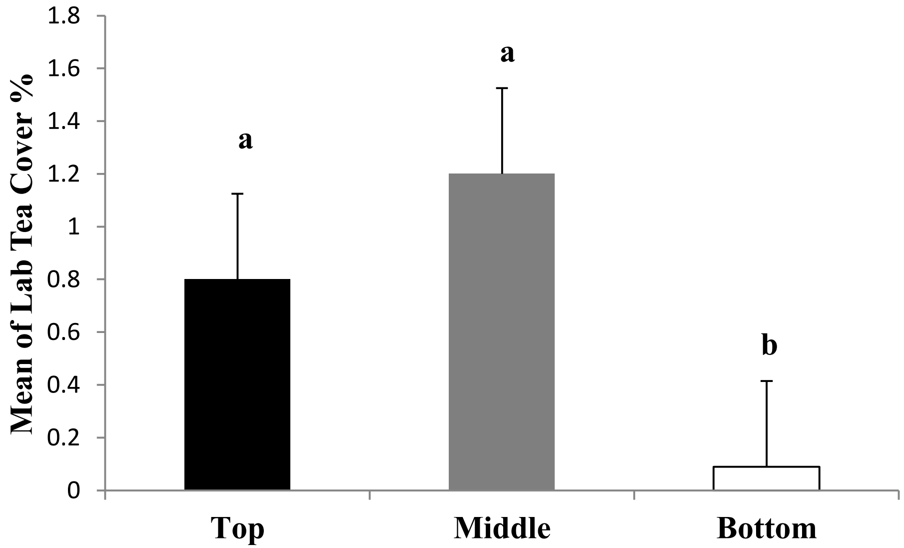


Figure 3.6. Comparison of Labrador tea cover across micro-topographic positions in plots receiving and not receiving peat in 2012 at the CNRL site. Means with different letters differ, $P<0.05$. Data analysis performed on transformed data, but original means shown for clarity.

A)


Mean of Lab Tea Cover %
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
a
a
b
Top
Middle
Bottom

B)

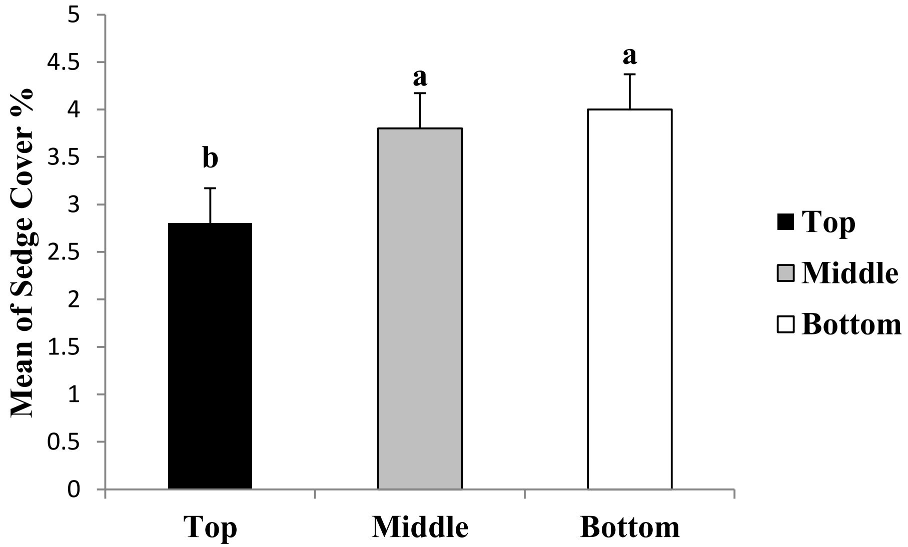
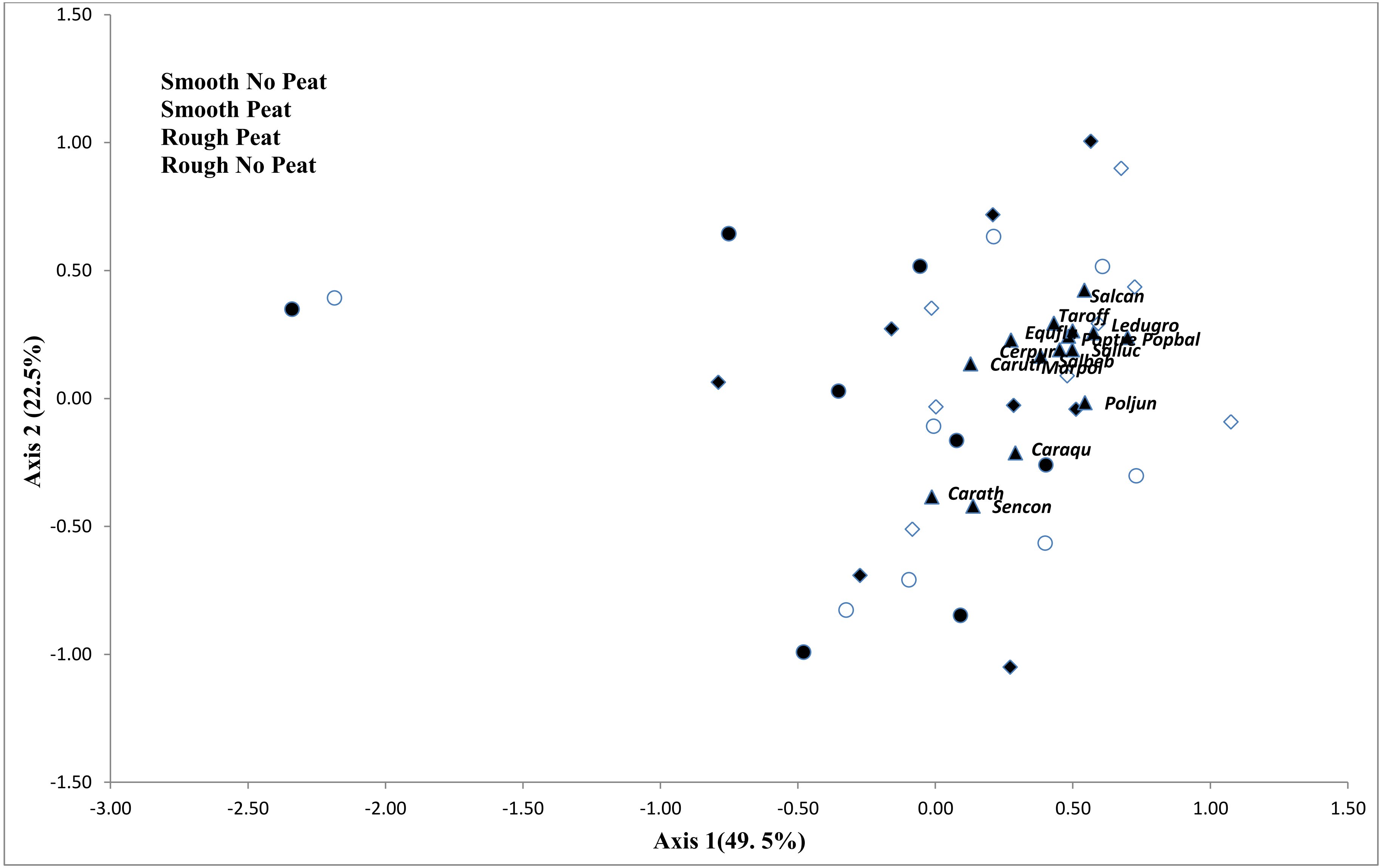
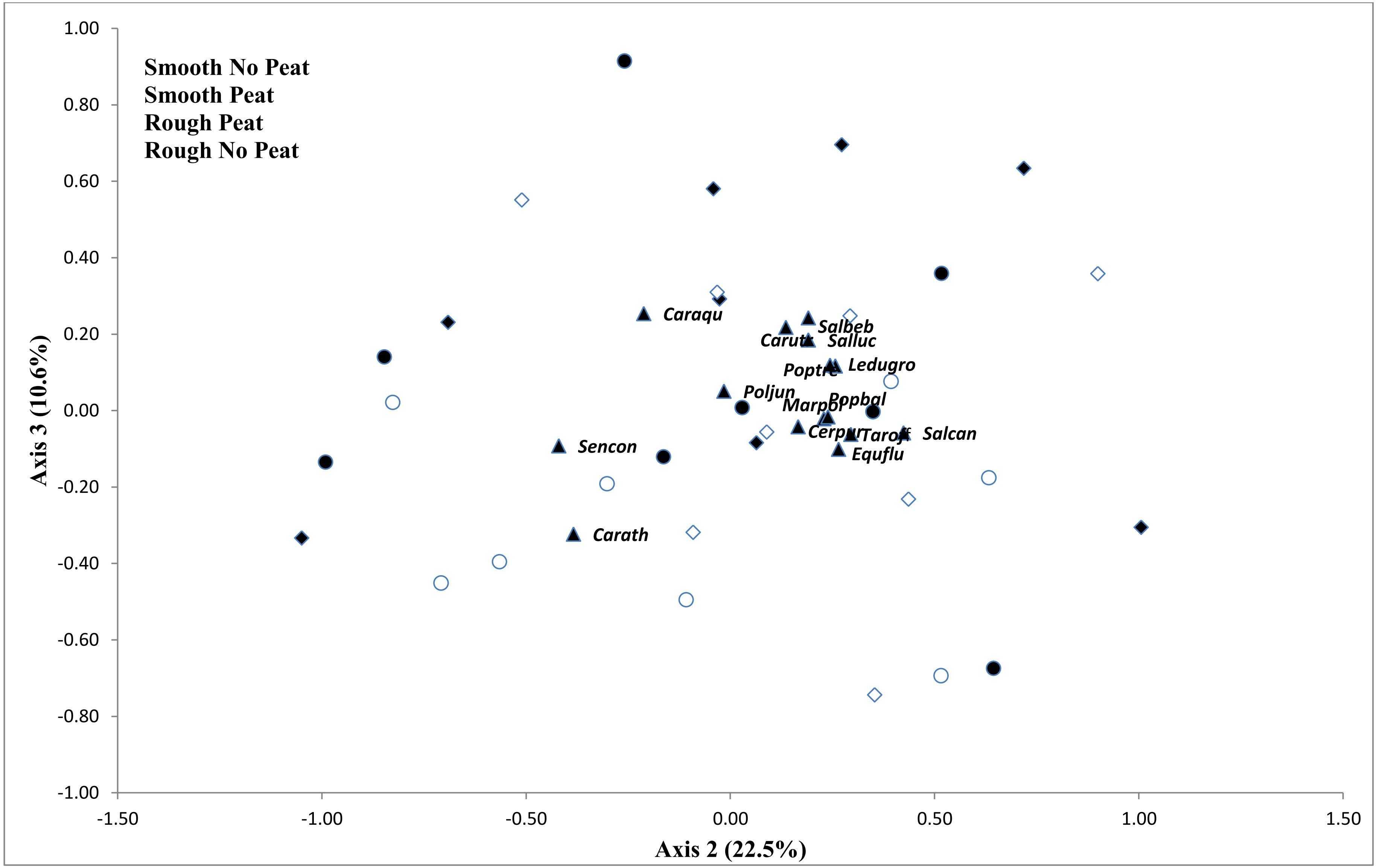


Figure 3.7. Comparison of the cover of A) Labrador tea and B) sedge, across micro-topographic positions within the rough treatments, as sampled in 2013 at the CNRL site. Within a response, means with different letters differ, $P<0.05$. Data analysis performed on transformed data, but original means shown for clarity.

A)


Smooth No Peat
Smooth Peat
Rough Peat
Rough No Peat
Salcan
Taroff
Ledugro
Equflu
Poptre
Popbal
Cerpur
Salluc
Carutr
Salbeb
Marpol
Poljun
Caraqu
Carath
Sencon
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-3.00
-2.50
-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Axis 2 (22.5%)
Axis 1(49. 5%)

B)



Smooth No Peat
Smooth Peat
Rough Peat
Rough No Peat
Caraqu
Salbeb
Carutr
Salluc
Poptre
Ledugro
Poljun
Marpol
Popbal
Cerpur
Tarof
Salcan
Equflu
Sencon
Carath
Axis 3 (10.6%)
Axis 2 (22.5%)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50

C)

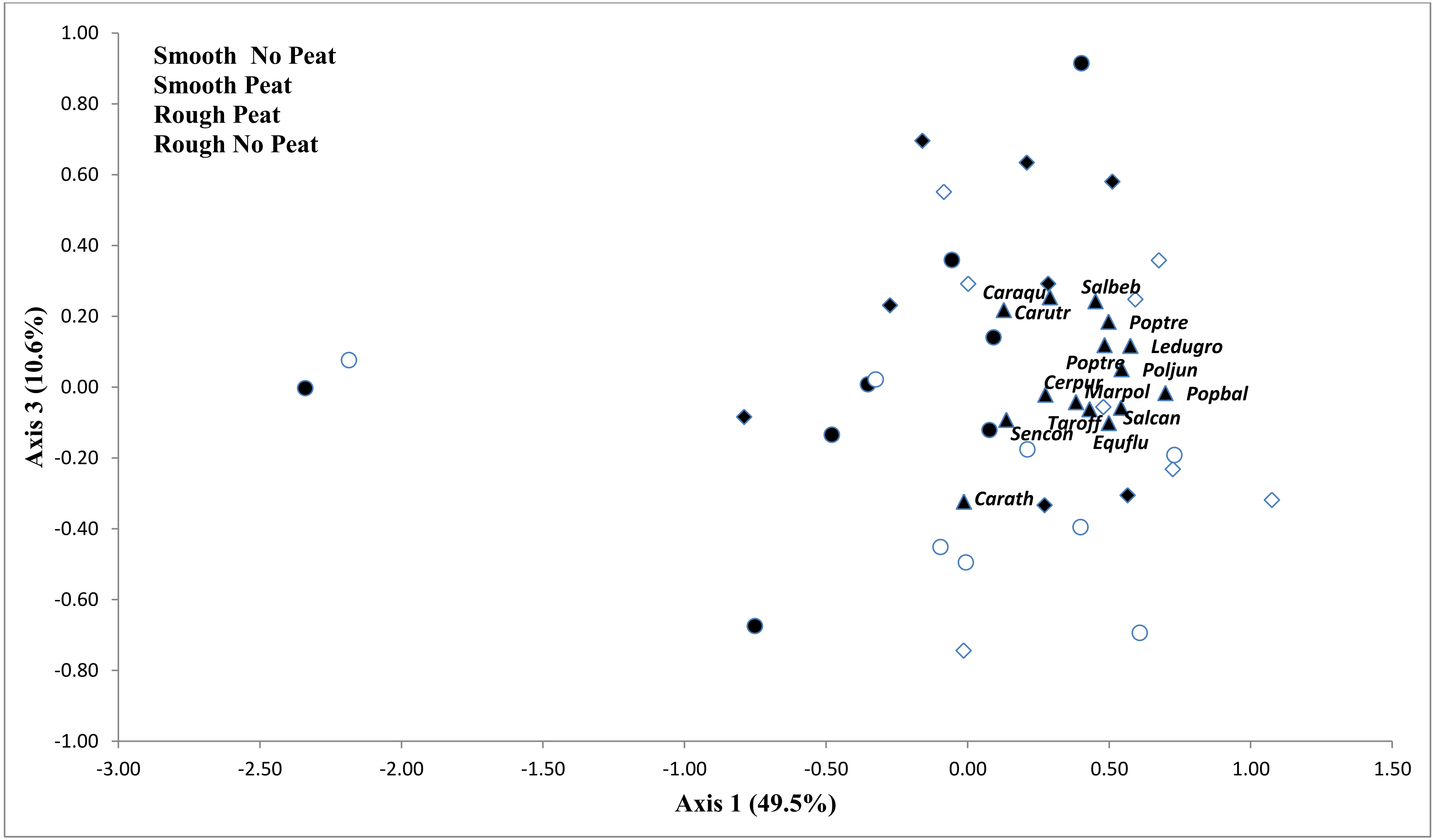


Figure 3.8. Results of the NMDS ordination analysis of plant composition data from the CNRL site in 2013. Treatment labels (solid and open symbols) indicate plots with and without peat, respectively. Species shown (triangle solid symbols) include popular and indicator plant species.

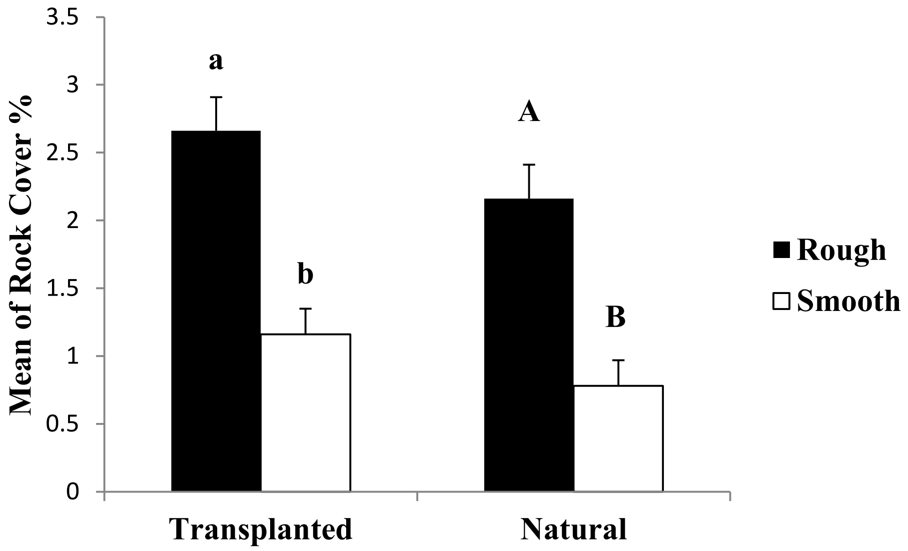


Figure 3.9. Comparison of exposed rock abundance between surface treatments on the natural and transplanted revegetation treatments in 2013 at the CNRL site. Within natural plots, means differ, $P<0.05$. Within transplanted plots, means differ, $P<0.10$. Data analysis performed on transformed data, but original means shown for clarity.

Figure 3.10. Photo of vegetation emergence from live peat in randomly chosen sampling trays grown under greenhouse conditions at the Vegreville Research Center (July 2012).

Chapter 4. SURFACE FEN REVEGETATION ON A MINERAL SUBSTRATE FOLLOWING PARTIAL ROAD REMOVAL

4.1. Introduction

Canada's boreal forest is a key habitat for many plant and animal species. In north-eastern Alberta, 40-50% of the boreal landscape is comprised of bog and fen peatlands (Vitt et al. 2011). Peatland ecosystems are characterized by a substantial accumulation of organic soil, and in boreal regions, mosses are often the predominant life form leading to peat -formation (Vitt and Wieder 2008).

The oil and gas industry within the Western Boreal Plains near Fort McMurray, Alberta, directly impacts the natural terrestrial surface cover, including fen peatlands, which comprise up to 65% of the landscape (Price et al. 2010). Roads and supporting infrastructure needed for oil/gas production and placed within fen peatlands require eventual removal, and revegetation of affected areas is required to achieve a land capability equal to that which existed prior to disturbance (Alberta Environment 2006).

The effectiveness of natural recovery to enhance species richness and plant densities in experimental wetlands has been shown in earlier studies (Smith and Kadlec 1983; McKnight 1992; Vivian-Smith and Handel 1996). Some revegetation approaches were attempted using transplanting of woody plant species (Carrera-Hernández et al. 2012). Other studies have examined fen revegetation by transplanting mosses and sedges (Chimner 2011). Sphagnum species (*S. fuscum, S. russowii*) were also found to have the greatest survival in areas having higher water tables (Waddington et al. 2003; Chirino et al. 2006), with an optimum water table level at or just below the soil surface (Graf and Rochefort 2010). Higher water tables have also been found to increase sedge survival, as Cooper and MacDonald (2000) found that *Carex aquatilis* transplants survived better at higher water table levels in a disturbed fen.

Other revegetation approaches have consisted of planting grasses, legumes and occasionally deciduous trees (*Populus* spp.) on the study pad area, although some have advocated removal of the entire pad leaving a large pond of open water (Native Plant Working Group 2001). Neither of these options returns the area to structural and functional similarity to pre-disturbance conditions. Future studies are required to determine whether the species appearing over time are responding to the hydrologic, physical, and chemical conditions of the substrate undergoing revegetation. Although peatland ecologists have long known the importance of the revegetation process, current understanding has not translated effectively into peatland restoration methodologies (Vitt et al. 2011).

Vegetation characteristics often indicate specific aspects of fen function (Mitsch and Gosselink 2000), and facilitate rapid assessment of fen health (Mack 2001; Simon et al. 2001; DeKeyser et al. 2003). Certain vegetation species are useful bio-indicators due to community features such as site fidelity, relatively high growth rates, ubiquity in fens, tolerances of a wide range of environmental conditions, and the relative ease of determining performance and survival in response to different treatments (Teels and Adamus 2002). Information on fen revegetation strategies is needed to guide industry activities, reclamation procedures, and subsequent monitoring to create a sustainable fen ecosystem that is consistent with the surrounding landscape.

Here I report on the results of a controlled field experiment conducted on a well-site access road initially constructed in a fen peatland, and now undergoing revegetation. Specific objectives of this study included the following:

(1) Evaluate the success of transplants (survival and/or growth) installed under contrasting peat amendment treatments;
(2) Quantify natural vegetation recovery in areas exposed to different peat application treatments;
(3) Characterize the composition of propagules present in archived stockpiled peat.

Information on the above objectives should assist ecologists with deciding which revegetation species and treatments to use to maximize fen revegetation, as well as understand the limitations associated with revegetating fen peatlands, such as hydrological and chemical features.

4.2 Materials and Methods

4.2.1. Study Site

This study site consists of a lease road undergoing removal near the JACOS Hangingstone oil sands collection facility situated 49 km southwest of Fort McMurray, Alberta (56º19´16.12´´ N; 111º39´00.34´´W; elevation approximately 550 m ASL). Oil sands are heavy (i.e. viscous) oils trapped in a sand layer under the ground. Unlike the open pit mines near Fort McMurray, the oil sands in this area are situated deeper underground, necessitating that other methods (i.e. *in-situ* removal) be used for oil extraction without open pit mining. One of the most common methods is "Steam-Assisted-Gravity-Drainage", or SAG-D. This is an extraction process whereby a pair of wells is drilled, with one carrying steam down into the oil sands deposit. Steam then heats the oil, causing it to flow into the second well, where it is collected and brought to the surface. The JACOS Hangingstone plant generates steam for injection and processes the oil by removing water. Oil is then transported to an upgrader facility for further processing. This particular plant is a “pilot” project intended to demonstrate that the oil deposit in the area can be successfully extracted. A larger "industrial-scale" plant will be built nearby in the next few years.

Fort McMurray has a borderline humid continental climate (Koppen climate classification *Dfb*) that is slightly warmer than a subarctic climate, with long, very cold winters and warm short summers. Temperatures average -19°C in January. Mid-summer (June through August) temperatures average 15.6 °C. Average annual precipitation for the area is 455.5 mm, with most falling during summer (June-August). Average annual snowfall is 155.8 cm over an 8-9 month period. About 70% of annual precipitation falls during April to August, with peak precipitation in June and July associated with intense convective thunderstorms.

The Central Boreal Mixedwood Natural Sub-region spans nearly 8° latitude. Modeled growing degree-days are fairly constant across the region, but are higher along the Athabasca River south of Fort McMurray. The study area contains intermixed glacial moraine, glacio-lacustrine, and organic deposits within the Central Mixedwood Natural Sub-region (Natural Regions 2006). Topographic relief in the area is generally limited, ranging from low hummocks to extensive plains. Soils are typically Brunisols or weakly developed Gray Luvisols on uplands over moderately fine textured parent material. Within depressional areas, soils are moderately well to poorly drained, and can range from Gleyed Luvisols or Gleyed Brunisols, to Gleysols, and more commonly, Organic soils. Mesisols are the dominant Organic soils occurring under fens and bogs, with Terric subgroups common as well. Fibric Mesisols, Fibrisols and occasionally Cryosols, are associated with bogs.

Vegetation within the study region is variable depending on several factors. Uplands contain a mix of aspen-dominated deciduous forest, mixed wood (aspen-white spruce) forests, and conifer forest of either white spruce or jack pine. Wet, poorly drained bogs or nutrient poor treed fens overlie almost half the area. The latter is the focus of this research. Black spruce stands tend to occupy moister portions of the landscape, with understories of Labrador tea, bog cranberry, peat moss, and feather moss, particularly on nutrient poor sites. Willow and dwarf birch shrublands with an understory of sedges and bluejoint (*Calamagrostis canadensis*) are also common wetland vegetation. Tamarack (*Larix laricina*), golden moss (*Tomenthypnum nitens*), forbs and sedges are associated with greater nutrient levels.

For this project, we utilized an access road traversing a treed poor fen to assess strategies for revegetation. This road was initially installed in 2000, but became redundant with other access routes, and as a result, is in the process of being decommissioned and reclaimed. The road is approximately 450 m long and was constructed by depositing clay fill over a textile liner placed directly on top of the existing peatland with no removal of peat. Fill was added until settling had ceased and the final grade was achieved. Peat depth adjacent to the road ranged from 1-2 m at the west end of the road to >5 m at the east end. Depth of road fill was also up to 5 m in the deepest sections. Vegetation on either side of the road is dominated by black spruce and tamarack with understories of Labrador tea, bog cranberry, willow and dwarf birch shrubs, together with sedges, peat and feather mosses.

4.2.2 Experimental Design and Treatments

Three steps were undertaken to test various strategies and facilitate revegetation. First, three portions of the road, each approximately 40 m in length, were lowered by about 0.8 m in January 2011, to reach the approximate water table and provide the hydric conditions needed for wetland re-establishment. The remaining road fill beneath the excavations was left intact, leaving a mineral substrate within the fen to be vegetated. Excavated areas were separated by a minimum of 20 m and served as blocks in the experimental design. Second, within each block, several treatments were undertaken to examine their effectiveness on vegetation recovery. Treatments included the following:

1) Natural recovery (no transplants or other propagule introduction);
2) Transplanted plugs of "cotton grass" (*Eriophorum vaginatum L. var. spissum*), commonly found within the adjacent fen (n= 9/plot or 108/block; N= 324);
3) Transplants of the shrub Labrador tea (*Ledum groenlandicum*) and black spruce (*Picea mariana*) (n= 9/plot or 108/block; N=324 of each species);
4) Live peat fragment transfer application (1-2 cm thick) consisting of the transfer of plant tissues contained within live peat (removed from the adjacent fen) containing various mosses and dwarf shrubs, such as bog cranberry;

In addition, each of the above 4 treatments was conducted with and without the addition of composted (i.e. dead) peat as a surface soil amendment, resulting in a total of 8 different treatments. Applications of composted peat were done using material salvaged from the fen during other construction projects in the area and stockpiled for several years. This peat amendment was applied to half of the treatments to assess the effect of alterations to soil quality during revegetation (Fig. 4.1).

Treatments were applied over the three fill-removal blocks in a completely randomized design, with 6 replicates of each treatment combination in each block (N=48 plots per block). Within each of the 3 blocks, plots were laid out in 3 rows (with treatments further stratified to 2 reps within each row), had dimensions of 1 m x 1 m, and were separated by a 1 m buffer between plots. Treatments were randomized within rows (i.e. n=2 of each treatment per row). All transplanting was completed by July 8th, 2011.

4.2.3 Transplanted Species and Natural Vegetation Assessments

The fate of all transplants was evaluated in each of 2012 and 2013 during early August. Survival was evaluated as the number of individual transplants alive in every plot (Appendix 2.1).

Composition of vegetation in all plots was completed August 11-15, 2013. Each plot was visually assessed for percent cover by species (Appendix 2.2). Unknown species that occurred only once in the plots were not included in statistical analyses (Shaughnessy 2010). Species difficult to identify were brought to the lab for identification. All nomenclature for vascular plants and mosses followed Moss (1983) and Jonson (1985), respectively.

In 2013, an additional 4 off-road control transects were established to assess the condition of the existing fen vegetation (for comparative purposes) (Appendix 2.3). Of these control transects, 2 were about 10 m upstream of the road (i.e. south), while 2 were downstream (i.e. north) of the road. Control plots were laid out in a systematic manner from a random starting point, and permanently marked to facilitate relocation (Fig. 4.2.). The purpose of these control transects was to estimate undisturbed conditions in the adjacent fen, and thereby provide a benchmark condition to determine how different the original fen was from the experimental treatments within the study site. Transect sampling was done by placing 1 x 1 m quadrat frames and nested 0.5 x 0.5 m quadrats, every 20 m along 148 m long transects, for a total of 16 quadrats assessed at the south and north transects, respectively. Quadrats were used to sample shrubs, small trees and sedge cover, and smaller quadrats were used for measuring herbaceous vegetation, mosses and lichens.

4.2.4 Environmental Measures

Environmental data on soil physical and chemical characteristics, hydrocarbon values, and moisture content, soil and water temperature, and water level (below ground level and relative to a standardized elevation) were assessed.

In August 2012, soil samples were randomly taken from each block at the JACOS road site and the surrounding fen, and analyzed for Na^{+}, K^{+}, Mg^{2+}, Ca^{2+}, PO_4^{3-}, SO_4^{2-}, pH, electrical conductivity, Mn^{3+}, Fe^{3+}, OM, TP and TKN. Within each block we collected six soil cores (5 cm diameter by 5 cm deep) from the natural recovery quadrats without peat addition. Sub-samples were bulked after first removing litter and any shoots. Additionally, six soil cores from the adjacent fen North and South of the road were extracted and combined within location for analysis. Samples were stored in plastic bags and kept in a cooler until sent for analysis to the Natural Resources Analytical Laboratory (NRAL) at the University of Alberta. In total, six bulked samples were analyzed from the JACOS site.

During August 11-15, 2013, soil samples were taken again from block 3 (blocks 1 and 2 were flooded), from plots both with (6 plots) and without live peat (6 plots) application. To sample the peat and non-peat plots separately, we took four cores in each plot, which were then bulked to a total of two samples: one from peat added, and one in the quadrats without peat. To sample the soil in the surrounding fen, eight soil cores per transect (four on each side) were removed and bulked for analysis.

Soil hydrocarbon content was analyzed in 2013 at the JACOS site and adjacent fen. For this assessment four soil cores were bulked for each of the two soil samples (one with peat, and one without peat) for block three, as well as the control fen transects (northwest control and south control). In total, six samples were stored in bottles until analyzed.

Metal concentrations (Ca^{2+}, Fe^{3+}, K^{+}, Mg^{2+}, Mn^{3+}, Na^{+}) in soil were analyzed using a Spectra AA 880 Atomic Absorption Spectrometer (Varian Australia Pty Ltd, Mulgrave, Victoria, Australia). The anion SO_4^{2-} was analyzed with a DX600 ion chromatogram (Westco Scientific Limited, *Sunnyvale*, *California*, *USA*). The anion PO_4^{3-}, total phosphorus (TP), and total nitrogen (TN) and potassium (TK), were evaluated using a Model 200 Smartchem Discrete Wet Chemistry Analyzer (Westco Scientific Limited, Sunnyvale, CA, USA). We determined organic C content using the loss on ignition method (Dean 1974). Electrical conductivity and pH were measured using an AR20 pH/conductivity meter (Fisher Scientific, Sunnyvale, CA, USA). Gravimetric moisture content was analyzed by weighing before and after drying (Carter 2001). Concentrations of benzene, toluene, ethylbenzene, and xylene were determined using a HP5890 Series II GC Gas Chromatograph (GMI Inc., Ramsey, MN, USA), while polyaromatic hydrocarbons were determined using an Agilent 7890A GC Gas Chromatograph (GMI Inc., Ramsey, MN, USA), consistent with the petroleum hydrocarbon monitoring protocol (Canadian Council of Ministers of the Environment 2001). All soil preparation and analyses were done by technicians at the University of Alberta Natural Resources Analytical Lab (NRAL) and the Kaizen Lab in Calgary, AB.

Groundwater monitoring wells were installed at the JACOS site before the study was initiated. Nine shallow groundwater wells were installed on the road (three per block). In addition, four wells were installed on the North side of the road in the adjacent fen, and another four on the South in the original fen (Fig. 4.3). Wells were constructed of perforated PVC piping 6.5 cm in diameter and capped at the end. A screening sock was placed over the perforated end to allow water to enter the well but reduce sediment and debris. Water level data were collected over the summer of 2012 and 2013 to determine the height of the water table across the study site (both road and surrounding fen).

Fen ground water samples were collected in August 2012 from the monitoring wells, placed in 200 ml plastic bottles, and transported to the NRAL facility at the University of Alberta for analysis. Three water samples were taken from each block on the road, and bulked to block level for analysis. In addition, four samples were taken on the north control transect and bulked, with another three taken from the south control and bulked. All water samples were tested for major anions and cations, as well as other key physical and chemical properties (Na^{+}, K^{+}, Mg^{2+}, Ca^{2+}, PO_4^{3-}, SO_4^{2-}, pH, electrical conductivity, Mn^{3+}, Fe^{3+}, NPOC and TN). The laboratory equipment used for the water samples was the same as for soil samples. Soil temperature was assessed with HOBO PROv2 data loggers (Onset Corporation, Bourne, MA, USA). Sensors were installed in June of 2012, and used to track temperatures through October of 2013. Soil digital temperature sensors monitored temperatures every hour at 5 cm depth within a randomly chosen plot within every block. Soil temperature probes were removed at the end of the growing season each year. Finally, HOBO data loggers in block 3 also measured water temperature to 0.2 ºC precision. Measures of water depth were obtained in each water-well on a monthly interval throughout the growing season (June through October, inclusive).

4.2.5. Examination of Stockpile Peat Composition

Samples of stockpiled peat were randomly taken from stockpiles on the berm around the JACOS pad. One hundred liters of composted peat was collected and subsequently grown out in the ALES greenhouse at the University of Alberta. Prior to analysis, samples were homogenized in a large container, and then spread evenly over 24 trays (54 cm long x 28 cm wide) in September 2013. Trays were kept at 22 ºC and at 16 hours daytime photoperiod, watered regularly to keep them moist, and assessed for any evidence of plant or bryophyte establishment for 16 weeks.

4.3. Data Analysis

Prior to analysis, all data were checked for normality and homogeneity of variances using Proc UNIVARIATE in Statistical Analysis Software v9.3 (SAS 9.3 Inc. 2012). Normality of residuals was tested using a Shapiro-Wilks test, and equality of variances was subsequently tested using a Levene's test in Proc GLM. Survival data were found to be non-normal for transplanted data ($P<0.05$). Data were analyzed separately by year (2012 and 2013) to assess immediate and near-term responses to the experimental treatments.

Survival data were subsequently analyzed using mixed model ANOVA for only one of the three species (cotton grass) due to extreme mortality of both black spruce and Labrador tea. A two-staged process was used to find the best model to determine fixed effects of peat addition (Anderson 2001). To evaluate overall effects of peat treatment, survival data were averaged in every row of every block and mixed model ANOVA of block, row within block, peat and peat by block was analyzed. Next, mixed model ANOVA of block, row by block, peat, peat by block and peat by row by block was tested. To assess peat effects on herb survival, results from the mixed model ANOVA with the smallest AICC were used.

To evaluate environmental conditions, species richness (i.e. vascular plant species plus bryophytes) and Shannon-Weiner diversity within plots, the fixed effects of revegetation treatment and peat addition on the cover of water, rock, soil, woody debris, litter, species richness and diversity were tested using a mixed model ANOVA. A multi-staged process was used to find the best model to determine fixed effects of peat addition and revegetation treatment. Data were averaged over all treatments in every row of every block. Next, data were analyzed using peat, revegetation treatment and peat by revegetation treatment as fixed effects, with block and all interactions of block (and rows therein) with the fixed effects as random. To find the smallest AIC_C of the mixed model ANOVA, results of different combinations were considered (Appendix 2.4).

Additionally, relationships between environmental variables (observed water levels, soil moisture and temperature) and the survival of transplanted cotton grass, as well as overall richness and diversity, were evaluated using Pearson correlations with Proc CORR in SAS 9.3. For this analysis, correlations were performed for response data only from those plots where environmental measures were directly taken. Environmental and vegetation data were also correlated separately for each of 2012 and 2013 using independent data, except soil moisture, which was only assessed in 2012. Due to the limited sample sizes (n=3), significance was set at $P<0.10$.

Treatment effects on detailed plant community composition during natural recovery of vegetation were examined using multivariate analytical techniques. To assess the specific effects of treatment impacts on late summer (August) vegetation and bryophyte composition, a permutation-based MANOVA (PerMANOVA) was used to determine whether composition differed among the fixed effects of revegetation treatment and peat application (Anderson 2001). PerMANOVA was performed using the Sorensen distance measure, with all analyses conducted in PC-ORD v5 (McCune and Mefford 1999). Significance was based on the proportion of randomized trials with an indicator cover greater than or equal to the observed cover value (McCune and Grace 2002) based on Equation 1:

$$P = (1+\text{number of runs} \geq \text{observed}) / (1+\text{number of randomized runs}).$$

This was supplemented with an indicator species analysis (ISA), which allows direct testing of correlation between individual plant species and fixed treatment classes using 4999 permutations (McCune and Grace 2002).

Finally, to assess patterns in compositional responses across all plots, nonmetric multi-dimensional scaling (NMDS) ordination was performed on all species level data from August 2013 using a Sorensen distance measure in PC-ORD (McCune and Grace 2002). This process facilitates visual separation among treatment classes, and can be followed up with correlations of these patterns (and resulting explanatory axes) with external environmental variables. Real data were run 250 times, as were the randomized data for the Monte Carlo test. A total of 500 iterations were used to obtain the final stable solution. Axes scores were interpreted based on Pearson correlations with all species found across the site, with $|r| > 0.24$ considered to be significant.

A multi-staged process was used to evaluate the extent to which plant community composition within the experimental plots had progressed towards the original fen condition, including in relation to the fixed effects of revegetation treatment and peat addition. As a first step, the similarity and dissimilarity between each of the 24 plots was compared to the composition in the original fen. This assessment used only the cover of all herb and bryophyte species, and averaged cover data across the 1 x 1 m plots [(i.e. all 6 replicates within each block, and across the 6 quadrats within the 2 upstream transects (i.e. 3 from each transect) and 2 downstream transects (i.e. 3 from each transect)]. This was done to maintain the same 'sample area size' for each experimental unit, which is necessary when comparing similarity between areas. Similarity was subsequently calculated using Jaccard's similarity coefficient (Jaccard 1912) using Equation 2:

$$S_J = a/(a + b + c), \text{ where}$$

a = number of species common to (shared by) quadrats,

b = number of species unique to the first quadrat,

c = number of species unique to the second quadrat.

In addition, dissimilarity was calculated using a Bray-Curtis index (Bray and Curtis 1957) using Equation 3:

$$Dij = \Sigma\, |Xij - Xik| / \Sigma(Xij + Xik),$$

j, *k* = individuals in each of the comparing sample,

Xij and Xik are the number of quadrats containing species i at site j or k,

|Xij - Xik|=absolute difference,

(Xij + Xik)=sum.

Finally, the number of establishing plants and cover of moss and lichens, emerging from the stockpiled peat, were recorded in samples grown in the greenhouse at the University of Alberta.

4.4. Results

4.4.1. Transplant Performance

As noted earlier, only cotton grass survival could be evaluated because of widespread mortality of black spruce (100 %) and Labrador tea (98.8 %). By the end of 2012 cotton grass survival was not affected by peat application, which ranged from 39.5 % (±34.4) on peat treated plots to 28.4 % (±29.1) on those without peat addition ($F=0.71_{1,2.71}$; P=0.47). In 2013, cotton grass again remained similar in survival, with 18.5 % (±36.6) survival on peat treated plots, and 11.8% (±24.5) in areas without peat ($F=0.22_{1,8.01}$; P=0.65). Finally, correlation of the survival and environmental data showed that transplanted cotton grass was negatively related to water level depth across the three experimental blocks in 2013 ($P<0.10$) (Table 4.1). In other words, plots with more water, as represented by a shallower water table, had lower cotton grass survival.

4.4.2. Plant Community Response

Species richness was not affected at the end of 2012 or 2013 by either the peat application or revegetation treatments. Richness ranged from 0 to 5 species per $1m^2$ on natural recovery plots over the two establishment years (2012-2013), and from 0 to 7 and 0 to 6 species m^{-2} within peat treated plots during 2012 and 2013, respectively. Richness was affected by a peat by revegetation interaction ($P<0.01$) but only in 2012 (Table 4.2). Richness was greatest within the fragment treated plots also receiving peat amendment, but only in comparison to natural recovery plots receiving peat (Fig. 4.4). Richness did not differ among revegetation treatments on plots without peat addition. Finally, correlation of the community and environmental data showed that species richness was negatively related to water level depth (i.e. increasing sub-surface water presence) across the three experimental blocks in 2013 ($P<0.10$) (Table 4.1).

Overall diversity ranged from 0 to 1.373 and 0 to 1.550 on plots with and without peat amendment in 2012, respectively. In 2013, diversity ranged from 0 to 0.941 and 0 to 1.038 on plots without and with peat amendment. Species diversity was not affected by peat application at the end of 2012 or 2013, nor by revegetation treatment and its interaction with peat (Table 4.2).

MRPP tests and comparison of species composition among the fixed effects of revegetation treatment and peat application, revealed significant differences in species composition among the revegetation and peat addition treatments after the first (2012) establishment year, and only the revegetation treatment after the second (2013) year (Table 4.3). Closer examination of the MRPP tests indicated the herb treatment was of greatest dissimilarity from the other treatments in both years, with limited differences between the woody, fragment and control treatments; the lone additional effect was a difference between the fragment and woody treatments in 2013 (Table 4.3).

The NMDS analysis of plant community data at JACOS in 2012 resulted in a two-dimensional ordination solution with a final stress of 4.51 in 2012. However, there was no solution found in 2013, although the P-value for a single axes (1-dimensional) solution was nearly significant ($P=0.059$). Correlation of the treatment and plant community attributes with the ordination axes from 2012 indicated that diversity, together with the cover of *Typha latifolia* and *Carex utriculata*, were correlated with axes 1 and 2 (Table 4.4). In addition block, peat and richness, together with the cover of several shrubs (*Vaccinium*, *Betula* and *Salix*) and *Sphagnum* mosses, were correlated only with axis 1. The associated indicator species analysis revealed that several mosses were positively associated ($P<0.05$) with the revegetation treatment (fragment) and peat amendment (Table 4.5). In addition, a variety of shrubs, forbs, sedges and grasses were positively related to revegetation treatment ($P<0.10$). Select shrubs and grasses were associated with peat amendment ($P<0.10$) (Table 4.5). Finally, the similarly analysis revealed that the various treatments tested on the road remained highly dissimilar in composition compared to the adjacent fen.

4.4.3. Environmental Conditions

Ground cover components did not differ in response to peat addition (Table 4.6). However, the cover of soil, open water and litter were affected by the interaction of revegetation and peat treatments in both years (Table 4.6). Additionally, litter cover varied between plots with different revegetation treatments (Table 4.6). Litter cover was greatest within the natural recovery plots lacking peat amendment compared to most other plots during 2012, including all of those receiving peat amendment (Fig. 4.5A). One year later, litter cover was once again greatest within natural recovery plots without peat addition, but only relative to woody transplant plots lacking peat addition (Fig. 4.5B).

Exposed water generally ranged from 40 to 50% among plots. Plots receiving an active revegetation treatment (woody, herb or fragment transplant) and no peat had more water than those control plots without peat addition (Fig. 4.5C). Open water did not differ among revegetation treatments on peat treated plots in 2012 (Fig. 4.5C). One year later, exposed water remained similar across revegetation treatments on peat treated plots, but water was greater on woody transplant plots without peat, but only relative to fragment and natural recovery plots lacking peat compared to those receiving fragments or no treatment (Fig. 4.5D).

Bare mineral soil did not differ across revegetation treatments on peat treated plots in the first establishment year (Fig. 4.5E). In contrast, within plots not receiving peat, exposed soil was greater within the natural recovery plots compared to the woody and herb plots in 2012 (Fig. 4.5E). One year later exposed soil was generally lower compared to the previous year, and soil did not differ among any plots (Fig. 4.5F).

In general, compared to the undisturbed fen in 2012, the JACOS road site had elevated levels of Ca^{2+}, Mg^{2+}, $SO4^{2-}$, Na^{+}, and Mn^{3+}, but lower levels of K^{+}, total nitrogen, potassium, phosphorus and organic matter (Table 4.7). Compared to the undisturbed fen in 2013, the JACOS road site had elevated levels of Ca^{2+}, Mg^{2+}, $SO4^{2-}$, Na^{+}, and Cl^{-}, and lower levels of K^{+}, total nitrogen and organic matter (Table 4.8). Soil pH values were greater on the road site compared with the undisturbed fen over the two years, and trace amounts of PO_4^{3-} and Fe^{3+} were detected in the soil during 2012 and 2013 (Tables 4.7, 4.8). Electrical conductivity within the road site and undisturbed fen were close to intermediate levels over the 2 years, but slightly greater on the road (conductivity= 314-559 µs/cm^{-1}, vs 136-209 µs/cm^{-1} in the adjacent fen).

Comparison of plots with and without peat amendment in 2013 showed soil samples taken from those plots lacking peat had greater levels of SO_4^{2-}, Na^{+}, Ca^{2+}, Mg^{2+}, Mn^{3+}, K^{+} ,Cl^{-} and electrical conductivity (Table 4.8). In contrast, soil organic matter, levels of Fe^{3+}, total nitrogen and phosphorus were greater within the peat addition plots during 2013 (Table 4.8).

Chemical properties of the ground water tended to differ between disturbed and undisturbed areas (Table 4.7). Concentrations of total nitrogen, Na^{+}, Ca^{2+}, Mg^{2+}, Mn^{3+}, and K^{+} were greater in water samples taken from the road. Trace amounts of PO_4^{3-} and Fe^{3+} were detected in both the disturbed and undisturbed fen. Water pH values were greater on the road site in comparison with the adjacent undisturbed fen over the two years. Electrical conductivity ranged from fresh water in the original fen (EC<100 µs cm^{-1}) to intermediate (EC =100-900 µs cm^{-1}) levels on the JACOS road.

Limited hydrocarbons were found within the soil samples (Table 4.9). Polyaromatic hydrocarbon F2 (C_{10}-C_{16}) values tended to be greater within plots not receiving peat compared to those with peat addition. However, hydrocarbons F3 (C_{16}-C_{34}) and F4 (C_{34}-C_{50}) were typically lower within plots lacking peat compared to those with peat addition (Table 4.9).

Elevational water levels indicate a generalized direction of water flow from SW to NE across the study site (Table 4.10). Water level on the south was higher than on the north due to the road effect (Appendix 2.5). Blocks one and two on the road had the highest water table relative to the ground surface over both study years (Table 4.11). Water levels also tended to increase at the site over the two years, but slightly decreased over time within the surrounding fen.

Average soil temperatures were 14.0 (± 4.2) ^oC and 14.4 (± 2.9) ^oC during the summer of 2012 and 2013, respectively. Average water temperature was 11.3 (± 1.6) ^oC. Detailed results are outlined in Table 4.12.

Finally, testing of the stockpiled peat for living propagules in the greenhouse indicated no germination after 4 months (Fig. 4.6). Thus, the potential of the composted peat to contribute directly to vegetation recovery appeared limited.

4.5. Discussion

4.5.1. Transplant Performance

Most of black spruce and Labrador tea plants were dead after the first (2012) establishment year. Excess moisture on the road would have altered soil structure and depleted O_2 levels, inducing anaerobic decomposition of organic matter, and reducing iron and manganese (Kozlowski 1991). This in turn, may have not only reduced growth, but also led to the widespread mortality of trees and shrubs. Soil inundation with water has previously been shown to inhibit root formation, branching, and growth in spruce and Labrador tea, as well as influence mycorrhizae, which may lead to decay of the root system (Kozlowski 1991). Unlike sedges, woody plants are less tolerant of prolonged flooding due to the different plant genotypes and rootstocks they are comprised of. Oxygen entry into woody plants occurs largely through lenticels on the stem (Coutts and Armstrong 1976). Blocking of lenticels inhibits oxygen diffusion from an anaerobic medium to roots, thereby preventing oxidation of the rhizosphere (Coutts and Armstrong 1976). Additionally, flooding of soil may adversely affect the distribution of woody plants because it can inhibit seed germination (Kozlowski 1991). Ultimately, to successfully use shrubs and trees for revegetating fens, a more effective drainage system may be required to improve plant survival and manage water supply on the road surface, which may include leaving the road at a higher elevation.

Unlike the woody transplants, cottongrass had the most favorable survival of all 3 species tested in both establishment years. However, cottongrass survival was not affected by peat amendment, although cover responses for this species suggested that the most favorable growth occurred on the study blocks with the least flooding. Reduced flooding would lead to more optimal moisture and aeration, and sufficient oxygen for root respiration (Blom and Voesenek

1996). Similar to that for woody species, flooding is a common stress factor for cottongrass, and affects growth via the slow diffusion rate of gases in water (Hoffman et al. 1971). Flooding results in low oxygen concentrations in submerged plant tissues, and hence a decreased respiration rate (Armstrong et al. 1991). However, cottongrass is more tolerant of flooding than black spruce and Labrador tea, possibly due to a greater capacity for oxygen absorption by aerial shoot tissues and diffusion out of roots (Coutts and Armstrong 1976). Cotton grass might also respond to soil anaerobic conditions by increasing the storage of oxygen within roots to survive periods of flooding (Coutts and Armstrong 1976).

Crawford (1989) also noted biochemical adaptations in plants to tolerate flooding, such as the accumulation of malate as the primary product of anaerobic respiration in select sedge species (i.e. *Carex rostrata*). In the absence of this process, toxic accumulation of ethanol can occur in response to increased flooding. Crawford hypothesized that tolerant plants survive flooding by homeostatic mechanisms that limits production of ethanol by shunting carbon into nontoxic organic acids such as malic acid. The malate might be linked to other substrate level phosphorylations or further oxidized with an alternative electron acceptor. Malate oxidation and ATP generation facilitates plant respiration. Finally, cottongrass may survive better under the same restrictive conditions such as low temperature and nutrient limitations, due to the high nutrient immobilization capacity associated with abundant biomass production. Previous studies have shown cotton grass can allocate proportionally more biomass and nutrients to slowly decomposing storage organs (stems and leafs sheaths) compared to rapidly decomposing organs (leaf blades) (Silvan et al. 2014). However, overall cotton grass survival decreased with increasing water level in the current study. Understanding transplanted sedge responses to flooding is essential for the revegetation management of fen ecosystems, and additional research is needed to identify strategies to improve the flood tolerance and/or survival of this species (Van der Valk et al. 1999).

Peat application did not have any benefits on cottongrass over the two years, suggesting the benefits of peat application for this sedge are lacking. In the absence of peat addition benefits, these results suggest the cost of peat application does not appear to be justified (Silvan et al. 2004). Moreover, the greenhouse evaluation of peat composition supports the notion that the stockpiled peat used here had no vegetative or seed propagules present to promote plant establishment.

High water tables on the road study blocks appear to be strongly regulated by water flow from and into the adjacent fen. This effect was likely responsible for the widespread spruce and Labrador tea mortality, as well as reduced sedge performance, especially within the most flooded block (block one on the west end). Moreover, long-term monitoring of cottongrass transplants and water levels should be conducted to fully evaluate the benefits of transplants for achieving fen revegetation. Due to the abundant water on the road, these results indicate it may have been better to leave the road elevated, or instead make provisions for water to move through the road, prior to attempting revegetation. Future research could also work to finding effective water pathways using drainage systems. Finally, additional revegetation approaches using other plant species that are more tolerant of flooding should be studied, including other species of cottongrass and *Carex spp.*.

4.5.2. Plant Community

Total species richness responded to the interaction of peat and revegetation treatment. Not surprisingly, richness was greater in plots receiving composted peat and the addition of live peat fragments. Supplementing these plots with organic matter increased species richness, primarily due to the presence of more shrubs, grasses and mosses. Species that were specifically associated with peat addition during revegetation included *Vaccinium myrtilloides, Alopecurus aequalis* and *Sphagnum spp.* As the composted peat did not cause the development of living plant propagules according to the greenhouse investigation, this suggests that these species simply preferred the modified soil conditions associated with peat treated plots.

This study confirms the usefulness of a peat amendment in facilitating fen revegetation. Improvements in seed bed and soil quality (nutrient and water status) may have favored establishment of these species. Peat acts as a thermal barrier keeping the surface soil cooler in the day and warmer at night (Price et al. 2003, Petrone et al. 2004). In addition, peat improves growing conditions for plants by increasing humidity under the peat (Groeneveld et al. 2007).

In contrast, diversity did not respond to the peat amendment and revegetation treatments, and other factors such as water depth appeared to be responsible for the variation in diversity among plots (Flinn et al. 1995). Overall diversity did not change in response to peat and revegetation. Plots that were mostly underwater ranged from only 1 to 4 different species. Such communities were often tall forb-dominated (*Typha latifolia*), sometimes with the inclusion of a short sedge (*Carex canescens*), the aquatic duckweed *Lemna minor*, or the tall statured grass *Beckmannia syzigachne* (Appendix 3.2). These species dominated the disturbed road, possibly due to their ability to thrive in the poor nutrient conditions of the soil and water environment found there (Thormann et al. 1999). Borgmann-Ingwersen and Jonas (2003) noted that the cover of forbs such as *Typha latifolia* was usually greatest where there are seep influences or standing water present. Duckweeds are adapted to various aquatic conditions due to their plant anatomy (roots are short and slender organs used to position and stabilize the plant in the water), and their additional tolerance of a wide range in pH (Smith 2013). Sedges such *Carex canescens* and

Eriophorum vaginatum tolerate open water, suggesting they have high phenotypic plasticity (Peterson et al. 2012). Boe and Wynia (1985) indicated American sloughgrass can survive in a wide range of salinity and water temperature. In contrast, plots closely associated with mosses (e.g. *Sphagnum grigrnsonii*, *Polytrichum strictum*) may have reflected soil modification through either peat fragment addition or composted peat amendment, because peat protects the mineral soil and retains moisture (Kangas et al 2014). In addition, compost might help to provide nutrients for plant roots. Although early pioneering species of vegetation such as *Equisetum arvense* can colonize treated sites early on, an excess of water has been shown to decrease species establishment (Zhang et al. 2011). Species possessing a tolerance of extensive fresh water flooding (Hook 1984) were widespread at the JACOS road site after two establishment years.

Overall, species richness and diversity were generally greater in plots treated with peat but which remained non-flooded, particularly in comparison to those undergoing recovery in heavily flooded conditions without peat addition. The marginal increase in both these responses appeared to be the direct result of the additional species installed during the transplantation process. Cheng and Coleman (1990) noted that cotton grass established rapidly during the early period after revegetation, and its presence improves habitat for the initiation and growth of other vascular plants and mosses. These results lend support for the notion that transplantation of cottongrass is an effective strategy to facilitate succession towards the end goal of revegetating and restoring these communities. Across all plots, we did not find any evidence for the presence of non-native plants designated provincially as a noxious weed in Alberta, presumably due to the inability to germinate in water.

4.5.3. Environment

Based on the chemistry results of hydrocarbon content, no or minimal hydrocarbon contamination was detected on the road nor within the surrounding undisturbed fen. This supports the notion that minimal contamination occurred during drilling and reclamation, and therefore should not limit fen revegetation attempts. In contrast, hydrologic conditions varied substantially across the road over the two years. This road corridor is acting like a dam (Fig. 4.2), creating greater flooding in all blocks of the road, with even higher water levels in the more western blocks - closer to the source of the water movement. Increased floodwater levels, coupled with more uncertainty in water levels, may make it harder to restore vegetation within the disturbed road (Smith and Medeiros 2013). To remedy this, improved drainage is needed over or under the road to allow water to flow more continuously across the area of the fen.

The road also has greater minerals, such as calcium (Ca), magnesium (Mg), sulfate (SO_4) and sodium (Na), in both the associated soil and water. In general, grasses and shrubs are more sensitive to variation in mineralogy (González-Alcaraz et al. 2014). Variation in plant species composition may also be linked to marked differences in soil salinity (higher on the road). Yuan et al. (2012) noted that soil salinity made the greatest contribution to species abundance and composition. For example, *Typha latifolia* is tolerant of high salt levels (Jesus et al. 2013). High salts impose both ionic and osmotic stresses on vegetation, resulting in an excess accumulation of sodium (Na) in plant tissues (Hasegawa et al. 2011). Additionally, if Na levels are high or not balanced with Ca and Mg, organic fen soils can be negatively affected. The positively charged Na cations attach to the negatively charged clay particles in the soil, causing the soil to be sticky when wet, and hard and impermeable when dry, both of which reduce rooting opportunities for vegetation (Ahmad and Sharma 2008). However, lower levels of potassium (K), total nitrogen and organic matter within soils on the road might contribute to the lower level of species richness (Jiping et al. 2006). Finally, the JACOS road also had a greater soil pH, which is known to favor herbs rather than mosses (Bragazza and Gerdol 1996).

4.6. Conclusion

Revegetation of this road allowance was impacted by flooding, and to a lesser extent, revegetation treatment, but not peat amendment. Vitt et al. (2011) also concluded that successful establishment by sedges and shrubs on mineral soils was not enhanced by amendments. Transplanting woody species (black spruce and Labrador tea) had poor success due to widespread mortality. However, cottongrass transplanting met with considerable success, and led to increased species richness. Negative relationships were found between water levels and cottongrass survival, and ensuing species richness. In general, flooding decreased both transplanted species survival and species richness. Vitt et al. (2011) also stated that water levels are key components of early wetland development.

Final revegetation of the JACOS road should be undertaken by including a drainage system that allows provisions for water to move through the road to decrease flooding. In addition, a greater use should be made of species with high tolerance to flooding, such as cotton grass or *Carex spp.*

Despite the positive signs of cottongrass establishment within the herb revegetation treatments, all treatments remained a long-way from recovery, with no treatment combinations having a species composition similar to that of the adjacent fen. Thus, communities undergoing revegetation will likely remain dissimilar from that of the undisturbed fen for many more years.

In addition, Vitt et al. (2011) suggested that early wetland plant communities can possibly be reconstituted on the rewetted mineral soils but observed that it is not known whether these communities will ultimately resemble adjacent natural communities. Further work is needed to develop innovative management strategies to facilitate revegetation in environments such as this. Over the long-term, peatland revegetation guidelines should be revised to reflect these and other results, although long-term monitoring is likely necessary to fully assess the effectiveness of the revegetation treatments undertaken here.

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Table 4.1. Pearson correlation coefficients (r) and associated significance for the relationship between various vegetation attributes (cotton grass survival, total richness and species diversity), and the environmental variables of depth to water, surface soil moisture, and soil temperature. Significant correlations at P≤0.10 are bolded. For water level, moisture and soil temperature analysis, data were grouped by block.

Environmental	Cotton Grass Cover		Richness		Diversity	
Attributes	*r*	P	*r*	P	*r*	P
			------------------ 2012 --------------------			
Water Level Depth (cm)	-0.89	0.30	-0.96	0.18	-0.98	0.11
Moisture (%)	-0.33	0.79	-0.88	0.31	-0.61	0.59
Soil Temperature (^{o}C)	0.81	0.40	0.19	0.88	0.58	0.60
			------------------ 2013 --------------------			
Water Level Depth (cm)	-0.99	**0.07**	-0.99	**0.08**	-0.91	0.28
Moisture[1] (%)	N/A	N/A	N/A	N/A	N/A	N/A
Soil Temperature (^{o}C)	0.72	0.49	0.87	0.33	0.76	0.44

[1] Moisture was analyzed only in the first establishment year due to the flooding block 1 and 2 in the second establishment year.

Table 4.2. Summary of ANOVA F-value results from the mixed model ANOVA evaluating native community richness and diversity in response to peat application and the revegetation treatments at the JACOS site during 2013. Significant responses at P≤0.01 are in bold.

Treatment	Richness		Diversity	
	2012	2013	2012	2013
Revegetation Treatment	$0.54_{3,54}$[1]	$2.76_{3,6}$	$1.07_{3,6}$	$1.00_{3,64}$
Peat	$0.51_{1,2}$	$0.51_{1,50}$	$4.62_{1,2}$	$1.00_{1,64}$
Peat*Revegetation Treatment	$\mathbf{4.23_{3,54}}$	$1.31_{3,50}$	$1.20_{3,24}$	$1.00_{3,64}$

[1] Subscripts indicate numerator and denominator degrees of freedom for each F-test, respectively.

Table 4.3. Summary of the MRPP results of fixed treatment effects on community composition in response to revegetation treatments and peat addition at the JACOS site in each of 2012 and 2013.

Treatment (& Comparison)	T	A	P
		---------------- 2012 ----------------	
Peat	-2.54	0.0114	0.0296*
Revegetation Treatment	-30.07	0.235	<0.0001****
Woody vs Herb	-22.3	0.233	<0.0001****
Woody vs Fragment	-1.47	0.01	0.084
Woody vs None	-0.127	0.001	0.307
Herb vs Fragment	-23.2	0.252	<0.0001****
Herb vs None	-22.6	0.246	<0.0001****
None vs Fragment	-1.06	0.008	0.128
		---------------- 2013 ----------------	
Peat	-1.197	0.0065	0.106
Revegetation Treatment	-5.5	0.0526	0.00057***
Woody vs Herb	-8.743	0.0882	<0.0001****
Woody vs Fragment	-2.779	0.0339	0.025*
Woody vs None	0.137	-0.0017	0.39
Herb vs Fragment	-3.044	0.03	0.018*
Herb vs None	-5.001	0.0523	0.0027**
None vs Fragment	-0.041	0.0005	0.32

****,***,**,* Indicates significance at P<0.0001, P<0.001, P<0.01 and P<0.05, respectively.

T = test statistics (difference between groups); A - chance-corrected within group agreement; P - probability evaluating differance due to the chance.

Table 4.4. Summary correlations between treatments or key species, with each of the 2 axes arising from the NMDS ordination of 2012 vegetation responses. Species shown include provincially important species and those with a P value <0.10 based on the indicator species analysis.

		2012 Ordination Axes (% Variance Represented)	
Factors and Descriptions		Axis 1 (87.4%)	Axis 2 (11.5%)
Treatment Vectors[1]			
B	Block	-0.464	
P	Peat	0.240	
Vegetation Responses			
R	Richness	-0.259	
D	Diversity	-0.243	0.286
Indicator Species[2]			
Erispi	Eriophorum spissum		-0.977
Vacmyr	Vaccinium myrtilloides	0.283	
Typlat	Typha latifolia	-0.917	0.312
Sphgir	Sphagnum girgensohnii	0.384	
Other Correlated Species[2]			
Betpum	Betula pumila	0.342	
Carutr	Carex utriculata	-0.630	0.284
Salcan	Salix candida	0.342	

[1] Treatment vectors show trends in overlays of the ordinations at a cutoff r value > |0.24|.

[2] Indicator and other correlated species show trends in overlays of the ordinations at a cutoff r value > |0.24|.

Taoble 4.5. Summary of Indicator Species Analysis of local plant species at the JACOS site in each of 2012 and 2013. Only species with significant indicator values (IV) are listed (P<0.10).

Growth Habit	Longevity	Plant Species	Revegetation Treatment			Peat Amendment		
			Preferred Class	IV[1]	P-value	Preferred Class	IV[1]	P-value
			------------------ 2012 --------------------					
Mosses		Sphagnum spp.	Fragment	45.0	0.0002	Peat	20.40	0.0240
Forbs	Perennial	Typha Latifolia				No Peat	64.00	0.0008
Forbs	Perennial	Equisetum Arvense	Woody	19.3	0.0692			
Shrubs	Perennial	Vaccinium Myrtilloides				Peat	9.70	0.0110
Grasses	Perennial	Alopecurus Aequalis				Peat	8.60	0.0540
Shrubs	Perennial	Ledum Groenlandicum	Woody	8.3	0.0570			
Sedges	Perennial	Eriophorum Spissum	Herb	86.1	0.0002			
Grasses	Perennial	Calamagrostis Canadensis				No Peat	12.50	0.0814
			------------------ 2013 --------------------					
Sedges	Perennial	Eriophorum Spissum	Herb	39.4	0.0002			
Forbs	Perennial	Typha Latifolia	Woody	30.2	0.0442			
Grasses	Annual	Beckmannia Syzigachne	None	9.3	0.0868			

Table 4.6. Summary of ANOVA F-value results from the mixed model ANOVA of ground cover conditions against the peat and revegetation treatments at the JACOS site during 2013.

Treatment	Litter		Open Water		Soil	
	2012	2013	2012	2013	2012	2013
Revegetation Treatment	**$4.65_{3,6}$**[1]*	**$3.37_{1,6.2}$***	$1.79_{3,6}$	$1.79_{3,6.03}$	$0.37_{3,6}$	$1.00_{3,6}$
Peat	$5.93_{1,2}$	$0.76_{1,3.82}$	0.071,3.8	$1,14_{1,3.82}$	$0.20_{1,2}$	$1.00_{1,2}$
Peat*Revegetation Treatment	**$6.69_{3,54}$*****	**$4.33_{3,53.9}$****	**$6.16_{3,48}$****	**$6.16_{3,48}$***	**$10.71_{3,54}$*****	**$5.55_{3,54}$****

*, **, *** Indicates significance at P≤0.10, P≤0.05 and P≤0.001 respectively.

Table 4.7. Chemistry of soil and water samples taken at the JACOS site and surrounding fen in the first establishment year (August 2012).

Location	Na^{+} mg/L	K^{+} mg/L	Mg^{2+} mg/L	Ca^{2+} mg/L	PO_4^{3-} mg/L	SO_4^{2-} mg/L	pH	EC µs/cm	Mn^{3+} mg/L	Fe^{3+} mg/L
					-------- Soil Chemistry --------					
Block 1	13.71	1.38	13.27	36.11	n.a.	17.28	8.21	323	0.87	<DL
Block 2	13.71	1.83	16.62	43.21	n.a.	9.86	8.33	314	0.61	<DL
Block 3	17.59	1.7	26.07	72.61	n.a.	41.01	8.52	559	0.31	<DL
North	5.67	13.1	2.38	5.03	n.a.	5.61	4.26	136	0.14	<DL
South	7.54	4.68	8.63	15.83	n.a.	3.21	3.96	181	0.44	1.09
					-------- Water Chemistry --------					
Block 1	11.67	2.9	48.41	104.71	n.a.	0.25	6.87	835	0.63	<DL
Block 2	6.21	1.81	34.19	85.69	n.a.	0.27	7.00	647	0.94	<DL
Block 3	7.62	1.91	28.67	72.66	n.a.	0.13	7.14	579	1.01	<DL
North	0.77	0.49	3.87	5.77	n.a.	0.21	6.09	64	0.04	<DL
South	3.03	0.86	8.27	7.37	0.56	0.16	6.09	101	0.04	<DL

n.a. Indicates not available. <DL Indicates levels were below the detection limit for Fe^{3+}

Table 4.7. Chemistry of soil and water samples taken at the JACOS site and surrounding fen in the first establishment year (August 2012) (continued).

Location	OM %	TP mg/L	TN mg/L	TP wt%	TN wt%	OC wt%
		-------- Soil Chemistry --------				
Block 1	0.72	0.76	1.89	0.03	0.07	
Block 2	0.73	0.67	1.07	0.03	0.04	
Block 3	0.71	0.72	1.37	0.03	0.05	
North	4.55	0.22	13.77	0.01	0.86	
South	4.69	0.16	12.30	0.01	0.74	
		-------- Water Chemistry --------				
Block 1					3.83	40.94
Block 2					2.78	40.18
Block 3					3.18	30.64
North					1.27	39.85
South					2.81	69.07

Table 4.8. Chemistry of soil samples taken at the JACOS site and surrounding undisturbed fen under peat treatment in the second establishment year (August 2013).

Location	Treatment	pH	EC µs/CM	Ca^{2+} mg/L	Fe^{3+} mg/L	K^{+} mg/L	Mg^{2+} mg/L	Mn^{3+} mg/L	Na^{+} mg/L	Cl^{-} mg/L	$PO4^{3-}$ mg/L	$SO4^{2-}$ mg/L	OM %	TN %	TP %
Block 3	No peat	8.04	500	60.64	0.15	1.39	21.52	0.49	21.05	18.61	n.a.	33.11	1.89	0.05	0.03
Block 3	Peat	8.12	324	31.41	1.29	1.34	13.22	0.21	13.44	11.93	n.a.	13.72	3.95	0.08	0.04
North/Control		3.43	176	5.08	0.96	11.25	2.14	0.10	3.53	2.65	11.02	2.71	95.69	1.08	0.04
North/Treatment		3.48	171	5.08	0.81	11.47	2.22	0.15	4.65	3.53	7.64	1.86	96.46	0.82	0.05
South/Control		3.49	209	5.91	1.31	12.29	2.42	0.23	8.18	4.68	8.22	4.36	96.16	1.01	0.05
South/Treatment		3.48	164	3.84	0.36	15.07	1.59	0.27	3.75	10.45	4.12	2.65	94.51	0.85	0.04

n.a. Indicates not available.

Table 4.9. Hydrocarbon chemistry of soil samples taken at JACOS site in Block 3 under peat addition, and the surrounding fen in the second establishment year (October 2013).

Location	Treatment	Benzene	Toluene	Ethylbenzene	Xylenes	F1 (C_6-C_{10})	F2 (C_{10}-C_{16})	F3 (C_{16}-C_{34})	F4 (C_{34}-C_{50})
Block 3	No Peat	<0.01	<0.01	<0.01	<0.02	<5	13	124	45
Block 3	Peat	<0.01	<0.01	<0.01	<0.02	<5	<10	704	549
North	Treatment	<0.01	<0.01	<0.01	<0.02	<5	<10	1041	930
North	Control	<0.01	0.279	<0.01	<0.02	<5	<10	943	1064
South	Treatment	<0.01	<0.01	<0.01	<0.02	<5	183	1639	1245
South	Control	<0.01	1.63	<0.01	<0.02	<5	<10	546	554

Table 4.10. Fen water levels showing relative height above sea level for various blocks across the JACOS site and within the surrounding undisturbed fen over two establishment years.

Location	June	July	August	September	October
			-------- 2012 --------		
Block 1					
B1-1	561.61	561.64	561.62	561.73	561.78
B1-2	561.52	561.61	561.65	561.75	561.69
B1-3	561.51	561.6	561.67	561.79	561.82
Block 2					
B2-1	561.20	561.31	561.27	561.43	561.47
B2-2	561.20	561.33	561.29	561.45	561.49
B2-3	561.21	561.33	561.31	561.46	561.49
Block 3					
B3-1	560.76	561.00	561.00	561.13	561.14
B3-2	560.85	561.15	561.00	561.22	561.25
B3-3	560.83	561.11	561.05	561.18	561.21
North					
C1	561.53	561.53	561.55	561.61	561.4
C3	561.27	561.43	561.50	561.55	561.31
C5	561.20	561.39	561.24	561.32	561.37
C7	560.99	561.05	561.09	561.28	561.17
South					
C2	561.33	561.19	561.27	561.54	561.39
C4	562.07	561.99	561.99	562.00	562.02
C6	561.84	561.71	561.75	561.84	561.77
C8	561.84	561.71	561.77	561.84	561.91
			-------- 2013 --------		
Block 1					
B1-1	561.69	561.81	561.73	561.66	561.62
B1-2	561.75	561.85	561.79	561.71	561.67
B1-3	561.79	561.90	561.83	561.75	561.72
Block 2					
B2-1	561.45	561.57	561.47	561.39	561.33
B2-2	561.47	561.62	561.51	561.43	561.37
B2-3	561.49	561.61	561.52	561.43	561.37

Table 4.10. Fen water levels showing relative height above sea level for various blocks across the JACOS site and within the surrounding undisturbed fen over two establishment years (continued).

Location	June	July	August	September	October
			-------- 2013 --------		
B3-1	561.09	561.18	561.11	561.07	561.03
B3-2	561.16	561.22	561.22	561.14	561.11
B3-3	561.11	N/A	N/A	N/A	561.05
North					
C1	560.84	561.26	561.25	560.78	561.14
C3	560.96	560.97	560.97	560.69	560.85
C5	560.85	560.82	560.81	560.75	560.73
C7	560.69	560.70	560.69	560.44	560.66
South					
C2	561.44	561.28	561.26	560.90	561.13
C4	561.73	561.91	561.89	561.81	561.79
C6	561.32	561.39	561.39	561.54	561.53
C8	561.99	562.04	562.04	561.59	561.29

N/A - Indicates data were not analyzed in pipe three due to the water temperature examination.

Table 4.11. Water depth values [cm (-) below or (+) above the soil surface] at various locations across the JACOS study site and surrounding undisturbed fen during each of the two study years.

Location	June	July	August	September	October
			-------- 2012 --------		
Block 1					h
B1-1	21.0	24.0	22.0	33.0	38.0
B1-2	18.0	27.0	31.0	41.0	35.0
B1-3	12.0	21.0	28.0	40.0	43.0
Block 2					
B2-1	13.0	24.0	20.0	36.0	40.0
B2-2	11.0	24.0	20.0	36.0	40.0
B2-3	12.0	24.0	22.0	37.0	40.0
Block 3					
B3-1	-17.0	12.0	7.0	20.0	21.0
B3-2	-12.0	18.0	3.0	25.0	28.0
B3-3	-17.0	11.0	5.0	18.0	21.0
North					
C1	28.0	27.5	30.0	36.0	15.0
C3	7.0	23.0	30.0	35.0	11.0
C5	6.0	25.0	10.0	18.0	23.0
C7	5.0	10.5	15.0	34.0	23.0
South					
C2	6.0	8.0	0.0	27.0	12.0
C4	16.0	-8.0	8.0	9.0	10.5
C6	18.0	5.0	9.0	18.0	11.0
C8	20.0	-.0	13.0	20.0	27.0
			-------- 2013 --------		
Block 1					
B1-1	29.0	40.8	33.1	26.0	22.0
B1-2	40.9	51.1	45.2	36.8	33.6
B1-3	40.3	51.4	44.5	35.9	33.5
Block 2					
B2-1	38.0	50.0	40.0	32.2	25.7
B2-2	38.0	52.6	42.0	34.0	28.0
B2-3	40.0	52.3	43.0	34.2	28.0

Table 4.11. Water depth values [cm (-) below and (+) above the soil surface] at various locations across the JACOS study site and surrounding undisturbed fen during each of the two study years (continued).

Location	June	July	August	September	October
			-------- 2013 --------		
Block 3					
B3-1	15.3	24.7	18.8	13.9	9.5
B3-2	19.4	25.2	25.0	17.4	14.0
B3-31	10.7	N/A	N/A	N/A	5.1
North					
C1	-41.0	0.5	-0.5	-47.5	-11.5
C3	-24.0	-23.2	-23.0	-51.0	-35.0
C5	-29.0	-32.2	-33.0	-39.5	-41.0
C7	-26.2	-24.0	-25.2	-50.4	-28.0
South					
C2	-83.0	1.0	-1.0	-36.9	-14.5
C4	-18.0	0.0	-2.2	-10.0	-12.5
C6	-34.0	-26.1	-27.5	-11.7	-13.5
C8	35.0	40.1	39.5	-9.2	-35.0

N/A - Indicates data were not analyzed in pipe three due to the water temperature examination.

Table 4.12. Mean soil and water temperature at the JACOS site over two establishment years.

Temperature	Location	June	July	August	September	October
				-------- 2012 --------		
Soil Temperature (°C)	Block 1	16.0	18.5	17.1	11.4	4.9
Soil Temperature (°C)	Block 2	15.8	19.6	18.3	12.5	5.8
Soil Temperature (°C)	Block 3	15.5	19.1	17.9	12.2	4.8
				-------- 2013 --------		
Soil Temperature (°C)	Block 1	15.1	17.1	17.0	13.6	7.2
Soil Temperature (°C)	Block 2	16.1	17.9	17.3	13.3	10.5
Soil Temperature (°C)	Block 3	15.8	17.9	17.6	12.9	6.9
Water Temperature (°C)[1]	Block 3	11.5	13.2	12.8	11.9	7.3

[1] Water temperature was examined in the second establishment year 2013.

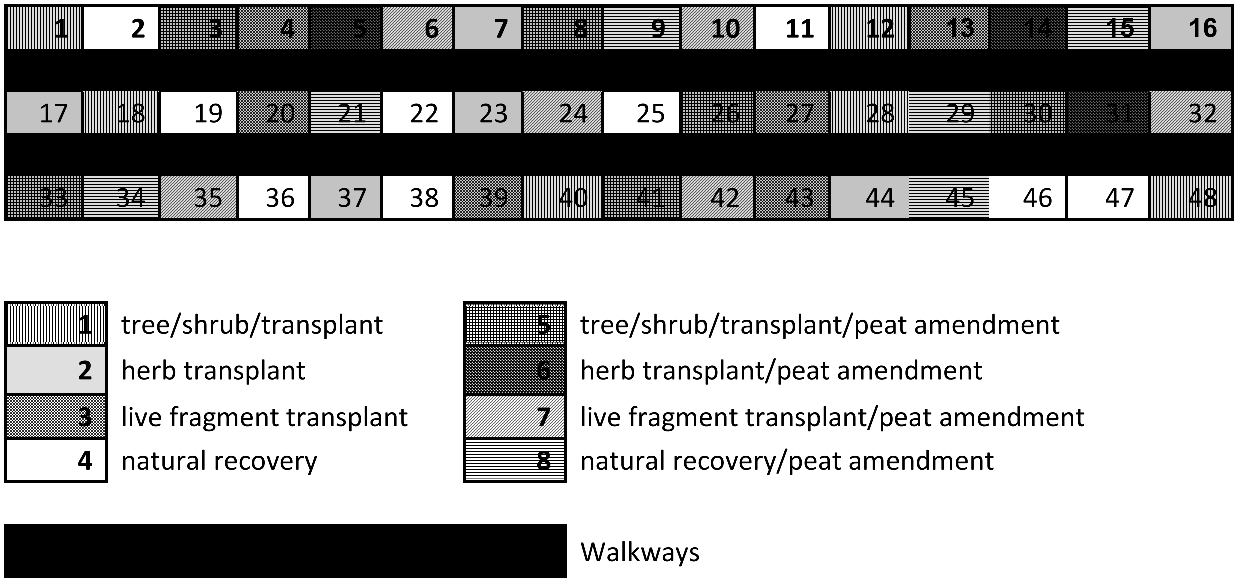

Figure 4.1. Sample layout of treatment plots within blocks. Eight treatments are randomized within each of three rows. There are two replicates of each treatment per row for 16 plots per row and 48 plots per block. Plots are 1m x 1m.

Figure 4.2. Satellite image of the JACOS study site illustrating the locations of control transects in the surrounding undisturbed fen.

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Figure 4.3. Satellite image of the JACOS study site illustrating the locations of water level measurement locations in the surrounding undisturbed fen.

B1, B2, B3 – pipes on the blocks 1, 2 and 3 of JACOS Road.

C1, C2, C3, C4, C5, C6, C7, C8 – pipes on the surrounding fen of JACOS Road.

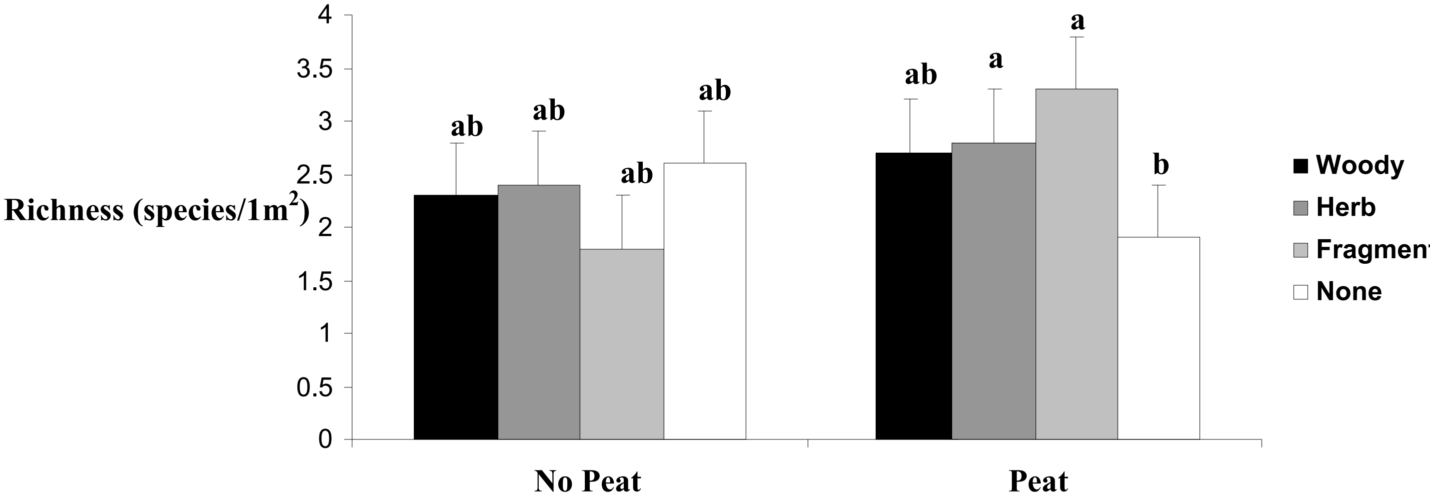
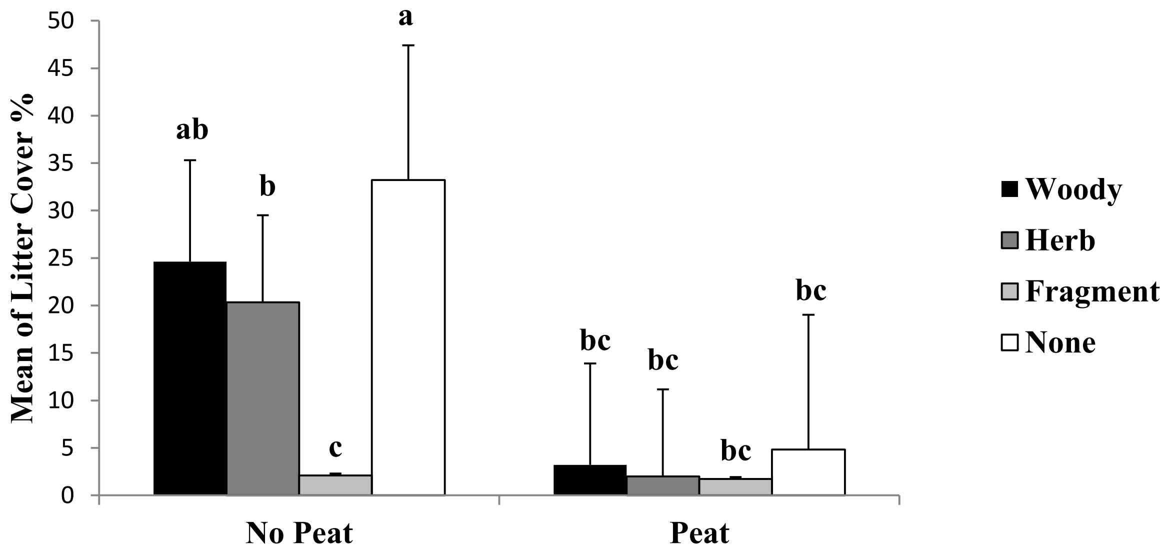


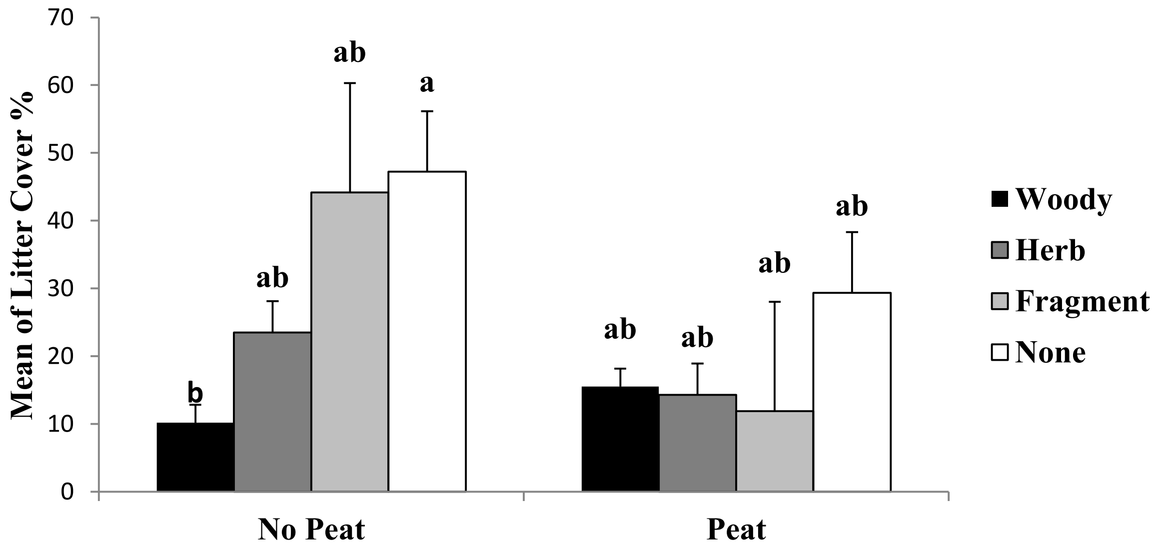
Figure 4.4. Comparison of mean species richness (±SE) among the various revegetation and peat treatments in 2012 at the JACOS site. Means with different letters differ, $P<0.05$.

A)



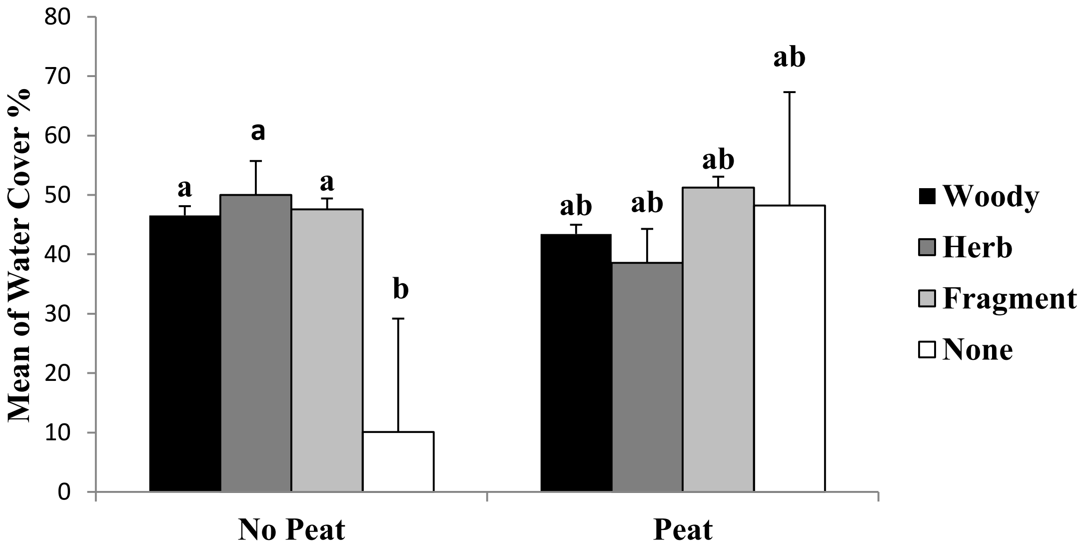
Mean of Litter Cover %
50
45
40
35
30
25
20
15
10
5
0
a
ab
b
c
bc
bc
bc
bc
No Peat
Peat
Woody
Herb
Fragment
None

B)



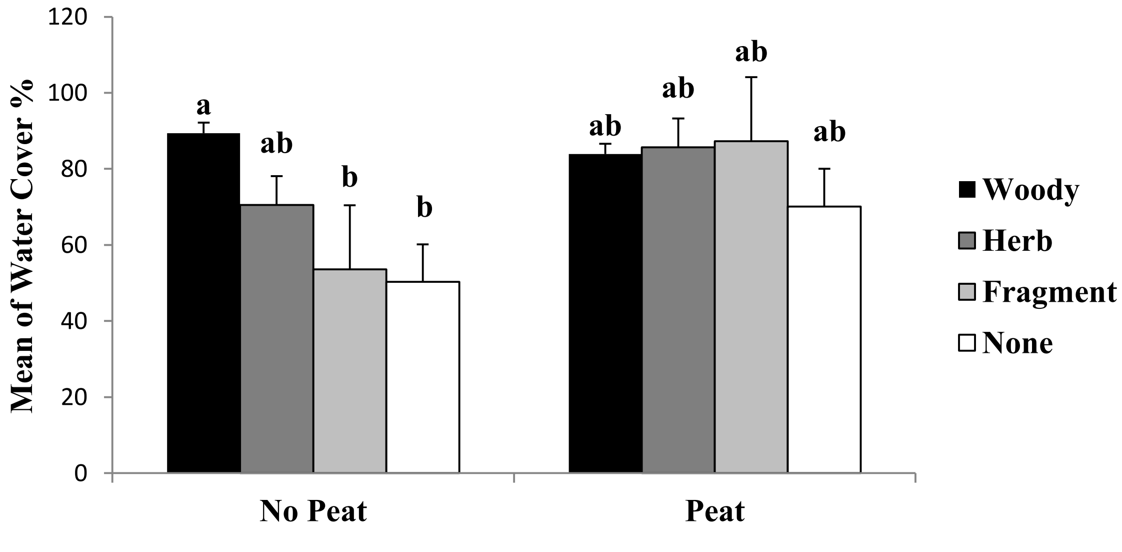
Mean of Litter Cover %
70
60
50
40
30
20
10
0
ab
a
ab
b
ab
ab
ab
ab
ab
No Peat
Peat
Woody
Herb
Fragment
None

C)



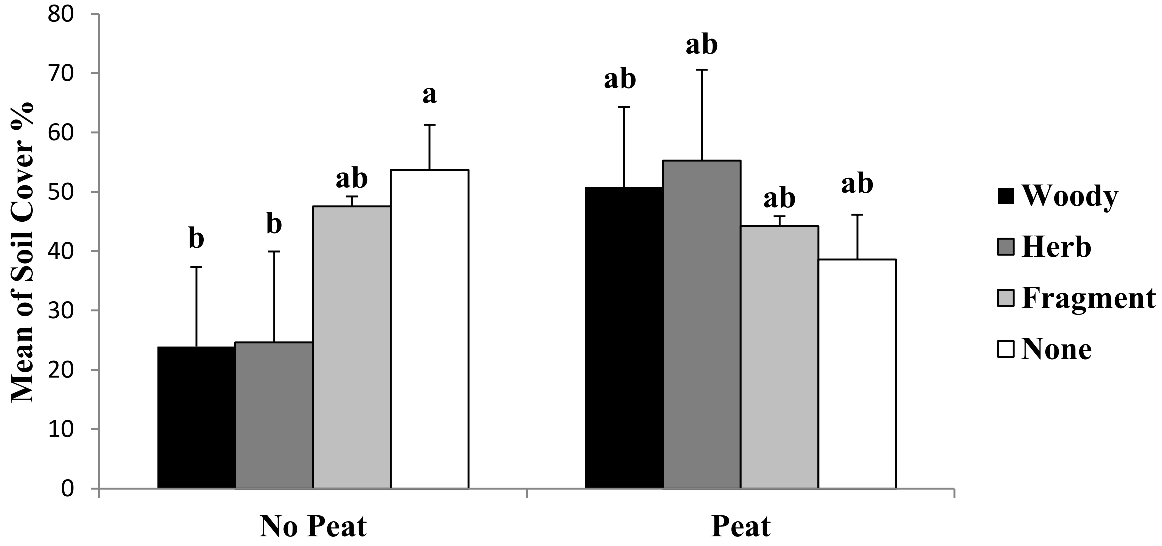
80
70
60
50
40
30
20
10
0
Mean of Water Cover %
a
a
a
b
ab
ab
ab
ab
No Peat
Peat
Woody
Herb
Fragment
None

D)



120
100
80
60
40
20
0
Mean of Water Cover %
a
ab
b
b
ab
ab
ab
ab
No Peat
Peat
Woody
Herb
Fragment
None

E)



F)

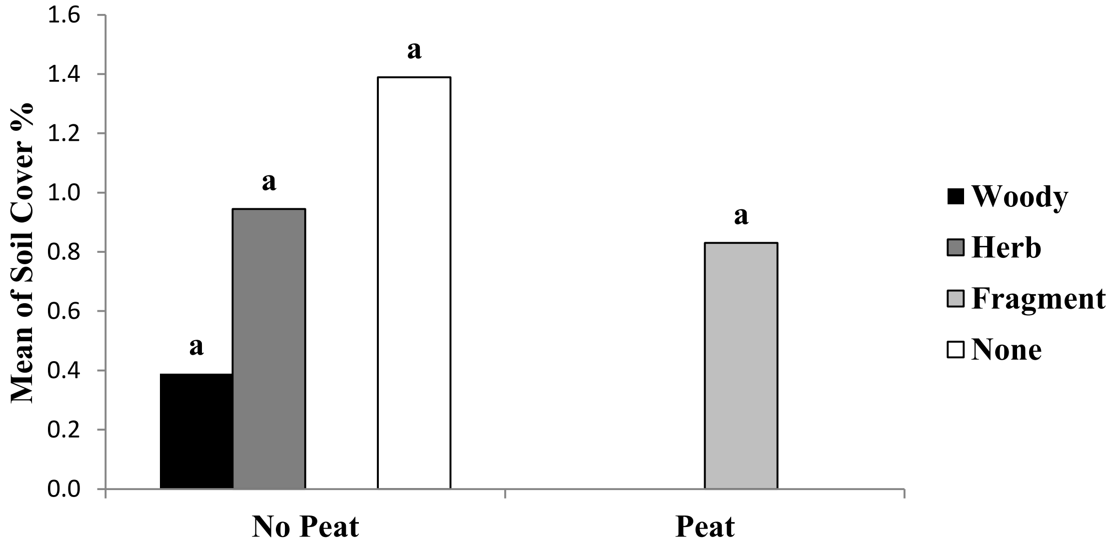


Figure 4.5. Comparison of mean (±SE) litter cover in A) 2012 and B) 2013, open water cover in C) 2012 and D) 2013, and exposed soil in E) 2012 and F) 2013, among revegetation and peat treatments at the JACOS site. Means with different letters differ, P<0.05.

Figure 4.6. Photo of vegetation emergence from stockpiled peat in randomly chosen sampling trays grown under greenhouse conditions at the University of Alberta for 16 weeks (December 2013).

Chapter 5. SYNTHESIS: FEN REVEGETATION IN THE OIL SANDS REGION OF NORTHERN ALBERTA

5.1. Summary

Given the ongoing disturbance of wetlands, the revegetation of fens in Northern Alberta will become increasingly important. Successfully revegetating reclaimed oil and gas infrastructure sites with acceptable vegetation communities will depend on a variety of factors including revegetation strategies such as the use of soil amendments (e.g. peat addition), live peat inoculation and vegetation re-establishment methods (e.g. transplants), as well as the deliberate use of microtopography to improve environmental conditions likely to promote revegetation. In general, practices for fen revegetation have not been well studied. Such knowledge is crucial given that fen revegetation is an integral component of sustaining the long-term health of fen wetlands and improving system resilience.

This research evaluated the success of transplants (in terms of their survival and/or growth) and other means of propagule introduction installed under different treatments (including with soil amendments) in Northern Alberta to provide information on plant growth and the effectiveness of revegetation strategies. In addition to examining the survival and growth of transplanted vegetation, this thesis also compared natural recovery of vegetation within disturbed and undisturbed areas. This research also showed that monitoring of both transplants and natural recovery, in concert with ongoing environmental conditions, provides useful information on overall function of fen revegetation processes. However, some relevant questions were left out of the scope of the research, such as varying quantities of soil amendment. Therefore, future investigations studying vegetation response to such practices may benefit our understanding of these processes.

The first research study (CNRL site) examined the survival of transplanted species under different treatments (peat inoculation, micro-topographical positions) and the natural recovery of fen vegetation on a lowland peat-mineral mix substrate, and compared disturbed with undisturbed areas. The second (JACOS) study investigated the survival of transplanted species under peat amendment, natural vegetation recovery in areas exposed to different peat application treatments and the vegetation performance of surrounding undisturbed fen.

Using both disturbed and original sites for both studies, the effects of environmental variables (pH, electrical conductivity, soil chemistry, soil and water temperature, and water level) on the survival of transplanted species, and on the composition and cover of fen vegetation, were investigated. Finally, index similarity and dissimilarity were studied between original and disturbed sites.

The results of the first study (Chapter 3) suggest that the addition of live peat, despite being applied to introduce propagules, might improve transplanted spruce and Labrador tea survival and spruce development, perhaps due to enhanced nutrient supply and water retention. The study showed that unlike that of the two woody transplant species, the survival of sedge was not affected by peat inoculation.

Maintaining a rough surface treatment tended to increase black spruce survival and relative height rate (RHR) at the CNRL site on the top and middle planting positions. This suggests that this physical treatment may be helpful for promoting fen revegetation, and that surface roughness might enhance the development, growth and survival of trees. The effect of this treatment for spruce development, observed over two years, appeared sufficient to conclude that this treatment could help contribute to long-term fen revegetation success. Price et al. (1997) also claimed that creation of surface microtopography alters the overall moisture content of the fen, which might be beneficial for the development of transplanted species. Therefore, my recommendation is to include surface roughness as one of the treatments during revegetation.

Similar to that of black spruce, the survival of Labrador tea was greater within the top and middle positions. Differences in Labrador tea survival over various micro-topographical positions tend to support the surface roughness application for revegetation. Unlike the two woody transplant species, sedge had the most favorable survival rates of all three species, with greater overall survival in both establishment years. However, surface roughness did not play a significant role for sedge transplanting and development, as least in the first two years.

I observed the survival of sedge, which had the most successful survival rates, was not affected by surface roughness. In addition, Kercher and Zedler (2004) claimed that sedge withstood flooded conditions. Raab and Bayley (2013) stated that *Carex* spp. is native to the region and local abiotic conditions of Northern Alberta. Based on these properties of sedge, I conclude that revegetation with sedges may be more favorable than spruce and Labrador tea (application) for initial fen revegetation.

With respect to the surface roughness treatment, I concluded that trees and shrubs should be planted on the top and middle topographical position, while sedges may be applied in all topographic positions. With respect to peat inoculation, I observed that live peat benefited trees and shrubs but not sedge. The best results for trees and shrubs were observed on top positions with peat inoculation. It is important to note that the worst results with trees and shrubs were on bottom positions regardless of peat inoculation treatment. This is also supported by Price et al.

(1997) who attributed the lower survival of vegetation on bottom positions to cooler soil temperatures and flooding resulting in oxygen deficiency.

This research also showed that peat inoculation did not enhance natural recovery, but that it actually decreased the abundance of many species during revegetation (Table 3.20). Malmer et al. (1994) also claimed that the presence of *Sphagnum* reduces the supply of nutrient resources to the vascular plants. Also, the transferred moss may need specific moisture conditions that were not maintained on our site. This suggests that there is a distinct difference between improving transplant establishment and promoting natural recovery of fen vegetation. It also indicates that effects of live peat addition depend on vegetation, timing, amount and relationships with the environmental conditions. As a result, further long-term monitoring is required, and more studies are needed to examine the effects of live peat material and how to properly apply it in various site conditions.

Similar to the performance of transplanted species, the natural recovery of woody species (trees and shrubs) and mosses was associated with rough surfaces. Microsite variability appear to lead to a greater variety of niches for the establishment of different species. Natural relief might therefore serve to improve desired revegetation. In contrast, aquatic sedges and ruderal (disturbance-adapted) forbs were associated with smooth surfaces. These forms of vegetation do not require surface roughness treatment.

Fields with irregular topography increase site variability. Mounds, ridges and other positive relief may remain dry and prevent plant establishment. On the other hand, frequent or prolonged flooding in depressions also lead to adverse conditions for plant establishment. Finally, more research is needed to understand the effects of micro-topographical positions responsible for preferential establishment of natural recovery on rough treatments.

No relationships were found between soil conditions and (a) the survival of transplants or (b) the richness or diversity of ensuing species. All treatments remain a long way from recovery (with Jaccard similarity values < 10%, and in the case of Bray-Curtis similarity, less than 5%). Consequently, significantly more time is required in order for these communities undergoing revegetation to become even 50% similar to the undisturbed fen.

Overall, on the practical side, I recommend applying sedge transplants for achieving revegetation, and use soil roughness for both active revegetation and natural recovery. On the scientific side, more research is required to understand the effect of live peat material on vegetation and monitor long-term outcomes of revegetation and development of natural recovery. A revegetation plan should also include some information on peat characteristics such as: peat thickness, type of peat (*Sphagnum* peat, sedge peat, etc.) and degree of decomposition of peat (Quinty and Rochefort 2003).

The second study (Chapter 4) did not show any evidence of beneficial effects of peat amendment (composted peat) for transplanted species over two years, but these results may have been more a result of flooding than a lack of benefit from the amendment. However, I did observe that the combination of live peat fragments and peat compost amendment tended to increase species richness, at least in the first year when flooding was less severe.

The greenhouse culture study indicated that the tendency noted above is probably not the result of addition of composted peat, as no live vegetation was produced from culturing the composted peat. On the other hand, live peat contained diaspores of *Sphagnum* mosses and other pioneer species that likely accelerated the formation of new vegetation and bryophytes. Therefore, the combination of composted and live peat might be beneficial for natural recovery due to the cooperative action of composted organic material and living parts of mosses. Overall, I observed neither live nor composted peat had much effect on vegetation establishment, but it was difficult to determine whether application of these materials was unjustified because of the confounding effects of flooding on plant performance.

As flooding was a major concern in my studies, water level changes were monitored. The second study showed that increased water levels decreased cotton grass survival and vegetation development. Steed and DeWald (2003) claimed that long-term inundation increases soil water storage capacity and might alter vegetation performance. Banach et al. (2008) stated that different plant species have different flooding tolerances. Thus, I recommend that information related to species flood tolerance, and to the timing and duration of flooding, be considered prior to fen revegetation. In addition, managing flooding through the use of drainage systems to manage seasonal water regimes may improve vegetation performance.

During my two-year study, all treatments remained a long way from recovery, with no treatment combinations producing a species composition similar to that of the adjacent fen. I anticipate that communities undergoing revegetation will likely remain dissimilar from that of the undisturbed fen for many more years. Long term monitoring is required.

Interpretations and conclusions from my two studies are based on two years of observations. It is inevitable that additional changes will occur within these communities, as this is the nature of succession. The presence of later successional species will likely increase; some non-native species may eventually be outcompeted, and species richness in fen communities within the site may increase. Long-term monitoring is therefore needed to determine what changes occur and when. The sites in this research represent an opportunity to conduct further research that would increase our understanding of succession and the trajectory and timeframe of natural recovery re-establishment, which are important indicators of reclamation success.

Transplantation is an effective strategy to increase revegetation and facilitate progress towards the end goal of restoring a fen community. We also saw that the richness and diversity of species were greater in transplanted areas than in those undergoing natural recovery. Thus, successful transplantation should be a recommended practice for fen revegetation guidelines. In general, transplanting is likely more effective with live or dead peat application in combination with surface roughness. Graminoid species such as sedges and cottongrass establish more easily and are more tolerant to varying site conditions than trees or shrubs. Therefore these species should be included as part of a progressive revegetation plan in areas where a native plant community is desired for the end land use.

5.2. Future Research

This research may therefore be used as a building block for further investigation. Related studies may undertake one or more of the following tasks:

1) Studying the effects of live peat on fen vegetation performance;
2) Characterizing the long-term survival of different transplanted species as indicators of ecological success;
3) Characterizing soil texture and determining whether it has an influence on community composition;
4) Identifying long-term soil water trends in fens and examining how they relate to ongoing community development;
5) Identifying soil nutrient trends in organic matter vs. mineral soil and examining how they relate to long term community development;
6) Studying the effect of micro-topographical positions responsible for preferential establishment of natural recovery on rough treatments, including of more species;
7) Examining the successional development of the communities as an indicator of ecological success;
8) Studying how the drainage system allows for water conditions in space and time conducive to supporting vegetation establishment and growth.

5.3.Literature Cited

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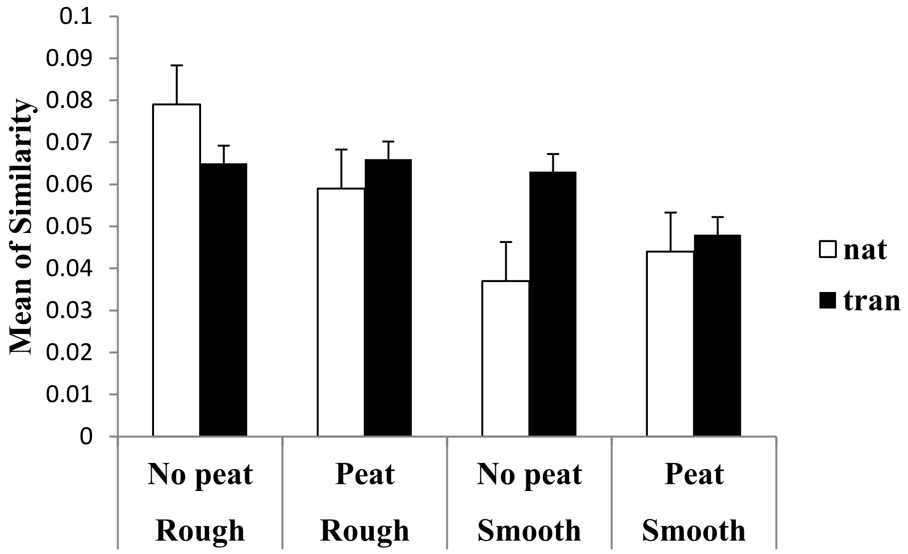
APPENDIX 1: Transplanted and vegetation species performance at CNRL site over two establishment years.

APPENDIX 1.1. Transplanted species survival at CNRL site over two establishment years.

Treatments			Black Spruce	Black Spruce	Labrador Tea	Labrador Tea	Carex spp.	Carex spp.
Peat	Surface	Position	2012	2013	2012	2013	2012	2013
No peat	Smooth	Middle	66.59	14.55	60.34	18.76	87.50	83.35
Peat	Smooth	Middle	79.14	12.51	60.39	12.51	100.00	72.93
Peat	Rough	Top	79.09	18.76	60.30	14.60	97.88	85.38
Peat	Rough	Middle	62.44	14.59	50.03	14.58	100.00	87.50
Peat	Rough	Bottom	43.76	0.00	39.65	0.00	100.00	87.50
No peat	Rough	Top	64.60	14.61	56.18	20.81	100.00	83.34
No peat	Rough	Middle	66.55	16.66	64.55	22.91	100.00	87.50
No peat	Rough	Bottom	60.35	2.09	60.35	4.18	100.00	85.38

APPENDIX 1.2. Comparison of Jaccard's similarity in species between treatments in 2013 at the CNRL site. Data analysis performed on transformed data, but original means shown for clarity.



APPENDIX 1.3. Species codes. Nomenclature as per United States Department of Agriculture PLANTS database.

Growth Form	Genus and Species	Common Name	Code
Trees	Larix laricina (Du Roi) K. Koch	Tamarack	Larlar
	Picea glauca (Moench) Voss	White spruce	Picgla
	Picea mariana (Mill.) Britton, Sterns & Poggenb	Black spruce	Picmar
	Populus balsamifera L. ssp. trichocarpa (Torr. & A. Gray ex Hook.) Brayshaw	Balsam poplar	Popbal
	Populus tremuloides Michx.	Trembling aspen	Poptre
Shrubs	Andromeda polifolia L. var. concolor B. Boivin	Dwarf bog-rosemary	Andpol
	Andromeda polifolia L. var. glaucophylla (Link) DC.	Bog-rosemary	Andpol
	Betula pumila L. var. glandulifera Regel	Dwarf birch	Betpum
	Ledum groenlandicum Oeder	Common Labrador tea	Ledgro
	Oxycoccus microcarpus - Vaccinium macrocarpon Aiton	Small bog cranberry	Oxymic
	Prunus virginiana L. var. demissa (Nutt.) Torr.	Choke cherry	Pruvir
	Ribes hudsonianum Richardson	Northern black currant	Ribhud
	Salix arbusculoides Andersson	Shrubby willow	Salarb
	Salix bebbiana Sarg.	Beaked willow	Salbeb
	Salix candida Flueggé ex Willd.	Hoary willow	Salcan
	Salix exigua Nutt.	Narrow-leaved willow	Salexi
	Salix glauca L. ssp. glauca var. villosa (D. Don ex Hook.) Andersson	Smooth willow	Salgla
	Salix gracilis Andersson var. rosmarinoides Andersson	Basket wollow	Salgra
	Salix lasiandra Benth. var. caudata (Nutt.) Sudw.	Pacific willow	Sallas
	Salix lucida Muhl.	Shining willow	Salluc
	Salix maccalliana Rowlee	Maccall's willow	Salmac
	Salix monticola Bebb	Moountain willow	Salmon
	Salix pedicellaris Pursh	Bog willow	Salpre
	Salix planifolia Pursh	Plane-leaved willow	Salpla

APPENDIX 1.3. Species codes. Nomenclature as per United States Department of Agriculture PLANTS database (continued).

Growth Form	Genus and Species	Common Name	Code
	Salix scouleriana Barratt ex Hook.	Scouler's willow	Salsco
	Salix serissima (L.H. Bailey) Fernald	Autumn willow	Salser
	Vaccinium angustifolium Aiton var. myrtilloides (Michx.) House	Low sweet blueberry	Vacmyr
	Vaccinium myrtilloides Michx.	Low bilberry	Vacmyr
	Vaccinium oxycoccos L.	Small bog cranberry	Vacoxy
	Vaccinium vitis-idaea L. ssp. minus (Lodd.) Hultén	Bog cranberry	Vacvit
Subshrubs	Pyrola secunda - Orthilia secunda (L.) House	One-sided wintergreen	Pyrsec
Forbs/herbs	Bidens cernua L. var. dentata (Nutt.) B. Boivin	Nodding beggarticks	Bidcer
	Caltha palustris L. var. palustris	Yellow marsh-marigold	Calpal
	Drosera rotundifolia L. var. comosa Fernald	Roundleaved sundew	Drorot
	Epilobium palustre L. var. grammadophyllum Hausskn.	Marsh willowherb	Epipal
	Fragaria vesca L. ssp. americana (Porter) Staudt	Woodland strawberry	Fraves
	Hieracium umbellatum L.	Narrow-leaved hawkweed	Hieumb
	Lemna minor L.	Common duckweed	Lemmin
	Melilotus officinalis (L.) Lam.	Yellow sweet-clover	Meloff
	Menyanthes trifoliata L.	Buck-bean	Mentri
	Petasites frigidus (L.) Fr. var. sagittatus (Banks ex Pursh) Cherniawsky	Palmate-leaved coltsfoot	Petfri
	Plantago major L.	Common plantain	Plamaj
	Polygonum amphibium L. var. stipulaceum Coleman	Water smartweed	Polamp
	Polygonum lapathifolium L.	Dockleaf smartweed	Polygo
	Potentilla palustris - Comarum palustre L.	Marsh cinquefoil	Potpal
	Ranunculus flammula L. var. filiformis (Michx.) Hook.	Creeping spearwort	Ranfla
	Ranunculus gmelinii DC	Yellow water-crowfoot	Rangme
	Ranunculus sceleratus L. var. multifidus Nutt.	Celery-leaved buttercup	Ranscr

APPENDIX 1.3. Species codes. Nomenclature as per United States Department of Agriculture PLANTS database (continued).

Growth Form	Genus and Species	Common Name	Code
	Rorippa palustris (L.) Besser	Marsh yellow cress	Rorpal
	Rubus arcticus L. ssp. acaulis (Michx.) Focke	Dwarf raspberry	Rubarc
	Rubus chamaemorus L.	Cloudberry	Rubcha
	Rubus pubescens Raf.	Dewberry	Rubpub
	Senecio congestus (R. Br.) DC.	Marsh ragwort	Sencon
	Smilacina trifolia - Maianthemum trifolium (L.) Sloboda	Three-leaved false seal	Smitri
	Sonchus arvensis L. ssp. uliginosus (M. Bieb.) Nyman	Perennial sow thistle	Sonarv
	Taraxacum officinale F.H. Wigg.	Common dandelion	Taroff
	Thalictrum venulosum Trel.	Veiny meadow rue	Thaven
	Trifolium hybridum L.	Alsike clover	Trihyb
	Trifolium pratense L.	Red clover	Tripra
	Typha latifolia L.	Common cattail	Trilat
	Vicia americana Muhl. ex Willd.	American vetch	Vicame
Horsetails	Equisetum arvense L.	Field horsetail	Eqarv
	Equisetum fluviatile L.	Swamp horsetail	Equflu
	Equisetum scirpoides Michx.	Dwarf scouring-rush	Equsci
Sedges	Carex aquatilis Wahlenb. ssp. altior (Rydb.) Hultén	Water sedge	Caraqu
And	Carex atherodes Spreng	Wheat sedge	Carath
Rushes	Carex bebbii Olney ex Fernald	Bebb's sedge	Carbeb
	Carex chordorrhiza Ehrh. ex L. f.	Prostrate sedge	Carcho
	Carex disperma Dewey	Two-seeded sedge	Cardis
	Carex houghtoniana Torr. ex Dewey	Sand sedge	Carhou
	Carex interior L.H. Bailey ssp. charlestonensis Clokey	Inland sedge	Carint
	Carex tenuiflora Wahlenb.	Sparse-leaved sedge	Carten
	Carex utriculata Boott	Small bottle sedge	Carutr
	Eleocharis acicularis (L.) Roem. & Schult.	Needle spike-rush	Eleaci
	Juncus alpinoarticulatus Chaix ssp. nodulosus (Wahlenb.)	Long-styled rush	Junalp
	Juncus bufonius L. var. occidentalis F.J. Herm.	Toad rush	Junbuf

APPENDIX 1.3. Species codes. Nomenclature as per United States Department of Agriculture PLANTS database (continued).

Growth Form	Genus and Species	Common Name	Code
	Scirpus caespitosus - Trichophorum cespitosum (L.) Hartm.	Tufted bulrush	Scicae
	Scirpus cyperinus (L.) Kunth	Wool-grass	Scicyp
Grasses	Agropyron trachycaulum (Link) Malte ex H.F. Lewis	Slender wheat grass	Agrtra
	Agrostis scabra Willd.	Rough hair grass	Agrsca
	Alopecurus aequalis Sobol.	Little meadow-foxtail	Aloaeq
	Beckmannia syzigachne (Steud.) Fernald	Slough grass	Becsyz
	Calamagrostis stricta (Timm) Koeler ssp. inexpansa (A. Gray) C.W. Greene	Narrow reed grass	Calstr
	Deschampsia cespitosa (L.) P. Beauv.	Tufted hair grass	Desces
	Hordeum jubatum L. ssp. breviaristatum Bowden	Foxtail barley	Horjub
	Phragmites australis (Cav.) Trin. ex Steud.	Common reed grass	Phraus
	Poa pratensis L. ssp. alpigena (Fr. ex Blytt) Hiitonen	Kentucky bluegrass	Poapra
	Triglochin maritima L.	Seaside arrow-grass	Trimar
Liverwort	Marchantia polymorpha L.	Green-tongue liverwort	Marpol
Mosses	Aulacomnium palustre (Hedw.) Schwägr.	Tufted moss	Aulpal
	Brachythecium rivulare Schimp.	Common verdant moss	Brariv
	Bryum caespiticium Hedw.	Tall clustered thread moss	Brycae
	Bryum pseudotriquetrum (Hedw.) G. Gaertn., B. Mey. & Scherb.	Felt round moss	Brypse
	Ceratodon purpureus (Hedw.) Brid.	Fire moss	Cerpur
	Climacium dendroides (Hedw.) F. Weber & D. Mohr	Common tree moss	Cliden
	Hylocomium splendens (Hedw.) Schimp.	Stair-step moss	Hylspl
	Hypnum lindbergii Mitt.	Clay pigtail moss	Hyplin
	Leptobryum pyriforme (Hedw.) Wilson	Long-necked bryum	Leppyr
	Meesia uliginosa Hedw.	Capillary thread moss	Meeuli
	Philonotis fontana (Hedw.) Brid. var. pumila (Turner) Brid.	Swamp moss	Phifon
	Polytrichum juniperinum Hedw.	Juniper moss	Poljun
	Polytrichum strictum Brid.	Bog hair-cap	Polsti
	Ptilium crista-castrensis (Hedw.) De Not.	Knight's plume	Pticri

APPENDIX 1.3. Species codes. Nomenclature as per United States Department of Agriculture PLANTS database (continued).

Growth Form	Genus and Species	Common Name	Code
	Sphagnum girgensohnii Russow	Girgensohn's peat moss	Sphgir
	Sphagnum warnstorfii Russow	Warnstof's peat moss	Sphwar
	Tomentypnum nitens (Hedw.) Loeske	Golden moss	Tomnit
Lichen	Cladina rangiferina (L.) Nyl.	Grey reindeer lichen	Claran

APPENDIX 2: Transplanted and vegetation species performance at JACOS site over two establishment years.

APPENDIX 2.1. Mean transplanted species survival within the JACOS road site over two establishment years.

Treatments		Labrador Tea %	Cotton Grass %	Cotton Grass %
		-------- *2012* --------		--- *2013* ---
NoPeat	Woody	1.23	n/a	n/a
NoPeat	Herb	n/a	28.39	15.43
NoPeat	Fragment	n/a	n/a	n/a
NoPeat	None	n/a	n/a	n/a
Peat	Woody	0.00	n/a	n/a
Peat	Herb	n/a	41.82	19.61
Peat	Fragment	n/a	n/a	n/a
Peat	None	n/a	n/a	n/a

APPENDIX 2.2. Mean plant species cover (%) at the JACOS road site for each block, averaged for each combination of peat and revegetation treatment, as assessed in early August 2013. A detailed master species list is provided in Appendix 2.6.

		No Peat Amendment				Peat Amendment			
Growth Form	Species	Woody	Herb	Fragment	None	Woody	Herb	Fragment	None
		------------------ Block 1 --------------------							
Forbs	Lemmin	0.0	0.0	0.0	0.0	0.0	0.2	0.8	0.0
	Typlat	42.5	25.0	38.2	13.5	45.8	10.0	18.5	38.3
Horsetail	Equarv	0.0	0.0	1.7	0.0	0.0	0.2	0.0	0.0
Sedges	Carcan	0.0	0.8	0.0	0.0	0.0	1.5	0.0	0.0
	Scicae	1.7	0.0	1.7	0.0	1.7	0.0	2.0	1.7
	Erispi	0.0	13.0	0.0	0.0	0.0	9.3	0.0	0.0
		------------------ Block 2 --------------------							
Forbs/	Lemmin	0.0	0.2	0.0	0.3	0.0	0.8	0.0	0.3
Herbs	Typlat	60.0	34.5	60.8	57.5	49.1	34.2	30.8	35.0
Sedge	Carcan	0.0	0.0	0.0	0.0	0.0	0.0	4.2	0.0
	Erispi	0.0	0.0	0.0	0.0	0.0	3.7	0.0	0.0
Grasses	Becsyz	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0
		------------------ Block 3 --------------------							
Shrub	Vacvit	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0
Forbs/	Polamp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Herbs	Typlat	75.0	63.3	53.3	73.3	70.0	35.8	48.5	56.7
Horsetail	Equarv	1.2	1.3	10.2	1.0	0.0	1.5	3.8	2.7
Sedge/	Carcan	1.3	0.3	1.0	0.0	1.7	1.0	3.7	0.0
Rushes	Erispi	0.0	33.3	0.0	0.0	0.0	42.3	0.0	0.0
	Junbuf	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.2
	Junnod	0.0	0.3	0.0	0.0	0.0	0.2	1.0	0.2
	Scicae	8.3	0.0	0.0	2.5	2.5	0.2	0.8	0.2
Grasses	Agrsca	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
	Aloaeq	0.2	0.5	0.5	0.3	0.0	0.7	1.0	0.2
	Becsyz	0.0	0.3	0.8	2.2	0.3	0.0	1.0	0.2

APPENDIX 2.3. Mean plant species cover within the surrounding undisturbed fen, as measured in early August 2013. A detailed master species list is provided in Appendix 2.6.

		South Transect		North Transect	
Growth Form	Species	Control	Treatment[1]	Control	Treatment[1]
Trees	Pinban	0.0	0.0	0.0	10.0
	Picgla	0.3	2.1	0.0	0.0
	Picmar	8.1	1.9	9.0	11.9
	Poptre	0.6	0.0	0.0	0.0
Shrubs	Andpol	0.8	0.0	0.9	5.6
	Betpap	3.1	0.0	0.0	0.0
	Ledgro	59.4	69.4	90.0	39.4
	Oxymic	13.5	11.6	2.8	17.0
	Prupen	4.4	0.0	0.0	0.0
	Salbeb	0.6	0.0	0.0	0.0
	Saldis	0.3	0.0	0.0	0.0
	Vaccae	14.4	1.9	9.4	19.4
	Vacmyr	8.1	0.0	0.0	0.0
	Vacvit	34.4	30.0	63.8	30.0
Forbs/herbs	Drorot	5.9	0.9	0.0	0.0
	Parpal	0.1	0.0	0.0	0.0
	Petsag	0.4	0.0	0.0	0.0
	Pyrsec	0.3	0.0	0.0	0.0
	Rubcha	5.6	0.6	10.1	1.1
Sedges	Carutr	1.9	0.0	0.3	0.6
	Eriang	2.9	5.8	0.0	5.0
Liverwort	Lopven	0.3	5.9	0.0	0.6
Mosses	Aulpal	5.0	0.0	0.4	2.5
	Ortspe	0.6	0.6	2.1	0.6
	Poljun	13.9	5.3	38.1	3.1
	Polstr	3.3	13.4	2.9	11.3
	Pticri	0.8	0.0	0.3	0.0
	Sphgir	0.0	0.0	0.0	0.3
	Sphvar	68.1	50.4	25.6	79.4
	Tomnit	0.0	0.4	3.1	1.3
Lichen	Claran	7.0	12.9	0.0	1.3

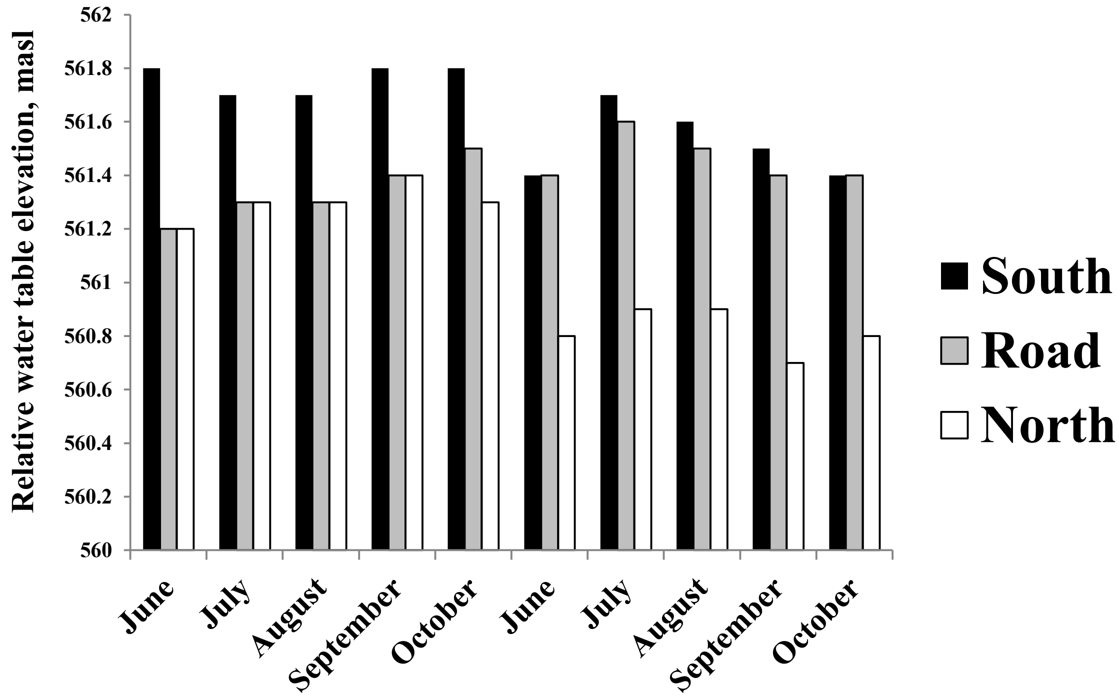
[1] All treatments combined.

APPENDIX 2.4. Mixed model ANOVA results with the smallest AICC to assess peat effects on herb survival.

(B R(B) T P T*P T*B P*B P*T*B T*R(B) P*R(B)
(B R(B) T P T*P T*B P*B P*T*B P*R(B)
(B R(B) T P T*P T*B P*B P*T*B T*R(B)
(B R(B) T P T*P T*B P*B P*T*B)
(B R(B) T P T*P T*B P*B)
(B R(B) T P T*P T*B)
(B R(B) T P T*P)
(B R(B) T P)

B – Block; R – Row; T – Revegetation Treatment; P-Peat Amendment.

APPENDIX 2.5. Relative water table elevation (masl) indicating the impediment of water flow by the road from the upstream (south) to downstream (north) sides of the road. Values are block averages for 3 wells within each of 3 blocks on the road and the averages of 4 wells on each side of the road in the adjacent fen for the two establishment years (2012-2013).



APPENDIX 2.6. Summary of nomenclature codes for those species documented at the JACOS site. Nomenclature as per United States Department of Agriculture PLANTS database.

Growth Form	Genus and Species	Common Name	Code
Trees	Picea banksiana - Pinus banksiana Lamb.	jack pine	Picban
	Picea glauca (Moench) Voss	white spruce	Picgla
	Picea mariana (Mill.) Britton, Sterns & Poggenb	black spruce	Picmar
	Populus tremuloides Michx.	trembling aspen	Poptre
Shrubs	Andromeda polifolia L. var. concolor B. Boivin	dwarf bog-rosemary	Andpol
	Betula pumila var. glandulifera	swamp birch	Betpum
	Betula papyrifera Marshall var. papyrifera	white birch	Betpap
	Ledum groenlandicum Oeder	common labrador tea	ledgro
	Oxycoccus microcarpus - Vaccinium macrocarpon Aiton	small bog cranberry	Oxymic
	Prunus pensylvanica L. f. var. pensylvanica	pin cherry	Prupen
	Salix bebbiana Sarg.	beaked willow	Salbeb
	Salix candida Flueggé ex Willd.	hoary willow	Salcan
	Salix discolor Muhl. var. overi C.R. Ball	pussy willow	Saldis
	Vaccinium caespitosum Michx.	dwarf bilberry	Vaccae
	Vaccinium vitis-idaea L. ssp. minus (Lodd.) Hultén	bog cranberry	Vacvit
Forbs/herbs	Drosera rotundifolia L. var. comosa Fernald	roundleaved sundew	Drorot
	Lemna minor L.	common duckweed	Lemmin
	Parnassia palustris L. var. montanensis C.L. Hitchc.	northern grass-of-parnassus	Parpal
	Petasites frigidus (L.) Fr. var. sagittatus Cherniawsky	palmate-leaved coltsfoot	Petfri
	Polygonum amphibium L. var. stipulaceum Coleman	water smartweed	Polamp
	Pyrola secunda - Orthilia secunda (L.) House	one-sided wintergreen	Pyrsec
	Rubus chamaemorus L.	cloudberry	Rubcha
	Solidago canadensis L.	canada golderod	Solcan
	Smilacina trifolia - Maianthemum trifolium (L.) Sloboda	false solomon's-seal	Smi tri

APPENDIX 2.6. Summary of nomenclature codes for those species documented at the JACOS site. Nomenclature as per United States Department of Agriculture PLANTS database (continued).

Growth Form	Genus and Species	Common Name	Code
	Typha latifolia L.	common cattail	Typlat
Horsetail	Equisetum arvense L.	common horsetail	Equarv
Sedges/Rushes	Carex canescens L. ssp. disjuncta (Fernald) Toivonen	short sedge	Carcan
	Carex utriculata Boott	small bottle sedge	Carutr
	Eleocharis acicularis (L.) Roem. & Schult.	needle spike-rush	Eleaci
	Eriophorum vaginatum L. var. spissum (Fernald) B. Boivin	sheathed cotton-grass	Erivag
	Juncus bufonius L. var. occidentalis F.J. Herm.	toad rush	Junbuf
	Juncus nodosus L. var. meridianus F.J. Herm.	knotted rush	Junnod
	Scirpus caespitosus - Trichophorum cespitosum (L.) Hartm.	tufted bulrush	Scicae
	Scirpus cyperinus (L.) Kunth	wool-grass	Scicyp
Grasses	Agrostis scabra Willd.	rough hair grass	Agrsca
	Alopecurus aequalis Sobol.	little meadow-foxtail	Aloaeq
	Beckmannia syzigachne (Steud.) Fernald	slough grass	Becsyz
	Calamagrostis canadensis (Michx.) P. Beauv.	Marsh reed grass	Calcan
Liverwort	Lophozia ventricosa (Dicks.) Dumort.	leafy liverwort	Lopven
Mosses	Aulacomnium palustre (Hedw.) Schwägr.	tufted moss	Aulpal
	Ceratodon purpureus (Hedw.) Brid.	fire moss	Cerpur
	Orthotrichum speciosum Nees var. elegans Warnst.	showy bristle moss	Ortspe
	Polytrichum juniperinum Hedw.	juniper moss	Poljun
	Polytrichum strictum Brid.	bog hair-cap	Polstr
	Ptilium crista-castrensis (Hedw.) De Not.	knight's plume	Pticri
	Sphagnum girgensohnii Russow	girgensohn's peat moss	Sphgyr
	Sphagnum warnstorfii Russow	warnstof's peat moss	Sphwar

APPENDIX 2.6. Summary of nomenclature codes for those species documented at the JACOS site. Nomenclature as per United States Department of Agriculture PLANTS database (continued).

Growth Form	Genus and Species	Common Name	Code
	Tomentypnum nitens (Hedw.) Loeske	golden moss	Tomnit
Lichen	Cladina rangiferina (L.) Nyl.	grey reindeer lichen	Claran