The use of peat applications and *Carex aquatilis* for peatland reclamation on post mined landscapes in northern Alberta, Canada

by

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Abstract

I investigated peatland reclamation factors in a wetland built on a former open-pit oil sands mine in northern Alberta, Canada. The primary research objectives were to investigate the persistence of peat placed in a newly constructed wetland, the survival and establishment of *Carex aquatilis* (water sedge), and if transplanting *C. aquatilis* produced quicker establishment than natural recruitment and broadcast seeding. The research was located in Syncrude Canada's reclaimed Sandhill Fen.

I examined influences of "initial peat thickness" (0, 5, or 30 cm), and "position relative to the water table" (measured as low, intermediate, and high), on peat's persistence, and the survival and establishment of *C. aquatilis* over two years. Low plots were submersed at the start of the study, intermediate plots were located very near to, or just above, the water table, and high plots were situated entirely above the water table. The study was replicated on four, specially designed, clay islands within the Sandhill Fen, and unplanted control plots were established beside each treatment plot.

Change in peat (measured as reduction in thickness) was dependent on both initial peat thickness, and position relative to the water table. Peat thickness did not increase under any combination of treatments. Peat reductions differed by elevation; however, peat located at intermediate positions reduced the least, suggesting that intermediate moisture conditions may minimize peat reductions and/or losses.

Carex aquatilis survival and establishment was dependent on position relative to the water table, but not initial peat thickness, suggesting that substrate type may not be important. Transplanting mature *C. aquatilis* plants appears to be a viable option for peatland reclamation, but maintaining an appropriate water table is critical. *Carex aquatilis* establishment through natural recruitment and broadcast seeding lagged in comparison to transplanting; therefore, transplanting *C. aquatilis* to a constructed peatland may contribute to quicker establishment of the species, thereby reducing potential colonization by unwanted species and contributing to accelerated development of peatland conditions.

Preface

This thesis is an original work by Mallory Hazell, with the assistance of Dr. Lee Foote, and Dr. Jan Ciborowski. Dr. Marie Claude Roy participated in the research design, and members of Dr. Jan Ciborowski's lab participated in data collection. Although the research, literature review, and statistical analysis were original work, the general research goals were part of an international collaboration on reclamation strategies at Syncrude Canada's reclaimed Sandhill Fen, led by Clara Qualizza, Carla Wytrykush and Jessica Piercey. No part of this thesis has been previously published.

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CHAPTER 1

Title: General introduction.

1.1. PEATLAND ECOLOGY

A peatland is a wetland ecosystem where net primary production (i.e. the production of plant biomass) exceeds the rate of decomposition, resulting in the accumulation of peat from dead and decaying plant material; primarily sedges and sphagnum moss (Wetlands International N.D.; Roulet 1991; Beckingham and Archibald 1996; Lahring 2003; Quinty and Rochefort 2003; Wieder et al. 2006; PERG 2009). Peatlands cover approximately 2-3% of the earth's surface, and are located in arctic, boreal, and tropical climates (Gore 1983; Immirzi et al. 1992; Gignac and Vitt 1994; Lappalainen 1996; Charman 2002). Despite their limited global coverage, peatlands have tremendous ecological value and societal benefits (Wieder et al. 2006; Gorham 1991; Joosten and Clark 2002).

Peatlands contain approximately 30% of the world's soil carbon (Gorham 1991), and play an important role in the global carbon cycle. Globally, they store over 550 giga-tonnes of carbon, which is twice the amount stored in all of the world's forests (Wetlands International N.D.). Peatlands can be used for forestry, peat is harvested for horticulture and fuel, and some peatland plants produce fruits that are consumed by people (Wieder et al. 2006). They are also important for the maintenance of biodiversity; because of their acidic conditions, they contain unique assemblages of plant species that contribute to landscape biodiversity, and are home to many rare or threatened species (Graham et al. 2016; PERG 2009; Wetlands International N.D.). They are regionally important for regulating water flow, and mitigating flood damage, because they can act as a buffer when precipitation is abundant and can draw down during dry periods (PERG 2009; Reeve et al. 2001). In addition, they are globally important for water purification, collectively filtering millions of litres of water a day (Henry 2002).

My research is located in the boreal region, which contains approximately 80% of the world's peatlands (Joosten and Clark 2002). Boreal peatlands develop when the average yearly precipitation is between 500 and 3000 mm, annual biotemperatures are between 3 and 6 degrees Celsius, and the potential evapotranspiration ratio is approximately 0.250 to 0.800 (Wieder et al. 2006). Given these conditions, approximately 24% of the boreal region is comprised of peatlands (Joosten and Clark 2002). Paludificaton (or swamp-forming) on poorly drained land is the dominant way peatlands develop in the boreal region. This occurs when peat forms directly on mineral soil in previously dry, vegetated areas; paludification is the result of a rising water table, and may take place in the absence of a water body (Almquist-Jacobson and Foster 1995; Anderson et al. 2003). Boreal peatlands also form by terrestrializing formerly aquatic habitats; terrestrialization occurs when vegetation gradually fills in shallow bodies of water, forming floating or grounded mats (Quinty and Rochefort 2003; Roulet 1991; Vitt 2006). Once established, peatland function and differentiation is influenced primarily by hydrology, climate, chemistry, substrate, and vegetation (Vitt 2006).

There are five generally recognized types of peatlands that fall (often with considerable overlap) on an oligotrophic-eutrophic nutrient gradient: Bogs, Poor Fens, Moderate Rich Fens, Rich Fens, and Extreme Rich Fens (Vitt 2006). These can be further categorized into subtypes depending on their unique vegetation assemblages. According to Beckingham and Archibald's (1996) *Field Guide to Ecosites of Northern Alberta*, bogs can be separated into one of two categories (Treed bog or Shrubby bog), and fens can be separated into five categories (Treed poor fen, Shrubby poor fen, Treed rich fen, Shrubby rich fen, and Graminoid Rich Fen). A fen's water source has a strong influence on the differentiation of peatland type. Ombrogenous waters come exclusively from rain and snow and are very low in nutrients; the resulting conditions promote the development of bog peatlands. Ground and surface waters contain dissolved minerals that increase the nutrient status of an ecosystem; these geogeneous waters generally result in the development of fen peatlands. Bogs are considered ombrotrophic, and fens are considered minerotrophic/mesotrophic. Eutrophic nutrient statuses are typically restricted to marshes and swamps (i.e. non peat forming wetlands). Where there is significant peat accumulation, a peatland may become elevated above the surrounding area; in this way, a fen could gradually become a bog as mineral inputs decrease due to a shift towards ombrogenous water inputs (PERG 2009; Quinty and Rochefort 2003).

Along the peatland nutrient gradient, pH varies from 3 to 9, with a pH of 5.5 being a fundamental division for many peatland plants (Vitt 2006). Stagnant (anoxic) water leads to acidic surface water conditions creating an environment where relatively few plant species can survive. Peatlands with a pH below 5.5 (generally bogs and very poor fens) are therefore floristically less diverse and contain more species characteristic of oligotrophic conditions (primarily peat mosses) than peatlands with a pH above 5.5. Less acidic peatlands are richer in true mosses. Bogs contain approximately 40 to 70% cover of *Sphagnum* mosses, and have notable *Picea mariana*, *Ledum groenlandicum*, and *Vaccinium vitis-idaea* cover (Beckingham and Archibald 1996). Noteworthy bog species include *Rubus camaemorus*, *Sphagnum fuscum*, and *Warnstorifa fluitans,* which is common in bog pools (Vitt 2006). Poor fens contain slightly less *Sphagnum* cover (~34-60%), and in addition to *Picea mariana* and *Ledum groenlandicum*, also contain *Larix laricina*, *Salix* and *Carex* species (Beckingham and Archibald 1996). *Warnstorfia exannulatus* is a moss species indicative of poor fens (Vitt 2006). Richer fens will not contain *Picea mariana*, and will have higher proportions of *Larix laricina*, *Salix* and *Carex* species (Beckingham and Archibald 1996). *Calamagrostis canadensis, Hamatocaulis vernicosus* and *H. lapponicus* are species indicative of moderate rich fens. *Scorpidium cossonii* is indicative of extreme rich fens (Vitt 2006), and *Carex* species dominate graminoid rich fens (Beckingham and Archibald 1996). *Betula glandulosa*, *Sphagnum riparium*, *Carex lasiocarpa*, *C. limosa*, and *C. rostrata* are common in a variety of fen peatlands (Gorham and Janssens 1992; Vitt 2000; Wheeler and Proctor 2002).

A defining characteristic of boreal peatlands is their peat substrate, which accumulates primarily from the decomposition of *Sphagnum* and *Carex* species. (Beckingham and Archibald 1996; Lahring 2003; Roulet 1991; Quinty and Rochefort 2003; Wieder et al. 2006). It can take thousands of years to develop deep peat deposits because peat accumulates very slowly (0.5-1.0 mm a year; PERG 2009). Over time, two distinct and important layers of peat develop; the acrotelm and the catotelm. The acrotelm is located near the surface and is subject to water table fluctuations and periodic air entry. It consists of relatively undecomposed peat that is porous and has a high hydraulic conductivity. The catotelm is located below the acrotelm and consists of highly decomposed peat that is permanently saturated with water (Quinty and Rochefort 2003; Holden 2005).

The relationship between vegetation, hydrology, and organic substrate composition has an important impact on peatland function; if one of these components is affected, the others are likely to change as well (Lavoie et al. 2009). For example, plant species composition can affect peat formation (sedge peat vs. sphagnum peat for example), and peat type can affect groundwater storage and movement, thereby influencing water table levels (Bhatti and Vitt 2012; Petrone et al. 2008). Peatland reclamation research is important because these unique conditions are difficult to create in a post-mined landscape, and because peatlands have been heavily affected by oil and gas operations in Northern Alberta (Pembina Institute. N.D.).

1.2. OIL SANDS MINING IN ALBERTA

Alberta is well known for its Athabasca oil sands operations, which expanded greatly beginning in 1967 (Alberta Energy 2017). Oil sands underlie approximately 142,200 km^2 of Alberta, and the Athabasca oil sands surface mining area covers more than 4,750 km^2 (Alberta Energy 2014). Oil is extracted by one of two methods depending on how deep the bitumen is located. Companies use the *In situ* method (steam-assisted gravity drainage – SAG-D) when bitumen is located too deep for surface mining, generally greater than 75 m below the surface. This method uses high temperature steam to melt the bitumen so it can flow to a producing well (Government of Alberta 2017). Surface mining requires the complete removal of ground layers, and therefore ecosystems, to expose the subsurface bitumen deposits (Government of Alberta 2017). Over 715 km^2 of the surface minable area in the Athabasca Oil Sands has been disturbed by surface mining, and by 2022, oil sands development will result in the estimated daily clearing of 18.6 ha (Pembina N.D.).

It is unclear how many wetlands have been lost or affected by oil sands disturbances in Alberta's surface minable area. Due to a lack of clear regulatory requirements and standardized industry reporting, one cannot compare vegetation records from pre- and post-mined landscapes, making it difficult to quantify the loss of wetland habitats (Rooney et al. 2012). In 2002, Canadian Natural Resources Ltd. produced a 2,277,376 ha vegetation cover map of Alberta's surface minable area; wetlands comprised 64% of the area, with fen vegetation the most dominant wetland type (Rooney et al. 2012). The map showed that there was a higher concentration of peatlands in Alberta's surface minable area (64%) than would be found throughout the Canadian boreal forest (~30%) (Henry 2002). Wetlands (fen peatlands in particular) have been greatly disturbed by oil and gas activity in northern Alberta, regardless of our ability to quantify the nature of those disturbances.

Most of the reclamation in the Alberta oil sands has focused on the creation of forested uplands, primarily at the expense of former peatlands (Rooney et al. 2012). The conversion of peatlands (pre-mining), to upland habitats (post-mining), reflected a lack of policies that valued wetlands, and our limited knowledge about how to reclaim them (Neff et al. 2007). Furthermore, in Canada a wetland must have a 40-cm thickness of peat to be classified as a peatland (National Wetlands Working Group 1997), and because peat accumulates very slowly (Trites and Bayley 2009), peatland development takes a long time. Where wetland reclamation is warranted, oil sands industries have focused their efforts on the creation, or restoration, of marshes (Kovalenko et al. 2013; Rooney et al. 2012) because they are less complex and easier to reclaim than peatlands (Lockey 2011). However, in recent years, there has been a regulatory shift to promote research on the feasibility of peatland reclamation (OSWWG 2000). With this in mind, Syncrude Canada Ltd. and Suncor Energy (in collaboration with many universities and researchers) developed pilot fen peatlands (Sandhill Fen and Nikanotee Fen) on former open-pit mine sites, to improve our knowledge and guide future peatland reclamation (BGC 2008; Wytrykush et al. 2012).

1.3. SYNCRUDE'S SANDHILL FEN

The Sandhill Fen (the Fen) is located approximately 46 km north of the city of Fort McMurray, Canada, on Syncrude's former East-In-Pit (EIP) mine (BGC 2008). The primary goal of the Fen, was to create initial conditions necessary for the development of a self-sustaining fen peatland, and to serve as an instrumented research watershed to guide future peatland reclamation projects. It was designed and constructed between 2008 and 2012, and has been operational since January, 2013 (BGC 2014); my research plots were established in the summer of 2013.

The 52-ha Fen was built on a former East-in-pit (EIP) tailings pond (actively mined from 1977 to 1999), and is underlain by sand-capped, soft tailings deposits. Of the 52 ha, approximately 17 ha were primary fen; the remaining 34 ha were upland areas designed to capture precipitation and direct it into the primary fen area. The Fen is approximately 1000 m long by 500 m wide, a conceptual design based on the average ratio of over 6000 natural fens (Wytrykush et al. 2012). The soft tailings deposit cap is 10 m deep, and is underlain by 35 m of composite tailings mixed with sand layers. Half a meter of fine-grained clay-till was placed over the soft tailings cap to establish a mineral soil base, which was then covered with 0.5 meters of recently salvaged peat. Peat was placed primarily to create hydrological conditions that might promote peatland development and to aid in the establishment of a native peatland plant community. Several characteristic fen species were seeded in the primary fen, and the constructed uplands were vegetated to A/B and D ecosites according to Natural Resource Canada's Ecosites of Northern Alberta (Beckingham and Archibald 1996). Other design components include a primary fen, vegetated swales, two experimental perched fens, a fresh water storage pond, and a drainage piping system. The Fen required many unique design components in order to overcome the challenges of creating a peatland on a post-mined landscape (refer to BGC 2008, BGC 2012, and Wytrykush 2012 for more information on the Sandhill Fen).

1.3.1. Reclamation Challenges

Surface mining removes all overburden (i.e. aboveground biomass), drains and removes muskeg, and then removes all underlying clay, silt, and gravel until oil sands deposits are exposed (Pembina Institute N.D). Because surface mining removes peatlands entirely, the challenge becomes designing and constructing a peatland and its contributing watershed, rather than just restoring one. Reclaiming a peatland directly on mine tailings presents physical and chemical challenges because mine tailings are sodic and saline, have limited organic matter, and no seed bank (Harris 2007). Mine tailings are a mixture of process water, sand, silt, and clay, and they contain salts, naphthenic acids (NAs) and other acid-extractable organics (Grewer et al. 2010; BGC 2010; Schramm et al. 2000; Fedorak et al. 2003), many of which are toxic to a range of organisms (Clemente and Fedorak 2005; Headley and McMartin. 2004; Scott et al. 2004).

Each time water is recycled for bitumen extraction, the solute content of the tailings increases, with sodium chloride reaching levels that are toxic for most freshwater peatland vegetation communities (Trites and Bayley 2009; Allen 2008; Cronk and Fennessy 2001; Vitt et al. 1993); the increase in sodium cations can elevate the electrical conductivity (EC) of wetlands constructed with mine tailings. Trites and Bayley (2009) found that the vegetation communities of most reclaimed wetlands in the oil sands resembled freshwater marshes, with a notable scarcity of bryophyte species. This is an important finding because bryophyte communities are a key component of freshwater boreal fens. Moss communities are typically not found where EC is above 0.3 mS cm^{-1}, and the EC of most wetlands reclaimed on mine tailings is between 0.4 – 27.7 mS cm^{-1} (Trites and Bayley 2009). It was recommended that the Sandhill Fen keep EC under 10 mS cm^{-1} to increase the probability of a successful and desirable vegetation community; although natural fens can have EC's in excess of this range, the primary ions responsible for conductivity are from calcium and magnesium cations, rather than from sodium cations that are prominent in mine tailings (BGC 2014). According to flushing estimates, it will take approximately 20 years to flush pore water from the soft tailings deposit in the Sandhill Fen, thereby reducing EC. During the first year after construction, freshwater was pumped into the primary fen from Mildred Lake to help reduce elevated EC levels (Wytrykush et al. 2012); when EC levels remained above optimal, water was drawn out of the Fen via a sophisticated underdrain system, creating space for additional freshwater to enter the Fen (BGC 2008).

Fen peatlands have constantly moving water, and water tables near to (or above) the surface for most of the year (National Wetlands Working Group 1997; Whittington and Price 2006). Artificially constructed topography is required to provide a source of surface and groundwater to constructed peatlands in a way that keeps water moving through the wetland while maintaining an appropriate water table. Boreal peatlands generally have relatively large, gently sloping, catchment areas (Beckingham and Archibald 1996), which cannot be duplicated when there is limited reclamation space. Syncrude's constructed Sandhill Fen watershed only encompassed 52 ha, and the catchment area was made up of fairly steep topography. To minimize the risk of unwanted stream channels forming, water from an upstream pond percolated through a gravel dam at its entry point, and coarse woody debris berms (made of tree branches and trunks) were constructed at 3 points across the width of the Fen to help distribute flows (BGC 2008).

Another challenge of peatland reclamation, and one of the foci of this thesis, concerns uncertainties of peat application; the amount of peat required to create conditions required for the development of a self-sustaining peatland is unknown. In addition, the thickness of peat fluctuates (Petrone et al. 2008) due to subsidence, shrinkage, compaction, and/or oxidation (the conversion of organic matter into carbon dioxide and other gases) (Price and Schlotzhauer 1999; Scothorst 1997; Stephens 1955), and we don't know how peat is affected by excavation, mixing, storage, transport and placement in a constructed setting. I address the fate of peat, and challenges surrounding peat application, in chapter 2.

Peat is an organic soil composed of dead plant material (predominantly from sedges and sphagnum moss) that is in varying stages of decomposition; it is generally formed in-place, and contains a wealth of microorganisms that serve to decompose the plant material (Rydin and Jeglum 2013). The peat used for my research was mixed with mineral soil (a combination of Holocene peat and Holocene/Pleistocene mineral soil) because peat and mineral soils are often salvaged together prior to mining activities. The peat-mineral mix was salvaged from Syncrude's North mine expansion in the winter of 2010 and 2011, and stored in stockpiles next to the Fen for several weeks or months prior to placement in the Fen in February and March of 2011 (BGC 2014). Syncrude placed 50 cm of this peat-mineral mix throughout the primary fen area of the Sandhill fen in 2011; however, in 2013 the depth of peat ranged from 10 to 76 cm (NWLR 2014). Several other soil parameters were found to be quite variable in the reclamation peat soils (Table 1 - 1).

Table 1 - 1. Conditions of peat located in the primary fen area of the Sandhill fen in 2013. My research used the same source peat. BDL means below detectable limit (NWLR 2014).

Peat Depth	Detection Unit	Ammonium-N	Nitrate-N	Phosphorus	Potassium	Sulphate-S	pH	EC (ds/m)
0-25cm	Mean	0.9	BDL	BDL	145	632.6	5.6	1.92
	Standard Deviation	0.21	BDL	BDL	7.07	606.72	0.61	1.16
	Low	0.7	BDL	BDL	140	82	4.6	0.49
	High	1	BDL	BDL	150	1370	6.9	3.87
25 cm to mineral soil	Mean	BDL	BDL	BDL	BDL	681	5.8	1.74
	Standard Deviation	BDL	BDL	BDL	BDL	707.34	0.59	1.09
	Low	BDL	BDL	BDL	BDL	150	4.8	0.38

A second focus of this thesis concerns the challenge of establishing peat-accumulating vegetation. Establishing peat-accumulating plants (i.e. sedges and mosses) is essential to the long term sustainability of peatland reclamation, but competition with invasive, weedy, and/or marsh species (such as *Typha latifolia* in the Sandhill Fen) create challenges. In addition, it remains unknown which species are best for initiation of peatland development. Sedges (i.e. *Carex* species) are thought to be good candidates for peatland reclamation because they accumulate peat (a necessity for peatland function) and are a rapidly growing pioneer species in peatland formation (Bloise 2007); however, which sedge species dominated early peatland comminutes is unknown, and we must rely on current autecology of sedge species to predict which species are best for peatland reclamation.

Species that are considered beneficial to peatland reclamation include, *Carex aquatilis, C. diandra, C. utriculata, C. bebbii, C. paupercula, C. lasiocarpa, C. rostrata, C. limosa, C. interior, Scirpus atrocinctus, S. microcarpus, Juncus tenuis* (Vitt et al. 2016), *Larix laricina* and *Salix spp*. (Koropchack et al 2012); however, of this list *Carex aquatilis* is a critically importance species because it occurs across a range of successional stages (Hauser and Scott 2006), is common in the boreal mixedwood ecoregion, is present in local fens, is a good peat accumulator, can tolerate a wide variety of environmental conditions, grows on both peat and mineral soils, and shows signs of salinity tolerance (Daly et al. 2012; Gignac et al 2004; Chapin 1981). I test conditions for the establishment of Water sedge (*Carex aquatilis)* in chapter 3.

Carex aquatilis is a perennial, monoecious graminoid that can grow up to 80 cm tall and live greater than ten years (Beckingham and Archibald 1996; Bernard 1990). It tends to grow in a dense tuft, but can produce both long and short rhizomes, which together form tiller clumps; this type of growth form is best for colonization and competition against unwanted species (Gignac et al. 2004; Bernard 1990). Rhizomatous shoots are produced in late summer, and again from winter to early spring (Bernard and Gorham 1978). Although reproduction is primarily through vegetative spreading (i.e. by rhizomes), *C. aquatilis* occasionally reproduces by seeds, which are produced in abundance and distributed primarily by water; the seeds are buoyant and can travel long distances (Gignac et al. 2004; Beckingham and Archibald 1996; Bernard 1990). Mature plants generally have 3 to 6 spikes on the main stem with male spikes always located terminally (Johnson et al. 1995). It begins flowering in May and June, and then goes to fruit for the remainder of the summer, senescing in early Fall. Shoots typically live for 12 to 18 months (Koropchack et al 2012).

1.4. GENERAL OBJECTIVES

The general objective of this thesis was to investigate potential peatland reclamation outcomes on a former open pit oil sands mine site in northern Alberta. The field studies in this thesis were conducted on Syncrude Canada's Sandhill Fen, described earlier. The thesis is organized into 4 sections, the general introduction comprising Chapter 1. The study described in Chapter 2, examined the persistence of different peat thicknesses two years after application in a constructed setting. Two peat thicknesses (5 and 30 cm) were assessed under a variety of semi-controlled moisture conditions, measured as position relative to the water table (high, intermediate and low). Findings from this study may inform recommendations on the use of peat for future peatland reclamation projects on former open pit oil sands mines.

A second study, described in Chapter 3, assessed the survival and establishment of transplanted water sedge (*Carex aquatilis)* under a variety of semi-controlled environmental conditions, namely soil moisture and peat thickness. Mature *Carex aquatilis* plants were transplanted into three peat thickness treatments (0, 5, and 30 cm) and three positions relative to the water table (high, intermediate and low). The study also assessed differences between the establishment of transplanted vs. natural and broadcast seeded *C. aquatilis*.

Chapter 4 summarizes and integrates the results of Chapters 2 and 3, discusses future research opportunities, and offers recommendations on peat and *C. aquatilis* use in future reclamation projects. Specific study objectives and details are provided in associated chapters. The findings from this thesis are important for future peatland reclamation knowledge, as both peat and vegetation establishment are important for the development of peatland conditions, and therefore meeting reclamation initiatives.

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CHAPTER 2

Title: The fate of peat in a constructed peatland on a former open pit mine in northern Alberta.

2.1. INTRODUCTION

The objective of this study was to assess the persistence of peat placed in a constructed peatland (i.e. a wetland that lacked full functionality and sustainability as a peatland during the study), on a former open-pit oil sands mine site in northern Alberta. Reclaiming a peatland on a mine site requires complete design and construction of a landscape on unspecified mine tailings. Such peatland design is a relatively new concept, for which little guiding research exists. Thus, there is a need to develop scientifically defensible criteria that can guide future peatland construction on such sites. To create suitable growing conditions, proper hydrology (i.e. water source, movement, and depth), salinity, vegetation, and substrate are needed. This paper addresses the suitability of substrate; particularly the use, amount, and persistence of reclamation peat placed in a constructed peatland setting.

The application of peat to a constructed peatland is thought to aid in natural peatland hydrology (Wytrykush et al*.* 2012), to restrict the movement of unwanted dissolved solutes from underlying tailings material (Nwaishi et al. 2015), to aid in soil moisture retention for plant roots (Walczak et al. 2002), when possible to provide a seedbank, and to serve as a substrate promoting the establishment of peatland bryophytes (Vitt and House 2015; Rochefort and Lode 2006) and vascular plants (Nwaishi et al. 2015). The thickness of peat needed to achieve these attributes, especially a combination of these features, is unknown. A thin layer of peat may be inadequate to restrict unwanted solute movement, or to facilitate peatland hydrological processes, but may suffice as a seedbank and substrate for some peatland bryophytes (Vitt and House 2015). A thick layer of peat may promote more natural peatland hydrology, but may not be necessary for the development of some desirable vascular plants (Farooq 2011).

In addition, the persistence of applied peat over time remains unclear; yet, this knowledge is essential for recommending peat applications best suited for peatland reclamation. Peat thickness fluctuates (Petrone et al. 2008) due to subsidence, shrinkage, compaction, and/or oxidation (the microbial respiration of organic matter into carbon dioxide and other gases; Price and Schlotzhauer 1999; Scothorst 1997; Stephens 1955). The thickness of the peat layer may also expand when wetted (Petrone et al. 2008) and/or the layer may be lost entirely due to water and wind erosion (McNeil et al. 2000; Campbell 2002). The rate at which peat decomposes depends primarily on the depth of the water table (i.e. moisture conditions) (Petrone et al. 2008; Rochefort and Lode 2006; Hilbert et al. 2000; Stephens 1955), soil temperatures (Wang et al. 2010), and to a lesser degree on the firmness and structure of the peat itself. For example, soft peat will shrink more readily than fibrous peat (Stephens 1955). Reclamation peat needs to be thick enough to withstand these changes and losses while still facilitating desired peatland functions. Observing reclamation peat (which has often been mixed with mineral soil and lacks the structure of peat formed in place) in a semi-controlled setting can help identify an optimal initial peat thickness for future constructed peatlands. The objective of this study was therefore to assess the persistence of two peat thicknesses (5 and 30 cm) under three semi-controlled moisture conditions.

This field study, on Syncrude Canada's reclaimed Sandhill Fen (a peatland constructed on a former open pit oil sands mine in northern Alberta), was designed to: (1) relate peat's persistence (measured as change in peat thickness) to general moisture conditions, measured as position of the peat-mineral soil interface relative to the water table, and (2) relate peat's persistence (measured as change in peat thickness) to initial peat thicknesses placed for reclamation. I hypothesized that: (1) peat thickness would decrease under dry conditions, and that peat may expand if completely submerged under water, and (2) that thicker peat applications would exhibit proportionally greater compression than shallower peat thicknesses. This is the first study of reclamation peat under semi-controlled conditions, in a constructed setting, that I am aware of.

2.2. STUDY SITE

The study was conducted in the Fort McMurray Region of Northeastern Alberta on Syncrude Canada Ltd.'s (Syncrude) constructed Sandhill Fen (the Fen), which is located approximately 46 km north (57^{N} degrees 02' 21.49" N, 111^{N} 35' 34.14 W) of the city of Fort McMurray, Canada (BGC 2008). The Fort McMurray Region is located in the Central Mixedwood Subregion of Alberta's Boreal Forest Natural Region, and is characterized by relatively short, warm growing seasons, and long freezing winters (Natural Regions Committee 2006); the average summer temperature is 13.5°C, and the average winter temperature is -13.2°C (Strong and Leggat 1992). The Central Mixedwood Subregion is the largest natural subregion in Alberta; it accounts for 25% of the province and peatlands constitute a large proportion of its area (Natural Regions Committee 2006). The Fen is therefore subject to the same climatic and environmental conditions as natural fens of this Region, and Subregion.

The primary goal of the Fen was to create initial conditions necessary for the development of a self-sustaining fen peatland, and to serve as an instrumented research watershed to guide future peatland reclamation projects. It was designed and constructed between 2008 and 2012, and has been operational since January, 2013 (BGC 2014); my research plots were established in the summer of 2013.

Built on the former East-In-Pit tailings pond (actively mined from 1977 to 1999), it is underlain by sand-capped, soft tailings deposits and is approximately 52 ha in size. Of the 52 ha, approximately 17 ha were primary fen; the remaining 34 ha were upland areas designed to capture precipitation and direct it into the primary fen area. Its shape (1000 m long by 500 m wide) is a conceptual design based on the average ratio of over 6000 natural fens (Wytrykush et al. 2012). The soft tailings deposit cap is 10 m deep, and is underlain by 35 m of composite tailings mixed with sand layers (BGC 2008). Half a meter of fine-grained clay-till was placed over the soft tailings cap to establish a mineral soil base to serve as subsoil for root establishment and prevent salt from underlying tailings pore water from entering the Fen. The clay-till was covered with 0.5 m of peat-mineral mix to create hydrologic conditions for peatland development and to aid in the establishment of a native peatland plant community (Wytrykush et al. 2012). The 0.5-m peat application depth was recommended to provide sufficient peat for plant establishment and to tolerate some loss of peat to erosion, floating, and/or settlement (BGC 2008; BGC 2014). The peat-mineral mix (a combination of Holocene peat and Holocene/Pleistocene mineral soil) was used because peat and mineral soils are often salvaged together prior to mining activities. The peat-mineral mix was salvaged from Syncrude's North mine expansion in the winter of 2010 and 2011, and stored in stockpiles next to the Fen for several weeks, or months, prior to placement in the Fen in February and March of 2011 (BGC 2014). Other Fen design components included the construction of uplands, vegetated swales, two experimental perched fens, a freshwater storage pond, and an underdrain piping system (Wytrykush et al. 2012).

The research plots were situated in the primary fen area, on four specially designed 1 m-thick clay islands (G, F, A and E), to determine the effects of initial peat depth, and position relative to water, on the persistence of reclamation peat (Figure 2 - 1). The clay used for the islands was a combination of Pleistocene glacial and glaciolacustrine till that was salvaged from the north mine advance in 2009.

Figure 2 - 1. Basic diagram of the Sandhill Fen; research plots were situated in the primary fen area, on four specially designed clay islands (G, F, A and E).

2.3. METHODS

2.3.1. Experimental Design

Three initial peat depths (0, 5 and 30 cm) and three positions relative to the water table (High, Intermediate, and Low) were established (i.e. a three by three, two factorial, split plot design). Plots with 0 cm of peat were primarily established for qualitative observation of peat movement, and a concurrent study on the survival and establishment of *Carex aquatilis* (see chapter 3); although they are not used in the analysis of this study, they are included in the description of the study design for ease of understanding, and visualizing, the randomization procedure. After the removal of plots containing 0 cm of peat prior to analysis, six treatment combinations remained (Table 2 - 1).

Because fens usually have fluctuating water tables (NWWG 1997), and there was incomplete control of the Fen's managed water table, the positions (High, Intermediate, and Low) were meant to represent a spectrum of realistic moisture conditions, whereby two heights relative to the water table (measured at each plots mineral-peat interface, or the bottom of the peat plot) were established for each category (Table 2 - 1); peat placed in "low" plots were submerged at the start of the study, plots located in the "intermediate" position were located very near to, or just above the water table, and plots in the "high" position were entirely above the water table. The variety of depths were selected and categorized to accommodate expected change in conditions (Table 2 - 1). In addition, changes in water table depth were not uniform throughout the Fen, and this variation was accounted for during data analysis by blocking each replicated island (water table depths were similar around each island, but not between islands).

Table 2 - 1. Treatment combinations and the two plot heights (measured at the mineral-peat interface, or the bottom of peat plots) relative to the water table, that were combined into categorical treatments of either “high”, “intermediate”, or “low.”

Treatment combination	Peat depth (cm)	Position relative to the water table	Position relative to the water table (cm)	
			A	B
1	5	High	60	45
2	5	Intermediate	35	25
3	5	Low	-15	-25
4	30	High	60	45
5	30	Intermediate	35	25
6	30	Low	-15	-25

Because of environmental constraints, treatments were applied at two plot sizes (i.e. a standard split-plot), which allowed for a complete block design across replicates. The study is replicated four times on clay islands G, F, A and E, located within the primary fen area of the Fen (Figure 2 - 1). To maintain homogeneity of the replicates, the islands were similar in size and topography, and all had a clay substrate.

Each island was divided into three zones (i.e. large plots) representing three elevations relative to the water table (High, Intermediate, and Low), and each zone was assigned six 1 x 1 m plots (i.e. small plots) organized into pairs along 3 transects that radiated from the centre of an island. A 30-cm wide band of geotextile was placed around plots located in the water to keep peat placed throughout the Fen from moving into the plots. Initial peat thicknesses (0, 5 or 30 cm) were randomly assigned to small plots and were arranged in rectangular solid forms. Of the six plots assigned to each zone, two had an initial peat thickness of 0 cm, two had an initial peat thickness of 5 cm, and two had an initial peat thickness of 30 cm. The small plots were arranged in three radial transects that faced different cardinal directions to account for variation in island aspect (except on island E because of that island’s unusual shape). A transect was randomly oriented by selecting a number between 0 and 360 degrees, and subsequent transects were oriented by adding 120 degrees to the initial compass direction; however, variation among transects due to aspect, or any other feature, was later determined insignificant to the study (Figure 2 - 2).

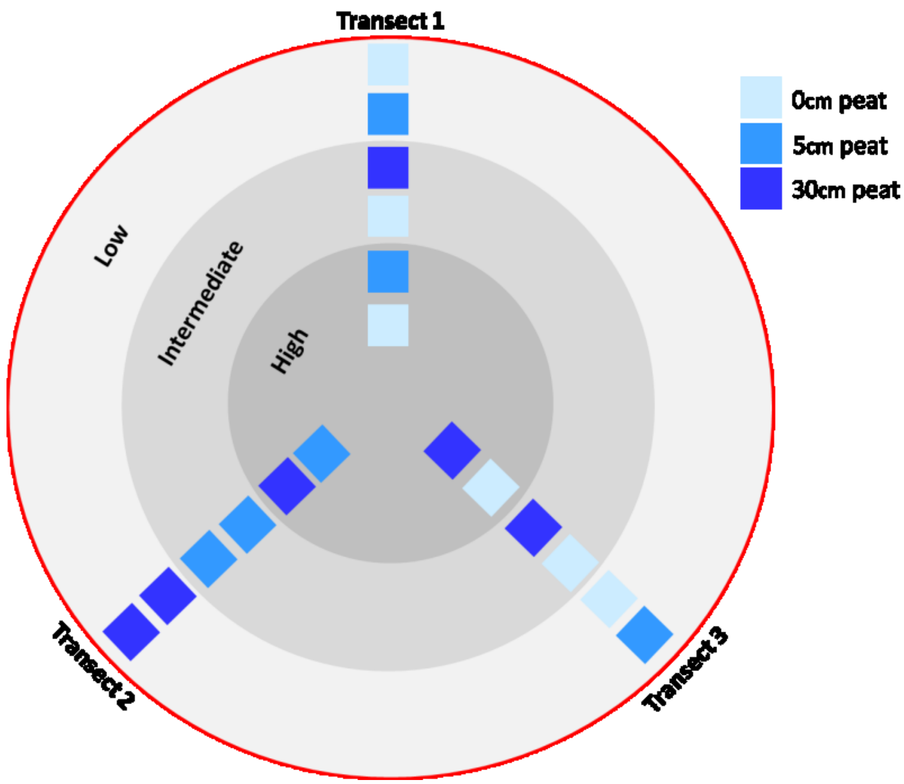

Figure 2 - 2. Schematic diagram (not to scale) of 1 x 1 m peat plots at three positions relative to the water table present on each of four clay islands. Peat placed in “low” plots were submerged at the start of the study. Plots located in the “intermediate” position were located very near to or just above the water table, and plots in the “high” position were entirely above the water table.

Peat plots were established in summer 2013, using the same peat (i.e. from the same source) placed in the primary fen; the peat was salvaged from Syncrude’s North mine advance in the winter of 2010 and 2011, and stockpiled as described earlier. It was collected using hand shovels, and transported in 20-L buckets to the study area, then carefully placed in individual plots (in a block shape) and levelled to the appropriate elevation by hand.

2.3.2. Data Collection

Peat thickness was measured the following two summers, in June 2014 and 2015. Peat thickness was measured (in cm) in the northeast corner, center, and southwest corner of each plot; the values were averaged and change in peat thickness was converted to a proportion (of the initial peat thickness), allowing plots with different initial peat depths to be compared. The resulting single measurement served as the response variable for each unique plot.

Peat thicknesses (distance from the surface to the mineral substrate) were primarily measured using a ruler; however, this was not practical for plots established in, or very near, the water because the soft underlying clay was difficult to distinguish from peat without visual aid. In this case, a soil profile was collected using a clear tube and the peat layer was then measured using a ruler.

2.3.3. Statistical Analysis

Plots with initial peat depths of 0 cm were removed from the data prior to analysis because their use in understanding change in peat thickness was not helpful. These plots were necessary for a subsequent study assessing the survival and spread of *Carex aquatilis* (see Chapter 3); however, they did provide some qualitative observations that aided in our knowledge and understanding of peat movement within a reclamation setting. This turned out to be an important and useful observation for future consideration.

Permutation ANOVA (analysis of variance), with 5000 replicates, was performed because the data did not fit the assumptions (i.e. normality and heterogonous variance) necessary for a parametric ANOVA. Analysis was performed at a significance level of α=0.05 with 95% confidence intervals, using the statistical software package “lmPerm” (Wheeler 2010) in R Program, version R-2.15.1 (R Core Team 2013). Variation among islands (and therefore variation among water table at each island) was accounted for by including island as a blocking factor within the permutation model. Permutation among all observations is not meaningful when a block needs to be considered, and R program handles this by projecting the design and observations into their unique block identifier (i.e. islands G, F, A, and E). According to the LmPerm package creator Robert E. Wheeler (2010), permutation analysis works well in this circumstance.

2.4. RESULTS

The Fen's annual average water table depth was 0.08 m in 2014, and 0.07 m in 2015. Water table depth fluctuated between -0.2 and 0.4 m (a total fluctuation of 0.6 m) in 2014, and between -0.4 and 0.5 m (a total fluctuation of 0.9 m) in 2015 (Spennato 2016). On average, the highest water table depths were noted in the spring, due to snow melt and spring rain events, followed by subsequent declines (i.e. a drying trend) throughout the summer (Spennato 2016). Although this study was designed to account for changes in water table depth, it is worth noting that higher water table depths during spring may have contributed to additional peat losses in "low" plots, by peat floating and/or washing away; subsequently, decreases in the water table depth throughout the summer may have accelerated drying in the "high" and/or "intermediate" plots.

During the two years following initial peat placement (measured in 2015), peat reduced in thickness, rather than expanded, in all plots except two. Peat from adjacent plots, with thicker peat applications, broke away and fell into these two plots; because the study was designed to assess changes to the original placed peat, these plots were omitted from the analysis. This study was not designed to address if changes in peat thickness represented a loss of peat, or simply compaction of existing peat; for the purpose of this study, peat reductions simply refers to a change in peat thickness. The greatest amount of peat reduction (absolute change and proportion of peat depth) took place in the plots that were initially placed under water (i.e. "low" plots), when the initial peat thickness was 30 cm ($\overline{X}$=22.5±2.78 cm; $\overline{X}$=75.3±9.28%). The smallest changes occurred in plots situated near to the level of the water table (i.e. intermediate plots), when the initial peat thickness was 5 cm ($\overline{X}$=0.63±0.24 cm; $\overline{X}$=12.5±4.79%) (Table 2 - 2; Figure 2 - 3).

Table 2 - 2. Mean peat reduction by position relative to the water table and initial peat thickness (cm) in 2015. n=8 for each treatment combination. Standard error in brackets.

Position Relative to Water Table	Initial Peat Thickness (cm)	Mean peat reduction (cm)	Mean peat reduction (%)
High	30	12.59 (1.43)	41.9 (4.82)
	5	1.63 (0.40)	32.5 (8.02)
Intermediate	30	8.10 (1.53)	26.9 (5.12)
	5	0.63 (0.24)	12.5 (4.79)
Low	30	22.5 (2.78)	75.3 (9.28)
	5	1.36 (0.50)	27.2 (10.09)

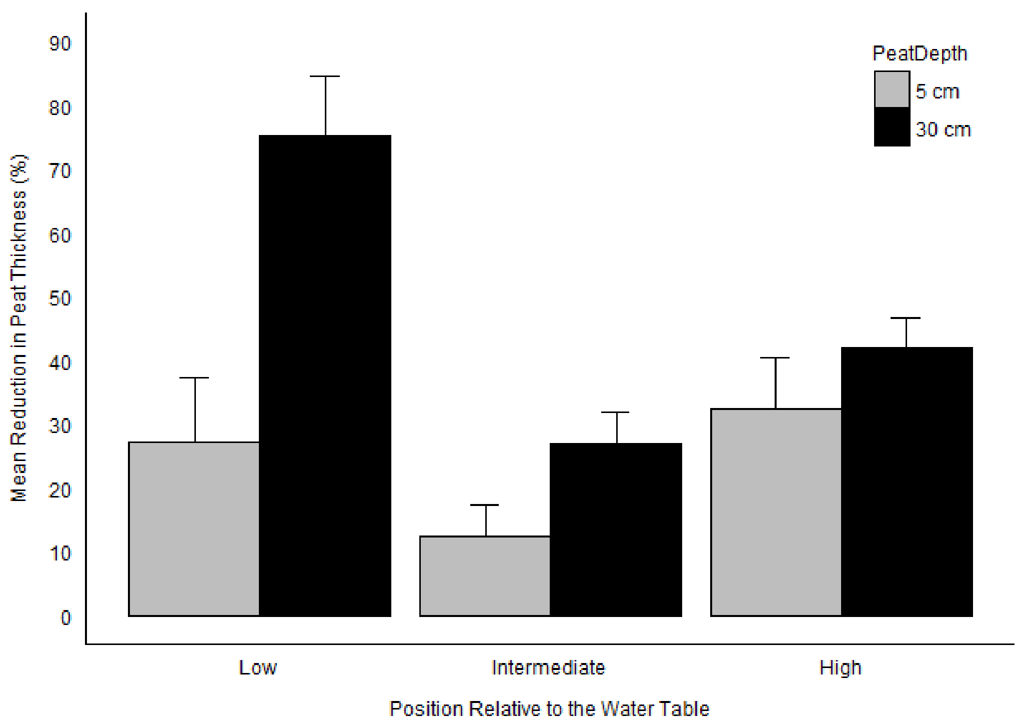

Figure 2 - 3. Mean (±SE; n=8) reduction in peat thickness (%) by treatment combinations in 2015.

Initial peat thickness (permutation ANOVA; P_{perm}=0.002), and position relative to water (permutation ANOVA; P_{perm}=0.002), had a significant effect on peat thickness at the end of two years. The interaction between initial peat thickness and position relative to water was not significant (permutation ANOVA; P_{perm}=0.145).

Table 2 - 3. Results of permutation ANOVA. Probabilities are based on F-statistics generated from 5,000 permutations of the original data.

Source	DF	SS	MS	F	Iterations	P
Initial Peat Depth	1	1557.0	1557.03	3.97	5000	**0.002****
Position Relative to Water	2	3533.4	1766.72	4.51	5000	**0.002****
Interaction	2	748.3	392.13	1.79	1044	0.145
Residuals	24	5260.2	219.18			

The persistence of peat whose initial thicknesses differed (30 vs. 5 cm) was statistically different after 2 years (permutation ANOVA; P_{perm}=0.0020) (Table 2 - 4; Figure 2 - 4) Peat plots with an initial thickness of 30 cm reduced in thickness proportionally more ($\bar{X}$=41.61±5.07%) than peat plots with an initial thickness of 5 cm ($\bar{X}$=26.24±5.07%). Peat in plots that were located in the low position lost the greatest proportion of their thickness ($\bar{X}$=45.21±11.10%), followed by plots in the high position ($\bar{X}$=37.19±4.68%), and peat in plots located in the intermediate position lost the least proportion of their thickness ($\bar{X}$=21.64±4.15%) (Table 2 - 4). Significantly less reduction in peat thickness was observed at the intermediate position than at either the high (permutation ANOVA; P_{perm}=0.005) or low (permutation ANOVA; P_{perm}=0.022) positions, but peat thickness reductions in the high and low positions were not statistically different (permutation ANOVA; P_{perm}=0.087) (Table 2 - 4; Figure 2 - 5).

Table 2 - 4. Mean peat reduction by individual treatments in 2015. Values with different letters indicate a significant difference between varieties within treatments, evaluated at p≤0.05. n=24. Standard error in brackets.

Treatment		Mean Peat Reduction (cm)	Mean Peat Reduction (%)
Initial Peat thickness	5 cm	1.32 (0.25)	26.24[a] (5.07)
	30 cm	12.49 (1.51)	41.61[b] (5.07)
Position Relative to the Water Table	High	7.12 (1.59)	37.19[a] (4.68)
	Intermediate	5.38 (1.48)	21.64[b] (4.15)
	Low	9.29 (3.99)	45.25[a] (11.10)

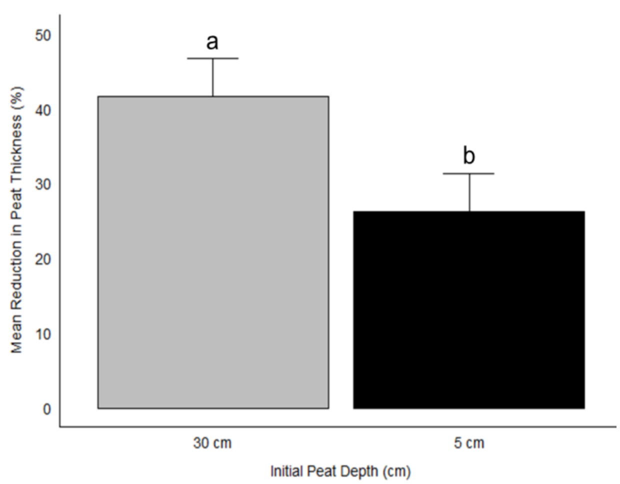

Figure 2 - 4. Mean percent reduction in peat thickness (±SE; n=24) by initial peat depth (cm), in 2015. Letters indicate significant differences calculated using a significance level of α=0.05.

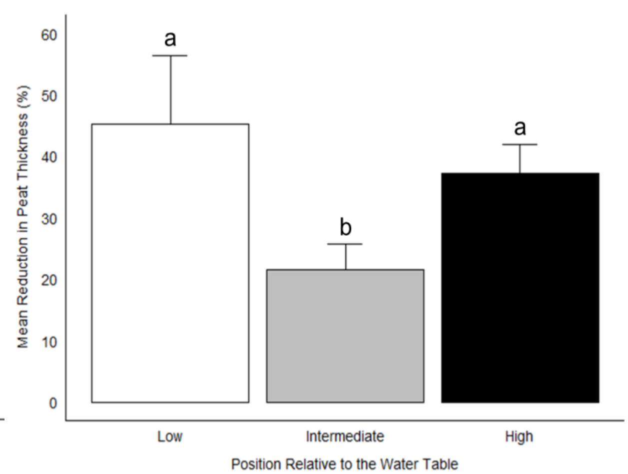

Figure 2 - 5. Mean percent reduction in peat thickness (±SE; n=24) by position relative to the water table (cm), in 2015. Letters indicate significant differences calculated using a significance level of α=0.05.

2.5. DISCUSSION

This study addressed fundamental questions regarding the thickness and persistence of reclamation peat, applied to a constructed peatland, on a former open-pit, oil sands mine in northern Alberta. Understanding the properties and persistence of peat (i.e. changes in thickness) in the early successional stages of a constructed peatland is crucial for determining the most effective use of this important reclamation material. Reclamation peat must be thick enough to withstand environmental changes and losses, while still providing desired peatland functions. In this study, reductions in peat thickness depended on both initial peat thickness, and its position relative to the water table. In addition, peat thickness subsided markedly in the first two years following placement, and there was no increase in peat thickness under any combination of analyzed treatments.

Overall, the reduction of peat observed in this study was greater than what has been observed in some natural peatlands, disturbed peatlands, and reclaimed peatlands; however, peat reduction cannot be directly compared because initial peat thickness, handling, and duration of measurement varied with each study. The greatest reduction of peat observed in this study was 22.5±2.78 cm (observed in 30 cm peat plots placed underwater in the “low” position; approximately 75% of the initial thickness), compared with 10 cm in a natural subarctic fen (Roulet 1991), 8 cm in a harvested peatland in Quebec (Price 2003), and 2.3 cm in Canada’s western boreal plain (Petrone et al. 2008). Petrone et al. (2008) noted that peat in disturbed peatlands subsided twice as much as material in undisturbed peatlands in Canada’s western boreal plain, but even the disturbed peatlands subsided markedly less than what was observed in this study. Reddy et al. (2006) found that in the lab peat subsided ~0.23 cm/y when water tables were held at the surface, and ~0.57 cm/y when the water table was 30 cm below the surface; these small values demonstrate the importance of field studies where peat is subjected to a wide range of environmental conditions (e.g. sunlight, humidity, wind, varying temperatures, and evapotranspiration) that may accelerate physical, chemical, and biological processes that lead to changes in peat thickness (Reddy et al 2006). The yearly reduction in peat observed in this study was also notably higher than what has been observed in a wide range of natural peatlands; 1.2 – 3.5 cm/y in North Carolina (Dolman and Buol 1967), 3 cm/y in the everglades (Stephens 1994), 1.4 – 2.5 cm/y in Florida (Shih et al. 1997; Shih et al. 1998), and 3.4 cm/y in New Zealand (Shipper and McLeod 2002).

An important observation was that peat located in the “intermediate” position (i.e. close to or at the water table) reduced statistically less than peat located in the low and high positions (Table 2 - 4; Figure 2 - 5), suggesting that ideal hydrology, or specifically water table elevation, may play a role in minimizing peat losses. I expected the position of peat (relative to the water table) to be important because subsidence is often a function of groundwater levels (Wosten et al. 2007; Wosten et al. 1997; Stephens 1955), and processes affecting peat thickness can be mitigated through water management (Tan and Amak 1989). Water table is important because moisture affects the rate of aerobic respiration, leading to peat decomposition, and therefore peat shrinkage as gaseous carbon evacuates. As peat dries, the rate of oxidation increases, causing peat to shrink; therefore, peat’s position relative to the water table will affect the process of oxidation (Gambolati 2003; Price and Schlotzhauer 1999; Scothorst 1997; Stephens 1955). Oxidation is believed to be the primary contributor to peat shrinkage above the water table because aerobic bacteria expedite the decomposition of peat. When anaerobic conditions prevail, microorganisms operate more slowly and plant material tends to accumulate (Stephens 1955).

In addition to water table depth (Petrone et al. 2008; Rochefort and Lode 2006; Hilbert et al. 2000; Stephens 1955), the rate at which peat decomposes is also influenced by soil temperature (Wang et al. 2010). In very dry conditions, temperature is the primary control of oxidation rates (Stephens et al. 1984; Rojstazer and Deverel 1995). In addition to being drier, peat located in the high position was expected to be warmer and more aerobic, thus, decompose more rapidly. The measurements taken from high and intermediate positioned plots corroborated this expectation. Peat located in the high position (therefore the driest), reduced in thickness more than peat located in the intermediate position (Table 2 - 4; Figure 2 - 5), suggesting that peat placed completely out of the water may be subjected to higher rates of decomposition. Because decomposition represents a permanent loss of peat (Waddington and McNeil 2002) these findings have important implications for meeting future peat thickness targets in a constructed setting.

The persistent loss of peat in dry plots could also be ascribed to wind erosion (Campbelle et al. 2002; Waddington and McNeil 2002; Zobeck 1991), as dry peat is more susceptible to wind erosion than wet peat due to its lightness (Puustjarvi and Robertson 1975), and because the force of particle cohesion is stronger in wet soils than dry soils (Chepil 1956). Furthermore, most disturbed or reclaimed peatlands have relatively sparse vegetation cover, and smooth surfaces, as compared to the moist and generally hummocky topography of natural peatlands; these flat, dry, and poorly vegetated sites may be subject to greater wind erosion than natural wetlands (Campbelle et al. 2002), suggesting that rapid establishment of vegetation on reclamation peat surfaces may help reduce wind erosion and therefore peat losses. However, although high positioned plots had little vegetation cover and were very dry (relative to natural peatlands), I suspect that wind erosion was not a major force of peat losses. During the summer months (June, July, and August) the prevailing wind direction in the Fort McMurray region is west (Alberta Agriculture and Forestry 2017), and I did not observe obvious erosion on the west side of my plots; peat losses appeared relatively uniform across plot surfaces. Nevertheless, some wind erosion may have occurred, and because moist peat is less susceptible to wind erosion (Campbelle et al. 2002), keeping the water table at, or near, the surface of newly applied reclamation peat may help reduce wind erosion. I suspect that greater moisture in peat located at the intermediate position (relative to the high position) may have limited decomposition rates and reduced wind erosion, thereby minimizing peat losses.

Prior to the study, it was difficult to anticipate how peat thickness would change in the low position plots (i.e. plots that were established under water) because of the Fen's pump system. Water table fluctuations can influence peat compression, shrinkage and expansion (Petrone et al. 2008), and plots in the low position experienced the most direct effects of changes in water table depth within the Fen. As water infiltrates the pore spaces of dry peat, the peat profile typically expands slightly (Petrone et al. 2008;

Kuhry and Turnunen 2006), but this was not observed year-after-year in this study. Peat thickness reduced in plots that were located under water throughout the duration of the study. Subtle differences in the peat profile may have occurred on a day-to-day basis depending on precipitation events and seasonal variation in water table elevation, but this study was not designed to detect such subtle variations (measurements were collected once annually). Even peat at the intermediate position that was wetted during rises in water table elevation, did not increase in thickness. This finding is not consistent with normal peat behaviour. Petrone et al. (2008) looked at changes in peat elevation after rainfall events and noted that peat expanded at all sites following re-wetting. The fact that I did not observe any peat expansion suggests that the physical and chemical alterations that reclamation peat undergoes during excavation and storage may have compromised peats ability to expand. Alternatively, peat that remains dry for some time can become hydrophobic and repel water (Wallis and Horne 1992). However, if peat is persistently "wetted," it will eventually lose its hydrophobic properties, and water will begin to infiltrate the pore spaces (Wallis and Horne 1992). Given this knowledge, I expected that peat located in plots underwater would eventually begin to expand (even if the peat had remained dry for an extended period of time) and this was not observed.

I observed substantial reductions in peat thickness in low positioned plots; slightly more than reductions observed in high positioned plots, but significantly (i.e. statically) more than the reductions observed in intermediate positioned plots. The reduction in peat thickness under water was likely the result of compaction, losses, or both. Peat is compressible under force (Price and Schlotzhauzer 1999); compression being the subsidence of peat below the water table due to the weight of overlying peat layers (Petrone et al. 2008). As the water table declines, top peat layers are no longer buoyed by the water column, and this additional stress may cause the pore structure of peat to collapse, and therefore peat to become denser (Petrone et al. 2008; Whittington and Price 2006). Peat compression reduces the thickness of peat layers and therefore lowers surface elevation (Glaser et al. 2004). Because peat plots located in the low position were initially placed underwater, and the water table fluctuated, compression is a likely explanation as to why peat reduced markedly in the low position. However, when water table depths at individual plots were compared to peat reductions at individual plots, no clear trend was observed, suggesting that there are likely additional factors involved.

Another explanation for the reduction in peat thickness in low positioned plots - and most pronounced in the 30 cm peat depth - was the possibility that some peat was lost through floating or washing away. While the Fen's topography was designed to keep the water table within 20 cm of the surface, freshwater was also pumped into and out of the Fen in an effort to stabilize the water table (Wytrykush et al. 2012; BGC 2008); therefore, flow rates and water table depth varied considerably during the first year of the study (see results section). Although geotextile fabric was used to keep peat from moving in and out of the submersed plots, snow and ice loading caused some barriers to fail, allowing peat from the surrounding primary fen area to freely move into the plots. Some plots with 0 cm of peat (placed for a complementary study), accumulated peat from the surrounding areas during the study. In addition, I observed varying peat depths throughout the Sandhill fen even though 50 cm of peat was spread relatively evenly during construction. More specifically, I observed a build-up of peat behind areas of thicker vegetation, suggesting that peat had washed down to these locations and become retained. In addition, natural peatlands are completely vegetated (Beckingham and Archibald 1996), but because newly reclaimed peatlands have limited vegetation cover, and incomplete root stabilization (Rochefort and Lode 2006), peat is more likely to move. Rochefort and Lode (2006) found approximately 65% of the surface of disturbed peatlands consisted of exposed bare peat, as opposed to 0% bare peat cover in natural peatlands. While the Fen exhibited extensive early vegetation cover after two years (Vitt et al. 2016), bare peat is more common than in natural peatlands. These observations suggest that reclamation peat is subject to movement in a constructed environment; however, the variable hydrological conditions created by the pump system may have contributed to peat movement in the Sandhill Fen.

Another important finding of this study was that the relative degree of peat reduction depended on initial peat thicknesses, at all positions relative to the water table; plots where peat was initially thicker (i.e. 30 cm) were subject to greater peat reductions and losses than plots with thinner initial peat thicknesses (i.e. 5 cm). In the low positioned plots, this can likely be explained by the weight of overlaying peat layers as the water table fluctuated, and thicker peat being more likely to wash away. However, the difference in peat reductions above the water may also be explained by the added exposure of 30 cm peat plots. Because peat plots were arranged in rectangular solid forms, the 30 cm peat plots had a surface area of 22,000 cm^2 ([100 x 100] + [4 x 30 x 100] cm), as opposed to a surface area of 12,000 cm^2 ([100 x 100] + [4x 5 x 100] cm) in the 5 cm peat plots. Thus, the 30 cm peat plots had an 80% greater surface area available for soil gas exchange (Stepniewski et al. 2011), greater sun exposure, and greater susceptibility to wind erosion. Greater sun exposure could lead to increased drying and temperatures, which play a role in the rate of oxidation (Wang et al. 2010). In addition, 30 cm plots were raised features on a relatively smooth landscape, which may have subjected them to greater erosion during wind or rain events (Waddington and McNeil 2002; Campbelle et al. 2002). The shape of the peat plots represented a study limitation; ideally I would have looked at changes in peat thickness at 30 and 5 cm placed over a large area to reduce the effects of added surface area. However, these observations are realistic to the extent that the 30 cm peat plots may have behaved similarly to peat hummocks, and variation in microtopography is desirable in reclaimed landscapes because it increases microhabitat heterogeneity (Gauthier et al. 2017).

Reclaiming an open pit mine requires the complete design and construction of a peatland, and its contributing watershed, on unspecified mine tailings. Few studies have addressed research needs under these circumstances, as very few peatlands have been constructed on former open pit oil sands mines. The Sandhill Fen offered a unique landscape by which to study the fate and behaviour of peat in a constructed peatland, and findings from this study may benefit future decisions regarding the use of peat substrates.

2.5.1. Study Limitations

The range of inference for this study is limited to the Sandhill Fen, which represents a novel ecosystem, so extrapolation of results should be used cautiously. The sample size was relatively small (48 plots in total); however, permutation ANOVA is robust for small data sets. The shape of my peat plots also represented a study limitation in that 30 cm peat plots had a greater surface area (and therefore greater exposure to sun and wind erosion) than the 5 cm peat plots; this may have contributed to differences in peat reductions between peat depths (30 vs 5 cm) in plots located above the water table.

2.6. CONCLUSION

Within the limitations of the experiment, I found that the persistence of reclamation peat varied with initial peat thickness and position relative to the water table. Peat thickness was markedly reduced two years following its placement, and peat thickness did not increase in any combination of treatments. Peat in plots located at intermediate positions (i.e. near the level of the water table), reduced the least, suggesting that intermediate level moisture conditions may minimize changes in peat thickness. Peat located in the high position, thus driest, was likely subject to greater decomposition, oxidation, and wind erosion. Peat located in the low position (i.e. wettest conditions) may have been influenced by compression and losses as the water table fluctuated. Plots with initial peat thicknesses of 30 cm subsided relatively more than initial peat thicknesses of 5 cm, suggesting that the added weight of additional peat, or the greater surface area of 30-cm thick peat plots may have contributed to greater compaction and/or losses. My results suggest that peat reductions and losses were the least in plots whose elevation was near that of the water table - at intermediate moisture levels. Initial peat substrate thickness declined by 10-70% over the first two years following their placement. Additional studies are needed to resolve the mechanisms responsible for the observed differences in rates of peat reductions and losses.

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CHAPTER 3

Title: Survival and establishment of transplanted *Carex aquatilis* in a constructed peatland.

3.1. INTRODUCTION

The objective of this study was to identify variables that can enhance the survival and establishment of *Carex aquatilis* (water sedge) transplanted into a constructed peatland (i.e. a wetland that lacked full functionality and sustainability as a peatland during the study), on a former open-pit oil sands mine in northern Alberta. Reclaiming a peatland on an open-pit mine requires complete landscape design and construction of a wetland, and its catchment basin, on unspecified mine tailings. Such reclamation is a relatively new concept for which there is little published research, or scientifically-based guidance. Establishment of a self-sustaining community requires the provision of suitable hydrology (i.e. water source, movement, and depth), water chemistry, substrate, and vegetation. This paper addresses vegetation; particularly the survival and establishment of *C. aquatilis* in a constructed peatland.

Establishing vegetation is important for peatland reclamation because plants can increase shade and moisture retention (Peng et al. 2004), stabilize soil (Hansen et al. 1988), reduce substrate erosion (Boggs et al. 1990), create microhabitats for bryophytes (Vitt and House 2015), contribute to peat accumulation (Vitt et al. 2016), prevent seeds from surrounding natural areas from blowing away, and collect thermal barriers of snow in winter (Peterson 2001). Plant species composition influences the ecological function of peat layers, so establishing appropriate plant species is critical for the establishment of desired ecological function (Graf 2009); however, which species to use for peatland reclamation remains unknown. Vegetation strategies generally aim to establish early successional plant communities promoting development of peatland conditions over time. Sedges are considered good candidates for peatland reclamation because, according to macrofossil analysis, they are dominant in the early successional history of most peatlands (Kubiw et al. 1989; Nicholson and Vitt 1990; Kuhry et al. 1992;

Yu et al. 2000), suggesting that sedge peat is a pioneer substrate in peatland formation (Bloise 2007). Daly et al. (2012) found sedges became established sooner, and began reproducing more quickly, than mosses and other vascular plants in a constructed fen peatland on a post-mined, oil sands landscape. They also found that sedges produced more biomass than mosses and other vascular plants, suggesting that they are a good candidate for quickly generating cover and creating a peat-accumulating system (Daly et al. 2012).

Water sedge (*Carex aquatilis*) is a good candidate for peatland reclamation because it occurs across a range of successional stages (Hauser and Scott 2006), is common in the boreal mixedwood ecoregion, is present in local fens (Johnson et al. 1995), is a good peat accumulator, can tolerate a wide variety of environmental conditions, and shows signs of salinity tolerance (Vitt et al. 2016; Daly et al. 2012). Furthermore, *C. aquatilis* has both long and short rhizomes, which together form tiller clumps; this type of growth form is ideal for colonization, and holding the site against unwanted species (Bernard 1990). Although *C. aquatilis* can tolerate a wide variety of conditions, we know little about optimal conditions for its survival, establishment, and spread. Water table depth is likely of primary importance, yet critical moisture thresholds or preferred moisture levels that promote fen species establishment have not been identified (Price and Whitehead 2004). In addition, *C. aquatilis* can grow on both mineral and peat substrates (Beckingham and Archibald 1996; Vitt et al. 2011), but which substrate type and thickness is best for establishing water sedge in a constructed setting is unknown. *Carex aquatilis* grows best on cold, moist soils (Pearce and Cordes 1987; Chapin and Stuart 1981), and because peat has better moisture retaining properties than mineral soils (Walczak et al. 2002) peat may facilitate better survival and establishment of *C. aquatilis* in a constructed setting than mineral soils; however, mineral soils may offer better physical support and contain more nutrients than peat.

This field study was designed to assess the survival and establishment of transplanted *C. aquatilis* under a variety of semi-controlled environmental conditions. The study was conducted on Syncrude Canada's reclaimed Sandhill Fen (57°02'22.0" N, 111°35'29.7"

W), and was designed to: (1) relate *C. aquatilis* survival and establishment to local soil moisture conditions, measured as position relative to the water table, (2) relate *C. aquatilis* survival and establishment to initial peat thicknesses placed for reclamation, and (3), assess differences between the establishment of transplanted vs. naturally recruited and broadcast seeded *C. aquatilis*. I hypothesized that: (1) *C. aquatilis* survival and establishment would be affected by water table elevation, such that there would be higher rates of survival and better establishment in wetter conditions (i.e. conditions with a higher water table), (2) *C. aquatilis* establishment and survival would be higher in peat substrates due to peat's ability to hold more water than mineral soils, and (3) transplanted *C. aquatilis* would have higher survival rates and greater establishment (i.e. coverage) than natural and broadcast seeded *C. aquatilis*.

3.2. STUDY SITE

The study was conducted in the Fort McMurray Region of Northeastern Alberta on Syncrude Canada Ltd.'s (Syncrude) constructed Sandhill Fen (the Fen), which is located approximately 46 km north (57ℕ degrees 02' 21.49" N, 111ℕ 35' 34.14 W) of the city of Fort McMurray, Canada (BGC 2008). The Fort McMurray Region is located in the Central Mixedwood Subregion of Alberta's Boreal Forest Natural Region, and is characterized by relatively short, warm growing seasons, and long cold winters (Natural Regions Committee 2006); the average summer temperature is 13.5°C, and the average winter temperature is -13.2°C (Strong and Leggat 1992). The Central Mixedwood Subregion is the largest natural subregion in Alberta; it accounts for 25% of the province and peatlands constitute a large proportion of its area (Natural Regions Committee 2006). The Fen is therefore subject to the same climatic and environmental conditions as natural fens of this Region, and Subregion.

The primarily goal of the Fen was to create initial conditions necessary for the development of a self-sustaining fen peatland, and to serve as an instrumented research watershed to guide future peatland reclamation projects. It was designed and constructed between 2008 and 2012, and has been operational since January, 2013 (BGC 2014); my research plots were established in the summer of 2013.

Built on the former East-In-Pit tailings pond (actively mined from 1977 to 1999), it is underlain by sand-capped, soft tailings deposits and is approximately 52 ha in size. Of the 52 ha, approximately 17 ha were primary fen; the remaining 34 ha were upland areas designed to capture precipitation and direct it into the primary fen area. Its shape (1000 m long by 500 m wide) is a conceptual design based on the average ratio of over 6000 natural fens (Wytrykush et al. 2012).

The soft tailings deposit cap is 10 m deep, and is underlain by 35 m of composite tailings mixed with sand layers (BGC 2008). Half a meter of fine-grained clay-till was placed over the soft tailings cap to establish a mineral soil base that would serve as subsoil for root establishment and prevent salt from underlying tailings pore water from entering the Fen. The clay-till was covered with 0.5 meters of peat-mineral mix with the intention of creating hydrologic conditions for peatland development and to aid in the establishment of a native peatland plant community, though many uncertainties surrounded this tentative goal (Wytrykush et al. 2012); The 0.5 m peat application thickness was recommended based on extensive expert consultation. Peat was to provide sufficient substrate for plant establishment and to tolerate some loss of peat to erosion, floating, and/or settlement (BGC 2008; BGC 2014). The peat-mineral mix (a combination of Holocene peat and Holocene/Pleistocene mineral soil) was used because peat and mineral soils are often salvaged together prior to mining activities. The peat-mineral mix was salvaged from Syncrude's North mine advance in the winter of 2010 and 2011, and stored in stockpikes next to the Fen for several weeks or months prior to placement in the Fen in February and March of 2011 (BGC 2014). Other design components of the Fen included constructed uplands, vegetated swales, two experimental perched fens, a fresh water storage pond, and a drainage piping system (Wytrykush et al. 2012).

The study was located in the primary fen area, on four specially designed clay islands (G, F, A and E), to measure the effects of initial peat depth, and position relative to the water table, on the establishment and survival of *C. aquatilis* (Figure 3 - 1). The 1 m-deep clay used in the Fen was a combination of Pleistocene glacial and glaciolacustrine till that was salvaged from the north mine advance in 2009.

Figure 3 - 1. Basic diagram of the Sandhill Fen; research plots were situated in the primary fen area, on four specially designed clay islands (G, F, A and E).

3.3. METHODS

3.3.1. Experimental Design

In June 2013, *Carex aquatilis* plants with robust and viable rhizomes were collected from a nearby wetland and transplanted into 1x1 m plots with one of three initial peat thicknesses (0, 5 and 30 cm), and situated at one of three positions relative to the water table (High, Intermediate, and Low) to identify the combination of conditions that would maximize survival and establishment (i.e. a three by three, two-factor design). The two treatments (initial peat thickness and position relative to the water table), each with three varieties, resulted in nine treatment combinations (Table 3 - 1). Because fens usually have fluctuating water tables (NWWG 1997), and there was incomplete control of the Fen's managed water table, the positions were meant to represent a spectrum of realistic moisture conditions, whereby two depths were established for each category; peat placed in low plots were submerged at the start of the study, plots located in the intermediate position were located very near to, or just above, the water table (thus had moist root conditions), and plots in the high position were entirely above the water table (Table 3 - 1). The variety of depths were selected and categorized to accommodate expected change in conditions. In addition, changes in water table depth were not uniform throughout the Fen, and this variation was accounted for during data analysis by blocking each replicated island (water table depths were similar around each island, but not between islands).

Table 3 - 1. Treatment combinations and their associated plot heights (measured at the mineral-peat interface, or the bottom of peat plots) that were combined into categorical treatments of either “high”, “intermediate”, or “low.”

Treatment Combination	Peat depth (cm)	Position relative to water	Position relative to water (cm)	
			A	B
1	0	High	60	45
2	0	Intermediate	35	25
3	0	Low	-15	-25
4	5	High	60	45
5	5	Intermediate	35	25
6	5	Low	-15	-25
7	30	High	60	45
8	30	Intermediate	35	25
9	30	Low	-15	-25

Because of environmental constraints, treatments were applied at two plot sizes (i.e. a standard split-plot), which allowed for a complete block design across replicates. The study is replicated four times on clay islands G, F, A and E, located within the primary fen area of the Fen (Figure 3 - 1). To maintain homogeneity of the replicates, the islands were similar in size and topography, and all had a clay substrate.

Each island was divided into three elevation zones (i.e. large plots) representing three positions relative to the water table (High, Intermediate, and Low), and each zone was assigned six 1 x 1 m plots (i.e. small plots). Initial peat thickness treatments (0, 5 or 30 cm) were stratified and randomly assigned to small plots. Of the six plots assigned to each zone, two had an initial peat thickness of 0 cm, two had an initial peat thickness of 5 cm, and two had an initial peat thickness of 30 cm. The small plots were arranged in three transects that faced different cardinal directions to account for variation in island aspect (except on island E because of the island's unusual shape). A transect was randomly oriented by selecting a number between 0 and 360 degrees, and subsequent transects were oriented by adding 120 degrees to the initial compass direction; however, variation among transects was later determined insignificant to the study (Figure 3 - 2).

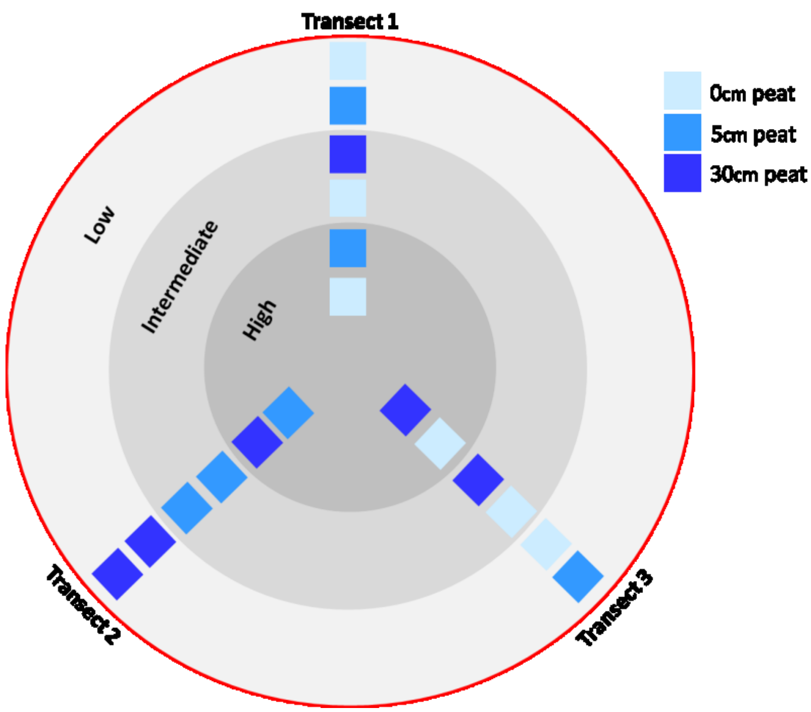

Figure 3 - 2. Schematic diagram of 1 x 1 m plots at three positions relative to the water table present on each of four clay islands. Plots in the "low" position were submerged at the start of the study. Plots located in the "intermediate" position were located very near to, or just above the water table, and plots in the "high" position were entirely above the water table.

Carex aquatilis plants were collected from a natural marsh in the Fort McMurray region (56˚30'50,31"N and 111˚16'17,47"W), and transplanted to the study plots on the same day. Plants were selected to ensure their quality and uniformity based on the following criteria: (1) a minimum of three green, healthy leaves, (2) a well-developed and healthy root system (with a minimum of three roots), and (3) a shoot length between 20 to 30 cm. Nine plants were randomly assigned to each treatment combination (i.e. each plot), and were planted in three rows of three, for a total of 648 plants in 72 plots. Vegetation around each plot was weeded back approximately 60 cm to reduce competition for the newly transplanted *C. aquatilis* plants, potentially aiding in their initial survival.

A small control plot (approximately 0.5 x 0.5 m in size) was established next to every treatment plot. These plots were examined for the presence of *Carex aquatilis* plants developing in the absence of transplanting and therefore provide an estimate of non-planted *C. aquatilis* establishment (i.e. plants that developed through natural recruitment and/or broadcast seeding).

3.3.2. Data collection

Plots were established in summer 2013, and *C. aquatilis* plants were assessed in June 2014 and 2015. In 2014, the number of living and dead *C. aquatilis* stems were counted to identify any treatment effect on overall survival rates after one year. Percent cover was also recorded. Counting individual stems was not practical in 2015, so percent cover was used as a proxy measure of *C. aquatilis* establishment. Water depths were measured in plots that contained water. Control plots were assessed in the same manner, and at the same time, as treatment plots.

3.3.3. Statistical analysis

A split-plot, 3 (position relative to the water table) x 3 (peat thickness) factorial Permutation ANOVA (analysis of variance), with 5000 computer-generated replicates, was performed because the data did not fit the assumptions (i.e. normality and heterogeneity of variance) necessary for a parametric ANOVA. Analysis was performed at a significance level of α=0.05 with 95% confidence intervals, using the statistical software package "lmPerm" (Wheeler 2010), in R Program, version R-2.15.1 (R Core Team 2013). Variation among islands was accounted for by including island as a blocking factor within the permutation model. Permutation among all observations is not meaningful when a block needs to be considered, and R program handles this by projecting the design and observations into their unique block identifier (i.e. islands G, F, A, and E). According to the LmPerm package creator Robert E. Wheeler (2010), permutation analysis works well in this circumstance. The same permutation ANOVA's were performed on subset data to make pairwise comparisons, and p-values were adjusted using the Bonferroni method.

The number of living *C. aquatilis* plants in 2014 was used to assess treatment effects on *C. aquatilis* survival, and the percent cover of *C. aquatilis* in 2015 was used to assess treatment effects on the establishment of *C. aquatilis*. Initial surface elevation of every plot was calculated by adding the peat thickness treatment to the elevation at which the plot was established, to better reflect actual surface relation to water levels. This represented the actual surface elevation (at the start of the study) at which *C. aquatilis* plants were growing in individual plots. Because water table depth fluctuated throughout the study, these depths only represent surface elevation at the commencement of the study; however, they provide more detailed information regarding the relationship between *C. aquatilis* and moisture than the categorical position data (High, Intermediate, Low).

A Mann-Whitney-Wilcoxon test (i.e. a non-parametric equivalent of a two-sample t-test) was used to assess any differences in *C. aquatilis* establishment (measured as percent cover in 2015) between transplanting (in treatment plots) and natural recruitment or broadcast seeding (in control plots). In addition, the 2015 percent cover of *C. aquatilis* in plots, was graphed alongside the percent cover of *C. aquatilis* in adjacent control plots, to visualize the difference in establishment between transplanted and non-planted (naturally recruited and/or broadcast seeded) plants.

3.4. RESULTS

The Fen’s annual average water table depth was 0.08 m in 2014, and 0.07 m in 2015. Water table depth fluctuated between -0.2 and 0.4 m (a total fluctuation of 0.6 m) in 2014, and between -0.4 and 0.5 m (a total fluctuation of 0.9 m) in 2015 (Spennato 2016). On average, the highest water table depths were noted in the spring, due to snow melt and spring rain events, followed by subsequent declines (i.e. a drying trend) throughout the summer (Spennato 2016). Although this study was designed to account for changes in water table depth, higher water table depths during spring may have flooded *C. aquatilis* in some low plots, potentially contributing to decreased *C. aquatilis* survival; subsequently, decreases in the water table depth throughout the summer may have accelerated drying in the high and/or intermediate plots, potentially contributing to decreased *C. aquatilis* survival.

In 2014, *C. aquatilis* survival was greatest in low positioned plots with peat thicknesses of 30 cm ($\bar{X}$=82±12%), and high positioned plots with 0 cm of peat had the lowest percent survival ($\bar{X}$=12±6.04%) (Table 3 - 3, Figure 3 - 3); however, the interaction between initial peat thickness, and position relative to water was not significant (permutation ANOVA; P_{perm}=0.778). Peat thickness did not have an effect on *C. aquatilis* survival (permutation ANOVA; P_{perm}=0.068), but position relative to the water table did (permutation ANOVA; P_{perm}=<0.001).

Table 3 - 2. Results of permutation ANOVA (*C. aquatilis* survival in 2014)

Source	DF	SS	MS	F	Iterations	P
Initial Peat Depth	2	2975	1487.5	4.62	1547	0.068
Position Relative to Water	2	30757	15378.5	47.80	5000	**<0.001***
Interaction	4	1287	321.7	0.41	229	0.778
Residuals	60	47405	790.1			

Table 3 - 3. Mean (±SE) *C. aquatilis* survival (percentage) in 2014 by treatment combinations. n=8 for all treatment combinations.

		Initial Peat Thickness		
		30 cm	5 cm	0 cm
Position Relative to the Water Table	High	31.75 (11.57)	17.88 (5.48)	12.38 (6.04)
	Intermediate	37.38 (12.44)	40.25 (14.87)	34.63 (13.86)
	Low	82.00 (12.41)	72.25 (12.44)	57.00 (12.44)

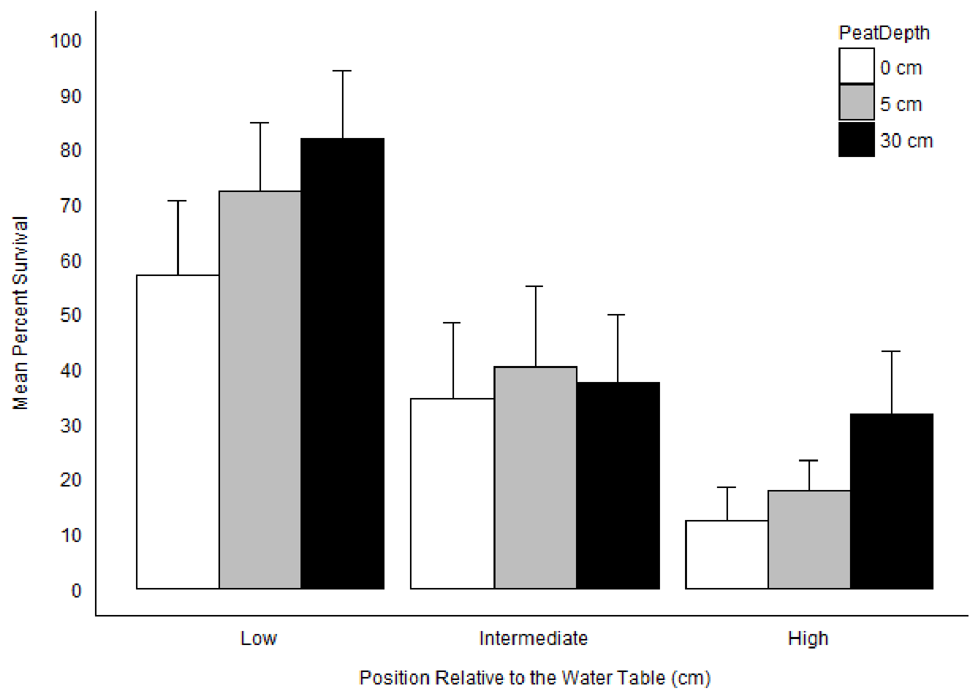

Figure 3 - 3. Mean percent *C. aquatilis* survival (±SE) in 2014 by treatment combination. n=8 for all treatment combinations.

As mentioned above, *C. aquatilis* survival (in 2014) was not dependent on initial peat thicknesses; therefore, there were no statistically significant differences between the 0, 5, and 30 cm peat treatments (Table 3 - 4; Figure 3 - 4). *Carex aquatilis* survival was not significantly different in the intermediate and high positions (P_{perm}=0.060), but survival in the low position was significantly different from the intermediate (P_{perm}=0.002) and the high (P_{perm}=<0.001) positions (Table 3 - 4; Figure 3 - 5).

Table 3 - 4. Mean percent *C. aquatilis* survival in 2014 by individual treatment. n=24 for each individual treatment variety. Values with different letters indicate a significant difference between varieties within treatments, evaluated at p≤0.05.

Treatment		Mean Survival (%)	Standard Error
Initial Peat Thickness	30 cm	50.38^{a}	8.18
	5 cm	43.46^{a}	7.93
	0 cm	34.67^{a}	7.53
Position Relative to the Water Table	High	20.67^{a}	4.82
	Intermediate	37.42^{a}	7.60
	Low	70.42^{b}	7.41

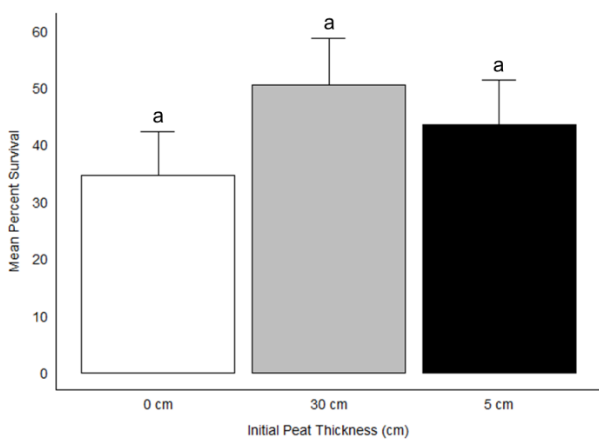

Figure 3 - 4. Mean percent survival (±SE) of *C. aquatilis* by initial peat thickness in 2014. Letters indicate significant differences calculated using a significance level of α=0.05.

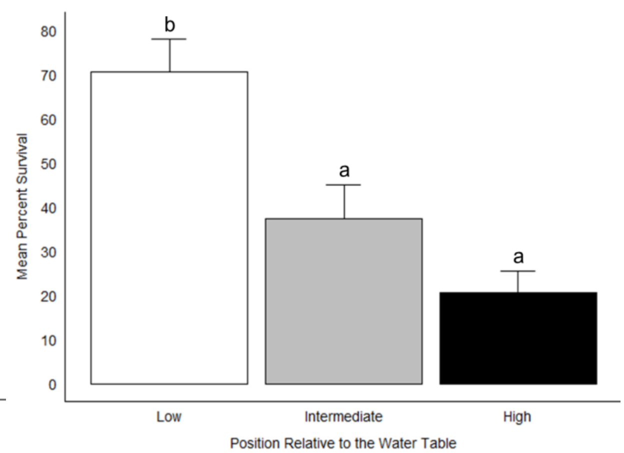

Figure 3 - 5. Mean percent survival (±SE) of *C. aquatilis* by position relative to the water table (cm) in 2014. Letters indicate significant differences calculated using a significance level of α=0.05.

In 2014, *C. aquatilis* survival was the highest ($\overline{X}$= 97±2.41%) when the plot surface was 15 cm above the initial water table height, and the lowest ($\overline{X}$=3±2.41%), when the plot surface was 45 cm above the initial water table height. Based on visualization of the data (using Figure 3 - 6), the greatest *C. aquatilis* survival was noted in plots with surface heights (relative to the initial water table) between approximately -20 and 15 cm. When plot surface heights were above 15 cm relative to the initial water table, *C. aquatilis* survival appeared to decrease substantially (Figure 3 - 6).

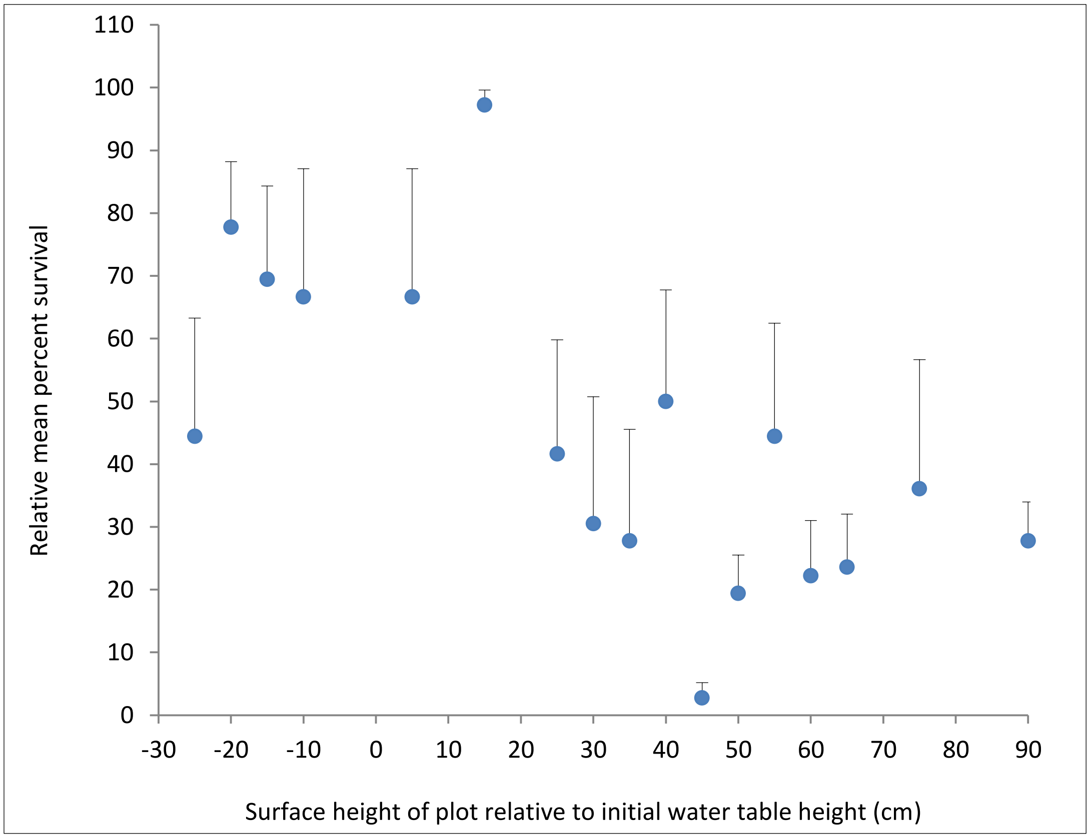

Figure 3 - 6. Relative mean percent survival (±SE) of *C. aquatilis* in 2014 (i.e. one year after transplant), based on surface plot height relative to water table height (cm) at study commencement.

In 2015, low positions with peat thicknesses of 30 cm had the greatest mean percent cover of *C. aquatilis* ($\overline{X}$=48±6.26%), and high positions with 0 cm of peat had the lowest mean percent cover ($\overline{X}$=1±0.91%) (Table 3 - 6, Figure 3 - 7). However, an interaction between initial peat thickness, and position relative to water was not significant (permutation ANOVA; P_{perm}=0.081). Peat thickness did not have an effect on *C. aquatilis* cover (permutation ANOVA; P_{perm}=0.102), but position relative to the water table did (permutation ANOVA; P_{perm}=<0.001).

Table 3 - 5. Results of permutation ANOVA (*C. aquatilis* survival in 2015)						
Source	DF	SS	MS	F	Iterations	P
Initial Peat Depth	2	578.9	289.4	0.84	1209	0.102
Position Relative to Water	2	15255.5	7627.8	42.6	5000	**<0.001*** **
Interaction	4	1372.4	343.1	1.92	4975	0.081
Residuals	58	10383.7	179.0			

Table 3 - 6. Mean (±SE) *C. aquatilis* cover in 2015 by treatment combination. n=8 for all treatment combinations.

		Initial Peat Thickness		
		30 cm	5 cm	0 cm
Position Relative to the Water Table	High	4 (1.57)	4 (1.24)	1 (0.91)
	Intermediate	6 (2.37)	8 (1.89)	9 (3.99)
	Low	48 (6.26)	33 (8.56)	27 (8.26)

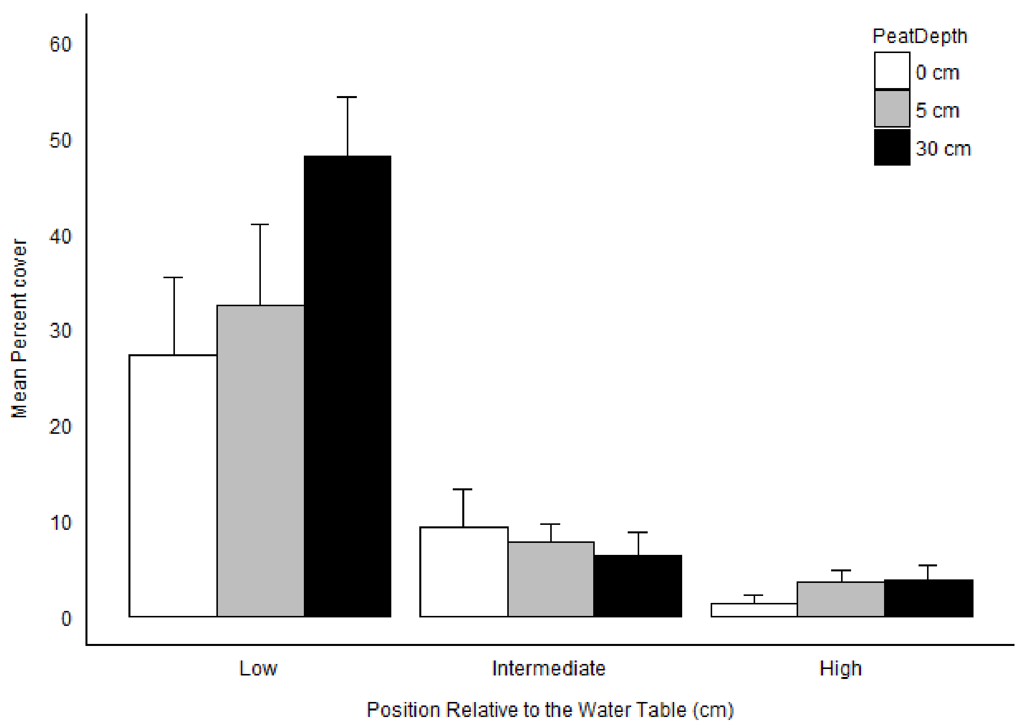

Figure 3 - 7. Mean percent *C. aquatilis* cover (±SE) in 2015 by treatment combination. n=8 for all treatment combinations.

Although initial peat thickness was not found to have a significant effect on *C. aquatilis* cover, plots with greater peat thicknesses yielded slightly higher levels of *C. aquatilis* cover (Table 3 - 7; Figure 3 - 8). *Carex aquatilis* cover was significantly different at all positions relative to the water table: high vs. intermediate (P_{perm}=0.010), high vs. low (P_{perm}=<0.001), and low vs. intermediate (P_{perm}=<0.001), with the highest cover observed in the low position (Table 3 - 7; Figure 3 - 9).

Table 3 - 7. Mean percent *C. aquatilis* cover in 2015 by individual treatment. n=24 for each individual treatment variety. Values with different letters indicate a significant difference between varieties within treatments, evaluated at p≤0.05.

Treatment		Mean Cover (%)	Standard Error
Initial Peat Thickness	30 cm	19^{a}	4.77
	5 cm	15^{a}	3.87
	0 cm	13^{a}	3.70
Position relative to water table	High	3^{a}	0.73
	Intermediate	8^{b}	1.61
	Low	36^{c}	4.66

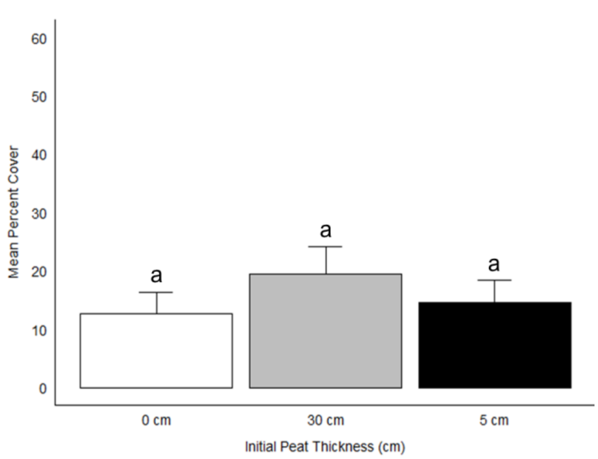

Figure 3 - 8. Mean percent cover of *C. aquatilis* (±SE) by initial peat thickness (cm) in 2015. Letters indicate significant differences calculated using a significance level of α=0.05.

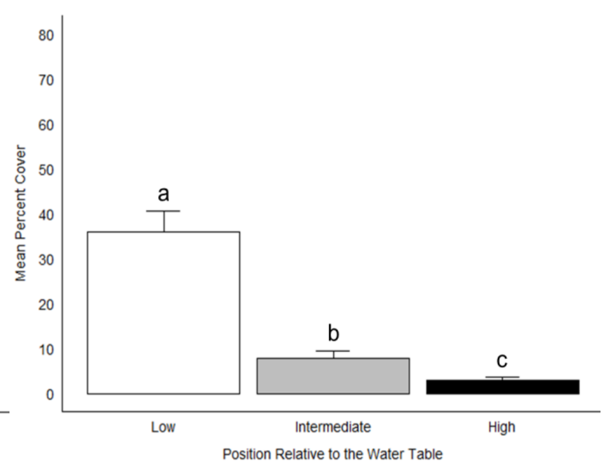

Figure 3 - 9. Mean percent cover of *C. aquatilis* (±SE) by position relative to the water table (cm) in 2015. Letters indicate significant differences calculated using a significance level of α=0.05.

In 2015, *C. aquatilis* cover was the highest ($\overline{X}$=54±8.17%) when the surface plot height was 15 cm above the initial water table height, and lowest ($\overline{X}$=1±1.08%) when surface plot height was 45 cm above the initial water table height. Based on visualization of the data (using Figure 3 - 10), the greatest *C. aquatilis* cover was noted in plots with surface heights (relative to the initial water table) between -25 and 15 cm. Cover was consistently lower in control plots (although a similar trend was shown with respect to moisture conditions) when compared with treatment plots (Figure 3 - 10), and a Mann-Whitney-Wilcoxon test demonstrated that *C. aquatilis* cover in control plots was statistically different from *C. aquatilis* cover in treatment plots (p=0.002). Based on visualization of the data (using Figure 3 - 10), *Carex aquatilis* cover in control plots was also highest in plots with surface heights (relative to the initial water table) between -25 and 15 cm. On average, cover in control plots was 8 percentage points lower than was observed in treatment plots; however, in the "ideal" growth range (i.e. -25 to 15 cm) control plots contained 16 percent less cover than treatment plots.

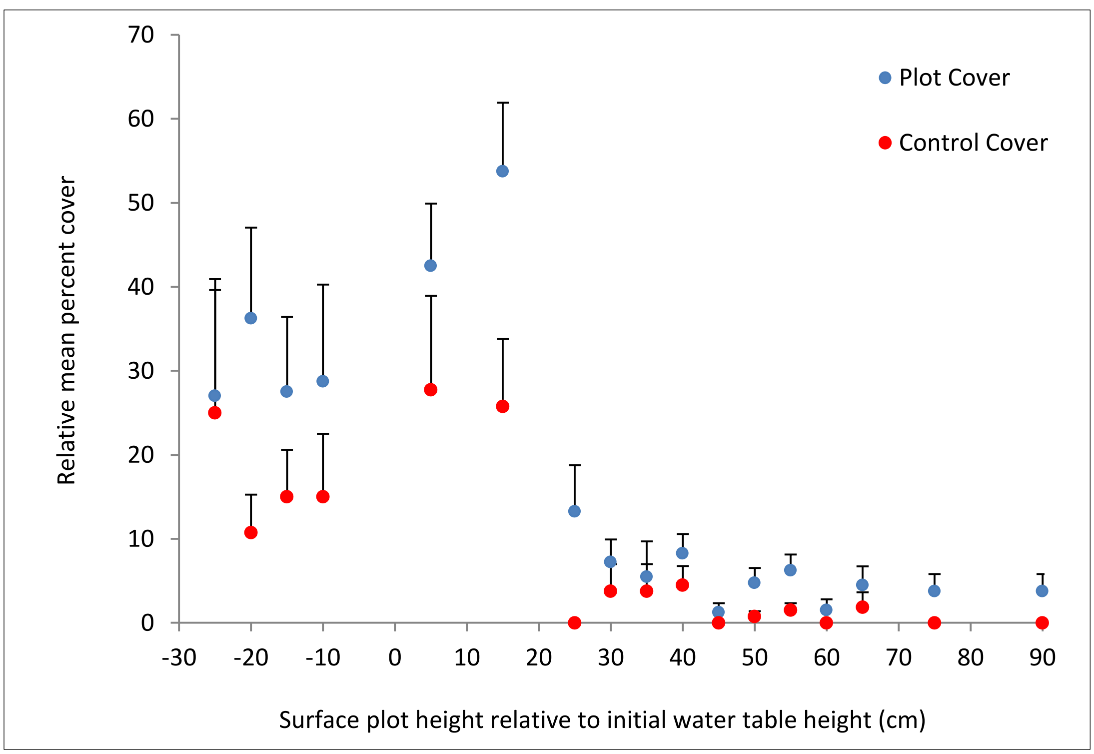

Figure 3 - 10. Relative mean percent cover (±SE) of *C. aquatilis* in 2015 (i.e. two years after transplant) in treatment (blue circles) and control plots (red circles), based on plot surface height relative to the water table (cm) at study commencement.

3.5. DISCUSSION

Understanding the conditions that promote survival and establishment of *C. aquatilis* is important because *C. aquatilis* is a prime vegetation candidate for wetland reclamation (Klopf 2010; Roy et al. 2014). I found that *C. aquatilis* survival and establishment depended on position relative to the water table, but not initial peat thickness, and by extension substrate type. Based on visualization of the data, I was able to determine a range of initial water table depths for which *C. aquatilis* had a better chance of survival and establishment in a constructed peatland. In addition, transplanting *C. aquatilis* appeared to be a good option for promoting establishment because control plots (colonized by *C. aquatilis* that germinated from broadcast seeding and/or naturally recruited plants) lagged in their establishment relative to mature, transplanted *C. aquatilis*.

3.5.1. The critical role of water

Water table depth plays a primary role in the distribution of sedge species (Daly et al. 2012; Vitt et al. 2011; Gignac et al. 2004; Mitsch and Gosselink 1993; Pearce and Cordes 1987; Chapin and Stuart 1981), and my results confirmed that the survival and establishment of *C. aquatilis* varied as a function of plot height relative to the water table. In 2014, *C. aquatilis* survival was highest in the low position (the plots initially established under water), and the level of survival was statistically greater than at both intermediate and high positioned plots; however, in 2015, the establishment of *C. aquatilis* was statistically different among all three heights, although still much greater in the low position. The average *Carex aquatilis* cover in intermediate and high positioned plots ($\overline{X}$=8±1.61 and $\overline{X}$=3±0.73% respectively) after 2 years was likely not sufficient to provide the vegetation functions desired for peatland reclamation, such as peat accumulation, soil stabilization, shade and moisture retention; however, plots that had sufficient moisture, clearly had enough *C. aquatilis* cover to provide habitat for bryophytes (qualitative observation only). The results suggest that moisture level (i.e. water table depth) is critical for early survival and establishment of *C. aquatilis*, and this corresponds (based on data visualization of Figure 3 - 6 and Figure 3 - 10) to a range of surface elevations relative to initial water table depths of approximately -25 to 15 cm.

My results are consistent with other studies that have assessed the survival of *C. aquatilis* in relation to moisture conditions. Gignac et al. (2004) looked at the abundance of vascular plants, bryophytes and lichens on 498 peatlands across Canada. They noted that *C. aquatilis* was restricted to wet, relatively open environments, where the water table depth was between -12 to 170 cm; however, *C. aquatilis* reached its maximum frequency of occurrence when the water table depth was 10 cm below the surface in natural stands. Cooper and MacDonald (2000), evaluated the relative sensitivity of *C. aquatilis* to changes in water table depth, and found that maximum water table depth had a significant effect on the percent survival of *C. aquatilis*. They noted that seedling survival was highest when the water table was within 10 cm of the soil surface, or at water table depths between -5 and 10 cm. Arp et al. (1999) found *C. aquatilis* growing in a narrow range of water depths (-5.1 to 5.5 cm) in four *C. aquatilis* dominated fens. I found that *C. aquatilis* survival (in 2014) and establishment (in 2015) was highest at initial water table depths between -25 and 15 cm. Although *C. aquatilis* inhabits a wide range of water table depths, as much as -80 to 170 cm (Hauser and Scott 2006; Cooper and MacDonald 2000; Brichta 1987; Jeglum 1971), my results (in combination with the above studies) indicate that the conditions most conducive for *C. aquatilis* survival and establishment may be restricted to a much narrower water table range (approximately -25 to 15 cm) in a constructed wetland.

3.5.2. The non-critical role of substrate

Carex aquatilis grows on both mineral and peat substrates (Vitt et al. 2011; Beckingham and Archibald 1996), but because more water is available to plants in soils with higher organic content (Walczak et al. 2002; Feustel and Byers 1936), I expected to see greater survival and establishment of *C. aquatilis* on peat substrates; however, this was not the case. Our results indicated that the use of peat, and/or various peat thicknesses, did not significantly affect the survival or establishment of *C. aquatilis*. This is particularly interesting in light of my previously discussed findings indicating the need for suitable moisture conditions; because peat has a higher water holding capacity than mineral soils (Farnham and Finney 1965; Fuestel and Byers 1936), one would (at the very least) expect peat to be beneficial at the fringe of *C. aquatilis'* preferred moisture conditions. Although peat substrates did not have a significant effect on *C. aquatilis* survival or establishment, we did see greater *C. aquatilis* survival and establishment on 30 cm peat substrates under certain conditions. For example, in 2014, *C. aquatilis* survival in the high position was notably higher on 30 cm peat plots than in 5 or 0 cm peat plots; however, by 2015, the percent cover of *C. aquatilis* in the high position was more similar among 30, 5 and 0 cm peat treatments. This suggests that a thicker (i.e. 30+ cm) peat treatment may be beneficial in the first year; however, moisture evaporates quickly from peat due to its large pore spaces, and I suspect this is why there was less benefit to peat in the second year.

Water evaporates from peat soils more rapidly than from clay soils; adding peat to mineral soils can cause them to lose water more quickly than mineral soils alone (Fuestel and Byers 1936). However, peat can also draw water upwards in a capillary fringe (Reddy et al. 2006; Waddington and Price 2000; Whitehead 1999; Verry 1997) thereby mitigating the effects of water loss through evaporation if the water table is within a certain distance from the soil surface. Highly decomposed peat can maintain a capillary fringe 60 cm above the water table, while less decomposed peat can maintain a capillary fringe 30 to 40 cm above the water table (Verry 1997). Whitehead (1999) found that moderately decomposed peat maintained a capillary fringe 30 cm above the water table. Given this knowledge, I would have expected more water to be available to *C. aquatilis* plants in peat plots, and therefore peat to have had a stronger role in the survival and establishment of *C. aquatilis* in this study. However, because peat plots were placed on a clay island, the impermeability of the clay layer may have limited the rate or amount of water that could have been drawn upwards from the water table, which represented an unfortunate study limitation. In addition, reclamation peat undergoes structural and chemical modifications during its initial harvesting, and subsequent storage, that may have impacted its ability to support hydrological functions such as capillary rise (Nwaishi et al. 2015). Peat amendments have been shown to increase the cover of *Carex* species (Rewers et al. 2012), so I suspect the quality of reclamation peat may have impacted its benefits to the survival and establishment of *C. aquatilis*.

Carex aquatilis survival and establishment was higher on 30 cm peat substrates in the low position, than it was on any other treatment combination. Figure 3 - 11 shows two adjacent plots in the low position on island E; Plot 11 had a mineral substrate and no *C. aquatilis* survival, whereas plot 12 had a 30 cm peat substrate and 100% survival. It looked deceptively like the peat substrate was contributing to the success of *C. aquatilis* survival; however, I suspect the cause of this difference to be related to differences in water table depth due to the addition of a peat substrate, rather than the peat itself. The surface of Plot 11 was 40 cm under water, whereas the surface of plot 12 (to which 30 cm of peat had been added), was only 26 cm under water. According to visualization of my data, *C. aquatilis* survival and establishment was highest when surface elevation was between -25 and 15 cm relative to the initial water table depth; so plot 12 was much nearer to ideal water table conditions than plot 11, likely facilitating *C. aquatilis* survival.

Figure 3 - 11. A comparison of two plots located in the low position relative to the water table on Island E; plot 11 (left) had a mineral substrate and no *C. aquatils* survival, whereas plot 12 (right) had a 30 cm peat substrate and 100% *C. aquatilis* survival.

My results suggest that *C. aquatilis* can become established in the absence of a peat substrate, which is consistent with other findings. Vitt et al. (2011) looked at the feasibility of establishing peatlands directly on mineral soils, and found that *C. aquatilis* could become established on mineral soils; however, they too noted that establishment was greater in wet plots than in dry plots, and stressed the importance of water table depth as a key component of early wetland development. In addition, most of the peatlands in northeast Alberta are thought to have formed directly on mineral soils through the process of paludification, so if the conditions of fen formation can be emulated on mineral substrates, peat may not be necessary for *C. aquatilis*; however, given the slow rate at which peat accumulates (PERG 2009), the creation of a peatland on mineral soils may only be feasible for meeting reclamation objectives over long periods of time. Furthermore, peat placement may help establish other peatland functions, regardless of whether it benefits *C. aquatilis*.

3.5.3. The value of transplanting

Sedges spread clonally, primarily through asexual reproduction (Hauser and Scott 2006; Cooper and MacDonald 2000; Bernard 1990), so reclamation projects that are not adjacent to natural ecosystems are unlikely to rapidly become colonized with sedges. Cooper and MacDonald (2000) demonstrated this by comparing natural peatlands to cutover peatlands, and noted that there was little colonization of sedges in mined peatlands. Based on their results, they advised against relying on natural recruitment as a reclamation strategy for reclaimed peatlands, and argued that sedge establishment is likely to be more successful through the transplantation of rhizomes, or greenhouse grown seedlings. I found that mature *C. aquatilis* plants could be successfully transplanted from a natural fen to a constructed setting, with relatively high levels of survival (that vary with the environmental conditions provided by reclamation), and that transplanting *C. aquatilis* provided somewhat quicker establishment after 2 years than was observed by natural recruitment and/or broadcast seeding (identified in adjacent control plots). Quick vegetation establishment is desirable because it limits the colonization of unwanted species (Bernard 1990), and contributes to the development of peatland conditions more rapidly (Daly et al. 2012).

Carex aquatilis in control plots (developing from natural recruitment or broadcast seeding) showed a similar survival and establishment trend with respect to moisture conditions; however, the overall survival and establishment was much lower (about half that observed in transplanted plots), suggesting that natural recruitment, and/or broadcast seeding, lags in development compared to transplanted mature plants. Although the establishment of non-planted *C. aquatilis* was lower, natural recruitment and/or broadcast seeding may be beneficial reclamation strategies as well. However, because sedges spread clonally, and control plots were directly adjacent to treatment plots (representing a study limitation), some of the *C. aquatilis* in treatment plots may have spread to control plots; therefore, the establishment of *C. aquatilis* through broadcast seeding and/or natural recruitment was possibly overestimated in this study. If the control plots were not located directly adjacent to the treatment plots, the establishment between transplanted and non-planted *C. aquatilis* may have been even greater.

I expected transplanted *C. aquatilis* to be more successful than broadcast seeding and/or natural recruitment, because mature plants are generally more tolerant of extreme conditions and environmental changes (Middleton 1999), and many wetland plants do not establish well from seed (Cronk and Fennessy 2001). Broadcast seeding has therefore produced relatively poor results for wetland species (Cronk and Fennessy 2001; Cooper and MacDonald 2000). Cooper and MacDonland (2000) looked at seed germination in cutaway fens in the Rocky Mountains of Colorado, and found that sedge species in particular had very low germination rates. Transplanting is a good alternative for species that do not establish well from seed, and transplanting rhizomes or plugs is an effective strategy for wetland species (Cooper and MacDonald 2000; van der Valk et al. 1999). Cooper and MacDonald (2000) found that seedlings grown in a greenhouse showed similar survival (50%) to transplanted rhizomes (51%); however, once seedlings were transplanted to a natural environment, they found that *C. aquatilis* established from rhizomes grew in a broader range of environmental conditions, and therefore had a greater chance of survival.

This study (in combination with other findings) demonstrates that transplanting mature *C. aquatilis* plants for peatland reclamation is likely a beneficial strategy, especially if rapid cover of the species is desired; however, although the establishment of non-planted *C. aquatilis* was lower, natural recruitment and/or broadcast seeding may be a beneficial reclamation strategy as well. In addition, Vitt et al. (2016) conducted a vegetation survey of the Fen in August, 2015, and characterized four distinct vegetation assemblages, two of which had impressive *C. aquatilis* cover (31.5% and 51.5% respectively), indicating that transplanting *C. aquatilis* may not be worth the required time and resources.

3.5.4. Study Limitations

The range of inference for this study is limited to the Sandhill Fen, which represents a novel ecosystem, so extrapolation of results should be used cautiously. The sample size was relatively small (70 plots in total); however, permutation ANOVA is robust for small data sets. I would have expected more water to be available to *C. aquatilis* plants in peat plots, but because peat plots were placed on a clay island, the impermeability of the clay layer may have limited the rate, or amount, of water that could have been drawn upwards from the water table. In addition, because sedges spread clonally, and control plots were directly adjacent to treatment plots, some of the *C. aquatilis* in treatment plots may have spread to control plots; therefore, the establishment of *C. aquatilis* through broadcast seeding and/or natural recruitment was possibly overestimated in this study.

3.6. CONCLUSION

Within the limitations of my study, I found that *C. aquatilis* survival and establishment was a function of position relative to the water table, and that the greatest survival and establishment occurred in plots where surface elevation (relative to initial water table depth) was between -25 and 15 cm. *Carex aquatilis* survival and establishment did not depend on substrate type in that survival and establishment were similar on both peat and mineral substrates, and among different peat thicknesses. Transplanting mature *C. aquatilis* plants appeared to be a viable option for peatland reclamation, but maintaining an appropriate water table was critical for their early survival and establishment. *Carex aquatilis* survival and establishment in control plots (containing natural or broadcast seeded plants) lagged in comparison to transplanted *C. aquatilis*, but showed a similar trend in relation to elevation treatments. Overall, transplanting *C. aquatilis* to a constructed peatland may contribute to quicker establishment of the species, thereby reducing the likelihood of colonization by unwanted species, and potentially contributing to accelerated development of peatland conditions; however, the overall cover of *C. aquatilis* in my control plots, and throughout the Fen, indicates that natural recruitment and/or broadcast seeding may be a beneficial reclamation strategy as well.

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CHAPTER 4

Title: Synthesis and future direction.

4.1. SUMMARY OF RESEARCH

To create suitable growing conditions in a constructed peatland, suitable hydrology (i.e. water source, movement, and depth), water chemistry, vegetation, and substrate are essential. I addressed components of peat substrates and vegetation in this thesis. The primary objectives of my research were to investigate the persistence of peat, and the survival and establishment of *Carex aquatilis* (water sedge) using a semi-controlled study design in Syncrude Canada's reclaimed Sandhill Fen; a peatland constructed on a former open pit oil sands mine in northern Alberta (BGC 2008, BGC 2012, and Wytrykush et al. 2012). Chapter one of this thesis set the context for my research by providing an introduction to peatland ecology, Alberta oil sands mining, and the challenges of constructing a peatland on a former open pit oil sands mine.

In Chapter two I: (1) related differences in initial peat thickness to general moisture conditions, measured as position relative to the water table, and (2) related reductions in peat thickness to initial peat thicknesses placed for reclamation. I hypothesized that: (1) Peat thickness would decrease under dry conditions, and that peat may expand if completely submerged under water, and that (2) thicker peat applications (30 cm) would experience proportionally greater compression than shallower (5 cm) peat applications. I found that reductions in peat thickness were dependent on both initial peat thicknesses, and peat's position relative to the water table. In addition, peat layers had become markedly thinner after two years following placement; unexpectedly, peat did not expand under any combination of treatments. Peat located at intermediate positions, relative to the water table, thinned the least, suggesting that intermediate level moisture conditions may minimize reductions in peat thickness. Peat located in the high positions (thus driest conditions) was likely subject to greater decomposition (because of oxidation through microbial respiration), and wind erosion. Peat located in the low positions (thus wettest conditions) may have been influenced by compression and/or losses as the water table fluctuated. Initial peat thicknesses of 30 cm reduced in thickness proportionality more than initial peat thicknesses of 5 cm, suggesting that the added weight of additional peat, or the added surface area of 30 cm peat plots, may have contributed to greater compaction and/or reductions.

Chapter three aimed to: (1) relate *C. aquatilis* survival and establishment to local soil moisture conditions, measured as position relative to the water table, (2) relate *C. aquatilis* survival and establishment to initial peat thicknesses placed for reclamation, and (3), assess differences between the establishment of transplanted vs. natural and broadcast seeded *C. aquatilis*. I hypothesized that: (1) *C. aquatilis* survival and establishment would be affected by moisture conditions, such that there would be higher rates of survival and better establishment in wetter conditions, (2) *C. aquatilis* establishment and survival would be higher in peat substrates than mineral soils due to peat's ability to retain moisture, and (3) transplanted *C. aquatilis* would have higher survival rates and greater establishment than natural and broadcast seeded *C. aquatilis*. I found that *C. aquatilis* survival (after 1 year) and establishment (after 2 years) depended on position relative to the water table, and the greatest survival and establishment was noted when surface height (relative to initial water table depths) was between -25 and 15 cm. *Carex aquatilis* survival and establishment was not dependent on initial peat thicknesses, and was similar on both peat and mineral substrates, suggesting that substrate type may not be important for the initial survival and establishment of *C. aquatilis*. *Carex aquatilis* survival and establishment in control plots (containing natural or broadcast seeded plants) was lower than transplanted *C. aquatilis*, indicating that transplanting might be a beneficial strategy for quick establishment; however, the cover of *C. aquatilis* in my control plots, and throughout the Fen, indicates that natural recruitment and/or broadcast seeding may be a beneficial reclamation strategy as well, particularly if rapid cover is not required.

4.2. PRACTICAL IMPLICATIONS AND RECOMMENDATIONS

The ultimate goal of peatland reclamation on post-mined landscapes is to produce a self-sustaining, peat-accumulating wetland, but we are still learning how, and if, this can be accomplished. To create growing conditions that will support peat-accumulating vegetation, proper hydrology is essential; however, the role of reclamation substrate (and how it interacts with hydrology) is unclear. A peat substrate is generally used with the following goals in mind: (1) to aid suitable peatland hydrology (Wytrykush et al. 2012), (2) to restrict the movement of unwanted dissolved solutes from underlying tailings material (Nwaishi et al. 2015), (3) to aid in soil moisture retention for plant roots (Walczak et al. 2002), and (4) to provide a seedbank and substrate for the potential establishment of peatland bryophytes (Vitt and House 2015; Rochefort and Lode 2006) and vascular plants (Nwaishi et al. 2015). The amount of peat needed to achieve these goals remains unclear; indeed, it is unknown whether reclamation peat can even provide these functions.

The 0.5-m thickness of peat-mineral mix used in the Sandhill Fen was selected to create hydrologic conditions for peatland development, and to aid in the establishment of a native peatland plant community, though many uncertainties surrounded that goal (Wytrykush et al. 2012). After researching the application of reclamation peat to a constructed peatland, and reviewing applicable literature, I believe reclamation peat (i.e. peat that has been mixed with mineral soil, and then physically and chemically altered during harvesting and storage) may not be capable of providing desired hydrological functions. This is supported by Nwaishi et al. (2015), who made a similar claim that "modifications to salvaged peat could impact its ability to support ecohydrological functions in a constructed peatland." It is not enough to simply apply a peat substrate (of any quality) and then create fen-like water table conditions; fen-like peat conditions are also required to help moderate and control the water table. Farooq (2011) also studied the use of peat substrates for peatland reclamation in Northern Alberta, and he too concluded that wetland reclamation depends on the proper restoration of hydrological properties of peat. While the height of the water table can influence peat (through subsidence or expansion), peat properties can also influence groundwater storage and movement, which in turn, can influence water table height (Petrone et al. 2008). Peat conditions must be conducive to storing, and transporting (both horizontally and vertically), groundwater in a way that reflects its movement in natural peatlands.

The ability of peat to retain and conduct water is a function of its internal pore structure (Clymo 1983), and natural peatlands have two distinct and important layers whose structure and level of decomposition play an important role in peatland hydrology. The acrotelm, located near the surface (generally the top 10 to 20 cm), is subject to water table fluctuations and periodic air entry. It consists of relatively undecomposed peat that is porous (i.e. has abundant macropores), and has a high hydraulic conductivity, which facilitates horizontal water movement. Because the pore space in this layer of peat is relatively large, it can hold a tremendous volume of water, thereby buffering against flooding when water tables rise (IUCN 2014; Holden 2005; Quinty and Rochefort 2003). In addition, the structure of acrotelm peat maintains moisture conditions that enable peatland species to out-compete non peat-accumulating species (IUCN 2014). The catotelm, which is located below the acrotelm, consists of highly decomposed peat that is permanently saturated with water. In contrast to acrotelm peat, this highly decomposed peat is more plentiful in mesopores and micropores that can draw water upwards through capillary action, thereby maintaining a water supply to the rooting zone of plants when the water table drops (IUCN 2014; Holden 2005; Quinty and Rochefort 2003).

The ability of the acrotelm and catotelm to buffer the effects of water table changes is extremely important because peatland vegetation is highly adapted to a stable water table (IUCN 2014), often occupying microhabitats that are no more than 10-20 cm in vertical range; a small drop in water table could represent an entire zonal range for certain vegetation assemblages (IUCN 2014). Without large macropores in the acrotelm, an increase in water table could flood an entire plant population; alternatively, without the effect of a strong capillary fringe in the catolem, water may become unavailable to the rooting zone of plants as the water tables drops. In addition, upland vegetation may start to colonize drying peat, and upland plants generally have root systems that will further accelerate peat drying (IUCN 2014). When peat is harvested for use as a reclamation substrate, it is heavily mixed (usually with underlying mineral soils), thereby destroying the distinctive actrotelm and catotelm layers that play a vital role in peatland hydrology. My research demonstrated considerable losses of reclamation peat in a constructed setting, much of which was likely due to erosion and peat floating away. I suspect that the lack of an acrotelm (with its porous conductive capacity) in reclamation peat, may have restricted subsurface water flow (particularly during rain events), thereby increasing surface flow, which may have fostered erosion and peat losses.

After reclamation peat is mixed during harvesting, it is stored in stockpiles (often for weeks to years) prior to being used for reclamation, and rapid drying occurs. Under these conditions, it is likely that the moorsh-forming (peat-mineralizing) process begins, causing irreversible loss of organic soil functions (Ilnicki and Jutta 2002); however, to my knowledge this process has never been studied in reclamation peat piles. The moorsh-forming process (MFP) is a globally recognized process by which organic soils (primarily those originating from fens) undergo physical and chemical alterations (e.g. increased N mineralization potential) after reclamation (generally for agricultural purposes, but here we can extrapolate); the level of moorsh-formation can be used as an indicator of soil quality (Okruszko and Ilnicki 2003). Progressive peat drying results in subsidence, oxidation, increased bulk density, decreased porosity, and decreased hydraulic conductivity, which all have an effect on evaporation and water cycling (Baird and Gaffney 1995; Minkkinen and Laine 1998; Price 2003). The decrease in porosity happens in a very particular way; the number of macropores and micropores are increased at the expense of mesopores, which is important because capillary rise depends heavily on the presence of mesopores (Ilnicki and Jutta 2002).

During dry summer months the capillary rise of groundwater supplies much of the moisture content in the rooting zone of peatlands (Gnatowski et al. 2002). In natural peatlands, well-decomposed peat can maintain a 60-cm capillary fringe, and moderately decomposed peat can maintain a capillary fringe of 30-40 cm (Olszta et al. 1990;

Whitehead 1999; Verry 1997; Szuniewicz 1977). Ilnicki and Jutta (2002) suggest that as peat dries and turns to moorsh (mineralized peat), it can only maintain a capillary rise of 10 cm, and that the water table would need to be maintained very close to the surface to support vegetation. Gnatowski et al. (2002) also found that capillary-rise is dependent on how far advanced the MFP is, and that a higher water table is required when peat is turning to moorsh. Szuniewicz (1977) found that the water table could not fall below 30 cm when the peat moorshing process was advanced. In profoundly transformed peat soils, the water table should be maintained immediately below the surface to ensure a sufficient supply of water to plants (Gnatowski et al. 2002). Moorsh layers generally form at the surface of peatlands, or agricultural systems that use peat soils, as the water table drops; in peat piles stored for reclamation, most rapid drying is also likely to occur at the piles' surface. When peat is moved from storage piles to the reclaimed peatland surface, further mixing of already compromised peat occurs. I found that *Carex aquatilis* survival and establishment was not related to the thickness of peat substrates; however, I suspect that if the study was repeated using non-compromised peat, and plots were not established on a mineral soil island (allowing better interaction of peat and water), the results may have been different. Peat amendments have been shown to increase the cover of *Carex* species (Rewers et al. 2012).

With these considerations in mind, maintaining the integrity of peat by harvesting it in layers (i.e. minimizing mixing), may be beneficial for peatland reclamation. In addition, placing the maintained layers in an area where they can be continuously wetted (by what measure is a topic for potential research), and then moved to the constructed wetland as quickly as possible, may also be beneficial. Continuous rewetting and transplantation of the acrotelm, from natural peatlands to disturbed sites, has been attempted with positive results; the transplanted acrotelm retains sufficient soil moisture, and allows plants to survive during periods of drought (Farooq 2011). Cagampan and Waddington (2008) found that transplanting an acrotelm and placing it on top of a cutover peatland resulted in reduced respiration rates because soil moisture was maintained.

For peatland reclamation on post-mined landscapes in the oil sands, transplanting a relatively thick layer of peat; the actrotelm (generally 10 to 20 cm) and a portion of the catotelm, could help dampen water table draw down (Daly et al. 2012; Price 2003; Whittington and price 2006) and increase the dispersion of contaminants, thereby delaying their passage to the rooting zone of plants (Renanezhad et al. 2010). A peat thickness greater than 40 cm would ensure that the majority of wetland plants are entirely rooted in peat, and meet the Canadian Wetland Classification System's guidelines for peatland classification (NWWG 1997); however, placing enough peat, such that the water table can drop substantially and still maintain an interaction with peat could be beneficial for peatland hydrology, especially in a constructed peatland where maintaining a stable water table is difficult; in 2015, the water table fluctuated 0.9 m in the Sandhill Fen, and fell -0.4 m below the soil surface by the end of the summer (Spennato 2016). Because well decomposed peat is capable of maintaining a 60 cm capillary fringe (Olszta et al. 1990; Whitehead 1999; Verry 1997; Szuniewicz 1977), 60 cm of peat may be a good reclamation target; however, my research demonstrated that the use of reclamation peat (i.e. peat that has been chemically and physically modified during extraction, storage and placement) would require a thicker peat application than the desired goal to compensate for compression, decomposition and losses. My research demonstrated that thicker (i.e. 30 cm) peat applications subsided more than thinner (i.e. 5 cm) peat applications; reducing in thickness up to 75 percent, but generally reducing in thickness approximately 40%. A 100 cm peat application may therefore be necessary to achieve an end goal of 60 cm, although I am uncertain if using a thick layer of reclamation peat is beneficial, because it may not provide the desired hydrological functions mentioned earlier. In addition, I acknowledge that using peat applications of this thickness would likely have additional financial, ecological, and regulatory challenges. My research also showed that peat reductions and losses were the lowest at intermediate moisture levels, suggesting a critical need to maintain an appropriate water table (if possible).

My research showed that *C. aquatilis* survival and establishment were a function of position relative to the water table, and that the greatest survival and establishment were in plots where surface elevation (relative to initial water table depth) was between -25 and 15 cm; however, it's important to note that while this range may be beneficial for *C. aquatilis*, it may not be suitable for other desirable vegetation, such as mosses and ericaceous shrubs. *Carex aquatilis* survival and establishment did not depend on substrate type in that survival and establishment were similar on both peat and mineral substrates, and among different peat thicknesses. Transplanting mature *C. aquatilis* plants appeared to be a viable option for peatland reclamation, but maintaining an appropriate water table is critical for their early survival and establishment. *Carex aquatilis* survival and establishment in control plots (containing natural or broadcast seeded plants) lagged in comparison to transplanted *C. aquatilis*, but showed a similar trend in response to elevation treatments. Overall, transplanting *C. aquatilis* to a constructed peatland may contribute to quicker establishment of the species, thereby reducing the likelihood of colonization by unwanted species, and potentially contributing to accelerated development of peatland conditions; however, the overall cover of *C. aquatilis* in my control plots, and throughout the Fen, indicated that natural recruitment and/or broadcast seeding may be a beneficial reclamation strategy as well.

4.3. FUTURE RESEARCH

Peatland reclamation depends on restoring the hydrological properties of peat (Farooq 2011), but the ability of reclamation peat to provide desired hydrological functions is unclear. A future study assessing the physical and chemical modifications that reclamation peat undergoes after harvesting and storage would be beneficial in addressing its ability to perform hydrological functions. A comparison between the functionality of the reclamation peat that is typically used, and "non-compromised" peat that is extracted in layers and continuously wetted prior to use (both in a lab and field setting), would enhance our knowledge of best-management practices for peatland reclamation; however, how to extract peat in layers and keep it continuously wetted also needs to be addressed.

I found that *C. aquatilis* survival and establishment did not depend on the thickness of peat substrates; however, I suspect that if the study was repeated using "non-compromised" peat (i.e. peat that was harvested in layers and kept wet prior to placement), and the water table was kept above the peat-mineral interface by using a thicker layer of peat (allowing better vertical interaction of peat and water), the results may have been different. Peat amendments have been shown to increase the cover of *Carex* species (Rewers et al. 2012), so a similar study using "non-compromised" peat would be valuable.

Based on early reclamation conditions of the Fen, it appeared that some initial peatland conditions (such as water table and flow, some peatland vegetation, and peat accumulation) can be created; however, future monitoring of the Fen is required to assess its future successional trajectory and the sustainability of peatland conditions. Peat substrates in the Fen were subject to substantial reductions and/or losses, which should be considered for future reclamation projects. Although peat applications did not appear to aid in the survival or establishment of *C. aquatilis*, peat is likely to provide benefits not addressed in this study. This study confirmed that *C. aquatilis* is a good candidate for peatland reclamation, as it became well established in the Fen through multiple mechanisms (e.g. transplanting of mature plants, broadcast seeding and natural recruitment). Findings from this study may benefit future peatland reclamation, but additional research is required to develop provincial peatland reclamation guidelines on post-mined landscapes.

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