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RESTORATION OF HEADWATER AND COASTAL FENS IN THE LAKE SUPERIOR BASIN OF UPPER MICHIGAN

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RESTORATION OF HEADWATER AND COASTAL FENS IN THE LAKE SUPERIOR BASIN OF UPPER MICHIGAN

By
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A DISSERTATION

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Preface

This dissertation is based on the following papers as referred by their chapter number, which are either published or in preparation for submission to ecological journals. Text throughout the document is written in first person plural to recognize the contribution of multiple authors. For the Chapter 2 paper, James Bess wrote grants for funding, designed and implemented the experiments, collected and analyzed all data and performed the bulk of the writing and editing. Dr. Rodney Chimner assisted with funding, developing experimental design, construction of experiments, analyzing data and writing. Laura Kangas assisted with constructing experiments, collecting and analyzing data and report writing. For the Chapter 3 paper, James Bess wrote grants for funding, designed and implemented the experiments, collected and analyzed all data and performed the bulk of the writing and editing. Dr. Rodney Chimner assisted with funding, developing experimental design, construction of experiments, analyzing data and writing. Dr. John Hribljan assisted with data collection, analysis and report writing, while Dr. Evan Kane assisted with data collection and analysis. In the Chapter 4 paper, James Bess wrote grants for funding, designed and implemented the experiments, collected and analyzed all data and performed the bulk of the writing and editing. Dr. Rodney Chimner and Dr. Casey Huckins assisted with funding, developing experimental design, analyzing data and writing.

Chapter 2. Bess, J., R. Chimner and L. Kangas. Ditch restoration in a large northern Michigan fen: vegetation response and basic pore water chemistry. *Ecological Restoration* 32(3): 260-274. ISSN 1522-4740 E-ISSN 1543-4079.

Chapter 3. Bess, J., R. Chimner, J. Hribljan and E. Kane. 2015. Gradients in pore water chemistry and vegetation in a restored northern Michigan fen. Manuscript.

Chapter 4. Bess, J, C. Huckins. and R. Chimner. 2015. A novel approach to establishing coastal wetlands on the south shore of Lake Superior. Manuscript.

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Initiative. The Nature Conservancy also provided us with maps, results of previous botanical surveys and on-site lodging. The Keweenaw Land Trust and Keweenaw Bay Indian Community were most generous in allowing me to use their properties for my coastal wetland restoration experiments. And finally, I would like to give special recognition to my wife Karen Bess for her endless support and encouragement. Without her help this dissertation would not have been possible. Thank you.

Dissertation Abstract

In 2009, research projects were initiated at Michigan Technological University to develop restoration techniques for headwater fens and coastal wetlands in the southern Lake Superior Basin in Michigan's Upper Peninsula. The primary focus of these was to quantify the efficacy of using locally collected seeds as a technique for wetland restoration. Two primary sites were selected, the Sleeper Lake Fen complex in Luce County and the Portage Waterway-Keweenaw Bay region of Lake Superior in Baraga and Houghton Counties. At the Sleeper Lake site, a combination of heavy machinery, seeding and mulch application was used to restore a 1.6 km ditch through a formerly pristine headwater fen. Pore water chemistry was measured in the undisturbed and restored fen to compare with vegetation data collected from the same locations for two growing seasons following restoration. At the two coastal sites along the Portage Waterway and Keweenaw Bay, a combination of seeds, natural fiber geotextiles and organic soil amendment (milled *Sphagnum* peat moss) were tested for restoration efficacy along 2, 33-m long sectors of shoreline, one site along the Portage Waterway in Houghton County and another along a former interdunal pond adjacent to Keweenaw Bay in Baraga County. Vegetation data were collected for three years following restoration. Both projects were successful in restoring diverse assemblages of native plants. At the Sleeper Lake site, pore water chemistry was found to correlate closely with several vegetative parameters and at the Portage Waterway and Keweenaw Bay sites, the organic amendment had variable results in enhancing vegetative establishment and survival. Fluctuating lake levels were important in determining vegetative establishment and

survival at the sites along Lake Superior. The results of these experiments are compared with other similar projects and discussed in relation to local conditions and potential for extrapolation across the Great Lakes region.

Chapter 1.0: Introduction

1.1 Fen Characterization and Distribution

Prior to the industrial revolution, peatlands covered roughly 4 million km^2 or 3 % of the Earth's land surface (Maltby and Proctor 1996). Peatlands were distributed across much of Siberia, northern Europe, Canada and the eastern US. In the tropics, peatlands occurred in parts of the Amazon and Congo river basins, Indonesia and Malaysia, while montane peatlands were found throughout Europe, South America, North America and parts of Africa, Australia and New Zealand. Siberia and Canada still contain large areas of fairly pristine peatland, but many thousands of hectares have been destroyed or negatively affected by forestry and mining activity, hydroelectric projects, atmospheric nitrogen deposition, wildfire and global climate change (Kremenetski et al., 2003, Poulin et al., 2004, Frey and Smith, 2005). In addition, a major reduction in peatland acreage has occurred in the tropics, Western Europe and the U.S. over the past 400 years (Wheeler, 1897, Parish et al., 2008, Keddy et al., 2009, Bain et al., 2011, Borlick, 2013).

Fens are peatlands characterized (in part) by their strong association with flowing groundwater and surface water (Crum, 1988, Amon et al., 2002, Bedford and Godwin, 2002, Rydin and Jeglum, 2006, Wieder and Vitt, 2006, Parish et al., 2008). These natural communities typically occur at breaks in stratigraphy or topography that create

hydrologic gradients, forcing ground water to approach or be released on the surface of the land (Amon et al., 2002). These groundwater release points have been referred to as “aquifer windows” (Wilcox et al., 1986).

In the Upper Midwest of North America, fens occur primarily on glacial till deposits, where groundwater passes through mixtures of rock, sand, silt and clay, acquiring dissolved minerals along the way (Almendinger and Leete, 1998a-b). In particular, as the glaciers passed south over the Niagaran Escarpment surrounding the northern Great Lakes, these large masses of ice ground down the limestone and dolomite bedrock forming much of this feature and incorporated an abundance of calcium and magnesium carbonates in the glacial till left when they receded (Boelter and Verry, 1977, Amon et al., 2002).

1.2. Fen Classification and Pore Water Chemistry

Given that the composition of glacial till is not uniform across the Midwestern landscape, there is great variation in the chemical composition of groundwater (including surface water) entering fens, as is true of other areas where fens occur (Bridgham et al. 1996, Bedford and Godwin, 2002). Groundwater is here defined as the water flowing from surrounding land into a peatland, pore water is the water occurring in interstitial spaces in saturated/inundated soils (basically groundwater or surface water that has interacted with peat soil and vegetation). Fens are typically described as occurring along a gradient from “poor” to “rich”, depending on the pH and electrochemical composition of the groundwater entering them (following Sjors, 1950, Slack et al. 1980, Swanson and

Grigal 1991, Heinselman1970, Thormann et al. 1999, McLaughlin and Webster, 2010). Poor fens are those having low pH and minimal mineral and carbonate content in their groundwater, while rich fens are those with high pH and increased levels of dissolved minerals, especially iron and carbonates of calcium and magnesium (Thompson, 1993, Almendinger and Leete, 1998b, Amon et al., 2002).

Carbonate ions raise the pH and (along with other particulate matter) electrical conductivity of groundwater and, in high concentrations, provide conditions that are hostile to the growth of plants not adapted to their presence (Glaser et al., 1990, Gignac et al., 1991, Nekola, 2004). Therefore, rich fens are not only defined by groundwater having increased carbonate and pH, but also by having unique plant assemblages adapted to these conditions (Slack et al. 1980, Motzkin, 1994, Nekola, 2004, Picking and Veneman, 2004). Conversely, poor fens (and bogs) are defined by low pH and carbonate levels and are vegetated with plant species adapted to more acidic conditions.

Calcium-rich fens are typified by plants often referred to as “calcifiles” or “calciphilic” given their ability to grow and persist in the presence of relatively high concentrations of calcium. Temperate and boreal North American rich fen floras are typically dominated by “brown mosses” (families Amblystegiaceae and others), sedges, grasses and a wide variety of herbaceous plants (or “forbs”), often including many rare or unusual species such as orchids and insectivorous plants (Bedford and Godwin, 2003). Poor fen and bog floras are characterized by many “acidofiles” or “acidophilic” species adapted to low pH conditions and low nutrient availability. These include *Sphagnum* mosses (Gignac et al., 1991), certain sedges and a variety of ericaceous shrubs.

Insectivorous plants like sundews (*Drosera* spp.) and pitcher plants (*Sarracenia* spp.) are also often found in these acidic peatlands, although they can be found in certain rich fens as well. Bogs can also contain rare and unusual plant species found nowhere else, although their overall plant species richness is typically much less than that found in fens (Locky and Bayley, 2006, Lamentowicz et al., 2010).

1.3 Fen Degradation, Conservation and Restoration

The relatively high nutrient composition and abundant organic matter in fen soils have made these habitats targets for agricultural production for many hundreds (if not thousands) of years (Beltman, et al., 1996, Jensen and Schrautzer, 1999, Lamers et al., 2002, Middleton et al., 2006a, Seer and Schrautzer, 2014). In some cases, these fens have been simply used as pasture or for haying (Wheeler and Giller, 1982, Middleton et al., 2006a-b), but many others have been ditched and drained to allow for peat extraction (Quinty and Rochefort, 2003, Waddington et al., 2009) or the use of heavy machinery to till soil and plant crops (Van Duren et al., 1997, Mälson et al., 2009, Davenport et al., 2014). In Europe and North America, hundreds of thousands of hectares of former fen have been drained and converted to agricultural production (Wheeler, 1897, Fisher et al., 1996, Hartig et al., 1997, Bedford and Godwin, 2002, Middleton et al., 2006b).

The current rarity of fens and their role as habitats for species of conservation concern and headwater protection has fueled a global effort to protect and restore these plant communities over the past ~20 years (Grootjans and van Diggelen, 1995; Beltman et al., 1996; Hald and Vinther, 2000; Bedford and Godwin, 2002; Lamers et al., 2002;

Cobbaert et al., 2004; van Diggelen et al., 2006; Drexler et al., 2009; van Loon et al., 2009; Klimkowska et al., 2010; Laine et al., 2011; Sikes et al., 2013; Seer and Schrautzer, 2014; Lamers et al., 2015). Fens also store vast amounts of carbon in their peat and muck soils and this role has further increased the importance of fen restoration in the eyes of governments, regulatory agencies and even the general public (Gorham, 1991; Tuittila et al., 1999; Joosten and Clarke, 2002; Glatzel et al., 2003; Turunen, 2008; Keddy et al., 2009; Komulainen, 2009; Waddington et al., 2009; Anshaari et al., 2010; Armstrong et al., 2010; Kimmel and Mander, 2010; Bain et al., 2011; Whitfield et al., 2011). These unique plant communities often occur at groundwater discharge sites and along the edges of waterways, where their soils and vegetation provide important ecological functions in filtering water, maintaining base flow for lakes, streams and rivers, and providing abundant dissolved organic matter, minerals and nutrients to aquatic systems (Schouwenaars, 1988, Mulqueen, 1986, De Mars and Garritsen, 1997, Schiff et al., 1998, Reeve et al., 2001, Price et al., 2003, Holden et al., 2006, Reeve et al., 2006).

Typically, the first step in fen restoration is to restore (to the level possible) the natural hydrology (Komulainen, 1999; Lode, 1999; Cooper and McDonald, 2000; Tuittila et al., 2000; Holden et al., 2006; Laine et al., 2011; Hedberg et al., 2012; Bork et al., 2013; Schimelpfenig et al., 2014). This can be done through removal of drainage tiles and plugging or filling of drainage ditches in order to re-saturate the dried peat soils. Given the great age of many fen drainage programs, this is not always an easy or straightforward task. Changes to site and regional hydrology (Okrusczko, 1995, Fisher et al., 1996, Tuittila et al., 1999-2000, Holden et al., 2004, Mälson et al., 2008), peat and

pore water chemistry (Van Duren, et al., 1998, Jansen et al., 2004), lack of appropriate fill material (Armstrong et al., 2009, Schimelpfenig et al., 2014) and subsidence (Schothorst, 1977, Drexler et al., 2009) can greatly limit the success of a fen restoration project (Komulainen et al., 1999, Pfadenhauer and Grootjans, 1999, Johnson and Valppu, 2003, Van Dijk, 2004, Miller, 2011, Hedberg et al., 2012-2013).

1.4 Project Overview

In the Lake Superior Basin, fens have received less attention than elsewhere, especially in regards to restoration (Epstein et al., 1997). What restoration research has been conducted and published has occurred in Minnesota (Johnson and Valppu, 2003). In Michigan, fen restoration has begun in the nearby Seney National Wildlife Refuge (Wilcox et al., 2006, Bork et al., 2013) that drains into northern Lake Michigan. While these research projects focused on headwater and lakeplain fens, there is apparently no published research on the restoration of coastal fens along Lake Superior in northern Michigan.

The goal of this research was to develop management techniques for two relatively common (but often human-impacted) fen types in the southern Lake Superior Basin: lake-side fens and headwater fens. In particular, these projects were undertaken to determine whether seeds could be used to restore these wetland types, as this would ultimately be much more economical than the standard practice of using nursery stock in restoring wetlands. If successful, this technique would also have the advantage of allowing for the use of locally-collected genetic stock for restorations, rather than

depending on the availability of nursery stock that might derive from genetic pools a considerable distance from the restoration site. Nursery stock taken from more temperate or austral zones might not be well-adapted to weather and soil conditions of more boreal sites such as those along Lake Superior. The efficacy of using biodegradable geotextiles, mulch and organic amendment (i.e. milled peat moss) in facilitating wetland plant germination and establishment in these two fen types was also of interest.

Chapters 2 and 3 focus on restoration efforts at a large, fairly undisturbed headwater fen complex in the eastern Upper Peninsula of Michigan near the town of Newberry (the Sleeper Lake Fen). Specifically, this research focused on firebreak restoration in an area of open fen, the firebreaks resulting from fire-fighting activities associated with a large (>7,250 hectares) wildfire in 2007. The use of large machinery was tested for replacing disturbed fen peat into the now water-filled firebreaks and the use of mulch, seed and *Sphagnum* moss diaspores to restore fen vegetation. Pore water sampling and analysis was also included, to determine if various pore water characteristics were associated with differential establishment of plant species in the restored ditch and whether there were any differences in chemistry between the restored and undisturbed fen and if these differences changed over time. Pore water constituents selected for comparison included Dissolved Organic Carbon (DOC), aromatic hydrocarbons, total Nitrogen (TN), pH, Electrical Conductivity, temperature, Al, Ca, Fe, K, Mg, Mn, P, Zn and several organic anions.

Vegetation was sampled to compare and contrast between restored and undisturbed fen and pore water chemistry. For the purposes of this study, “undisturbed”

fen refers to the vegetation and peat next to the ditch that was not excavated during firebreak construction. It is understood that this fen had tracked vehicle traffic along both sides of the ditch during firebreak excavation and restoration (in addition to a recent, hot fire) or had peat spoils covering it for 2 years and therefore is not technically undisturbed. This term is used solely to compare the newly restored and highly disturbed ditch with the unditched fen habitat adjacent to it. Vegetation and pore water sampling in the undisturbed fen was undertaken ~4 meters away from the edge of the ditch, presumably outside the track width of the bulldozer used for firebreak creation and the excavator used for restoration. The peat surface and vegetation in this zone was visually undistinguishable from adjacent fen further away from the ditch.

Chapter 4 focuses on the creation/restoration of two coastal fens on the shores of Lake Superior along the Keweenaw Peninsula in the western portion of Michigan's Upper Peninsula. Here I tested the use of seeds for coastal wetland restoration in conjunction with natural, biodegradable geotextiles. This research also tested the potential benefit(s) of using organic amendment, in the form of milled peat moss, for establishing wetland vegetation on coastal sites. Vegetation was sampled over a three-year period to track shifts in species composition and cover over time and under fluctuating lake water levels.

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Chapter 2.0 Ditch Restoration in a Large Northern Michigan Fen: Vegetation Response and Basic Pore water Chemistry[1]

2.1 Abstract

Following a prolonged drought, more than 7,250 ha of a large fen complex in Michigan's Upper Peninsula burned in late summer of 2007. As part of fire-fighting efforts, over 48 km of bulldozed firebreaks were made in and around the peatland. In 2008, the State of Michigan restored over 32 km of firebreak in upland areas, but 14.5 km through the fen proper remained as open-water ditches. In the fall of 2009, we restored 2 km of ditch by replacing spoils with an excavator. In addition to ditch filling, we conducted experimental plantings of 18 species of vascular plants and 6 mosses to test the effectiveness of seeding, moss diaspore application and mulching. Surveys during the first and second summers found vigorous re-growth of vegetation both within the treatment quadrats and the controls. Contrary to most published results, the unmulched quadrats had the greatest vegetative cover and richness of plant species, followed by the mulched quadrats and the unplanted controls. By 2011, mean vegetative cover on the treatment quadrats had exceeded the undisturbed ones. Our results indicate that filling is an excellent method of ditch restoration in fens and that seeding increases both plant cover and species richness. Conversely, the addition of moss diaspores and mulch were apparently unnecessary in this case, as moss cover in treatment and control quadrats was similar along the length of the ditch, likely because of the perennially high water table and the presence of living diaspores in the replaced spoils.

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2.2 Introduction

Peatlands are of global importance because of their role in filtering groundwater, providing base flow and nutrients for streams and rivers, as habitat for many unique species and as repositories for carbon (Parish et al., 2008). Although they cover only 3% of the Earth's surface, peatlands contain 12-30% or more of terrestrial carbon stocks (Gorham, 1991; Joosten and Cowenberg, 2008) and 10% of the earth's fresh water (Joosten, 2008). They are also concentrated refugia of biodiversity (Minayeva, 2008; Whitfield et al., 2011). Unfortunately, many peatlands have been altered or destroyed through human activity. Current estimates are that 25% of the world's peatlands have been destroyed or significantly altered in the past few hundred years (Silvius et al., 2008).

Given their perennially high water table, the only effective way for humans to access and exploit most peatlands has been to drain them. For example, millions of hectares of Scandinavian and Baltic peatland forests have been ditched and drained for timber production (Mälson et al., 2008, Lode, 1999, Mälson et al., 2010, Laine et al., 2011), with more than half of Finland's peat forests drained and converted for timber production (Paavilainen and Paivanen, 1995, Turunen et al., 2002, Turunen, 2008). Many UK, northern European and Russian peatlands have been drained for peat cutting and removal for fuel (Hartig et al, 1997, Bain et al., 2011, Kollmann and Rasmussen, 2012).

In Canada (and the northern US) peatlands are drained to facilitate peat harvesting, with more than 93.7 million cubic meters extracted annually for use in the horticultural trade (Canadian Sphagnum Peat Moss Association, 2012). The tropical

peatlands of Indonesia and Malaysia are being drained for logging, subsistence agriculture and replacement with biofuel plantations (Silvius et al., 2008, Page et al., 2009, Aanshari et al., 2010, Jauhiainen et al., 2012). Elsewhere in Britain, Europe and the U.S., millions of hectares of temperate fens have been drained for agricultural uses (Fisher et al., 1996, Hartig et al, 1997, Roberts, 1999, Joosten and Clarke 2002, Silvius et al., 2008, Drexler and Deverel, 2009).

Ditches can negatively impact fens in numerous ways. Lowering the water table increases the aerobic portion of the peat strata (the “acrotelm”), leading to an increased decomposition rate and subsidence of the peat (Schothorst, 1977, Okruszko, 1995, Lode, 1999, Holden et al., 2004, 2006a-b, Drexler and Deverel, 2009, Hedberg et al., 2012). Peat subsidence leads to a decrease in soil pore size and hydraulic conductivity, further drying the peatland and leading to changes in vegetative composition (Boelter, 1972, Mulqueen, 1986, Schouwenaars, 1988, Eggelsmann et al., 1993, Fisher et al., 1996, Vasander et al., 1996, Vasander et al., 2003, Miller, 2011; Hedberg et al., 2012). Subsidence also leads to larger fluctuations in groundwater levels, which can increase the amount of organic matter leaving affected peatlands, turning them from net carbon sinks to carbon sources (Schiff et al., 1998, Tuittila et al., 1999, Glatzel et al., 2003, Holden et al., 2004, 2006a-b, Laitinen et al., 2008, Armstrong et al., 2010, McLaughlin and Webster, 2010). Changes in dissolved organic carbon (DOC) can also lead to changes in species and functional groups within the vegetation community of peatlands (Armstrong et al., 2012).

In fens, drainage ditches can also cut off the flow of mineral-rich groundwater, leading to a reduction in nutrients and an increase in bulk density and acidification of the peat (De Mars et al., 1996, Van Duren et al., 1997, De Mars et al., 1997, Komulainen et al., 1999, Holden et al., 2004, Boomer and Bedford, 2008, Mälson et al., 2008, Hedberg et al., 2012). Dried peat is also very light and friable, making it highly susceptible to wind erosion (Campeau and Rochefort, 1996) and fire (Busque and Arsenault, 2005, Camill et al., 2009, O'Donnell et al., 2009, Ronkainen, 2013).

For projects attempting to restore peatland hydrology, ditches can be actively restored either by filling them entirely or plugging the ends or sectors of ditch with dams (Price, 1996, Tuittila et al., 2000, Howie et al., 2009, Armstrong et al., 2009, Mälson et al., 2010, Ketcheson and Price, 2013, Laine et al., 2011, Bellamy et al., 2012, Hedberg et al., 2012, 2013, Schimelpfenig et al., 2014). Most ditches are plugged because of cost or the oxidation of spoils piles results in a lack of appropriate fill material (Holden et al., 2004). Sometimes there is also concern (often unfounded) that complete filling of the ditch will result in a larger flooded area, negatively affecting adjacent landowners (Hedberg et al., 2012; Holden et al., 2004). Further complicating peatland restoration efforts is the general lack of a viable seed bank in older (>10 years) ditched and excavated sites (Jansen et al., 2004, Graf et al., 2008, Mälson et al, 2010). The perennially saturated soil, fragile vegetation and general inaccessibility of many fens also limit the use of heavy machinery in restoring all but the driest sites. Additionally, very few fen restoration projects have been studied (and reported on) in the Upper Great Lakes

region (Kowalski and Wilcox, 2003, Johnson and Valppu, 2003, Wilcox et al., 2006, Bork et al., 2013).

Despite these potential difficulties, our goal was to test methods for restoring a newly dug (2 year old) ditch created as part of an extensive fire break system in a large fen in Michigan's Upper Peninsula. Our objectives were to: 1) test the effectiveness of using heavy machinery to replace recently excavated peat back into the ditch, 2) test the effectiveness of experimental plantings of seeds, moss diaspores and mulch, and 3) determine if basic groundwater characteristics (pH, electrical conductivity) varied along the restored ditch and if this variation was correlated with variation in plant species colonization.

2.3 Methods

2.3.1 Study Site

Prior to European settlement, Michigan's Upper Peninsula contained approximately 950,000 hectares of peatlands, of which ~185,000 hectares were open sedge, forb and moss dominated communities (Comer et al., 1995, Slaughter and Cohen, 2010). Among the largest and previously least disturbed peatlands in Michigan is the Sleeper Lake Fen complex (also known as the "Two-Hearted Lowlands") in Luce County (Latitude 46°29'17.17"N, Longitude 85°30'52.96"W). The fen complex covers over 20,000 ha and was spared much of the ditching and logging efforts of the late 19th and early 20th centuries that affected other Michigan peatlands. Large sectors of this wetland

complex are owned by the State of Michigan and The Nature Conservancy, as both State Forest and Nature Preserve, and it is relatively roadless and inaccessible.

Sleeper Lake Fen occupies a former glacial lake plain (glacial Lake Minong) and drainage channel deposited by melt water from the retreating Laurentide ice sheet ~11,400 cal yrs BP (Loope et al., 2010, Krist and Lusch, 2004). The lakeplain slopes gradually to the southeast and is crisscrossed with low (1-3 m) to tall (15-20 m) transverse and parabolic dunes vegetated primarily with virgin red, white and jack pine forest and barrens. Several spring-fed lakes are located in the fen proper, the largest being Sleeper and McMahon. The fen complex is also the headwaters of several rivers, including the Augur, Dawson, Two-Hearted and numerous creeks feeding into the Tahquamenon. The local climate is greatly influenced by Lake Superior, with an average annual rainfall of 81 cm and snowfall of 312 cm (USFWS, 2009). Annual average temperature is 5.1° C (Wilcox et al., 2006) and annual growing season is approximately 119 days (USFWS, 2013). Locally the lakeplain contains two very high quality examples of patterned fen.

The fen caught fire via lightning strike in August of 2007 following a prolonged, La Niña-related drought, ultimately burning more than 7,200 ha over a 3 month period. During the fire, over 48 km of firebreak were bulldozed in and around the fen complex. Firebreaks in open sedge fen varied from 1-3 m in width, 1-1.5 m in depth and 2.6-several km in length. Following the fire, precipitation returned to normal and the water table rose, turning the peatland firebreaks into water-filled ditches, some with appreciable flow. The State of Michigan repaired ~32 km of the ditch lines throughout much of the

uplands in 2008, but ~14-15 km through the wettest portions had become so saturated that there were concerns machinery would become stuck or cause further damage to the fen vegetation.   The Nature Conservancy and State of Michigan asked the authors to develop a plan for restoring these wetland ditches.

2.3.2 Ditch Filling/Peat Replacement

A 2.6 km sector of ditch through grass and sedge-dominated fen (lat. 46°27’13.23”N long. 85°28’33.01”W) was chosen for experimental restoration (Figure 2.1). When this 3 m-wide firebreak was initially dug, the peat was curled upside down along one side of the ditch, with vegetation remaining alive along many sectors following the fire. Given the width of the ditch, we decided to use a full-size, 19-ton excavator to replace spoils during the fall of 2009. The excavator operator used timber floats to minimize disturbance of the peat surface and tamped down and "leveled-out" the peat once it was replaced in the ditch. The operator also made a special effort to flip over many of the living peat chunks, so their stratigraphy and microtopography more closely matched that of the undisturbed fen.

2.3.3 Experimental Design

Prior to restoration, the undisturbed vegetation along the 2.6 km ditch was observed to vary markedly in plant species composition and dominance. Therefore, we divided the restoration site into 4 sectors along the ditch (Figure 2.1), with each representing one of four "plant associations" observed in the adjacent, undisturbed fen:

1. *Carex oligosperma-Chamaedaphne calyculata-Betula pumila- Sphagnum* spp. Wooded Poor Fen (Plots #1-5).
2. *Andromeda polifolia-Carex magellanica-Iris versicolor-Vaccinium macrocarpon* Open Fen (Plots #6-10);
3. *Aster borealis-Carex lasiocarpa-Galium brevipes-Salix* spp.-*Scutellaria galericulata*- Rich Shrub Fen (Plots #11-15);
4. *Doellingeria umbellata-Calamagrostis canadensis-Carex sterilis-Viburnum cassinoides* Rich Shrub Fen (Plots #16-20).

Sectors ranged from 83 m (Sector 1) to ~400 m (Sectors 2-4) in length and, within each, we established five replicates of three, 3-meter square experimental planting treatments consisting of: 1) no plant - control, 2) seed only, and 3) seed, moss diaspores and mulch, resulting in a total of 60 research plots. These plots were placed in relatively homogenous areas of restored peat within each Sector. Wholly inundated areas were avoided, as were large clumps of sedge turf and shrub root masses. Plot placement within each set of 3 treatment types was randomly chosen to reduce potential bias.

2.3.4 Seed and Moss Collection and Planting

A total of 4 kilograms of seeds were hand collected on-site, from 18 species of wetland plants, for use in the restoration (Table 2.1). Species were selected for collection based on their common occurrence and relative abundance in either the undisturbed, burned fen or the adjacent, unburned fen. Seeds were dried, cleaned, weighed and sorted into individual, identical, 75g seed mixes for each seeded plot. The seed mix included 6

sedges and rushes (*Carex magellanica, C. oligosperma, C. utriculata*, *Dulichium arundinaceum*, *Eriophorum virginicum* and *Scirpus atrovirens*), 2 grasses (*Calamagrostis canadensis* and *Glyceria canadensis*), 6 forbs (*Doellingeria umbellata, Iris versicolor, Oclemena nemoralis, Rumex orbiculatus, Solidago uliginosa* and *Symphiotrichum boreale*) and 4 shrubs (*Aronia melanocarpa, Betula pumila, Nemopanthus mucronatus* and *Viburnum nudum cassinoides*). Seed mixes were stored in 1 gallon Ziploc™ bags and kept refrigerated until planting. Immediately prior to use they were placed in a cooler on ice. Individual seed mixes were then chosen randomly from the cooler for spreading onto the 40 research plots to receive seed (20 mulch, 20 no mulch). Seed was hand broadcast evenly over each of the 3 x 3 m research plots.

We used four species of *Sphagnum* (*S. angustifolium, S. magellanicum, S. papillosum* and*, S. rubellum*) along with *Polytrichum commune* and *P. stricta* as our moss component. These were the most common species in adjacent, unburned fen. Mosses were hand collected from the adjacent, unburned portion of the fen and the lower, brown (”dead”) portions removed with scissors. The remaining moss was cut into 2.5 cm sectors (per Campeau and Roquefort, 1996, Roquefort and Lode, 2001, Graf and Roquefort, 2010) and placed in 19-liter plastic buckets. Three buckets were filled with mixed, chopped *Sphagnum* and one smaller 3.75 liter bucket was filled with freshly chopped *Polytrichum* spp. We attempted to place an even amount of the four *Sphagnum* species in each bucket. *Polytrichum commune* was much more common than *P. stricta* (~3:1), and our mix reflected this.

For each of the 20 seed-moss-mulch plots, a 5.7-liter plastic box was filled with chopped moss at a 10:1 ratio of *Sphagnum* to *Polytrichum* by volume. The moss fragments were spread by hand over the entire 3-m square plot (after vascular plant seeds were placed) providing approximately 30% cover. Moss diaspores were immediately covered with a mulch of dead *Calamagrostis canadensis* and/or *Carex* spp. foliage cut into ~45 cm lengths. Eighteen, 19-liter buckets of mulch were collected on-site and spread over the 20, 3 x 3 m mulch treatment plots, with a final cover target of approximately 70%. Following seeding, diaspore planting and mulching, permanent 1-m square "sampling quadrats" of 2.5cm diameter PVC tubing were placed in the center of each of the 3 x 3 m research plots. This was done to reduce edge effect on our subsequent data collection and analyses.

2.3.5 Groundwater Monitoring and Pore water Sampling

Initial groundwater monitoring wells were installed in the center of the restoration area (sector 2), with 1 on each side of ditch to monitor water levels prior to, and following, restoration. Monitoring wells consisted of 1.5-m long sectors of 8 cm dia. perforated PVC pipe. The outer portion of the perforated pipe was covered with nylon landscaping mesh and secured with zip-ties to prevent sediment from entering the pipe. The bottom of the pipe was covered with a PVC cap to prevent infiltration of peat. Solinst™ (Georgetown, ON, Canada) Leveloggers were placed in each well, which provided hourly monitoring of the water table. A Solinst™ (Georgetown, ON, Canada)

Barologger was also placed in one of the wells to monitor barometric pressure for calibrating the Levelogger data.

Pore water sampling was undertaken to see if observed differences in vegetation along the ditch line correlated with changes in groundwater chemistry (pH and electrical conductivity). Sampling was undertaken in November 2010, early May 2011 and late July 2011 to track changes across a growing season. Samples were collected with a 500 ml syringe attached by Nalgene hosing to a 1.5 m sector of 0.64 cm dia. stainless steel tube (similar to a Pushpoint Sampler™ as described by US EPA (US EPA, 2013)). Every effort was made to minimize disturbance of the peat profile while collecting samples (e.g. minimizing compression of the local peat through standing or walking).

During each sampling event, 60 samples were collected from along the length of the restored ditch: in each Sector, 5 samples from the ditch and 5 each from undisturbed vegetation on each side (total of 15 samples from each of the 4 Sectors). The ditch samples were taken from each of the no mulch research plots and the undisturbed samples were taken at points parallel with the no mulch plots and ~3-4 m from edge of ditch. All pore water samples were collected with the sipper at 25 cm beneath the peat surface. Clumps of shrubs and sedge tussocks were avoided, to reduce variability in depth of sample. Prior to gathering each pore water sample, the sipper tube was placed into the sampling location and the syringe filled and purged several times with local water. Samples were taken only after excess organic matter (resulting from sampler insertion into the peat) had been purged from the local collection site and sampler. From each sample, temperature, electrical conductivity and pH were measured in the field

using an YSI Model 63 hand-held meter. The pH meter was calibrated with pH 4 and 7 buffers prior to each sampling event. The sensor was rinsed thoroughly with distilled water between sampling points to minimize potential for cross contamination.

2.3.6 Vegetation Monitoring and Statistical Analysis

Vegetation composition and cover data were collected from each of the 60, 1-m square ditch research quadrats in August of 2010 and 2011. Data on undisturbed vegetation was collected in August, 2010 from 40 1-m square quadrats (5 on each side of ditch in each sector (10 per sector) placed in undisturbed fen vegetation adjacent to the ditch and parallel to each of the no mulch treatment plots. Data on the undisturbed vegetation was collected only in 2010, as species composition and cover in these plots was not observed to change greatly over the 2-year period and the thick layer of *Carex* litter inhibited the growth of any additional seedlings.

For the purposes of this study, "undisturbed" fen refers to the vegetation and peat next to the ditch that was not excavated during firebreak construction. It is understood that this fen had tracked vehicle traffic along both sides of the ditch during firebreak excavation and restoration (in addition to a recent, hot fire) and therefore is not technically undisturbed. This term is used solely to compare the newly restored and highly disturbed ditch with the unditched fen habitat adjacent to it. Vegetation and pore water sampling in the undisturbed fen was undertaken 3-4 meters away from the edge of the ditch, presumably outside the track width of the bulldozer used for firebreak creation

and the excavator used for restoration. The peat surface and vegetation in this zone was visually undistinguishable from adjacent fen further away from the ditch.

Plants were identified to species whenever possible, although many vegetative sedges, grasses and young mosses could only be determined to genus. Voss' three-volume "Michigan Flora" (Voss, 1972, 1985, 1996) was used for determinations and the most recent names for our flora were obtained from Voss and Reznicek (2012) and the USDA PLANTS Database (USDA-NRCS, 2012). Vegetative cover was estimated visually by two observers and a consensus was reached for each species to the nearest percentage. Cover was assessed on a per-species or taxon basis and, given the multiple strata of plant growth, total vegetative cover for individual quadrats often exceeded 100% when values for individual species/taxa were tallied together.

A nested analysis of variance (ANOVA) was used to compare a number of parameters by ditch sector, treatment type (mulched, seeded, control) and undisturbed versus restored peat. Analyzed parameters included total vegetative cover, vascular plant cover, forb cover, grass cover, Cyperaceae cover, bryophyte cover, vascular plant species richness, forb species richness, bare peat and litter. Tukey's Studentized Range Test for comparison of means was run for each of these parameters, comparing mean values among Sectors and treatments, to see which were significantly different from one another. P-values < 0.05 were considered significant for the ANOVA and Tukey's results. SAS 9.1 software (Proc ANOVA - SAS Institute, Inc., Cary, NC) was used to calculate ANOVAs and Tukey's tests. SigmaPlot (Systat Software, Inc., San Jose, CA) was used to generate regression scatter plots, equations, R^2 values and associated *p*-

values. For discussion purposes, regression analysis is provided only for the 2011 data as this gave time for vegetation to become established, sedges to grow and become more easy to identify and values should more closely approximate those recorded in the undisturbed fen.

2.4 Results

2.4.1 Depth to Water Table and Pore Water Chemistry

The depth to water table at the study site varied with seasonal precipitation patterns, with the water table being highest in winter/spring and lowest in mid to late summer (Figure 2.2). In May of 2009, prior to restoration, the east side (down-flow gradient) of the ditch in sector 2 had the slightly higher water table, indicating the ditch might be draining water away from the northern portions of the fen and depositing it in the central portion (sector 2). Additionally, spoils were placed on the up-flow side (west) of the ditch, which may have allowed water from the north to flow south and then out into the east side of sector 2. Flow was also observed in this direction in the ditch prior to restoration. However, following ditch restoration in October of 2009, the depth to water table remained roughly similar to pre-restoration levels and oscillations (Figure 2.2).

Pore water pH and electrical conductivity increased from the south end of the ditch (Plots 1-5: Sector 1) to the north end (Plots 16-20: Sector 4) (Appendix 2.1; Figure 2.3). Water temperature along the ditch varied over the course of the growing season (Figure 2.3). In May, it increased from south (Sector 1) to north (Sector 4), but in summer the gradient reversed, with temperature decreasing as the ditch approached the

large transverse dune at the north end of the site, where ground water likely originated (Figure 2.1). November pore water temperatures were similar along much of the ditch (mean temp. in Sectors 1-3 ranged from 6.1 – 9.0° C), but were somewhat lower at the north end (mean temp. 5.4° C in Sector 4). Water temperatures in the adjacent undisturbed fen followed the same trend but were lower than those in the ditch during all three sampling periods (Appendix 2.1).

2.4.2 Vegetation Results - 2010

Surveys in 2010 found excellent re-growth of vegetation in the restored ditch, especially within the seeded treatment quadrats and (to a lesser degree) the unplanted controls (Table 2.2, Figure 2.5, Appendix 2.2A-C). In the ditch, the unmulched quadrats had the greatest overall vegetative cover across the 4 sectors (156%), followed by the mulched (146%) and controls (126%). The undisturbed vegetation quadrats adjacent to the ditch had 188% overall plant cover, averaged across the two sides and 4 sectors (Table 2.2). Among the two treatments and controls, unmulched quadrats had the greatest percent cover of vascular plants (145%), Cyperaceae (79%), grasses (26%) and forbs (34%). The control quadrats had the least vascular cover (108%) and Cyperaceae cover (55%); the undisturbed fen had the lowest percent cover values for forbs (25%) and grasses (15%) (Figure 5). Analysis of variance testing found significant treatment effects in all parameters except forb and litter cover (Table 2.3).

Mean control (126%) and undisturbed (188%) total vegetative cover were significantly different from one another (Figure 2.5). Total vegetative cover averaged

143% along the length of the ditch, across the two experimental treatments and control quadrats. Vascular cover was significantly greater in the undisturbed versus control quadrats (162% vs 102%) and Cyperaceae cover greater in the unmulched versus the control quadrats (78% vs 55%). Shrub cover (31%) and Bryophyte cover (43%) were significantly greater in the undisturbed fen versus the three treatments. Vascular species richness was significantly greater in the seeded treatments (14%) versus the control (10%) quadrats. Litter cover was significantly greater in the undisturbed fen (60%) versus the three treatments (~1%, each) and bare peat provided significantly greater cover in the control (52%) versus the two seeded treatments (37% and 35%, respectively) or the undisturbed fen quadrats (3%). Total plant species richness was greatest in the mulched and unmulched quadrats (47 and 46 species, respectively), followed by the controls (42 species) and undisturbed fen (40 species total).

The ditch sectors also varied with respect to plant cover and species richness. Analysis of Variance (ANOVA) of the 2010 data found a strong sector effect across all vegetation parameters except total cover by Cyperaceae (Table 2.3). Looking at just the unmulched quadrats, sector 4 had the greatest overall vegetative cover (194%), followed by sector 1 (151%), while sectors 2 and 3 had the least (138% each). The difference in total vegetative cover between sectors 3 and 4 was significant. Mean unmulched vegetative cover across the four sectors was 155%. In sector 4, vascular plant cover varied from 190% in the unmulched quadrats to 143% in the controls. This pattern was repeated in sectors 1 and 3 but the control quadrats had the greatest vascular plant cover (136%) in sector 2 (Tables 2.2 and 2.3, Appendix 2.2). Mean vascular plant cover was

126% along the length of the ditch, averaged across the three treatments. Grass cover was also much greater in the unmulched quadrats, with sectors 4 (56%) and 3 (32%) having significantly greater cover than sectors 2 (10%) and 1 (5%). Conversely, the unmulched quadrats of sectors 1 and 2 had greater cover by Cyperaceae (101% and 80%, respectively) than sectors 3 and 4 (62% and 71%). Despite these high values, 2010 mean vegetative cover among the two treatment types and control quadrats (143%) was still less than in undisturbed quadrats adjacent to the ditch (mean cover 180%).

Bryophyte cover also varied by Sector and treatment. In 2010, total bryophyte cover was greatest in 1ector 1under mulch (61%) and decreased sharply past the middle of sector 2, where it had only 16% cover under mulch. Bryophytes were barely present in sectors 3 and 4, with cover values ranging from only 1-7% cover. Across the 4 sectors, mulch and moss diaspore addition were marginally beneficial (21% bryophyte cover) versus unmulched (14%) and control (18%) quadrats and there were no statistically significant difference among these means. However, in sector 1 (where *Sphagnum* and *Polytrichum* did best) bryophyte cover values were much closer between mulched (61%) and control (53%) quadrats. ANOVA showed a strong sector*treatment effect for this parameter ($P<0.0001$) and a strong sector*treatment effect for shrub cover ($P<0.002$). Total plant species richness in the restored ditch (52 taxa) was much greater than that in the adjacent undisturbed fen (40 taxa) (Appendix 3).

2.4.3 Vegetation Results - 2011

Variation in treatment effects on vegetative parameters observed in 2010 was less apparent in the 2011 data (Table 2.3, Figure 2.5, Appendix 2.2A-C). Overall, total vegetative cover was identical in the mulched and unmulched quadrats (214% - averaged among the 4 sectors) and vascular plant cover (181% and 185%, respectively), Cyperaceae cover (123% and 120%), grass cover (27% and 32%) and forb cover (28% and 29%) were statistically indistinguishable. The control quadrats continued to have significantly lower total vegetative cover and lower values for all other vegetative parameters, except for forb cover (33%), which was slightly greater than that in the mulched, unmulched and undisturbed quadrats (28%, 29% and 25%, respectively), but these differences were not statistically significant.

Bryophyte cover across all 4 sectors was only slightly greater in the mulched quadrats (33%) than the unmulched or controls (29% each), but was still less than in the undisturbed fen quadrats (45%). None of these differences were statistically significant. Total vegetative cover in the restored ditch was 198% (averaged across treatments and Sectors), exceeding than in the undisturbed fen (180%). However, total vegetative cover was still significantly less in the control quadrats (165%) than the other two treatments (214%), but not the undisturbed fen (188%).

Overall plant species richness was identical between the mulched and unmulched quadrats (45 taxa) and only slightly less in the control quadrats (43 taxa), although composed of different species. Total plant species richness in the ditch (49 taxa), although less than observed in 2010 (52 taxa), still exceeded that of the adjacent,

undisturbed fen (40 taxa - Appendix 2.3). However, there was significantly greater mean vascular plant and forb species richness in the undisturbed fen quadrats, indicating reduced variance among the undisturbed fen quadrats.

As in 2010, vegetative cover and species richness continued to vary by sector in 2011 (Appendix 2.2A-C). Averaged across the two treatments and controls, sector 1 had the greatest vegetative cover (217%), followed by 4 (202%), 2 (191%) and 3 (180%). Sector 3 had the greatest plant species richness (40 taxa), followed by sectors 4 (36), 2 (23) and 1 (15). Cyperaceae continued to be the dominant plant group (based on cover) in all quadrats, with sectors 1 and 2 having the greatest cover (131% and 112%, respectively), followed by 3 (98%) and 4 (92%). Bryophyte cover values continued to be significantly higher (at alpha = 0.05) in sectors 1 and 2 (versus sectors 3 and 4) and in sector 1 the average cover values were identical (80%) among the treatment and control quadrats (Appendix 2.2A-C). Overall plant species richness and distribution varied between sectors, treatments, controls and the undisturbed fen (Appendix 2.3). Fifty seven plant taxa were observed in the ditch quadrats from 2010-2011, while only 40 were observed in the undisturbed fen. A total of 8 plant species were observed in the undisturbed fen that were not seen in the ditch quadrats, while 25 were observed in the ditch quadrats but were absent from the undisturbed fen. All were native wetland plants.

2.4.4 Vegetation, pH and Electrical Conductivity

Total grass cover, forb cover, forb species richness and overall species richness increased with increases in pH (and electrical conductivity) both years, with the 2011

data plotted in Figure 2.4. Conversely, bryophyte vegetative cover was inversely related to rises in pH and electrical conductivity. In only two years following restoration, vegetative parameters in the restored ditch closely approximated those in the adjacent, undisturbed fen (Figures 2.5 and 2.6).

2.5 Discussion

Prior to firebreak/ditch creation in 2007, Sleeper Lake Fen was the second largest non-ditched northern fen in the state of Michigan. Invasive species such as purple loosestrife (*Lythrum salicaria*), reed canary grass (*Phalaris arundinacea*) and giant reed (*Phragmites australis*) were absent and even native cattails (*Typha latifolia*) were rarely observed in the fen complex. This allowed for the development of a rich assortment of native plant diaspora in the underlying peat, as evidenced by the vegetation observed in our control quadrats (Figure 2.5, Appendices 2.2-2.3). Given that our ditch spoils were only two years in age, they likely contained many live seeds, rhizomes and other diaspora, which quickly germinated after re-wetting. Spoils also had little time to decompose and subside, allowing the excavator operator to fill the ditches to a level consistent with adjacent undisturbed fen.

One of the most interesting results of our study was the pore water chemistry and how it related to vegetative cover. The strong temperature gradient along the ditch was indicative of the flow of groundwater from the large, transverse dune complex that formed the north edge of our research site. Water temperature at the north end of the site (in both the ditch and the undisturbed fen) was constant across the growing season and

always colder than the southern portion of the site during the summer months. Water samples from this region always had higher pH and electrical conductivity readings than the rest of the site. These factors appear to have a strong influence on the species composition of vegetation in both the restored and the undisturbed fen. The high pH and electrical conductivity of the pore water had a strong negative influence on bryophyte cover (especially *Sphagnum* mosses), yet a positive one on cover by grasses and forbs.

The rapid return of vegetative cover and plant species richness to levels approximating those in the adjacent, undisturbed fen (as observed in our study) runs contrary to many other peatland ditch restoration efforts (Van Duren et al., 1997, Tuittila et al., 2000, Cobbaert et al., 2004, Jansen et al., 2004, Van Dijk et al., 2004, Graf et al., 2008, Howie et al., 2009, Mälson et al., 2008, Miller, 2011, Bellamy, 2012). Most of these peatland restoration projects have taken place on previously mined or farmed sites, where little or no seed bank remained and the peat had dried completely, become compacted and/or the surface subsided. In these situations, ditch plugging or filling only rewetted a portion of the former fen and wetland vegetation only grew in close proximity to the former ditches or created pools (Bellamy et al., 2012, Peacock et al., 2012, Komulainen et al., 1999). We believe our results at Sleeper Lake Fen differ because of three factors: 1) the pristine nature of the peatland vegetation and seed bank, 2) the relative youth of the ditch spoils, and 3) a perennially high water table.

In most peatland ditch restoration projects, long periods of time (often >30 years) have elapsed between ditch creation and restoration efforts (Schouwenaars, 1988, Okruszko, 1995, Komulainen et al., 1999, Lode, 1999, Cobbaert et al., 2004, Holden et

al., 2004, Van Dijk et al., 2004, Mälson et al., 2008, Armstrong et al., 2009, Howie et al., 2009, Anshaari et al., 2010, Laine et al., 2011, Hedberg et al., 2012, Schimelpfenig et al., 2014). This time lag has allowed for most ditch spoils to decompose and subside to the point where there is no longer enough organic soil left to fill the ditches completely. This is why most peatland restoration projects have relied on ditch plugging instead of complete filling. Ditch plugging can be an effective method for peatland restoration, but the resulting ditches often remain water-filled for most of the growing season, with vegetation occurring only as a fringe along the saturated edges (Komulainen et al., 1999, Schimelpfenig et al., 2014).

2.6 Implications for Practice

A fundamental tenet of peatland restoration has been the need for mulch in establishing vegetation on re-wetted peat soils, especially for re-establishing peat-forming mosses. Previous studies found that the extreme temperature and moisture fluctuations on disturbed peat surfaces required mulch to retain moisture and mediate large temperature fluctuations (Campeau and Rochefort, 1996, Lode, 1999, Rochefort and Lode, 2001, Cobbaert et al., 2004, Jansen et al., 2004, Mälson and Rydin, 2007, Chimner, 2011). In northern latitudes and high altitudes, freeze-thaw cycles typically dislodge young plants before they can become established and mulching helps reduce the effects of these disturbances (Chimner, 2011). We believe the perennially high water table and rich assortment of living diaspores in the spoils at Sleeper Lake Fen mediated these

extremes and allowed for the rapid establishment of a thick sod of fen sedges and other plants (Figure 2.6).

Our results indicate this restoration as a whole was successful and that addition of seeds added to both vascular plant cover and species richness. It appears that moss diaspore addition and mulching were only marginally useful in enhancing the growth of *Sphagnum* or *Polytrichum* species at this site. The perennially high water table at the site keeps the surface saturated at all times and, in conjunction with a healthy diaspore bank in the peat, likely resulted in the survival and proliferation of *Sphagnum* mosses in the unmulched and control quadrats, neither of which received moss diaspore applications. By 2011, cover values for *Sphagnum* mosses were roughly identical among the three treatment types in Sector 1 (see Appendix 2.2). Our study also found mulch to be unnecessary for (and possibly even detrimental to) the germination and establishment of vascular plants. Therefore, in fens having perennially high water tables and relatively young spoils (i.e. <5 years in age), mulch addition may not be needed for the establishment of a diverse vegetative cover, saving effort, time and money.

The density of seed application used in this study resulted in an immediate, thick growth of monocots across all treatment quadrats (that were previously bare peat) by summer of 2010. This heavy seeding may have played a role in reducing species richness within the quadrats, particularly shrubs. Many young *Aronia, Betula, Nemopanthus* and *Viburnum* seedlings observed in 2010 could not be relocated in 2011 and competition with sedges is thought to be a potential reason for their general exclusion from the local flora. There was also regrowth of some sedge and forb plants surviving in the rewetted

peat that added to vegetative cover in many quadrats, including controls. Given these observations, a reduction in seed amounts for sedges might be considered for a more diverse plant community. Despite these potential limitations, our treatment quadrats still had species richness values greater than adjacent, undisturbed fen vegetation, across all four sectors, with those in sectors 3 and 4 being nearly 50 percent greater. Overall species richness was also much greater in the restored (57 species) versus the undisturbed (40 species) quadrats, and contained 26 native wetland species not observed in the adjacent undisturbed fen.

Overall, seed, moss diaspore and mulch application were very cost effective for this project, working out to $90.36 per each 3 x 3 meter restoration plot, including seed/moss/mulch collection, processing, planting, oversight and excavator costs. Total cost was $8,720.00. The excavator costs were $6,000.00 of this total. Nursery stock would have cost ~$1.00/plant and, at a minimum of 144 plants per restoration plot (1 plant every 30 cm), would have cost at least $144.00 per plot, or $5,760.00 for entire experiment, not including delivery charges, labor for planting or excavator expenses. Planting at a quick rate of 120 plants per hour, this would have taken 48 hours to complete. At a minimum pay rate of $10.00/hour, costs would have been at least $480.00.

To approximate the density and diversity of plants that we had with seeding, I would have recommended planting on 15 cm centers, or 441 plants per 3 m^2 restoration plot, for a total cost of $17,640.00, just for the restoration plots. Labor would have been an additional $1,470.00, minimum. Adding an additional plant in the center of each 15

cm planting square would result in 765 plants per restoration plot, for a total nursery stock cost of $30,600.00. This would have taken a minimum of 255 hours to plant and would have cost at least $2,550.00. Several of the species we used in our restoration (e.g. *Carex magellanicum, C. oligosperma*, *Eriophorum virginicum*, *Oclenema nemoralis* and *Symphyotrichum boreale*) would be nearly impossible to find at a commercial nursery and would have required us to produce our own stock. Seed of these species, which are rarely available, cost $1,320.00 to $4,240.00 per kilogram or more. Additionally, given the unconsolidated nature of the recently replaced ditch peat, actual planting of nursery stock at this site would have been highly problematic.

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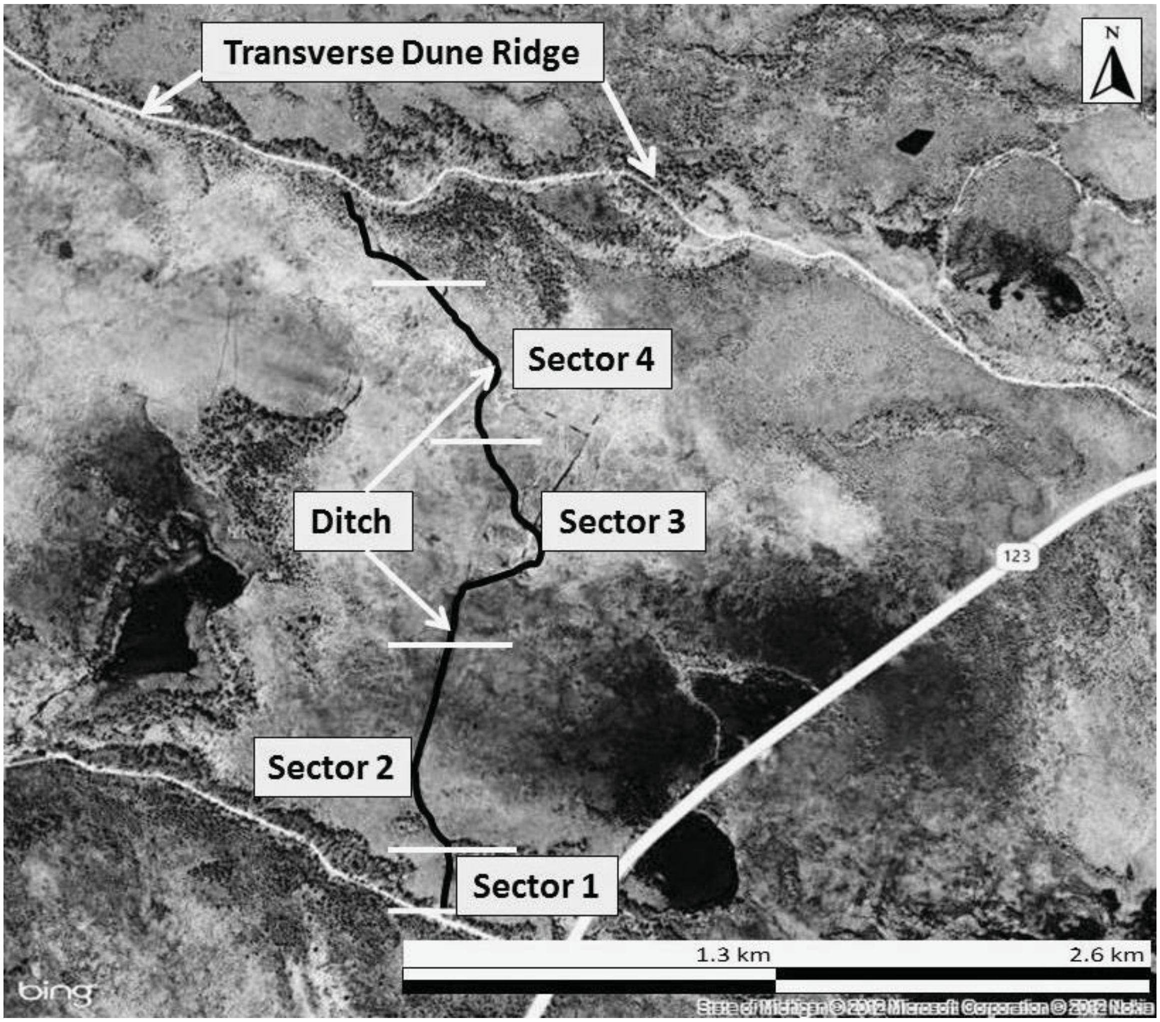


Figure 2.1. Aerial view of the Sleeper Lake Fen restoration site showing the ditch, sectors 1-4 and transverse dune ridge. Source: “Sleeper Lake Fen.” **Bing Maps, Microsoft, Inc.** Accessed September 20, 2012.

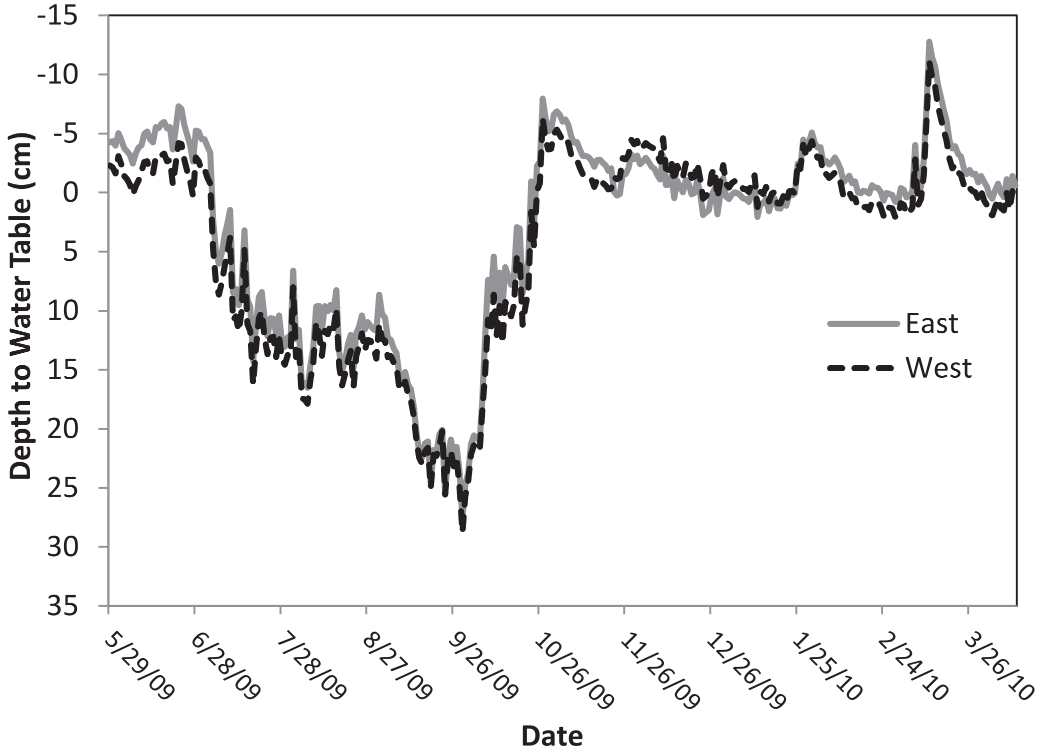


Figure 2.2. Water table levels before and after ditch restoration (2009-2010) at the Sleeper Lake Fen site. The ditch was filled in late October, 2009. [0 = peat surface and negative values are the water table above peat surface.]

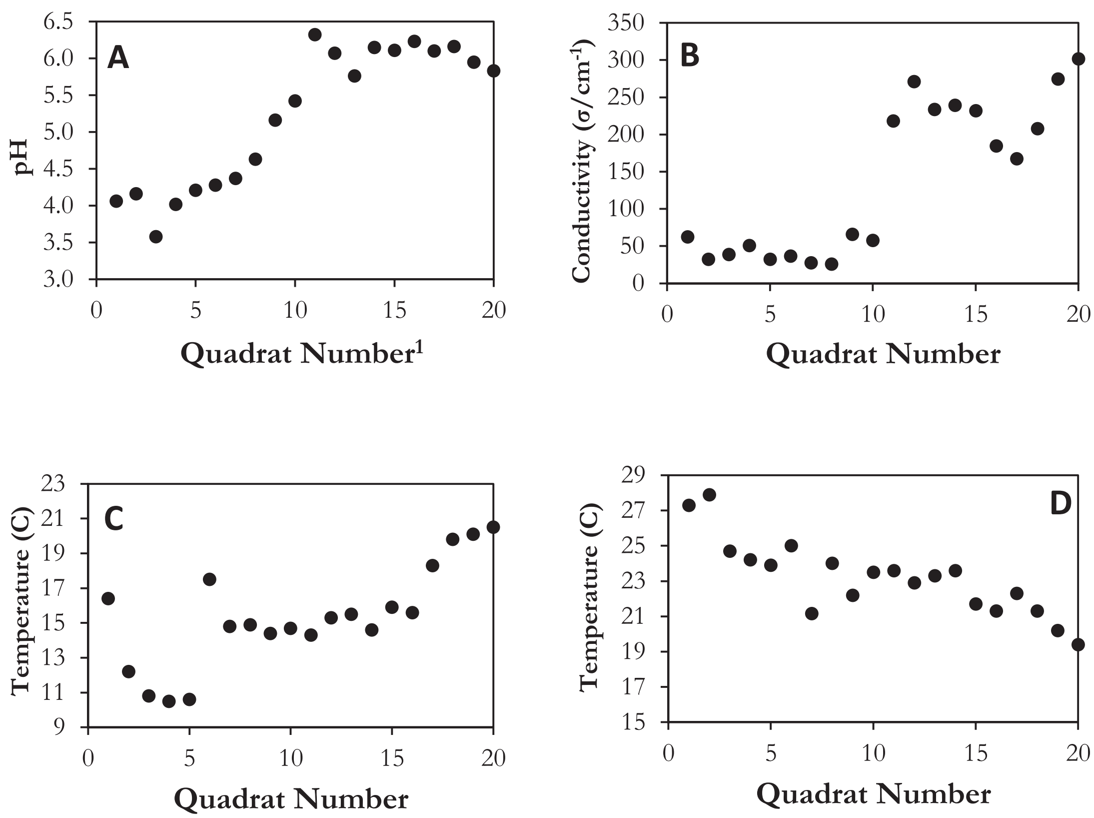


Figure 2.3. Variation in pH, electrical conductivity and temperature along the ditch (2011 data) at the Sleeper Lake Fen restoration site. A.) pH by quadrat number; B.) Electrical conductivity by quadrat number; C.) Spring temperature by quadrat number; D.) Summer temperature by quadrat number.

1: Quadrats #1-5 = Sector 1 (south end of ditch), #6-10 = Sector 2, #11-15 = Sector 3, #16-20 = Sector 4 (north end of ditch).

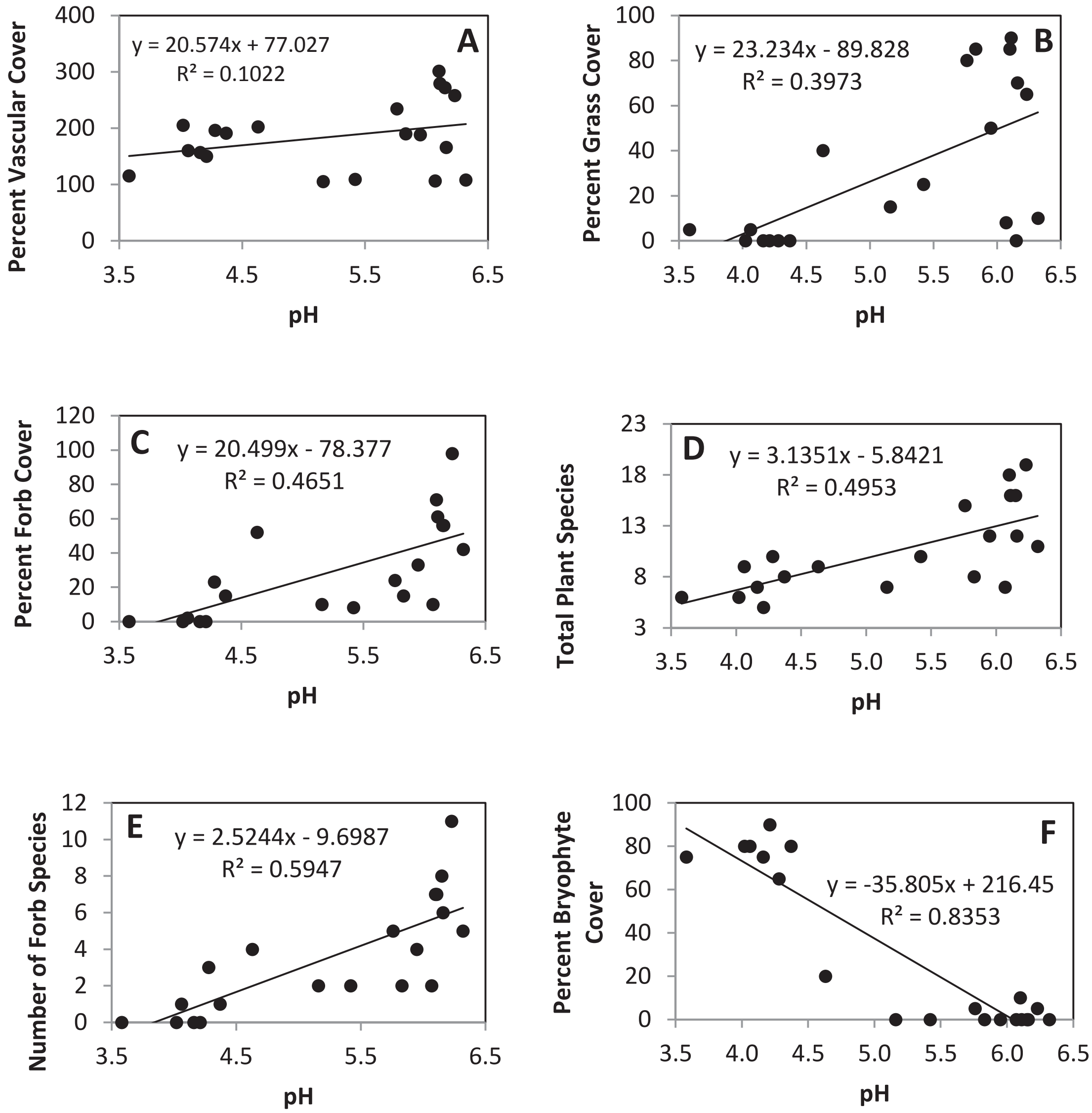
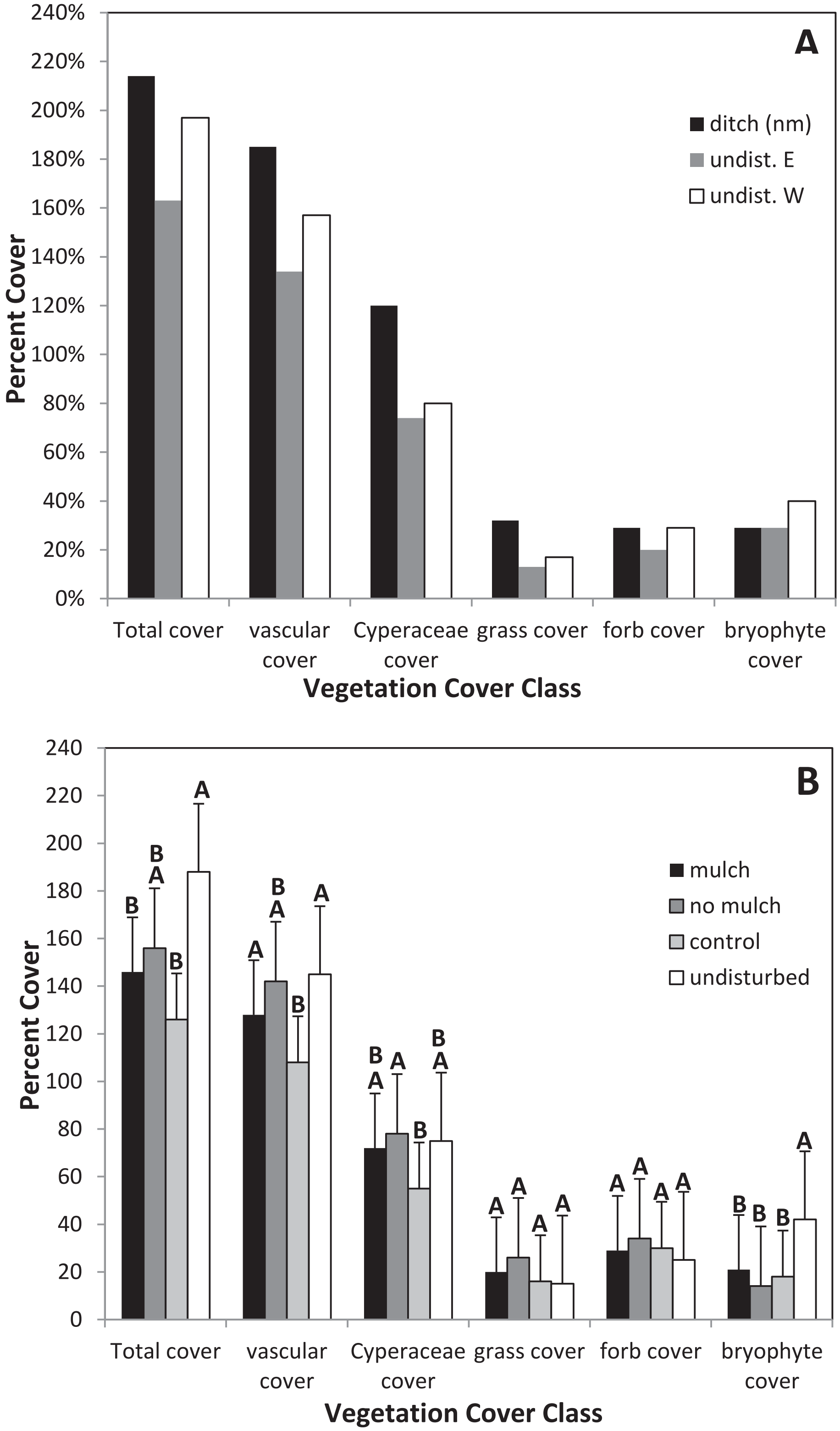


Figure 2.4. Regression analysis of pH versus various vegetation cover classes in the restored ditch (2011 No Mulch data) at the Sleeper Lake Fen site. A.) pH vs vascular species cover (p-value = 0.169), B.) pH vs grass cover (p-value = 0.003), C.) pH vs forb cover (p-value = 0.007), D.) pH vs overall plant species richness (p-value = 0.001), E.) pH vs forb species richness (p-value < 0.001), F.) pH vs Bryophyte cover (p-value < 0.001).


A
Percent Cover
240%
220%
200%
180%
160%
140%
120%
100%
80%
60%
40%
20%
0%
ditch (nm)
undist. E
undist. W
Total cover
vascular cover
Cyperaceae cover
grass cover
forb cover
bryophyte cover
Vegetation Cover Class
B
Percent Cover
240
220
200
180
160
140
120
100
80
60
40
20
0
mulch
no mulch
control
undisturbed
Total cover
vascular cover
Cyperaceae cover
grass cover
forb cover
bryophyte cover
Vegetation Cover Class

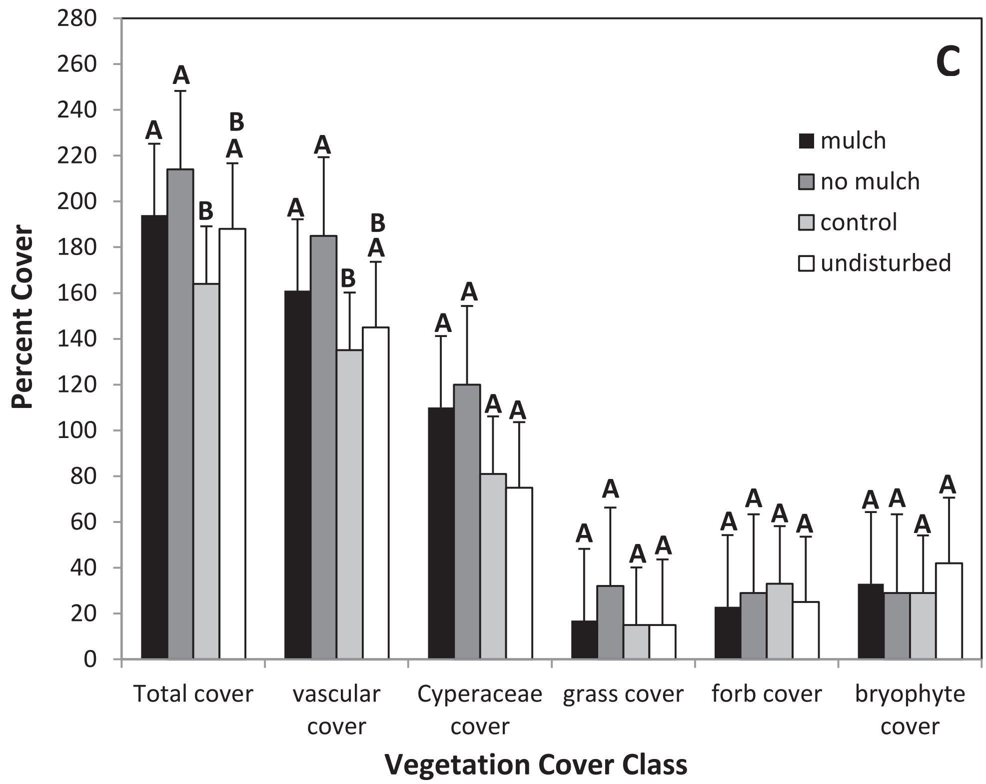


Figure 2.5A-C. Mean (se) values for vegetative cover classes at the Sleeper Lake Fen restoration site. A.) 2011 ditch no mulch (nm) treatment vs undisturbed fen on E and W side of ditch, showing similarity of values for various vegetative parameters B.) 2010 ditch treatments and controls vs undisturbed fen, and C.) 2011 ditch treatments and controls vs undisturbed fen. Cover values are averages across the four sectors. Undisturbed E and W values are averages from the quadrats in undisturbed fen on each side of the restored ditch. In 5B and 5C, letters above means represent results of Tukey's tests – means sharing the same letter are not statistically different at alpha = 0.05.

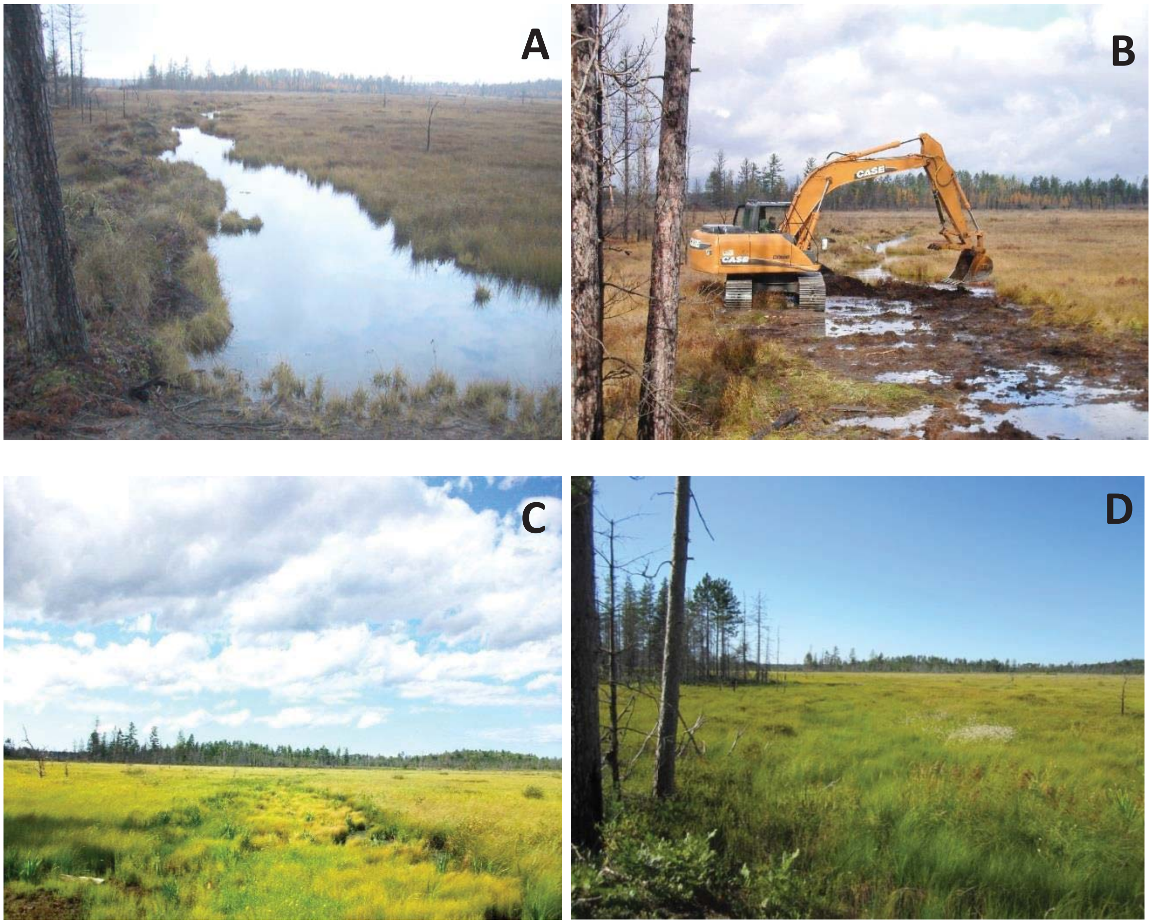


Figure 2.6. Photographic time sequence of ditch restoration 2009-2011 at the Sleeper Lake Fen site. Photographs from top of dune between Sectors 1 and 2, view to northwest into sector 2: note tree line in central background as reference point. A.) Ditch prior to restoration (2009); B.) Ditch immediately following restoration (2009): C.) Ditch vegetation after 1 year growth (2010): D.) Ditch vegetation after 2 years growth (2011 - white patch in right center of photo is *Eriophorum virginicum* growing in restoration plots 6A-B).

Table 2.1. Plant species and seed amounts used (grams per 3-m^2 research plot) in the Sleeper Lake Fen restoration site.

Scientific Name	Common Name	Seed per 3m^2 Plot (g)
Shrubs		
Aronia melanocarpa	Chokeberry	3.0
Betula pumila	Bog Birch	1.3
Nemopanthus mucronatus	Winterberry	0.5
Viburnum nudum cassinoides	Withe Rod	5.6
Forbs		
Doellingeria umbellata	Flat-Topped White Aster	2.2
Iris versicolor	Northern Blue Flag	20.0
Oclemena nemoralis	Bog Aster	0.4
Rumex orbiculatus	Greater Water Dock	0.7
Solidago uliginosa	Bog Goldenrod	0.7
Symphiotrichum boreale	Northetrn Bog Aster	0.2
Grasses, Rushes and Sedges		
Calamagrostis canadensis	Canada Bluejoint	5.3
Carex magellanica	Boreal Bog Sedge	14.0
Carex oligosperma	Fewseed Sedge	8.8
Carex utriculata	Northwest Territory Sedge	1.0
Dulichium arundinaceum	Three-Square Sedge	2.2
Eriophorum virginicum	Tawny Cottongrass	4.7
Glyceria canadensis	Rattlesnake Manna Grass	2.7
Scirpus atrovirens	Dark Green Bulrush	2.0
Mosses		
Polytrichum commune	Common Haircap Moss	0.05 L
Polytrichum strictum	Narrow Haircap Moss	0.05 L
Sphagnum angustifolium	Narrowleaf Peatmoss	1.4 L
Sphagnum magellanicum	Magellan's Peatmoss	1.4 L
Sphagnum papillosum	Papillose Peatmoss	1.4 L
Sphagnum rubellum	Red Peatmoss	1.4 L
	Total Grams Seed per Plot:	**75.3**
	Total Moss per Plot:	**5.7 L**

Table 2.2. Percent cover values for vegetation classes in restored ditch (no mulch) vs undisturbed fen in 2010 at the Sleeper Lake Fen restoration site.

Date	**August, 2010**									
Plot Type	**Restored - No Mulch**									
Sector	**1**		**2**		**3**		**4**		**Ditch Total**	
	x̄	**SD**[1]	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**
Total Vegetation	151	32	138	39	144	83	186	44	**155**	**53**
Vascular	111	32	161	33	137	81	180	38	**147**	**54**
Cyperaceae	101	34	118	42	62	33	62	17	**86**	**32**
Grasses	5	0.4	9	9	32	32	56	29	**26**	**28**
Forbs	3	2	33	18	38	22	48	28	**31**	**26**
Bryophytes	40	17	16	8	2	2	6	8	**16**	**18**
Shrubs	1	1	0.4	3	4	5	6	6	**3**	**4**
Bare Peat	33	12	43	23	45	28	16	1	**34**	**21**
Open Water	0	0	0	0	0	0	0	0	**0**	**0**
Litter	0	0	0	0	5	8	0	0	**1**	**4**

Date	**August, 2010**									
Plot Type	**Undisturbed (2010 data)**[2]									
Sector	**1**		**2**		**3**		**4**		**Ditch Total**	
	x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**
Total Vegetation	210	28	222	24	164	13	154	16	**188**	**34**
Vascular	127	30	147	19	157	17	149	16	**145**	**22**
Cyperaceae	71	13	76	14	80	17	72	15	**75**	**14**
Grasses	0	0	11	11	16	15	33	21	**15**	**17**
Forbs	1	2	26	6	46	12	26	6	**25**	**17**
Bryophytes	83	10	75	16	7	5	6	5	**42**	**38**
Shrubs	55	31	34	15	15	13	18	14	**31**	**24**
Bare Peat	0	0	0	0	12	10	2	4	**3**	**7**
Open Water	0	0	0	0	12	10	2	4	**3**	**7**
Litter	60	8	68	9	42	16	69	12	**60**	**15**

1: SD = Standard Deviation

2: Undisturbed vegetation values are averages of values taken from undisturbed fen on the east and west sides of the ditch.

Table 2.3. ANOVA results for independent t-tests on each of the vegetation cover classes - mean vegetation parameters by sector and treatment type vs undisturbed vegetation (2010-2011) at the Sleeper Lake Fen restoration site.

	2010						
Restoration Parameter	**Root MSE**	**y1^ Mean**	**y1 P-value**	**R-Square**	**Sector P-val**	**Treat P-val**	**Treat|Sector P-val**
Vegetative Cover	43	154	.0007*	0.43	.027*	.0003*	0.093
Vascular Cover	41	131	.0031*	0.39	.0003*	.026*	0.430
Cyperaceae Cover	27	70	0.196	0.24	0.208	.043*	0.632
Grass Cover	19	19	<.0001*	0.51	<.0001*	.028*	0.946
Forb Cover	15	29	<.0001*	0.64	<.0001*	0.33	.048*
Shrub Cover	12	11	<.0001*	0.64	.036*	<.0001*	.002*
Bryophyte Cover	11	24	<.0001*	0.89	<.0001*	<.0001*	<.0001*
Vascular Diversity	3	13	<.0001*	0.68	<.0001*	.001*	0.104
Forb Diversity	2	5	<.0001*	0.64	<.0001*	.030*	0.149
Bare Peat	17	32	<.0001*	0.66	<.0001*	<.0001*	0.378
Litter	7	16	<.0001*	0.95	0.86	0.46	<.0001*

	2011						
Restoration Parameter	**Root MSE**	**y1^ Mean**	**y1 P-value**	**R-Square**	**Sector P-val**	**Treat P-val**	**Treat|Sector P-val**
Vegetative Cover	53	194	0.158	0.25	0.156	0.017*	0.806
Vascular Cover	48	161	.017*	0.34	.004*	0.336	0.970
Cyperaceae Cover	38	100	0.003*	0.39	0.098	<.0001*	0.589
Grass Cover	20	22	<.0001*	0.55	<.0001*	0.024*	0.597
Forb Cover	17	29	<.0001*	0.61	<.0001*	0.48	0.33
Shrub Cover	12	11	<.0001*	0.64	0.027*	<.0001*	0.001*
Bryophyte Cover	16	34	<.0001*	0.84	<.0001*	0.04*	0.14
Vascular Diversity	3	10	<.0001*	0.73	<.0001*	.0001*	<.0001*
Forb Diversity	1	4	<.0001*	0.84	<.0001*	.0001*	<.0001*
Bare Peat	15	19	<.0001*	0.66	<.0001*	<.0001*	.036*
Litter	17	34	<.0001*	0.61	<.0001*	<.0001*	0.493

* = Significant at the alpha = 0.05 level.

^ = y1 mean is the mean value for the given parameter across the three treatments types and undisturbed vegetation plots.

Appendix 2.1A. Variation in porewater parameters for restored (no mulch) vegetation among the four sectors at the Sleeper Lake Fen restoration site (2010-2011). Values are an average of the 5 replicates per sector.

Date	2010 - November									
Plot Type	Ditch - Restored: No Mulch									
Sector	1		2		3		4		Total No Mulch	
	x̄	SD[1]	x̄	SD	x̄	SD	x̄	SD	x̄	SD
Elect. Cond.	40	21	36	30	202	162	221	136	**124**	**60**
Temp.	6.1	0.6	9	1.1	7.3	1.1	5.4	0.7	**7**	**0.8**
pH	4.11	0.21	4.6	0.56	6.4	0.3	6.4	0.11	**5.4**	**1.01**

Date	2011 - May									
Plot Type	Ditch - Restored: No Mulch									
Sector	1		2		3		4		Total No Mulch	
	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD
Elect. Cond.	41	16	27	7	135	81	162	108	**117**	**84**
Temp.	12.1	2.5	15.3	1.3	15.1	0.7	18.9	2	**16.5**	**2.9**
pH	3.87	0.14	4.66	0.5	6.16	0.12	5.83	0.32	**5.32**	**0.96**

Date	2011 - July									
Plot Type	Restored - No Mulch									
Sector	1		2		3		4		Total No Mulch	
	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD
Elect. Cond.	43	13	43	18	239	20	227	58	**151**	**100**
Temp.	25.6	1.9	23.2	1.5	23	0.8	20.9	1.1	**24.2**	**2.1**
pH	4.01	0.25	4.77	0.5	6.08	0.2	6.05	0.16	**5.47**	**0.92**

1: SD = Standard deviation

Appendix 2.1B. Variation in porewater parameters for undisturbed vegetation among the four sectors at the Sleeper Lake Fen restoration site (2010-2011). Values are an average of the 5 replicates per sector.

Date	**2010 - November**									
Plot Type	**Undisturbed[1]**									
Sector	**1**		**2**		**3**		**4**		**Total Undisturbed**	
	$\bar{x}$	**SD**	**$\bar{x}$**	**SD**	**$\bar{x}$**	**SD**	**$\bar{x}$**	**SD**	**$\bar{x}$**	**SD**
Elect. Cond.	41	4	26	4	104	70	146	34	**79**	**130**
Temp.	5.7	0.3	6.6	0.7	5.3	0.4	5.6	0.5	**5.8**	**1.6**
pH	3.94	0.04	4.88	0.56	6.26	0.24	6.19	0.1	**5.32**	**1.07**

Date	**2011 - May**									
Plot Type	**Undisturbed[1]**									
Sector	**1**		**2**		**3**		**4**		**Total Undisturbed**	
	$\bar{x}$	**SD**	**$\bar{x}$**	**SD**	**$\bar{x}$**	**SD**	**$\bar{x}$**	**SD**	**$\bar{x}$**	**SD**
Elect. Cond.	43	4	36	6	108	56	128	15	**79**	**48**
Temp.	14.2	0.8	14	0.4	14.6	0.5	16	0.8	**14.7**	**1**
pH	3.77	0.1	4.5	0.62	6.06	0.21	5.96	0.14	**5.07**	**1.02**

Date	**2011 - July**									
Plot Type	**Undisturbed[1]**									
Sector	**1**		**2**		**3**		**4**		**Total Undisturbed**	
	$\bar{x}$	**SD[2]**	**$\bar{x}$**	**SD**	**$\bar{x}$**	**SD**	**$\bar{x}$**	**SD**	**$\bar{x}$**	**SD**
Elect. Cond.	52	8	50	16	214	87	167	57	**121**	**86**
Temp.	23.4	0.9	22.2	0.6	21.1	0.6	20.5	1	**22.3**	**1.3**
pH	3.9	0.08	4.8	0.53	6.1	0.33	6	0.07	**5.44**	**0.96**

1: Undisturbed value is average of east and west side values

2: SD = Standard deviation

Appendix 2.2. Variation in mean percent vegetative cover among the 4 sectors and 3 treatment types from 2010 to 2011 at the Sleeper Lake Fen restoration.

Year	2010 (August)										2011 (August)									
Plot Type	Restored - Mulch										Restored - Mulch									
Sector	1		2		3		4		Mean		1		2		3		4		Mean	
	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD
Total Veg.	159	38	139	22	118	67	169	40	**146**	**45**	228	31	223	90	197	71	209	54	**214**	**66**
Vascular	111	48	123	14	113	65	166	41	**128**	**47**	148	33	176	70	194	69	207	52	**181**	**62**
Cyperaceae	88	33	78	36	54	37	69	18	**72.4**	**31**	146	34	137	72	103	37	106	32	**123**	**50**
Grasses	3	2	9	8	19	7	49	40	**20.1**	**26**	0	0	19	18	39	20	49	37	**27**	**29**
Forbs	4	2	35	2	35	18	40	14	**28.6**	**20**	0.6	0.8	19	9	44	18	46	29	**28**	**26**
Bryophytes	61	10	16	12	4	4	3	2	**21.1**	**25**	80	5.5	47	31	2.8	4.3	2	4	**33**	**36**
Shrubs	2	1	1	2	5	7	7	4	**4**	**4**	1.4	2	0.6	1.2	8.4	12	7	7.5	**4**	**8**
Diversity	19	2	26	2	34	7	32	3	**27.8**	**6**	12	2	10	5	35	5	29	5	**22**	**6**
Bare Peat	28	11	43	16	58	30	20	14	**37.3**	**22**	2	2	16	19	50	19	39	16	**27**	**24**
Open Water	0	0	0	0	0	0	0	0	**0**	**0**	0	0	5	10	0	0	0	0	**1**	**6**
Litter	0	0	0	0	5	7	0	0	**1**	**4**	19	17	20	7	18	9	37	19	**23**	**16**

Year	2010 (August)										2011 (August)									
Plot Type	Restored - No Mulch										Restored - No Mulch									
Sector	1		2		3		4		Mean		1		2		3		4		Mean	
	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD
Total Veg.	151	32	138	39	138	74	195	41	**156**	**53**	237	34	194	73	201	78	224	55	**214**	**64**
Vascular	111	32	129	33	137	81	190	34	**142**	**54**	157	32	161	49.1	200	86.4	221	56.7	**185**	**59**
Cyperaceae	101	34	80	42	62	33	71	17	**78.5**	**32**	153	34	122	47.8	119	59.1	86	33.8	**120**	**47**
Grasses	5	0.4	10	9	32	32	56	26	**25.8**	**28**	2	3	16	17.1	38	43.6	71	14.7	**32**	**34**
Forbs	3	2	36	18	39	22	57	25	**33.8**	**26**	0.4	1	22	18	39	21.5	55	32.4	**29**	**28**
Bryophytes	40	17	9	8	2	2	5	7	**14**	**18**	80	6	33	37.3	1	2	3	4	**29**	**36**
Shrubs	1	1	3	2.95	4	5	6	5	**4**	**4**	2	3	1	1	4	8	7	8	**4**	**6**
Diversity	18	2	28	2	33	5	28	3	**26.8**	**5**	11	1.4	19	1	29	4	31	4	**23**	**4**
Bare Peat	33	12	44	23	45	28	16	1	**34.6**	**21**	5	4	14	16.7	38	26.6	25	15	**21**	**20**
Open Water	0	0	0	0	0	0	0	0	**0**	**0**	0	0	0	0	0	0	0	0	**0**	**0**
Litter	0	0	0	0	5	7	0	0	**1**	**4**	15	12	18	15.2	20	24.5	49	21.9	**25**	**22**

Year	2010 (August)										2011 (August)									
Plot Type	Restored - Control										Restored - Control									
Sector	1		2		3		4		Mean		1		2		3		4		Mean	
	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD	x̄	SD
Total Veg.	113	33	152	61	94	19	147	32	**126**	**46**	187	21	156	49	143	37	173	38	**165**	**36**
Vascular	60	19	136	63	93	18	143	30	**108**	**50**	107	25	124	41	143	37	168	34	**135**	**41**
Cyperaceae	51	26	64	30	46	15	61	13	**55**	**23**	93	31	76	25	72	23	84	18	**81**	**26**
Grasses	0	0	8	9	11	6	44	32	**16**	**24**	0	0	7	14	13	12	41	18	**15**	**20**
Forbs	0.2	0.4	52	23	32	9	36	10	**30**	**23**	0	0	39	18	53	6.4	41	24	**33**	**25**
Bryophytes	53	23	16	9	1	1.3	4	6	**18**	**24**	80	5.5	32	28	0	0	5	6.3	**29**	**35**
Shrubs	9	8.6	11	17	4	6.6	2	2	**7**	**11**	14	13	2	4	5	7.7	2	2.4	**6**	**9.4**
Diversity	12	2	24	3	21	1	28	3	**21**	**6**	9	1	18	3	24	2	28	3	**20**	**3**
Bare Peat	43	22	45	22	75	8.4	43	14	**52**	**22**	4	5	12	19	63	12	25	21	**26**	**27**
Open Water	0	0	0	0	0	0	0	0	**0**	**0**	0	0	10	20	0	0	0	0	**2.5**	**12**
Litter	0	4	0	0	5	7.7	0	0	**1**	**4**	25	18	17	19	13	5	47	25	**25**	**22**

Appendix 2.3. Plant species richness and distribution at the Sleeper Lake Fen restoration site (2010-2011).
1 = presence, blank = absence; Undist. = undisturbed fen.

	Ditch		Undist.	Ditch		Undist.	Ditch		Undist.	Ditch		Undist.	Spp. Richness	
Species	**2010**	**2011**	**2010**	**2010**	**2011**	**2010**	**2010**	**2011**	**2010**	**2010**	**2011**	**2010**	**Ditch**	**Undist.**
Agrostis hyemalis				1			1	1		1	1		**1**	
Alnus rugosa												1		**1**
Andromeda polifolia						1								**1**
Aronia melanocarpa	1			1	1		1	1		1			**1**	
Betula papyrifera	1												**1**	
Betula pumila	1	1	1			1	1	1	1	1	1		**1**	**1**
Bidens cernua								1					**1**	
Calamagrostis canadensis	1	1		1	1	1	1	1	1	1	1	1	**1**	**1**
Campanula aparinoides					1		1	1	1	1	1	1	**1**	**1**
Carex canescens		1			1								**1**	
Carex lasiocarpa				1	1		1	1	1	1	1	1	**1**	**1**
Carex magellanica	1	1	1		1	1			1				**1**	**1**
Carex oligosperma	1	1	1	1	1	1		1					**1**	**1**
Carex sterilis								1	1		1	1	**1**	**1**
Carex stricta									1		1		**1**	**1**
Carex utriculata	1	1		1		1	1	1	1			1	**1**	**1**
Carex sp.	1			1			1	1		1	1		**1**	
Chamaedaphne calyculata	1	1	1	1	1	1							**1**	**1**
Cicuta bulbifera				1			1	1	1	1	1	1	**1**	**1**
Cladonia lichens			1											**1**
Doellingeria umbellata				1			1	1		1	1		**1**	
Dulichium arundinaceum	1	1		1	1		1	1		1	1		**1**	
Epilobium leptophyllum	1									1			**1**	
Equisetum sp.							1	1		1	1		**1**	
Eriophorum tenellum				1	1								**1**	
Eriophorum virginicum	1	1		1	1		1	1			1		**1**	
Eriophorum viridi-carinatum		1	1	1				1	1		1	1	**1**	**1**
Euthamia graminifolia								1					**1**	
Feather Moss				1		1	1	1		1	1	1	**1**	**1**
Galium brevipes				1	1	1	1	1	1	1	1	1	**1**	**1**
Glyceria canadensis				1	1		1	1	1	1	1		**1**	**1**
Iris versicolor	1	1		1	1	1	1	1	1	1	1	1	**1**	**1**
Juncus spp.	1			1			1			1	1		**1**	
Larix laricina			1											**1**
Lycopus uniflorus				1	1	1	1	1	1	1	1	1	**1**	**1**
Lysimachia terrestris				1	1	1	1	1	1	1	1	1	**1**	**1**
Marchantia sp.										1	1		**1**	
moss spp.									1	1			**1**	**1**
Oclemena nemoralis		1		1							1		**1**	
Pinus resinosa			1											**1**
Polytrichum spp.	1		1	1	1	1	1	1	1	1	1	1	**1**	**1**
Populus tremuloides										1			**1**	

Appendix 2.3 cont'd. Plant species richness and distribution at the Sleeper Lake Fen restoration site (2010-2011).
1 = presence, blank = absence; Undist. = undisturbed fen.

	Sector 1			Sector 2			Sector 3			Sector 4			Total Plant Spp. Richness	
	Ditch		Undist	Ditch		Undist	Ditch		Undist	Ditch		Undist		
Species	**2010**	**2011**	**2010**	**2010**	**2011**	**2010**	**2010**	**2011**	**2010**	**2010**	**2011**	**2010**	**Ditch**	**Undist.**
Potentilla palustris	1			1	1		1		1	1		1	**1**	**1**
Potentilla sp. 2										1	1		**1**	
Rubus spp.								1		1	1		**1**	
Rumex orbiculatus	1			1			1	1		1	1		**1**	
Salix spp.				1	1		1	1	1	1	1	1	**1**	**1**
Sarracenia purpurea			1											**1**
Scirpus atrovirens	1				1		1	1		1	1		**1**	
Scirpus cyperinus		1			1		1	1		1	1		**1**	
Scutellaria galericulata							1	1	1	1	1	1	**1**	**1**
Smilacina trifolia							1	1				1	**1**	**1**
Solidago uliginosa	1			1			1	1	1	1	1	1	**1**	**1**
Sparganium sp. (?)				1									**1**	
Sphagnum spp.	1	1	1	1	1	1	1	1	1	1	1	1	**1**	**1**
Spirea alba							1	1	1	1	1		**1**	**1**
Symphyotrichum boreale							1	1		1	1	1	**1**	**1**
Triadenum fraseri				1	1	1	1		1	1		1	**1**	**1**
Typha latifolia								1					**1**	
Utricularia spp.				1			1	1	1				**1**	**1**
Vaccinium angustifolium			1											**1**
Vaccinium macrocarpon	1	1	1	1		1	1	1	1			1	**1**	**1**
Vaccinium myrtilloides			1											**1**
Viburnum cassinoides	1						1						**1**	
Viola (hybrid?)									1					**1**
Viola lanceolata				1									**1**	
Viola mackloskeyi						1	1	1		1	1		**1**	**1**
Total Taxa	**22**	**15**	**14**	**33**	**23**	**17**	**37**	**40**	**27**	**37**	**36**	**23**	**58**	**40**

Chapter 3.0 Gradients in Pore water Chemistry and Vegetation in a Restored Northern Michigan Fen[2]

3.1 Abstract

In 2009, a wetland firebreak restoration project was initiated at a large, previously pristine, fen complex in Michigan's Upper Peninsula (Sleeper Lake Fen). The site had experienced a large-scale wildfire during an extended drought in 2007 and many firebreaks were dug throughout the fen complex. When water levels returned to normal, many of these firebreaks became water-filled ditches, some with appreciable flow. A 1.6 km long ditch was selected for intensive, experimental restoration - replacing the excavated peat and planting with a native seed mix. A pore water sampling plan was also implemented, to track changes in water chemistry in the undisturbed and restored fen over time. We identified strong, within-site gradients in pore water chemistry, particularly in Ca, Fe, Mg and Zn, that corresponded with gradients in vegetative parameters in both the restored ditch and adjacent undisturbed fen. The effects of these chemical gradients on plant species colonization and establishment in the restored ditch is discussed and compared with the conditions in the undisturbed fen and the results of other fen studies.

2: Bess, J., R. Chimner, J. Hribljan and E. Kane. 2015. Gradients in Pore water Chemistry and Vegetation in a Restored Northern Michigan Fen. *Manuscript*.

3.2 Introduction

Fens are a specific type of peatland sustained by surface or ground water inputs, as opposed to bogs that receive the vast majority of their water from rainfall (Rydin and Jeglum, 2006). Ground and surface water typically contain dissolved minerals such as Ca, Fe, Mg and Mn (which are often absent or in low concentrations in rainwater) and these habitats support unique floras and faunas, often containing species of conservation concern (Spiels, 1999; Bedford and Godwin, 2003; Cohen and Kost, 2008; Cohen et al., 2010).

Changes in water chemistry can occur when fens are degraded through peat mining, draining or conversion to agricultural and silvicultural production, especially when diversionary ditches cut-off the flow of mineral-rich groundwater to the wetland. Nutrient levels are also altered, typically leading to spikes in total nitrogen, phosphorous and/or sulfur (DeMars et al., 1996; Boeye, et al., 1997; van Duren et al., 1997; Olde Venterink et al., 2001; Hajkova and Hajek, 2003; Rozbrojová and Hajek, 2008; Zak et al., 2008-2009). Accumulation of metals is an additional concern, particularly iron, which can build up to levels that have been shown to negatively impact the growth and survival of certain fen plants (Snowden and Wheeler, 1993).

In conjunction with habitat fragmentation, these human-caused water table manipulations and resultant changes in pore water chemistry have caused the rapid replacement of many temperate zone native fen floras with aggressive wetland habitat generalist and non-native or upland plant species which can require many years of control efforts to remove and replace with native species (Boelter, 1972, Beltman et al., 1996, De

Mars et al., 1996, Fisher et al., 1996, Hald and Vinther, 2000, Large, 2001, Patzelt et al., 2001, Cobbaert et al., 2004, Jansen et al., 2004, Anshaari et al., 2010, Klimkowska et al., 2010, Soomers et al., 2013). Given these hazards, it is important to develop a well thought out plan prior to implementing restoration, especially when funds, materials and labor are limited (Grootjans and Van Diggelen, 1995, Lode, 1999, Joosten and Clark, 2002, Clewell et al., 2005, Trepel, 2007, van Loon, 2009). Fundamental to the success of such a plan is an understanding of the hydrology and pore water chemistry of a given site and how these abiotic factors can affect the establishment and proliferation of plant species used in the restoration (Van Duren et al., 1998, Price et al., 2003, Andersen et al., 2006, Page et al., 2009, Lamers et al., 2015).

In this paper, we detail a restoration project implemented in 2009 at a large fen in northern Michigan, USA and discuss the potential effects of pore water chemistry on the success of our restoration project. The restoration site is part of the 20,000 hectare Sleeper Lake Fen complex in central Luce County. In August of 2007, a drought and lightning- induced wildfire burned more than 7,200 hectares of fen, conifer swamp and pine barrens. As part of the fire-fighting program, bulldozers were used to create 48 km of firebreaks around and in the wetland. Firebreaks in the open fen and conifer swamp became water-filled ditches following a rise in the local water table in 2008. Our restoration project restored a 2.6 kilometer section of ditch through open fen at the south end of the burn area (lat. 46°27’13.23”N long. 85°28’33.01”W) by returning peat spoils and revegetating with native plant seeds and moss diaspores in. Undisturbed vegetation along the ditch varied considerably from the southern to northern end so we divided the

ditch into 4 sectors, based on these differences, as part of our experimental design. In each sector, we planted identical seed and moss mixtures to test how plant germination and growth was altered by ditching and pore water chemistry. These seed mixes were composed of species occurring in the adjacent burned and unburned fen at Sleeper Lake.

Pore water sampling was undertaken following initial restoration. Fen plant species are known to be sensitive to pore water chemistry, so we wanted to determine if plant species composition in the undisturbed fen varied with changes in concentration of certain pore water chemical components. We were also interested in how the pore water chemistry in the restored ditch might vary from that in the adjacent undisturbed fen and if there was differential germination and establishment among the plant species used in our ditch restoration in relation to these chemical components. Finally, we wanted to monitor whether porewater and vegetative characteristics in the restored ditch became more like those of the undisturbed fen or developed along a different trajectory.

Our objectives were to 1.) Quantify if changes in vegetative composition in the undisturbed fen corresponded with changes in pore water chemistry; 2.) Document establishment and vegetative cover among the plant species in our seed mixture relative to pore water chemical components; 3.) Determine if variability in pore water chemistry related to overall re-vegetation success in the restored ditch, and 4.) Determine if vegetation and pore water characteristics in the restored ditch became more like those of the adjacent, undisturbed fen over time or developed along different trajectories.

3.3 Methods

3.3.1 Study Site

In 2009, a ditch restoration project was implemented at the Sleeper Lake Fen complex in Michigan's Upper Peninsula (Bess et al., 2014, Figure 3.1). This fen complex is part of the larger Two-Hearted Lowlands region which serves as the headwaters for several rivers and streams that feed into Lake Superior. Average annual high temperatures ranges from -4.4° C in January to 25.5° C in July and annual precipitation averages 78.38 cm and peaks in August-September (USDA-NRCS, 2012a). Following a protracted drought in 2007, the fen complex experienced a large-scale wildfire event in August of that year which burned for three months. During firefighting operations, the Michigan Department of Natural Resources (MIDNR) bulldozed over 48 km of firebreaks in and around the fen.

The peat at our study site is very dense (1-2 m thick) and dominated by sedge and grass remains, with pockets of *Sphagnum*-dominated peat. The lowermost peat layers are highly humified, dark brown to black peat and muck and sit on a bed of mucky fine sand. The wetland soils adjacent to the larger sand dunes of Rousseau Fine Sands are classified as Dawson-Greenwood-Loxley mucks and mucky peats, while the majority of the peat in the open fen is listed as Histosols of peat and muck or Aquents, depending on the degree of ponding (USDA-NRCS, 2012a). The firebreaks within the peatland were dug down to the mineral soil layer in most cases, completely disturbing the peat profile. Once rainfall restored the water table to pre-drought conditions, the firebreaks became water-filled ditches, many with appreciable flow. Bess et al., 2014 addressed the experimental

design, methods of restoration and initial response of vegetation in a 1.6 km long sector of ditch and how differences in basic pore water parameters affected the vegetation response in the restored ditch. This study examines additional pore water characteristics such as elemental composition, dissolved organic carbon (DOC) and macronutrients at this site and how these may have affected the success of the restoration and distribution of plant species along the restored ditch.

3.3.2 Experimental Design

The ditch was divided into 4 sectors based on variation in undisturbed vegetation adjacent to the ditch as detailed in Bess et al., 2014. For our experimental plantings, we hand collected seeds of 18 species of native wetland plants and diaspores of 6 moss species. For the ditch restoration, 60, 3 x 3 meter square restoration plots were established, with five replicates of three experimental planting treatments consisting of: 1) no plant - control, 2) seed only, and 3) seed, moss diaspores and mulch. These plots were placed in the center of the former ditch, in physically similar areas of restored peat within each sector. Inundated areas were avoided, as were large sections of turf and woody debris. Plot placement within each set of 3 treatment types was randomly chosen to reduce potential bias. For vegetation monitoring, 1 x 1 m square quadrats were placed in the center of each ditch restoration plot and 5 on each side of the ditch (per sector) in adjacent undisturbed fen (and roughly parallel to the ditch no mulch quadrats) but 3-4 meters from the edge of the ditch. This provided a total of 100 vegetation sampling quadrats - 60 in the ditch and 40 in adjacent undisturbed fen. The placement of

vegetation sampling quadrats was done to minimize edge effect in both the ditch and the undisturbed fen.

Groundwater monitoring wells were placed along the ditch line to record fen hydrology, initially a single pair in Sector 2 (1 on each side of ditch) prior to restoration and then 3 more pairs (one pair each in sectors 1, 3 and 4) following restoration. Monitoring wells consisted of 1.5 m long sectors of 8 cm dia. perforated PVC pipe inserted to the mineral soil. The outer portion of the well was covered with nylon landscaping mesh and secured with zip-ties. The bottom of the well was covered with a PVC cap to prevent infiltration of peat. Solinst™ Leveloggers (Georgetown, ON, Canada) were placed in each well to provide daily monitoring of the water table. A Solinst™ Barologger placed in one of the wells in Sector 2 provided barometric compensation for all pressure transducers.

3.3.3 Vegetation Sampling

Vegetation composition and cover data were collected from each of the 60, 1-m square ditch research quadrats in August of 2010 and 2011. Data on undisturbed vegetation was collected in August, 2010 from 40 1-m square quadrats (5 on each side of ditch in each sector (10 per sector) placed in undisturbed fen vegetation adjacent to the ditch and parallel to each of the no mulch treatment plots. Data on the undisturbed vegetation was collected only in 2010, as species composition and cover in these plots was not observed to change greatly over the 2-year period and the thick layer of *Carex* litter inhibited the growth of any additional seedlings.

For the purposes of this study, “undisturbed” fen refers to the vegetation and peat next to the ditch that was not excavated during firebreak construction. It is understood that this fen had tracked vehicle traffic along both sides of the ditch during firebreak excavation and restoration (in addition to a recent, hot fire) and therefore is not technically undisturbed. This term is used solely to compare the newly restored and highly disturbed ditch with the unditched fen habitat adjacent to it. Vegetation and pore water sampling in the undisturbed fen was undertaken ~4 meters away from the edge of the ditch, presumably outside the track width of the bulldozer used for firebreak creation and the excavator used for restoration. The peat surface and vegetation in this sampling zone was visually undistinguishable from adjacent fen further away from the ditch.

Plants were identified to species whenever possible, although many vegetative sedges, grasses and young mosses could only be determined to genus. Voss’ three-volume “Michigan Flora” (Voss, 1972, 1985, 1996) was used for determinations and the most recent names of our flora were obtained from Voss and Reznicek (2012) and the USDA PLANTS Database (USDA-NRCS, 2012b). Vegetative cover was estimated visually by two observers and a consensus was reached for each species to the nearest percentage point. Cover was assessed on a per-species or taxon basis and, given the multiple strata of plant growth, total vegetative cover for individual quadrats often exceeded 100% when values for individual species/taxa were tallied together.

3.3.4 Pore water Sampling and Analysis

Pore water sampling was undertaken in November 2010, early May 2011 and late July 2011 to track changes across a growing season. Samples were collected with a 500 ml syringe attached by Nalgene tubing (with a stopcock) to a 1.5 m sector of 0.64 cm dia. stainless steel tube (similar to a Pushpoint Sampler™ as described by US EPA (US EPA, 2013)). All pore water samples were collected at 25 cm beneath the peat surface. Effort was made to minimize disturbance of the peat profile while collecting samples. During each sampling event, 60 samples were collected from along the length of the restored ditch; in each sector, 5 samples were collected from the restored ditch and 5 each from undisturbed vegetation on each side of the ditch (15 samples from each sector).

The ditch samples were taken from each of the "no mulch" research plots and the undisturbed samples were taken at points parallel with the no mulch plots and ~3-4 m from the edge of ditch, where the undisturbed vegetation data were collected. Clumps of bushes and sedge tussocks were avoided. Prior to gathering each sample, the sampler tubing and syringe were placed in the peat and filled and purged several times with local water. Samples were taken for analysis only after excess organic matter (resulting from sampler insertion into the peat) had visibly dissipated from the local collection site and sampler. Temperature, electrical conductivity and pH were measured in the field using an YSI Model 63 hand-held meter. The pH meter was calibrated with pH 4 and 7 buffers prior to each day's sampling effort, for each sampling period (Fall 2010, Spring 2011,

Summer 2011). The sensor was rinsed thoroughly with distilled water (and then local water) between each sampling point to minimize potential for cross contamination.

Pore water samples were stored in 120 ml high density polyethylene (HDPE) Nalgene bottles in a cooler on ice and were filtered through a Sterlitech™ (Sterlitech Corporation, Kent, WA) 0.45 μm nylon membrane filter within 24 hours of collection, split into two 40-60 ml aliquots and one half fixed (acidified) with hydrochloric acid until pH was ~2 for dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) analysis. Aliquots were placed in brown, opaque 60 ml HDPE Nalgene bottles and those being tested for organic acid, element, and ionic compounds frozen. A small aliquot (~5ml) was placed in a glass vial and refrigerated for use in spectrophotometer analysis ($SUVA_{254}$). Elemental analyses were conducted within 30 days of collection (using a PerkinElmer Optima DV inductively-coupled plasma optical emission spectrometer (ICP-OES) – PerkinElmer Corporation, Waltham, MA) and included aluminum (Al), calcium (Ca), Iron (Fe), Potassium (K), Manganese (Mn), Magnesium (Mg), Phosphorus (P) and Zinc (Zn).

The organic acids and anions, Bromide (Br^-), chloride (Cl^-), fluoride (F^-), nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{-3}), sulfate (SO_4^{-2}), acetate, propionate, formate, and oxalate were measured using a Dionex ICS 2000 Ion Chromatograph (Dionex Corporation, Bannockburn, IL, USA). The acidified samples were stored on ice, returned to lab, and refrigerated at 4° C prior to DOC and TDN analyses via a Shimadzu TOC-V Combustion Analyzer with a TNM-1 Total Nitrogen module (Shimadzu Scientific Instruments, Columbia, MD, USA) with a detection limit of 0.05 mg L^{-1} and 0.5 μg L^{-1}

respectively. Pore water SUVA absorbance was measured at λ = 254 nm with a Spectramax M2 Microplate Reader (Molecular Devices LLC, Sunnyvale, CA) using a 1 cm quartz cuvette and reverse osmosis (RO) water for the blank.

Specific ultraviolet absorbance ($SUVA_{254}$) was calculated from absorption at λ = 254 nm divided by sample DOC concentration ($SUVA_{254}$ is reported in units of L mg C^{-1} m^{-1}). Each sample was tested twice and if there was a discrepancy between the two subsamples, an average value was recorded. Discrepancies were in hundredths of milligrams. The value of $SUVA_{254}$ is as an indicator of pore water aromaticity (Weishaar et al., 2003). This value can be affected by the presence of ferric iron (Fe^{+3}) because of UV absorbance by that iron species (Levia and Carlyle-Moses, 2011). Despite not measuring it directly, we likely had fairly high levels of ferric iron in some of our pore water samples given the presence of ferric iron precipitates throughout the northern half of the restoration site. The fall 2010 ditch sample $SUVA_{254}$ and Fe concentrations had a fairly high correlation ($r^2 = 0.53$), as did the undisturbed samples ($r^2 = 0.49$). The spring 2011 ditch samples were less strongly correlated ($r^2 = 0.23$) as were the undisturbed samples ($r^2 = 0.38$). Given this, there is an indication of pore water iron concentration (which was used as a proxy for Fe^{+3}) affecting the $SUVA_{254}$ readings for our samples, possibly making the readings from sectors 3 and 4 artificially high because of additional UV absorbance by ferric iron in the samples.

3.3.5 Statistical Analysis

We compared total vascular species cover and diversity, grass, forb and sedge cover, forb diversity and moss cover to pore water parameters Al, Ca, Fe, Mg, Mn, Zn, DOC and TDN. Percent cover of individual plant species was also compared against various pore water constituents and comparisons were made between Sectors and undisturbed versus restored fen. Analysis of variance (nested ANOVA) was used to determine whether there were significant differences in the variation of pore water and vegetative parameters among the sectors and undisturbed versus restored fen. P-values $\leq$ 0.05 were considered statistically significant. Linear regression was used to calculate correlations between pore water and vegetative characteristics and select plant taxa (note: correlations between pH, electrical conductivity and vegetative characteristics are given in Bess et al., 2014). SAS software (Proc-ANOVA, SAS Institute, Inc., Cary, NC) was used to calculate ANOVA's, while correlations, regression plots and equations were derived using SigmaPlot 12.0 (Systat Software, Inc., San Jose, CA).

To compare and contrast the floras of the restored and undisturbed fen, we used Nonmetric Multidimensional Scaling (NMS) ordination (PC-ORD 6.0, 2014 - MjM Software Design, Gleneden Beach, OR). The default settings for Sorenson's (Bray-Curtis) distance measure were selected, with a maximum of 6 axes and 200 iterations. Starting coordinates were random, with 1 reduction in dimensionality at each cycle. No penalty was assessed for ties in values for a given species among the compared floras. The analysis used a total of 50 runs with real data and 50 with randomized data; we selected a medium speed vs thoroughness setting. To see how the pore water chemistry

data might be affecting the distribution of plant species within our study area, we included pore water parameters as a secondary matrix to be run simultaneously with the vegetation data from the ditch and undisturbed fen. Pore water parameters included pH, electrical conductivity, Ca, DOC, Fe, TDN, P and Zn. Matrix dimensionality was determined by selecting the solution with a final stress less than 20, a Monte Carlo test p-value < 0.05, and a minimum reduction of five points of stress with the addition of an axis. Two axes were ultimately selected for the scatterplot and output.

3.4 Results

3.4.1 Hydrology

The water table at the study site varied with seasonal precipitation patterns, being highest in late winter and spring and lowest in late summer to fall (Figure 3.2). Water table heights differed between the undisturbed fen on either side (East or West) of the ditch (Figures 3.2 to 3.6). Prior to restoration, the fen on the west side (up gradient) of the ditch in the central portion of the research site (sector 2) had the slightly higher water table (~1-2 cm; Figure 3.2). Following ditch restoration in October of 2009, the water table quickly equilibrated between the two sides of the ditch throughout the growing season until late May of 2011, when the water table on the east side rose sharply and remained higher (by 5-10 cm) than on the west until the end of monitoring in late July of 2012 (Figure 3.4).

Following replacement of peat spoils into the ditch, Sector 1 had both the highest (west side) and lowest (east side) water tables (relative to soil surface) during the course

of our sampling and this difference averaged 10-20 cm (Figure 3.3). Sectors 2 and 3 also had discrepancies between the water table heights on the east and west sides, with sector 2 having the east side water table higher by 5-7 cm (Figure 3.4) and sector 3 having the west side higher by 5-7 cm (Figure 3.5). This difference was particularly pronounced from winter of 2011 through summer of 2012. Sector 4 had the water table roughly equivalent on both sides, with that on the east being slightly higher by 1-2 cm in the winter and spring (Figure 3.6). These differences were recorded throughout the monitoring period, from May, 2011 through July, 2012. Mean depth to water table values are given in Figure 3.7.

3.4.2 Pore water Chemistry

3.4.2.1 Dissolved Organic Carbon (DOC)

Mean DOC levels were similar between the ditch and undisturbed fen samples from fall 2010 through summer 2011 (Figures 3.8 and 3.9; Table 3.1). Overall, levels were slightly higher in the summer samples and lower in the fall (Figure 3.10). Sector 1 had the highest concentrations (mg/L) of DOC from fall 2010 through summer 2011, in both the ditch and undisturbed fen, except for the spring 2011 ditch samples, in which the mean DOC level was somewhat higher in sector 2, although variance made this difference statistically insignificant. Relatively low levels of DOC (6-45 mg/L) were recorded in most of the undisturbed and ditch samples, although the ditch had elevated levels of DOC (>80 mg/L) in several plots in the November 2010 and May 2011 samples (Figures 3.8 and 3.9, Table 3.1). However, the DOC levels in the ditch were within the

range of values recorded in the undisturbed fen by July 2011, despite a general increase in average DOC concentrations across all sectors and ditch versus undisturbed fen (Figures 3.9 and 3.10A, Table 3.1). There were no statistically significant differences in overall DOC levels between the restored ditch and undisturbed fen when averaged across the 3 sampling periods, although differences were statistically significant among sectors in both the undisturbed and restored fen (Table 3.2).

3.4.2.2 Aromatic Hydrocarbons

Specific Ultraviolet Absorbance ($SUVA_{254}$) analysis of our pore water samples found varying amounts of aromatic hydrocarbons among the Sectors and ditch versus restored peatland (Figure 3.8, Table 3.1). Aromatic hydrocarbon levels were weakly correlated with DOC concentrations (Figure 3.8). In November, 2010, the restored ditch had the highest overall mean $SUVA_{254}$ values (1.66), followed by the west side undisturbed (1.03) and the east (0.93). Within the undisturbed fen, sector 4 had the highest $SUVA_{254}$ values (1.56), followed by sectors 1 (1.07), 3 (0.97) and 2 (0.32). In the restored ditch, sectors 3 and 4 had the highest mean $SUVA_{254}$ values (2.70 and 2.20, respectively), while those in sectors 1 and 2 were lower (1.11 and 0.63, respectively).

By May of 2011, $SUVA_{254}$ readings increased (especially in sector 2) and evened out considerably among the sectors and treatments (Figure 3.8, Table 3.1). In the undisturbed fen, sector 4 still had the highest mean values (2.17), but the other three sector means were similar to one another (1.46-1.59; Table 3.1). In the ditch samples, only sectors 1 and 3 had values higher than those in the undisturbed fen (means = 2.13

and 1.84, respectively), while $SUVA_{254}$ values for sector 2 and 4 samples were less than in the undisturbed fen (Table 3.1). Linear regression of DOC concentration vs $SUVA_{254}$ showed moderate correlation between the two across both sampling dates, however, differences among sectors and between undisturbed vs restored fen were statistically insignificant (Table 3.2).

3.4.2.3 Metals

Dissolved metals in the pore water also varied with respect to sector and ditch versus undisturbed peatland during the spring and summer 2011 sampling periods (Table 3.1). Sector 1 had the lowest Ca, Fe, Mn and Mg levels, in both the restored ditch and undisturbed fen, while sectors 3 and 4 had high concentrations of these elements (Figure 3.11, Table 3.1). Conversely, Sector 1 pore water had the highest concentrations of dissolved Al and Zn, corresponding with low pH and electrical conductivity in this sector of the ditch (Table 3.1). Differences among both sectors and treatments (i.e. restored unmulched vs undisturbed fen) were statistically significant for some of these elements (Table 3.2). In both restored and undisturbed fen plots, increases in Ca, Mg and Mn concentration were positively correlated with increases in pH (Figure 3.11). Overall, mean 2011 Ca and Fe pore water concentrations were similar in both the undisturbed and the restored fen along the length of the ditch (Figure 3.10).

3.4.2.4 Macronutrients

Across all sectors, P and K levels were significantly lower in the undisturbed fen samples (0.0 - 0.1 mg/liter), but were relatively high in many of the disturbed ditch plots (0.0 - 1.89 mg/L; 0.2 - 2.17 mg/L respectively - Tables 3.1, 3.2). The highest P concentrations were in the May, 2011 ditch plots in sectors 1 to 3 (Table 3.1), but concentrations dropped to undetectable levels in the vast majority of the summer, 2011 samples (Table 3.1). Low concentrations of TDN (~1 mg/L) were recorded in November, 2010 from the undisturbed fen, while the ditch samples had high spikes of TDN (>7 mg/L) in several plots (Table 3.1). Differences between restored and undisturbed fen were statistically insignificant (Table 3.2). Levels of TDN were higher in all sectors (both disturbed and undisturbed) in the May and July 2011 samples (Table 3.1). Nitrites were at levels below our detection threshold throughout the course of our study and nitrates didn't appear in detectable concentrations until July of 2011, when they were found in sectors 3 and 4. Pore water ratios of C:N, C:P, N:P, K:P and Fe:PO4 indicated low dissolved macronutrient concentrations, and many of the differences in nutrients and nutrient ratios were statistically significant among sectors and treatments (Table 3.2). However, 2011 mean levels of N, P and K were similar in the undisturbed and restored fen along the length of the restored ditch, with a few samples having high concentrations of P and K in the restored fen (Figure 3.10).

3.4.2.5 Anion/Organic Acid Concentrations

November 2010 pore water samples contained a number of ionic compounds at relatively low concentrations (<0.5 ppm; Table 3.3). Fluoride, sulfate and oxalate were found in roughly equal amounts in the restored and undisturbed samples while others, like chloride, acetate and propionate, were all found in higher concentration in the restored ditch plots (Table 3.3). Formate was almost completely absent from the undisturbed plots and, in the ditch, occurred primarily in sectors 1 and 2. Phosphate had a peculiar distribution, being found almost exclusively in sector 4, disturbed and undisturbed fen alike (except for an isolated high reading of 1.29 ppm from sector 2: ditch plot 9). Bromide, NO_3^- and NO_2^- were completely absent from all samples (both disturbed and undisturbed) in 2010.

By May 2011, the anions and organic acids had shifted in concentration and, in some cases, distribution across our sampling area (Table 3.3). Bromide, nitrite and nitrate remained absent and acetate nearly disappeared from all samples. Formate was gone from the undisturbed fen, but remained present in much of ditch sector 2. Chloride and oxalate concentrations increased 2-4 times across all sampling areas. Phosphate was unrecorded from nearly all of the undisturbed samples (except for sector 1: undisturbed west plot 1) and, in the ditch, was found in measureable quantities only in sectors 1 and 2. Sulfate remained in similar quantities as in the fall of 2010, but became more localized in distribution, being absent from the undisturbed fen in sector 3 and the east side plots in sector 4.

July 2011 samples had anion and organic acid compositions similar to those from May, but with the addition of low amounts of nitrate, especially in the undisturbed fen plots (Table 3.3). Sulfate and chloride concentrations increased somewhat and became more widespread across the sampling plots, both disturbed and undisturbed. Phosphates almost completely disappeared, with just a couple undisturbed plots in sectors 1 and 2 having measureable amounts. Formate became more patchily distributed and nearly disappeared from the ditch plots, while oxalate increased in concentration somewhat and became more widely distributed across all plots. Comparisons of organic acids and anions found no strong correlations between these chemicals and vegetative parameters, with only a few even having r^2 values of 0.10.

3.4.3 Vegetation

Variation in forb, grass and bryophyte cover, along with forb and vascular diversity were correlated with gradients in Ca, Fe, Mg and Mn concentrations along the ditch (Figures 3.12 and 3.13). In the undisturbed fen and restored ditch, grass and forb cover, and forb and vascular plant diversity increased with these parameters, while moss cover (especially cover by *Sphagnum* spp.) decreased with increases in the concentration of these elements. Conversely, *Sphagnum* cover increased with increases in Al and Zn, while vascular diversity, forb diversity and forb and grass cover all decreased with increases in these two elements.

The distribution of several plant species along the ditch line were found to correlate strongly with certain chemical components of the pore water. In particular, the

calcifilic forbs *Campanula aparinoides*, *Cicuta bulbifera, Doellingeria umbellata, Galium brevipes, Potentilla palustris, Rumex orbiculatus, Scutellaria galericulata, Smilacina trifolia, Solidago uliginosa, Symphyotrichum boreale* and *Viola macloskeyi* were either found exclusively or had their maximum cover values recorded in the high Fe/high Ca/high pH portions of the fen (Table 3.4). The sedges *Carex lasiocarpa* and *Carex sterilis* had similar distributions. This association was most pronounced in the restored ditch (Table 3.4). Conversely, *Sphagnum* mosses, *Carex canescens, C. magellanica, C. oligosperma, Chamaedaphne calyculata* and *Eriophorum virginicum* were found only (or primarily) in the low Fe/low Ca/low pH portions of the study site (Table 3.5).

The NMS ordination showed sorting of the vegetation quadrats among the four sectors and between the restored and undisturbed fen (Figure 3.14). The main differentiation was along Axis 1, representing the scale from poor to rich fen, which was most closely associated with pH, Ca, Fe, Zn and electrical conductivity, with Mg and Mn aligning somewhat with differences between restored and undisturbed vegetation in Sectors 3 and 4. Vectors for Ca and Fe clustered tightly with the vector for electrical conductivity along Axis 1. Phosphorous appeared to be strongly aligned with Axis 2, which showed the separation between the restored and undisturbed vegetation. The monocots *Dulichium arundinaceum* and *Eriophorum virginicum* appear to be major drivers of plot separation along Axis 2, as they were found only in the restored ditch and were present in most of the plots (especially *D. arundinaceum*). This difference between

restored and undisturbed fen was also associated with the shrub cover, which was fairly minimal in the restored ditch plots.

3.5 Discussion

In fens, disturbance history, hydrology, soils and water chemistry are especially important in shaping restoration planning and determining which plant species can be successfully used in the restoration. These abiotic factors will ultimately determine which plant species germinate, become establish and proliferate. Therefore, pre-restoration surveying, sampling and planning is essential to a successful restoration project. In the present study, repeated site visits prior to restoration uncovered rather sharp boundaries in the vegetative composition of the undisturbed fen along the ditch line. Subsequent pore water analysis found these differences to be closely associated with changes in porewater chemistry. We also found there to be seasonal differences in porewater chemistry (Tahvanainen, et al., 2003).

Our NMS ordination shows that differences in vegetative composition were associated with pH and electrical conductivity gradients along Axis 1, following the classic concept of poor to rich fen (Tahvanainen, 2004). Cover by *Sphagnum* spp. and *Carex oligosperma* were closely associated with the poor fen, low pH end of the gradient. Metals concentrations were also associated with Axis 1, with relatively higher concentrations of Zn associated with the low pH end of the spectrum and higher Ca, Fe, Mg and Mn concentrations associated with the rich fen, higher pH end of the spectrum. *Carex magellanica* cover was associated with the increasing Zn gradient, while

Calamagrostis canadensis cover followed the Mg gradient (along with *Campanula aparinoides* and *Solidago uliginosa*). *Lysimachia terrestris* cover increased with higher pH and *Glyceria canadensis* was associated with the higher pH and Mn gradients (along with *Carex sterilis, C. stricta* and *Viola macloskeyi*). Other fen water studies have found pH, electrical conductivity, Ca, Fe, K, Mg^{+}, N, PO_4 and ratios such as N:P and Fe:PO_4 to be primary determinants of plant species richness and distribution (Cooper and Andrus, 1994; Mullen et al., 2000; Gunnarsson et al., 2000; Bragazza and Gerdol, 2002; Hajkova and Hajek, 2003; Tahvanainen et al., 2004; Mileti et al., 2005; Geurts et al., 2008-2010; Zak et al., 2008; Pawlikowski et al., 2013). As a potential explanation for some of these vegetative differences along pH gradients, Ström and associates (1994) found that "acidifuge" (= calcifilic) plant species they studied produce relatively large amounts of oxalate and citrate, which allows them to more efficiently solubilize P and Fe, respectively. Conversely, they found that "calcifuge" (= acidophilic) species produce lesser amounts of these acids, which might limit their ability to solubilize P and Fe, particularly in high pH environments. We found pore water oxalate levels were fairly even among sectors and restored vs undisturbed plots, so this may not be a limiting factor at our site. Additionally, Crowley and Bedford (2011) found that mosses influence P cycling in rich fens through control of redox conditions and microbial and fungal activity in the upper layers of the peat strata. In our study, P concentrations were similar along the length of the ditch in the spring, 2011 samples but highest in the disturbed ditch. Phosphorous was completely absent from the nearly all of the summer 2011 pore water samples, likely because of uptake by growing plants.

Along Axis 2, differences were also observed in our data between the undisturbed and restored vegetation and were associated with concentrations of P, which were greater in the restored ditch plots, despite only appearing in the May, 2011 ditch samples and in very low levels (0.02mg/L) in the July samples from the undisturbed plots in Sectors 1 and 2. A relatively small number of herbaceous species were strongly defining characteristics for vegetation in the restored ditch, particularly the presence and cover by *Dulichium arundinaceum* and *Eriophorum virginicum*, which were completely absent from the undisturbed vegetation plots and were included in the seed mix used in restoration. *Dulichium* is of particular interest as it was a fairly small component of the seed mix yet provided substantial cover in all sectors, especially 3 and 4. It also appeared in the unplanted control plots, so must have been present in the local seed bank. The only place where it was found growing locally was a disturbed portion of the fen along a firebreak ca. 1km away from the restoration site, where peat had been scraped away, exposing the underlying mucky sand. Here it co-occurred with other species rarely observed at the fen complex, such as *Agalinis purpurea*, *Drosera intermedia* and *Scheuchzeria palustris*. This suggests that seed present in the seed bank at our restoration site were likely quite old, possibly several hundred to a few thousand years in age. *Eriophorum virginicum* occurred in the nearby unburned fen and it is assumed it was previously present in the burned area but was eliminated from the local flora when the upper peat layer was burned off during the wildfire, taking the shallowly rooted *E. virginicum* rhizomes with it. *Symphyotrichum boreale* and *Carex lasiocarpa* were strong factors defining the undisturbed plots in Sectors 3 and 4 and *S. boreale* was absent from

the restored ditch plots, despite being included in our seed mix. *Carex lasiocarpa* also occurred in the restored ditch, but at lesser cover values. The lack of shrub cover in the restored ditch was also apparently a factor driving the separation of the restored and undisturbed sites along Axis 2 in our NMS analysis.

Given the relatively undisturbed nature of our site and its surroundings, along with the lack of agriculture in the general vicinity, water chemistry analysis showed no large imbalance in macronutrient concentrations as is often the case in disturbed, temperate zone fens surrounded by heavily human-altered landscapes (Wassen and Barendgregt, 1992, Rozbrojová and Hajek, 2008, Geurts et al., 2008-2010, Hettenbergerová et al., 2013). Our results show that pre- and post-restoration vegetation and water sampling should occur over the entire restoration site, whenever possible, as what may superficially appear to be a homogeneous region can have sharply defined changes in abiotic parameters which will, in turn, limit the plant species that can be established during restoration. Our study also shows that it is important to look at multiple pore water parameters, as a site's chemical complexity may not be revealed if only pH or electrical conductivity is measured. It is also important to be careful about extrapolating methods and results from other studies as sites vary greatly in geography and chemistry, thus requiring site-specific methodology based on the results of your initial investigative surveys and sampling.

As an example, Snowden and Wheeler (1993) found that growth of several British fen forbs was negatively affected by the presence of dissolved iron (i.e. the plants expressed "iron toxicity") even at relatively low concentrations (10 – 25 mg/L),

compared to our results. In contrast, we found the exact opposite, with most of our forb species occurring only in the high iron plots (6 – 50 mg/L), including ones closely related to those in the British study. In particular, the forbs *Campanula aparinoides*, *Cicuta bulbifera, Doellingeria umbellata, Galium brevipes, Potentilla palustris, Rumex orbiculatus, Scutellaria galericulata, Smilacina trifolia, Solidago uliginosa, Symphyotrichum boreale* and *Viola macloskeyi* were either found exclusively or had their maximum cover values recorded in the high iron portions of the fen. This association was most pronounced in the restored ditch (Table 3.4).

Iron-rich fens are apparently quite diverse, in terms of water chemistry, ranging from acidic sites with little in the way of buffering agents such as Ca and Mg (Chimner et al., 2010, Reiche et al.,2008, Hájková and Hájek, 2004, Tahvanainen, 2003) to those like the Sleeper Lake Fen in which high iron levels are accompanied by circumneutral pH and relatively high concentrations of these elements (Fleming et al., 2014, Vollrath, 2012, Zou et al., 2011, Wang, 2011, Haaijer et al., 2008, Emerson and Weiss, 2004, Johnson and Steingraeber, 2003, Bendell-Young, 1999). It is probable that Ca and Mg carbonates are causing the higher pH readings for our site, which may have buffered the effects of iron toxicity on forb growth, as alluded to by Snowden and Wheeler (1993). We believe our observed difference in iron effects is due to the perennially high water table, sheet flow of surface water throughout much of the growing season and complex water chemistry at Sleeper Lake Fen, where high pH, Ca and Mg levels are coupled with similarly high levels of dissolved iron. This is supported by the research of Aggenbach et al. (2013) who found high levels of Fe accumulation in drained fens in the Netherlands,

concluding that high concentrations of this metal had an inhibiting effect on fen plant growth following hydrologic restoration, which was compounded by the loss of Ca and Mg through drainage-related redox and leaching. However, it should be noted that their iron levels were orders of magnitude greater than any we recorded for the Sleeper Lake Fen restoration site.

Both our study and that of Snowden and Wheeler (1993) found that monocots do well under high iron conditions. Snowden and Wheeler thought this was related to a "superior oxidative-detoxification system" although they did not elaborate on just what such a system might be. They may have been referring to the ability of many wetland monocots to use "channels" of aerenchyma tissue to draw air (especially O2) from their leaves down to their root zone for respiration during periods of inundation. Snowden and Wheeler also believed that monocots dominated in such conditions because of a generally slower growth rate; however the monocots in our study were observed to grow much faster than associated dicots and quickly dominated all of our sampling plots. We also found calciphilic sedges such as *Carex lasiocarpa* and *C. sterilis* dominating the sedge fauna in our high iron/calcium plots but were absent from the lower pH plots (those with pH values less than 5.5). Acidophilic sedges such as *Carex magellanica*, *C. oligosperma* and *Eriophorum virginicum* were absent from the high iron/high pH portion of our study site, despite their inclusion in the seed mix used in our restoration.

Dissolved organic carbon (DOC), composed of carbohydrates, peptides, organic acids, alcohols and similar chemicals (Sachse et al., 2005) less than 0.45 µm in length, is one of the most biologically important components of peatland water. In peatlands that

discharge into adjacent aquatic systems, DOC provides the basic building sectors for aquatic food webs and can responsible for a large portion (4-8%) of primary production in these systems (Kolka et al., 2008). The production, cycling, discharge and decomposition of DOC is dependent upon a number of factors, especially hydrology (Schiff et al., 1998), moisture (Kane et al., 2010), temperature (Koehler et al., 2009; Preston et al., 2011) and peat composition or quality (Laiho et al., 2003; Wickland et al., 2007, Armstrong et al., 2012). In diked or ditched and drained peatlands, DOC cycling and discharge are interrupted (Hribljan et al., 2014). Restoration (especially re-wetting) of degraded peatlands is known to increase production of DOC, often for extended periods following restoration (van Dijk et al., 2004, Laine et al., 2006). Webster and McLaughlin (2010) associated DOC concentrations with fen hydrology in the northern Lake Superior Basin of Ontario, positing that increased DOC concentrations decrease along the fen pH continuum, from poor to rich, with rich fens having higher water tables and low concentrations of DOC. Their undisturbed rich fen sites had ~13mg DOC/L averaged across 4 growing seasons (2005-2008), compared to our undisturbed DOC averages of 34mg/L averaged across the 2010-2011 sampling period. The DOC levels in our restored ditch were nearly identical at 35mg/L for the same sampling period. In contrast, Höll et al. (2009) recorded mean DOC levels much higher than ours, with 50mg/L and 66mg/L, respectively, in their comparison of a long-rewetted (20 years) and moderately drained fen in southern Germany. The comparatively low level of DOC in both our undisturbed and restored fen plots likely was a result of the pristine nature of the

fen complex and its surrounding uplands, the perennially high water table and relative youth of the re-wetted peat.

In our study, peat was excavated from the ditch and placed as a berm on one side, where it dried for 2 years prior to replacement. Peat replacement into the ditch resulted in a slurry of finely shredded sedge peat, chunks of consolidated peat and wood. The levels of DOC in the ditch were initially higher than in the undisturbed fen following restoration in 2010, likely the result of initial leaching of DOC from the partially decomposed peat. However, by July of 2011, DOC levels had essentially equilibrated between the restored and undisturbed fen (Figures 3.9 and 3.10). The 2011 data also gave some indication of DOC transport out of the ditch in Sectors 2 and 4, where DOC levels were higher on the east (down flow) side of the ditch than the west (up flow). Organic acids are also often found in elevated concentrations in restored fens, although our data were inconclusive. Fluoride, chloride and oxalate concentrations increased over the course of our study, but this occurred in both the ditch and the undisturbed fen and the increases in oxalate were likely due to increased plant and microbial productivity (Lane, 1994, Ström et al., 1994).

Throughout the course of this study, DOC levels were highest in Sector 1, in both the restored ditch and the adjacent, undisturbed fen (Table 1). This was probably because sheet flow of surface water in this sector was limited by low sand dunes that cut the area off from the rest of the fen, allowing DOC levels to build up over time. The dense cover of *Sphagnum* mosses in this portion of the fen may have also added to the DOC through production of carbonaceous photosynthates, although shifts to cover by vascular plants

can increase DOC production through introduction of additional carbon inputs, like root exudates or litter accumulation, or manipulation of the water table through increased evapotranspiration (Fenner et al., 2009). Vestgarden et al. (2010) found similar gradients in DOC, with *Sphagnum*-dominated, acidic mires having higher DOC concentrations at the 20-30 cm depth than those dominated by other acidic moorland/mire species such as *Calluna* (heather) or *Molina caruleae* (moor grass). Their mean DOC concentrations (<10 mg/L) were well below ours (~34 mg/L) and these differences are likely a reflection of variation in site hydrology, primary productivity and peat composition. The fairly rapid equilibration of DOC levels in the undisturbed and restored fen across our study site was likely due to a combination of factors, such as the short time period that the peat remained dry and oxidized (2 years), the sheet flow of large volumes of water through the site and the perennially high water table. The high water table limits aerobic microbial decomposition of the peat and thus the production of DOC.

3.6 Implications for Practice

Our data suggest a strong association between plant species distribution/cover and water chemistry at Sleeper Lake Fen. Water chemistry was also shown to have a strong influence on which species germinated, established and proliferated in our restored plots, even over the short period of time that we sampled (2 years post-restoration; Bess et al., 2014). Therefore, we believe an understanding of site water chemistry (especially pH, electrical conductivity, macro-nutrient, Ca and Fe concentrations) is essential to developing a successful fen restoration project.

In particular, the occurrence of the most diverse flora in the most iron-rich portion of our site was a surprise and runs counter to the published information on iron and fen vegetation (Snowden and Wheeler, 1993, Aggenbach et al., 2013). The co-occurrence of relatively high iron, Ca and TDN levels with low P (coupled with the most diverse and dense cover of forbs) is also in opposition to much of the published information on fen vegetation (Boeye, et al., 1997; Wassen and Barendregt, 1992; Mullen et al., 2000; Olde Venterink et al., 2001; Hajkova and Hajek, 2003; Rozbrojová and Hajek, 2008; Geurts et al., 2008-2010; Zak et al., 2008-2009; Crowley and Bedford, 2011; Hettenbergerova et al., 2013; Pawlikowski et al., 2013), further supporting the importance of understanding site water chemistry when developing peatland restoration programs.

On sites with remnant vegetation, plant species composition can be used as a proxy for pore water chemistry and seed or nursery stock mixes used in restoration should closely mimic the existing vegetation. However, in completely denuded, prior mined or agricultural sites, understanding porewater chemistry will be crucial to the success of a restoration project. Most wetland plants have narrow ranges of tolerances for various soil/porewater parameters such as pH and calcium or iron concentration. High levels of macronutrients like N, P or K favor the growth of non-native and weedy invasive species like reed canarygrass or hybrid cattails, species whose occurrence and proliferation can be serious obstacles to successful natural area restoration. In addition, many native peatland plant species will simply not grow or are quickly outcompeted once certain nutrient concentration thresholds are crossed (Glaser et al., 1990; Gignac et al., 1991; Bedford et al., 1999; Hajkova and Hajek, 2003-2004).

Inexpensive pH kits can be purchased to provide basic information on porewater acidity/alkalinity and relatively inexpensive meters can be purchased to accurately sample for electrical conductivity and total dissolved solids (US$40.99 - HM Digital COM-80 HydroTester EC/TDS Meter at www.marinedepot.com), calcium concentration (US$49.00 HI758 Marine Calcium Checker® HC at www.hannainst.com) or iron concentration ($58.39 HACH Iron Color Disc Test Kit, Model IR-18B at www.hach.com). Information on soil (peat) organic matter, nitrogen, phosphorus and potassium can be obtained from local USDA extension offices or, for water samples, through local universities with photospectrometers (typically ~US$1.00/element/sample).

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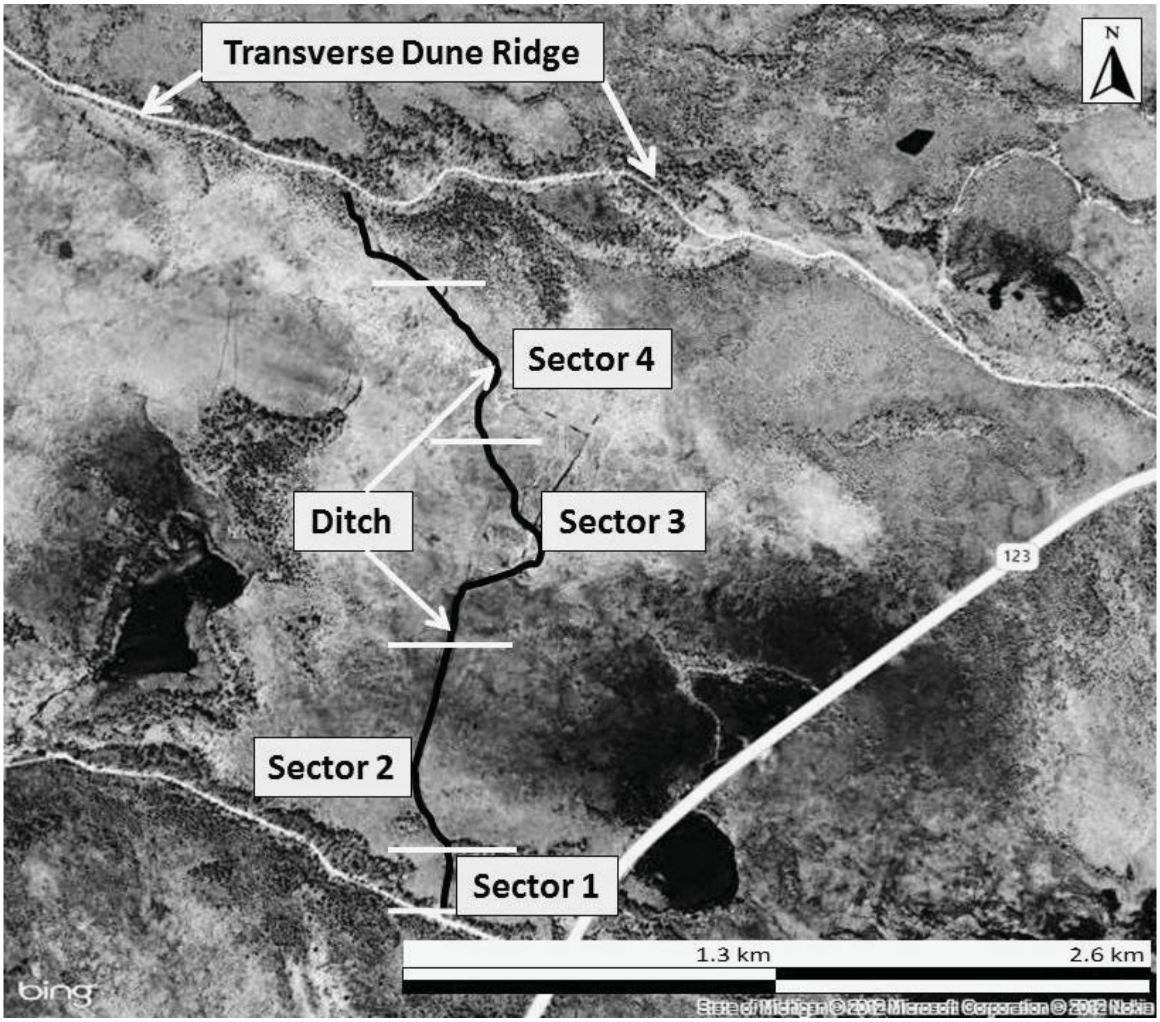

Figure 3.1. The Sleeper Lake Fen restoration site showing location of ditch, dune ridge and sampling sectors. Source: "Sleeper Lake Fen." **Bing Maps, Microsoft, Inc.** Accessed September 20, 2012.

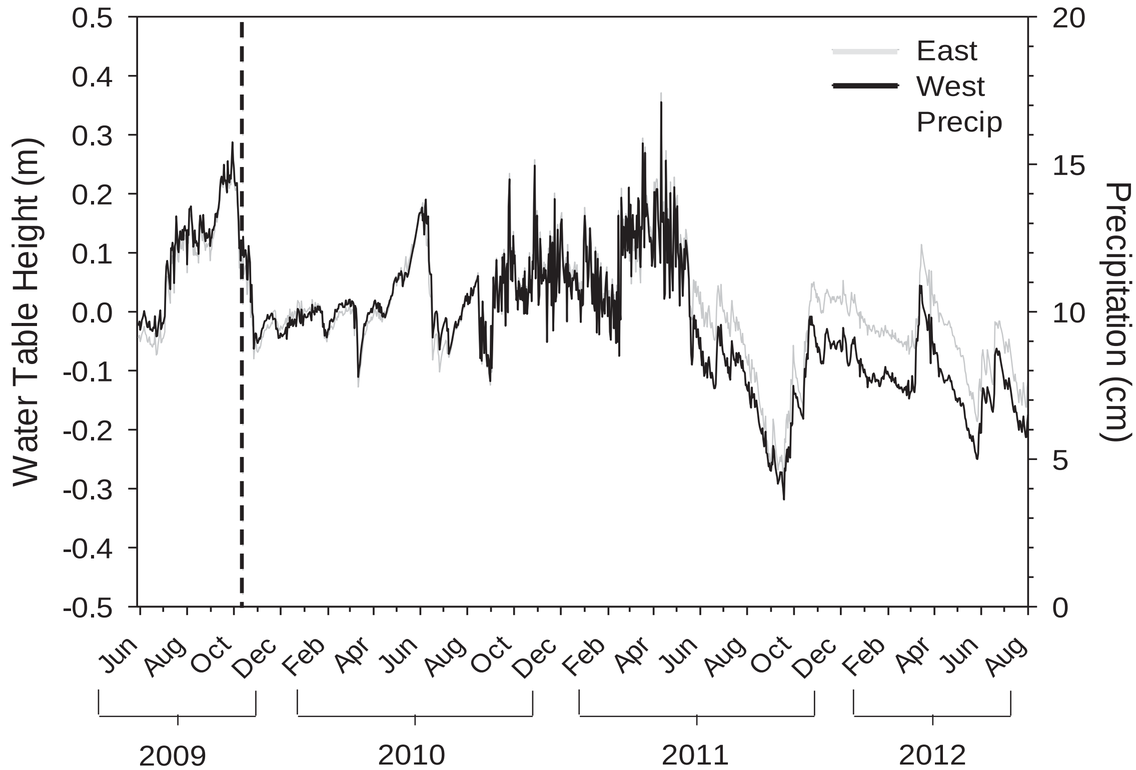

Figure 3.2. Water table height in sector 2 of the Sleeper Lake Fen restoration site with local (Newberry, MI) precipitation data before and after restoration (2009-2012). Dashed line shows when ditch filling was completed.

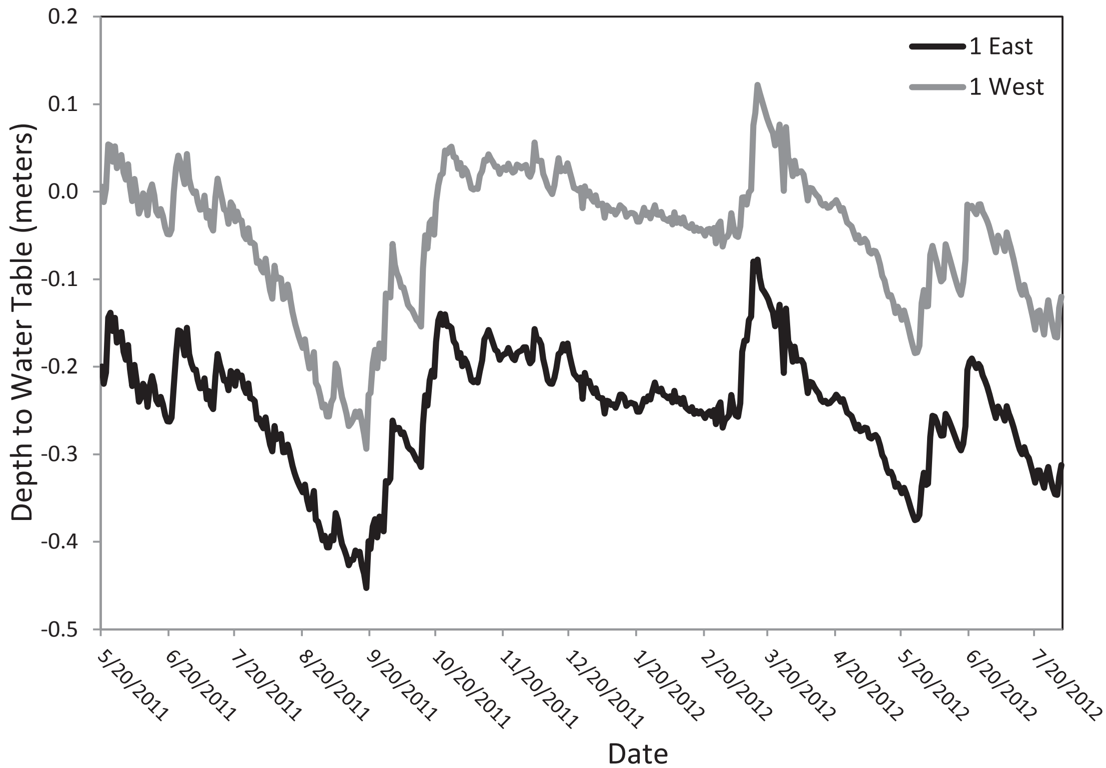

Figure 3.3. Water table heights in sector 1 following restoration at the Sleeper Lake Fen site (2011-2012).

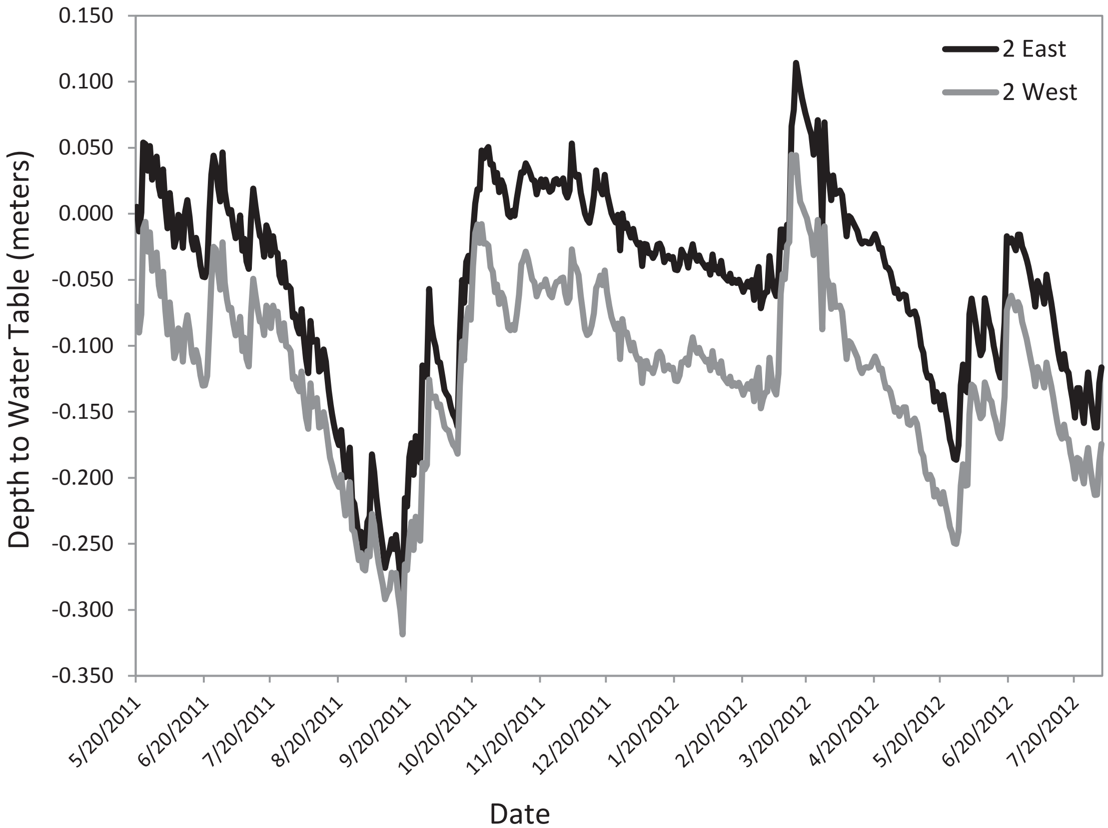

Figure 3.4. Water table heights in sector 2 following restoration at the Sleeper Lake Fen site (2011-2012).

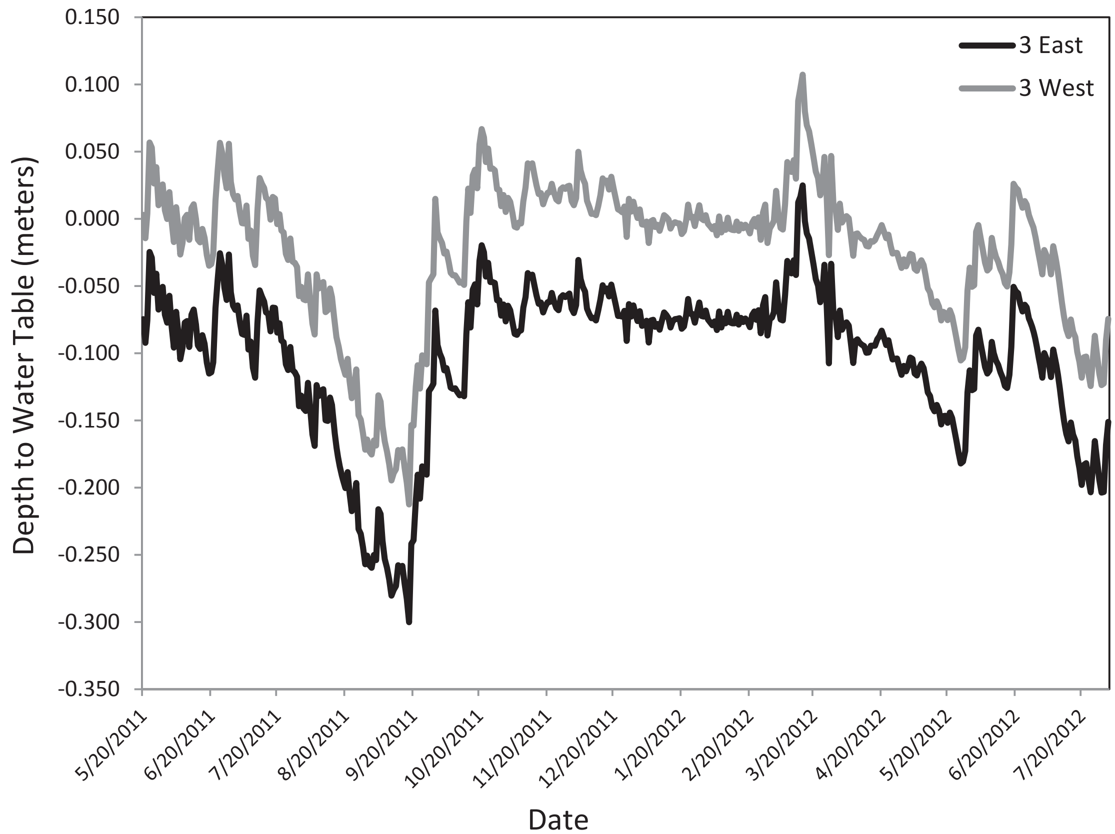

Figure 3.5. Water table heights in sector 3 following restoration at the Sleeper Lake Fen site (2011-2012).

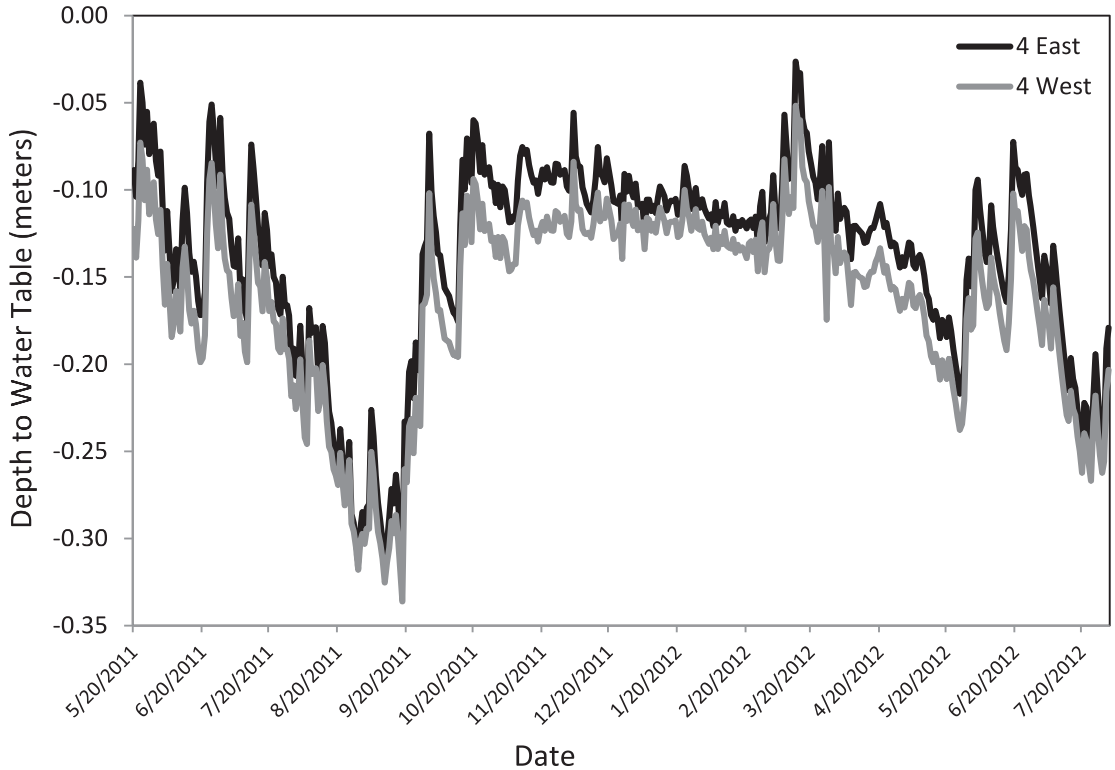

Figure 3.6. Water table heights in sector 4 following restoration at the Sleeper Lake Fen site (2011-2012).

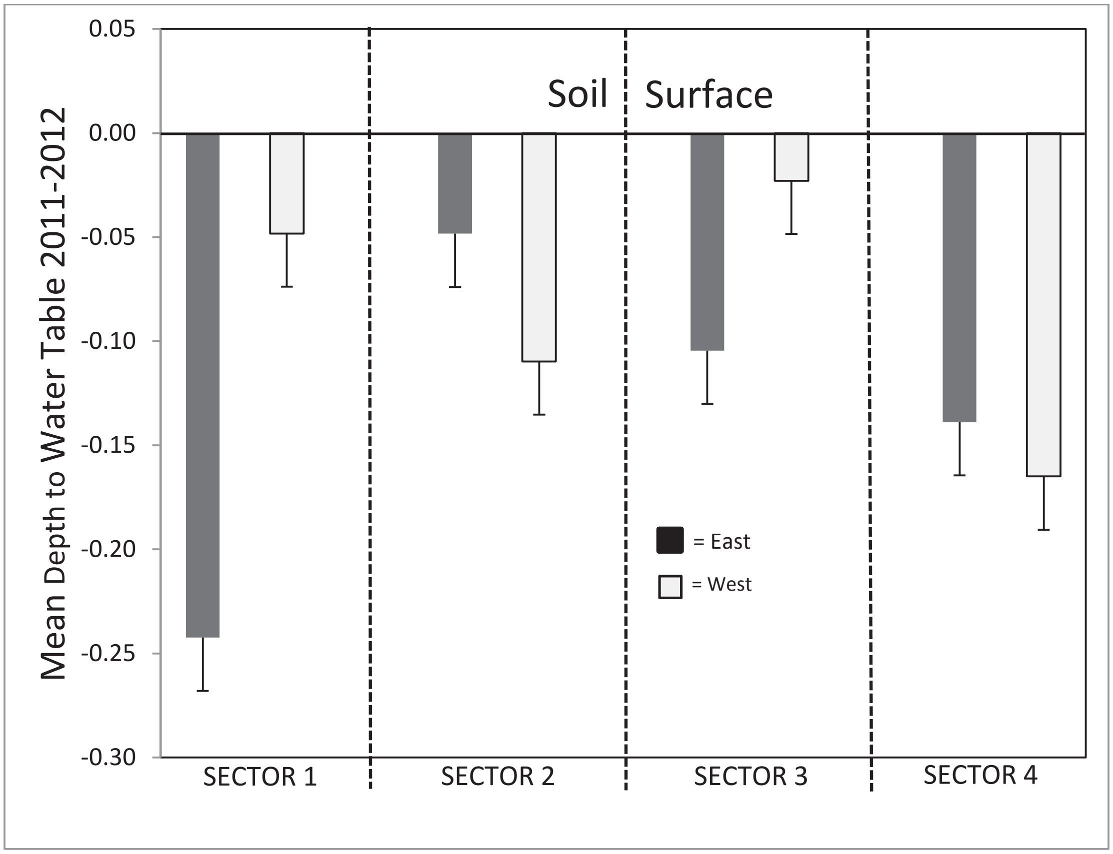

Figure 3.7. Mean depth to water table in the four sectors of the Sleeper Lake Fen restoration site from May, 2011 through August, 2012. Bars represent standard error.

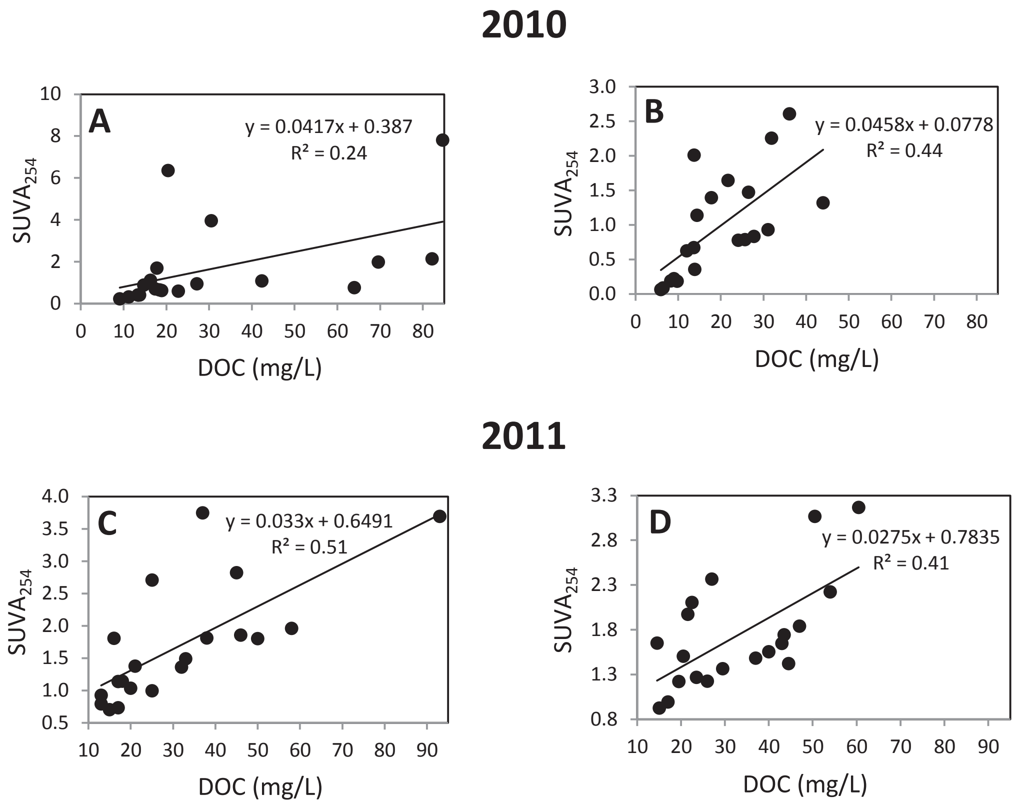

Figure 3.8. Regressions of $SUVA_{254}$ vs DOC concentrations at the Sleeper Lake Fen restoration site. A.) Restored ditch (November, 2010), B.) Undisturbed fen (November, 2010), C.) Restored ditch (May, 2011), D.) Undisturbed fen (May, 2011). $SUVA_{254}$ = Specific Ultraviolet Absorbance at 254nm wavelength; DOC = Dissolved Organic Carbon.

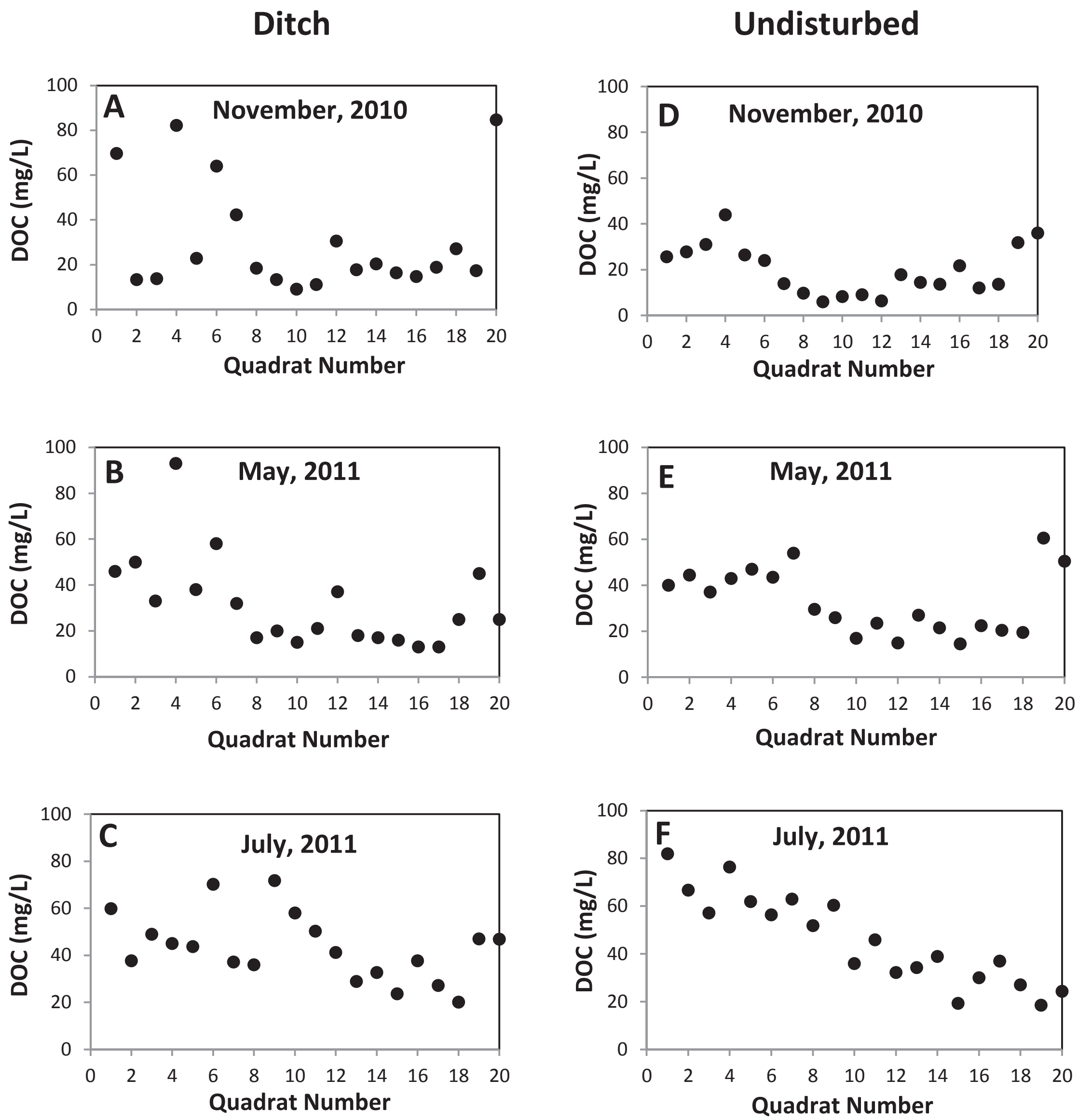

Figure 3.9. Correlation of DOC concentration vs quadrat number in the restored ditch and undisturbed fen at the Sleeper Lake Fen restoration site (November, 2010 to July, 2011 data). Quadrat 1-5 are in sector 1 at south end of ditch, quadrats 6-10 are in sector 2, quadrats 11-15 are in sector 3 and quadrats 16-20 are in sector 4 at north end of ditch.

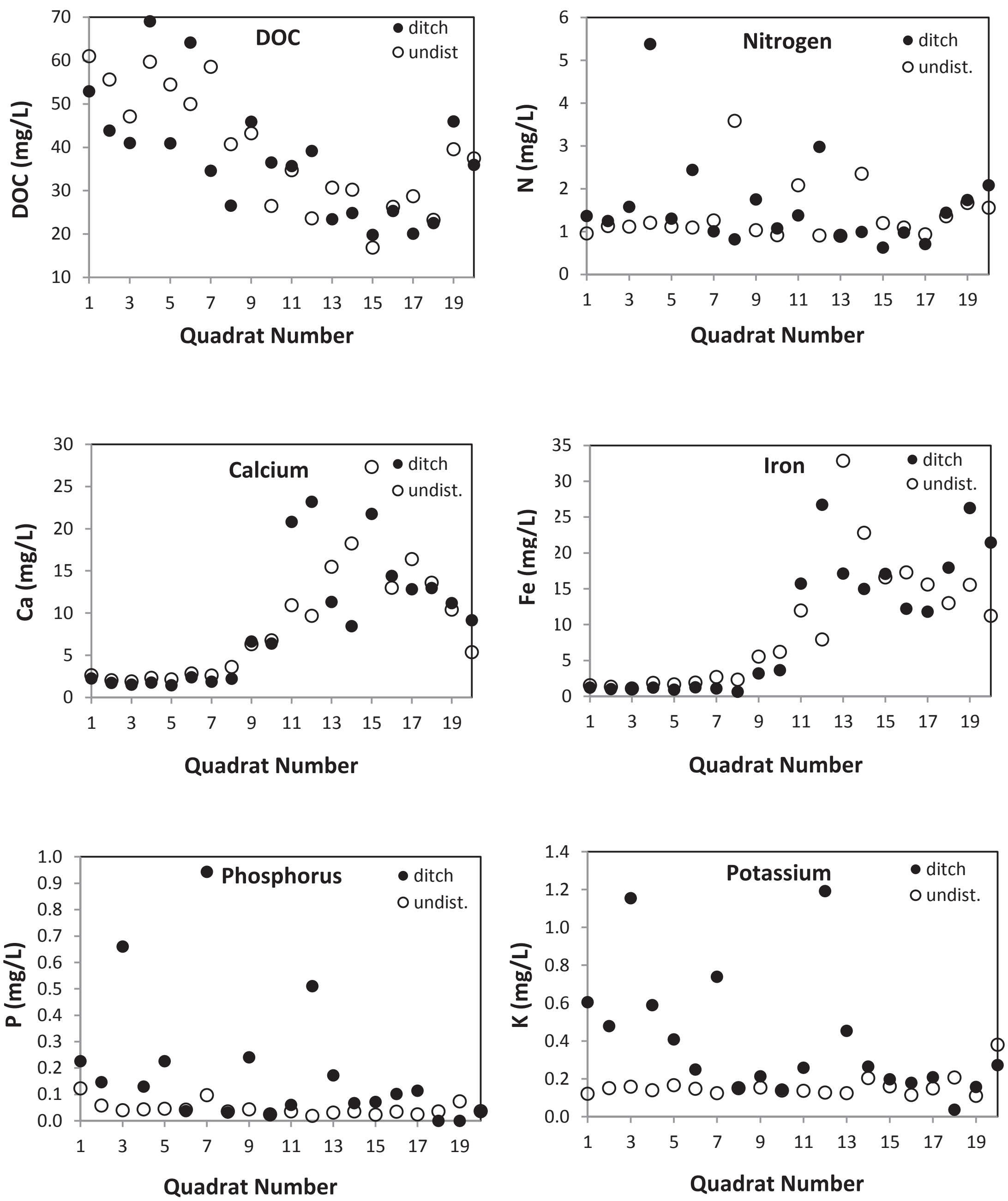

Figure 3.10 Comparisons of 2011 mean porewater chemical data between the ditch (●) and undisturbed (○) fen quadrats at the Sleeper Lake Fen restoration site.

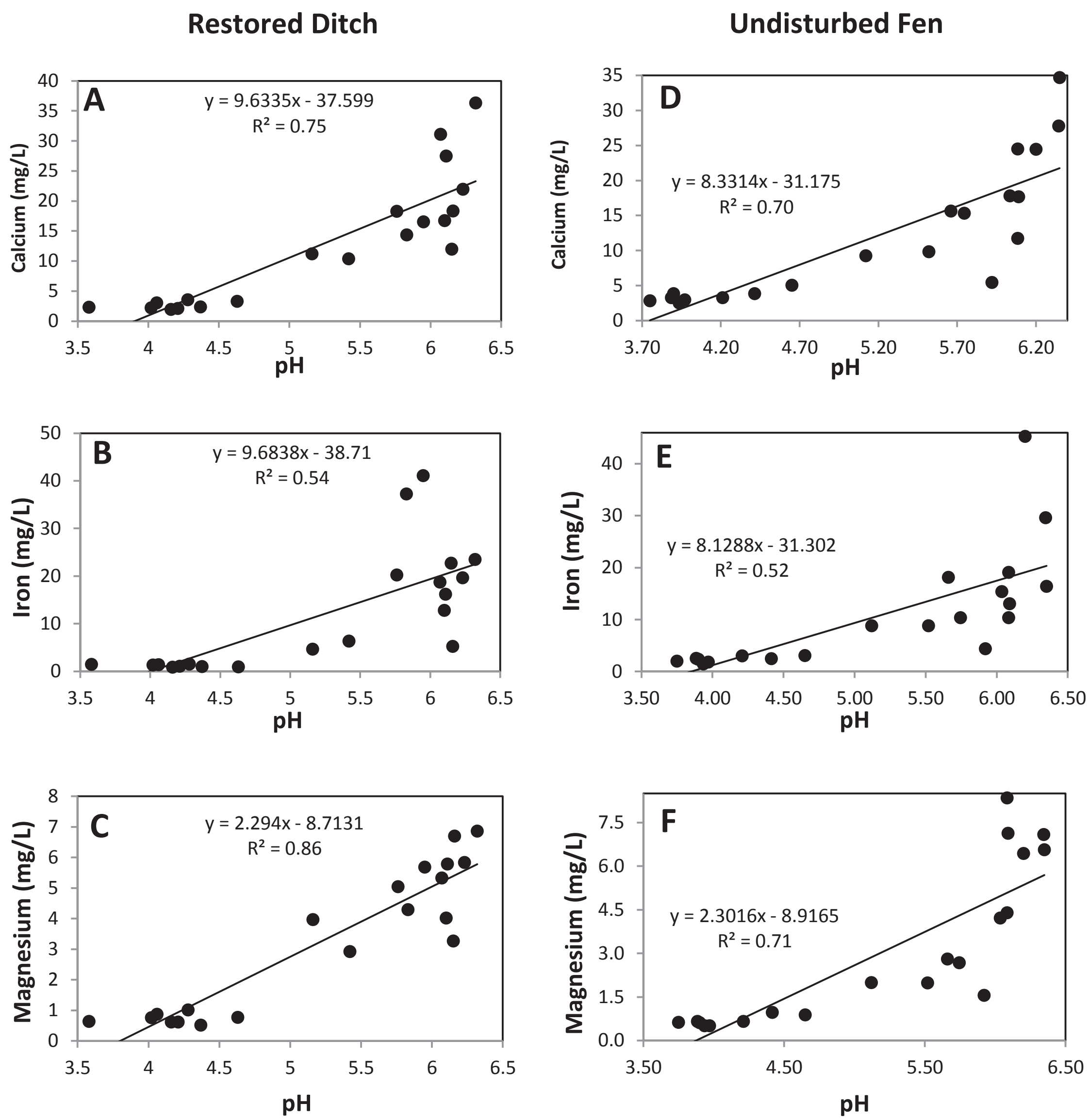

Figure 3.11A-G. Regressions of metals concentrations vs pH in the restored ditch and undisturbed fen at the Sleeper Lake Fen restoration site (July, 2011 data). A-C = restored ditch, D-F = undisturbed fen.

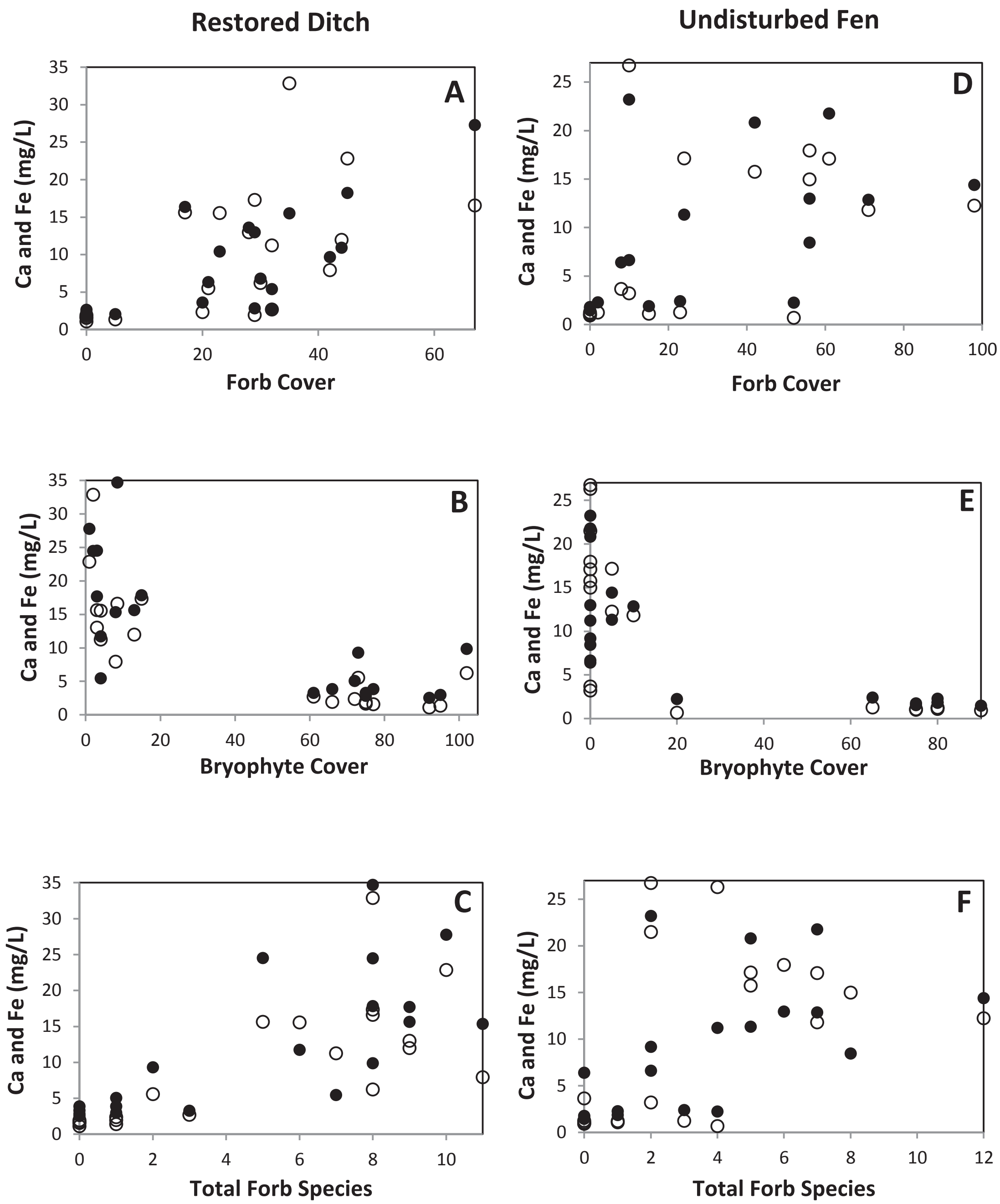

Figure 3.12A-F. Correlation of 2011 vegetative parameters vs mean 2011 Ca, Fe and Mg concentrations in the undisturbed fen and restored ditch at the Sleeper Lake Fen site. A-C) restored ditch, D-F) undisturbed fen. Solid circles = Ca, open circles = Fe.

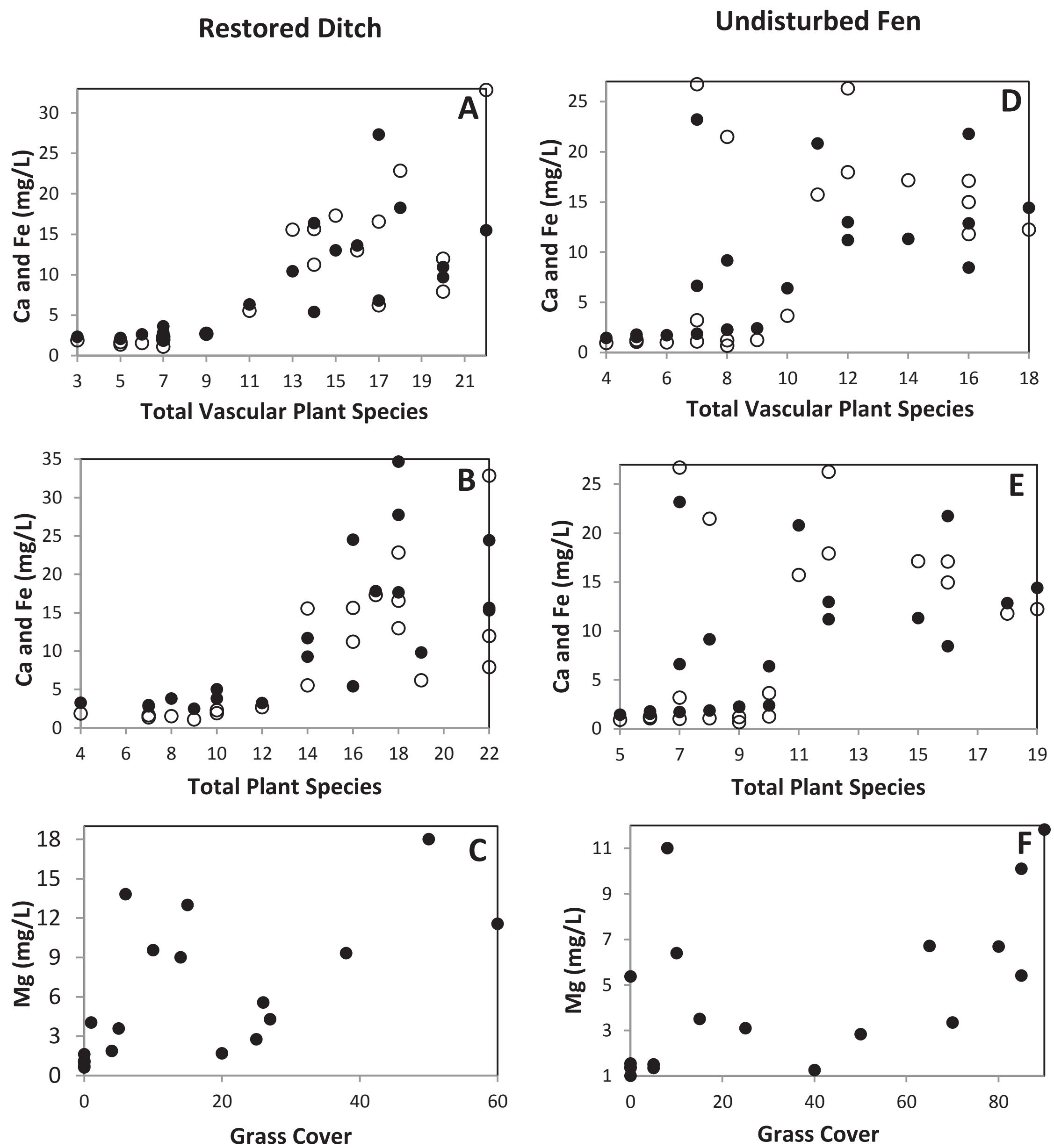

Figure 3.13. Correlation of 2011 vegetative parameters vs mean 2011 Ca, Fe and Mg concentrations in the undisturbed fen and restored ditch at the Sleeper Lake Fen restoration site. A-C) undisturbed fen, D-F) restored ditch. Solid circles = Ca or Mg, open circles = Fe.

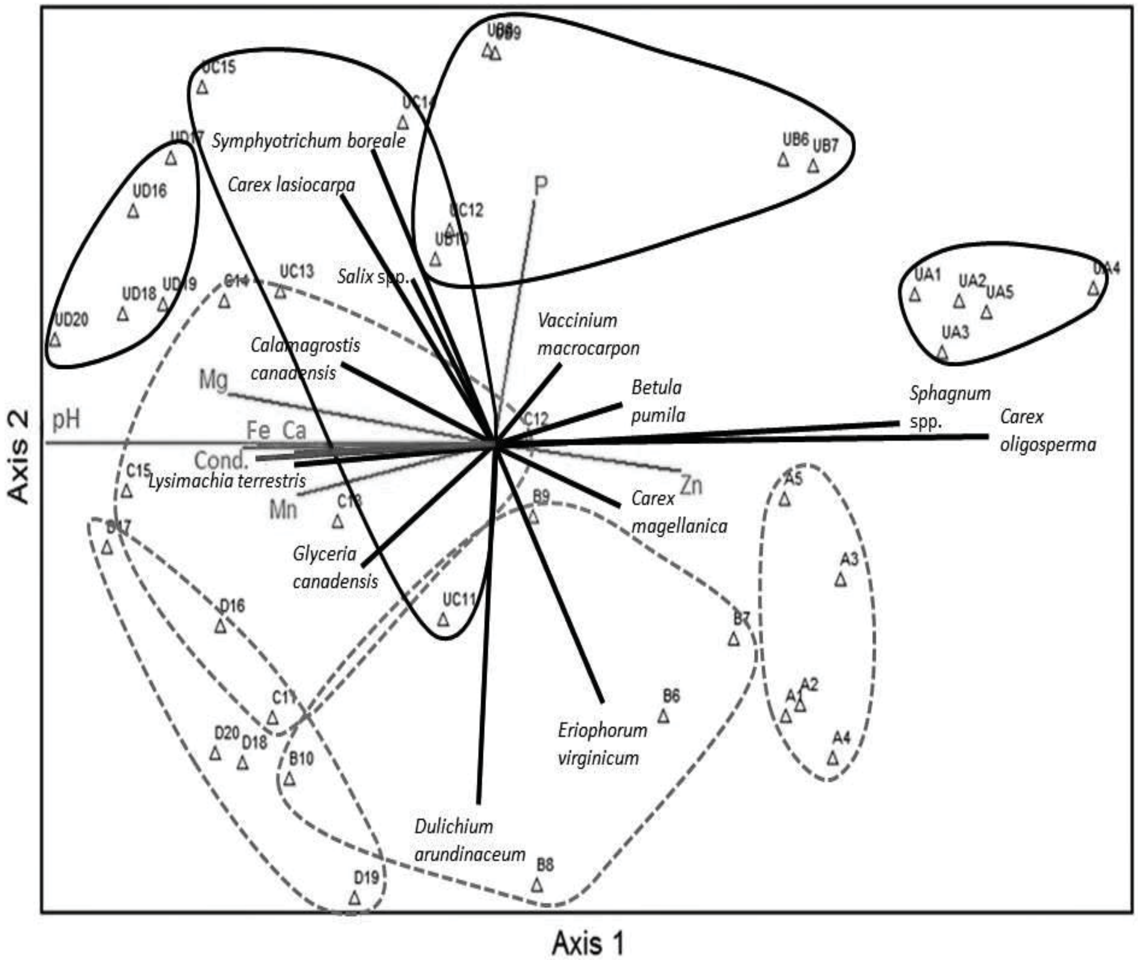

Figure 3.14. NMS ordination of restored and undisturbed vegetation with pore water parameters at the Sleeper Lake Fen restoration site. Groups with solid black boundaries are undisturbed plots (U). A-D = Sectors 1-4, respectively. Boundaries drawn around groupings are for illustrative purposes only as they have no statistical significance.

Table 3.1. A) November, 2010 and B) May, 2011 Pore water chemistry among the four sectors in restored and undisturbed peatland at the Sleeper Lake Fen restoration site. Restored values are means across the 5 sampling plots in each sector; undisturbed values are averaged across the 10 sample plots (5 from each side) in each sector.

A

Date	2010 (November)									
Plot Type	Restored - No Mulch					Undisturbed				
Block	1	2	3	4	Ave.	1	2	3	4	Ave.
EC[1]	40	36	202	221	**124**	41	26	104	146	**79**
Temp.[2]	6.1	9.0	7.3	5.4	**7.0**	5.7	6.6	5.3	5.6	**5.8**
pH	4.11	4.62	6.38	6.37	**5.37**	3.94	4.88	6.26	6.19	**5.32**
DOC[1,3]	40	29	19	33	**30**	31	12	12	23	**20**
SUVA[4]	1.1	0.6	2.7	2.2	**1.7**	1.1	0.3	1.0	1.6	**1.0**
TN[1,3]	2.2	1.7	1.6	1.3	**1.7**	0.9	0.6	0.7	1.0	**0.8**
Al[3]	*	*	*	*	*	*	*	*	*	*
Ca	*	*	*	*	*	*	*	*	*	*
Fe	0.45	0.30	15	15	**5**	0.57	0.38	16	24	**6**
K	*	*	*	*	*	*	*	*	*	*
Mn	*	*	*	*	*	*	*	*	*	*
Mg	*	*	*	*	*	*	*	*	*	*
P	*	*	*	*	*	*	*	*	*	*
Zn	*	*	*	*	*	*	*	*	*	*

B

Date	2011 (May)									
Plot Type	Restored - No Mulch					Undisturbed				
Block	1	2	3	4	Ave.	1	2	3	4	Ave.
EC[1]	41	27	135	162	**91**	43	36	108	128	**79**
Temp.[2]	12	15	15	19	**15**	14	14	15	16	**15**
pH	3.87	4.66	6.16	5.83	**5.13**	3.77	4.50	6.06	5.96	**5.07**
DOC[1,3]	52	28	22	24	**32**	42	34	41	35	**38**
SUVA[4]	2.1	1.2	1.8	1.7	**1.7**	1.5	1.5	1.6	2.2	**1.7**
TN[1,3]	3.1	1.4	1.3	1.2	**1.8**	1.0	0.9	0.6	1.0	**0.9**
Al[3]	0.42	0.20	0.20	0.10	**0.23**	0.31	0.30	0.20	0.25	**0.27**
Ca	1.2	1.7	9.2	6.7	**4.7**	1.4	2.7	9.2	8.1	**5.3**
Fe	1.0	1.0	16	13	**7.8**	1.0	2.3	13	17	**8.2**
K	1.1	0.40	0.5	0.10	**0.5**	0.16	0.10	0.20	0.15	**0.15**
Mn	0.02	0.01	0.09	0.08	**0.05**	0.00	0.01	0.07	0.07	**0.04**
Mg	1.8	2.4	11	6.1	**5.4**	1.3	3.3	12	17	**8.4**
P	0.6	0.5	0.35	0.10	**0.38**	0.10	0.09	0.06	0.09	**0.09**
Zn	0.04	0.03	0.02	0.02	**0.03**	0.05	0.03	0.01	0.02	**0.03**

* = data not collected; 1: EC = Electrical Conductivity, DOC = Dissolved Organic Carbon, TN = Total Nitrogen 2: Temp. is degrees Centigrade, 3: all elements are in mg/L; 4: SUVA is Specific UV Absorbance at 254nm/cm-1

Table 3.1. C) July, 2011 Pore water chemistry among the four sectors in restored and undisturbed peatland at the Sleeper Lake Fen restoration site. Restored values are means across the 5 sampling plots in each sector; undisturbed values are averaged across the 10 sample plots (5 from each side) in each sector.

Date	2011 (July)									C
Plot Type	Restored - No Mulch					Undisturbed				
Sector	1	2	3	4	Ave.	1	2	3	4	Ave.
EC[1]	43	43	239	227	**138**	52	50	214	167	**121**
Temp.[2]	26	23	23	21	**23**	23	22	21	20	**22**
pH	4	5	6	6	**5**	4	5	6	6	**5**
DOC[1,3]	47	55	35	36	**43**	63	54	34	27	**45**
SUVA[4]	*	*	*	*	*	*	*	*	*	*
TN[1,3]	1	1	1	2	**1**	1	1	1	1	**1**
Al[3]	0.39	0.40	0.38	0.25	**0.36**	0.46	0.45	0.26	0.19	**0.34**
Ca	2	6	25	18	**13**	3	6	24	15	**12**
Fe	1	3	20	23	**12**	2	5	24	12	**11**
K	0.18	0.18	0.45	0.20	**0.25**	0.14	0.14	0.13	0.20	**0.15**
Mn	0.05	0.04	0.26	0.22	**0.08**	0.01	0.03	0.21	0.13	**0.10**
Mg	1	2	5	5	**3**	1	1	5	5	**3**
P	0.00	0.00	0.00	0.00	**0.00**	0.02	0.02	0.00	0.00	**0.01**
Zn	0.04	0.03	0.02	0.02	**0.35**	0.04	0.04	0.02	0.02	**0.03**

* = data not collected; 1: EC = Electrical Conductivity, DOC = Dissolved Organic Carbon, TN = Total Nitrogen 2: Temp. is degrees Centigrade, 3: DOC, TN and all elements are in mg/L; 4: SUVA is Specific UV Absorbance at 254nm/cm^{-1}.

Table 3.2. ANOVA results for pore water parameters in undisturbed fen and restored ditch at the Sleeper Lake Fen restoration site (2010-2011 data).

	Undisturbed Fen vs Restored Ditch							
Porewater Parameter	**Root MSE**	**y1 Mean[1]**	**y1 F-stat**	**y1 P-value**	**Sector Effect P-val**	**Treat Effect P-val**	**Sector*Treat p-val**	**R^2**
Aluminum	0.09	0.30	5.11	0.0006*	<.0001*	0.92	0.39	0.53
Calcium	3.97	8.72	13	<.0001*	<.0001*	0.98	0.98	0.74
Iron	4.68	9.20	18	<.0001*	<.0001*	.008*	.018*	0.80
Magnesium	2.73	5.03	10	<.0001*	<.0001*	0.12	0.07	0.69
Manganese	0.04	0.08	20	<.0001*	<.0001*	.015*	0.58	0.81
Phosphorus	0.18	0.12	1.75	0.133	0.39	.014*	0.53	0.28
Potassium	0.21	0.28	4.14	0.002*	0.11	.0009*	.047*	0.48
Zinc	0.01	0.03	5.53	0.0003*	.0001*	.031*	0.20	0.55
Total DOC	11	34	3.33	0.009*	.0006*	0.54	0.96	0.42
Total Nitrogen	1.10	1.49	0.51	0.82	0.96	0.44	0.47	0.10
C:N Ratio	7.84	26	4.01	0.003*	.001*	0.53	0.10	0.47
C:P Ratio	608	755	2.40	0.043*	0.09	0.69	0.04*	0.34
Fe: PO4 Ratio	4731	8932	19	<.0001*	<.0001*	.008*	0.02*	0.81
K:P Ratio	2.80	4.18	1.12	0.37	0.13	0.72	0.64	0.20
N:P Ratio	31	35	2.36	0.046*	0.08	0.06	.048*	0.34
SUVA	0.89	1.50	1.56	0.18	0.08	0.23	0.59	0.26

*: Significant at the alpha =0.05

1: Mean values are averages of May vs July, 2011 porewater samples, except for DOC, total N and Fe, which include November, 2010 porewater values as well.

Treat = Treatment (undisturbed fen or restored ditch)

Table 3.3. Organic acid and anion concentrations (ppm) measured in pore water samples from the A) restored ditch and B) undisturbed fen at the Sleeper Lake Fen restoration site (2010-2011).

A

Year	Sector No.	DITCH (ppm)								
		F⁻	Cl⁻	NO3	SUL	PHO	ACE	FOR	PRO	OXA
Nov., 2010	**1**	0.00	0.58	0.00	0.10	0.04	0.64	0.47	0.13	0.08
	2	0.00	0.35	0.00	0.18	0.26	1.99	2.69	0.17	0.07
	3	0.05	0.74	0.00	0.19	0.00	0.26	0.07	0.20	0.04
	4	0.04	0.19	0.00	0.15	0.19	0.02	0.03	0.14	0.21
	Mean	**0.02**	**0.47**	**0.00**	**0.15**	**0.12**	**0.73**	**0.82**	**0.16**	**0.10**
May, 2011	**1**	0.02	1.70	0.00	0.21	0.15	0.00	0.01	0.00	0.06
	2	0.02	1.94	0.00	0.22	0.21	0.00	0.07	0.00	0.17
	3	0.00	2.12	0.00	0.16	0.00	0.00	0.00	0.00	0.00
	4	0.03	0.42	0.00	0.15	0.00	0.00	0.00	0.00	0.14
	Mean	**0.02**	**1.54**	**0.00**	**0.19**	**0.09**	**0.00**	**0.00**	**0.00**	**0.09**
July, 2011	1	0.00	0.94	0.01	0.24	0.00	0.00	0.02	0.00	0.29
	2	0.02	0.76	0.01	0.20	0.00	0.00	0.06	0.00	0.19
	3	0.04	3.57	0.05	0.50	0.00	0.00	0.00	0.00	0.06
	4	0.02	1.47	0.08	0.20	0.00	0.00	0.00	0.00	0.09
	Mean	**0.02**	**1.69**	**0.04**	**0.29**	**0.00**	**0.00**	**0.02**	**0.00**	**0.16**

B

	Sector No.	UNDISTURBED (ppm)								
		F⁻	Cl⁻	NO3	SUL	PHO	ACE	FOR	PRO	OXA
Nov., 2010	**1**	0.01	0.14	0.00	0.09	0.00	0.01	0.00	0.11	0.07
	2	0.02	0.21	0.00	0.13	0.00	0.01	0.00	0.12	0.06
	3	0.03	0.28	0.00	0.14	0.00	0.03	0.01	0.13	0.03
	4	0.05	0.20	0.00	0.07	0.12	0.02	0.00	0.15	0.06
	Mean	**0.03**	**0.21**	**0.00**	**0.11**	**0.03**	**0.02**	**0.00**	**0.13**	**0.06**
May, 2011	**1**	0.01	1.70	0.00	0.24	0.02	0.00	0.03	0.00	0.17
	2	0.02	1.69	0.00	0.13	0.00	0.00	0.01	0.00	0.08
	3	0.00	1.59	0.00	0.00	0.00	0.03	0.05	0.00	0.05
	4	0.02	1.47	0.00	0.13	0.00	0.00	0.01	0.00	0.07
	Mean	**0.01**	**1.61**	**0.00**	**0.13**	**0.00**	**0.01**	**0.02**	**0.00**	**0.09**
July, 2011	1	0.00	0.92	0.03	0.25	0.05	0.01	0.04	0.00	0.22
	2	0.01	0.70	0.03	0.19	0.09	0.06	0.07	0.00	0.21
	3	0.02	0.73	0.02	0.23	0.00	0.05	0.08	0.00	0.17
	4	0.02	0.94	0.03	0.18	0.00	0.00	0.03	0.00	0.11
	Mean	**0.01**	**0.82**	**0.03**	**0.21**	**0.03**	**0.03**	**0.05**	**0.00**	**0.18**

1: F = fluoride, Cl = chloride, NO3 = nitrate, SUL = sulfate, PHO = phosphate, ACE = acetate, FOR = formate, PRO = propionate, OXA = oxalate

Table 3.4. Pore water characteristics and maximum cover values for calciphilic plant species in the undisturbed and restored fen at the Sleeper Lake Fen restoration site - A.) 2010 undisturbed fen data, B.) 2011 restored ditch data.

A

Scientific Name	Max Cover	Sector	Plot #	pH	EC[1]	Fe[2]	Ca[2]	Mg[2]	DOC[1,2]	TN[1,2]
Campanula aparinoides	20	4	20E	5.89	71	3	4	0.8	22	0.9
Doellingeria umbellata	10	4	20E	5.89	71	3	4	0.8	22	0.9
Galium brevipes	25	3	15W	6.37	307	20	36	7.0	28	0.9
Potentilla palustris	18	3	12W	5.83	100	11	14	2.3	30	1.0
Scutellaria galericulata	6	4	20E	5.89	71	3	4	0.8	22	0.9
Smilacina trifolia	6	4	18E	6.01	182	12	18	5.9	21	0.6
Solidago uliginosa	30	3	15W	6.37	307	20	36	7.0	28	0.9
Symphyotrichum boreale	12	3	14W	6.30	241	26	28	6.0	36	1.0
Viola macloskeyi	6	4	20E	5.89	71	3	4	0.8	22	0.9

B

Scientific Name	Max Cover	Sector	Plot #	pH	EC[1]	Fe[2]	Ca[2]	Mg[2]	DOC[1,2]	TN[1,2]
Campanula aparinoides	15	4	17C	6.10	167	13	17	4	27	0.9
Cicuta bulbifera	8	4	17B	6.10	167	13	17	4	27	0.9
Doellingeria umbellata	12	4	16B	6.23	184	20	22	6	38	1.3
Epilobium leptophyllum	5	4	16B	6.23	184	20	22	6	38	1.3
Galium brevipes	40	4	16A	6.23	184	20	22	6	38	1.3
Potentilla palustris	15	2	10C	5.42	57	1	2	3	58	1.6
Rumex orbiculatus	12	4	17B	6.10	167	13	17	4	27	0.9
Scutellaria galericulata	10	4	17B	6.10	167	13	17	4	27	0.9
Smilacina trifolia	5	3	14B	6.15	239	7	5	7	33	1.3
Solidago uliginosa	8	4	17B	6.10	167	13	17	4	27	0.9
Symphyotrichum boreale	10	3	14C	6.15	239	7	5	7	33	1.3
Viola macloskeyi	15	4	17C	6.10	167	13	17	4	27	0.9

1: EC = Electrical Conductivity, DOC = Dissolved Organic Carbon, TN = total Nitrogen.
2: values are in mg/L.

Table 3.5. Pore water characteristics and maximum cover values for acidophilic plant species in the undisturbed and restored fen at the Sleeper Lake Fen restoration - A.) 2010 undisturbed fen data, B.) 2011 restored ditch data.

A

Scientific Name	Max Cover	Sector	Plot #	pH	EC[1]	Fe[2]	Ca[2]	Mg[2]	DOC[1,2]	TDN[1,2]
Betula pumila	35	1	1E	3.89	55	2	3	0.6	96	1.8
Carex magellanica	30	2	8W	4.47	32	4	6	1.0	53	1.3
Carex oligosperma	80	1	5E	3.71	50	2	2	0.5	54	1.3
Chamaedaphne calyculata	40	1	5W	3.79	40	2	3	0.8	70	1.5
Eriophorum virginicum	0	-	-	-	-	-	-	-	-	-
Feather Moss (Hypnaceae)	50	2	6W	4.15	39	3	6	1.5	67	1.3
Polytrichum spp.	40	1	5E	3.71	50	2	2	0.5	54	1.3
Sphagnum spp.	100	1	3W	3.92	44	2	3	0.8	66	1.5
Vaccinium macrocarpon	60	2	8W	4.47	32	4	6	1.0	53	1.3

B

Scientific Name	Max Cover	Sector	Plot #	pH	EC[1]	Fe[2]	Ca[2]	Mg[2]	DOC[1,2]	TDN[1,2]
Betula pumila	5	1	1A	4.06	62	1	3	0.9	60	1.4
Carex magellanica	80	2	6C	4.28	37	2	4	1.0	70	1.4
Carex oligosperma	80	1	4B	4.02	51	1	2	0.8	45	1.6
Chamaedaphne calyculata	40	1	4C	4.02	51	1	2	0.8	45	1.6
Eriophorum virginicum	70	1	2C	4.16	32	1	2	0.6	38	1.0
Feather Moss (Hypnaceae)	10	4	16C	6.23	184	20	22	5.8	38	1.3
Polytrichum spp.	5	4	17B	6.10	167	13	17	4.0	27	0.9
Sphagnum spp.	90	1	5B	4.21	32	1	2	0.6	44	1.1
Vaccinium macrocarpon	20	3	11C	6.32	218	23	36	6.9	50	1.6

1: EC = Electrical Conductivity, DOC = Dissolved Organic Carbon, TN = total Nitrogen.

2: values are in mg/L.

Chapter 4.0 A Novel Approach to Establishing Coastal Wetlands on the Southern Shore of Lake Superior[3]

4.1 Abstract

In 2009, a project was begun to establish coastal wetland vegetation on the south shore of Lake Superior in the Keweenaw Peninsula of western Upper Michigan. Two, 33 m by 4 m sectors of coastline were selected that represented common coastal features in the region; one site was a filled, weedy yard edge and the other was covered with stamp sands left over from copper mining activities in the early and mid-twentieth century. Whereas other published freshwater coastal wetland restoration projects have used nursery stock to quickly establish vegetative cover, we wanted to test if seeds could be used as an economical alternative or supplement. Natural fiber geotextiles were used to hold the soil and seeds in place while the plants germinated and became established. Locally collected seeds from 47 wetland plant species were weighed into individual seed mixes for each site and cold stratified for 3 months. The 33 m long sectors of coastline were divided into 3 zones; emergent, wet meadow and shrub; planted with seeds appropriate for each zone and covered with geotextiles. Alternate plots were treated with 5cm of milled peat moss prior to hand-broadcasting seeds, to test for effects on seedling growth. Germination and establishment of wetland vegetation was successful at both sites within 2 months and the wet meadows in particular were heavily vegetated with a diverse mix of wetland plant species for the 3 years following planting. Fluctuating

3: Bess, J. and R. Chimner. 2015. A Novel Approach to Establishing Coastal Wetlands on the Southern Shore of Lake Superior. *Manuscript*.

water levels and the addition of peat moss influenced vegetative growth and survival. Costs were minimal compared to nursery stock, with our seed and labor costs totaling $2,298 for both sites, one-quarter or less of the cost of using nursery stock.

4.2 Introduction

Coastal wetlands exist at the terrestrial-aquatic interface where they provide critical habitat and perform invaluable ecosystem functions. In addition, coastal wetlands are hotspots for primary production, which directly and indirectly enhances habitat and secondary production for a diverse array of fish and wildlife (Jude and Pappas 1992, Prince et al. 1992, Brazner 1997, Tanner et al., 2004, Sierszen et al. 2006, Timmermans et al. 2008, Urizarski et al., 2008). They also provide enormous value by protecting shorelines from erosion and filtering nutrients and sediments before they enter aquatic systems (Mitsch and Wang 2000, Kriegger 2003). Pristine coastal wetlands also maintain very high degrees of biological diversity, especially with regards to species of conservation concern (Christie and Bostwick 2012, Albert, 2003, Denny, 1994).

Fresh-water coastal wetlands once covered more than 424,000 hectares in the Great Lakes Basin (U.S. EPA, 2009). Since Europeans began modifying the regional landscape in the early 1800's, more than 50% of these wetlands have been destroyed, with an estimated 214,000 hectares remaining (U.S. EPA, 2009). Many of these remaining wetlands are degraded or facing on-going threats such as coastline hardening (placing of rip-rap or seawalls), dredging and channelization, agricultural runoff, climate change and invasive species (Kling, et al., 2003, Dahl and Stedman, 2013). Dahl and

Stedman estimate that 20-30,000 hectares of Great Lakes coastal wetlands were lost between 1978 and 2005 alone (and long after legislation was passed to ensure their protection). These losses and continuing degradation have had catastrophic effects on fisheries, waterfowl populations, water quality and biodiversity (Albert, 2003; U.S. EPA, 2009; Danz et al. 2007; Dahl and Stedman, 2013). Being cognizant of these losses and their effects on the regional environment and local economies, the U. S. and Canadian governments have instituted programs to catalog remaining wetlands, identify the threats they face and institute restoration projects (US EPA, 2009; Dahl and Stedman, 2013).

In the past few decades, numerous projects have been undertaken to restore Great Lakes coastal wetlands, but results have been inconsistent or unknown due to lack of sufficient monitoring (Wilcox and Whillans 1999; Mitsch and Wang 2000). There has also been a lack of knowledge transfer to provide practitioners with up-to-date methods. Furthermore, most of these restoration projects have been conducted in the lower Great Lakes, compared to cold northern wetland types as in Lake Superior where much less is known (Wilcox and Whillans 1999).

In the Keweenaw Peninsula, additional wetland acreage was covered with "stamp sand" deposits left over from copper mining in the early and mid-20th century (MIDNR, 1987; Kolak et al. 1998; Kerfoot et al. 1999). The coarse nature of these sands leads to rapid drainage and little retention of organic matter, which inhibits natural wetland regeneration. Our objective was to test the efficacy of using seeds to restore coastal wetlands such as fens. Prior to this research project, Great Lakes coastal wetland restorations used live cuttings or nursery stock for planting (Wilcox and Whillans 1999).

Two sites were selected that represented the most common conditions currently present on local coastal lands, allowing us to determine if our methodology has potential for widespread application for coastal wetland restoration elsewhere in the Great Lakes. We also wanted to determine if biodegradable geotextile materials were useful in facilitating restoration of coastal wetland vegetation by seeding and whether the addition of organic matter (milled peat moss) enhanced seed germination and seedling establishment.

4.3 Methods

4.3.1 Site Selection and Preparation

Two Lake Superior coastal sites were selected for restoration on the Keweenaw Peninsula in the western Upper Peninsula of Michigan; the "Marsin Center" (or "Marsin") and "Sand Point" (Figure 4.1). Permission was granted by the property owners and necessary permits were obtained from the U. S. Army Corp of Engineers (USACE) and Michigan Department of Environmental Quality (MDEQ) prior to site preparation and construction of experimental plantings.

4.3.1.1 Marsin Center

The Marsin Center (Marsin) is a property owned by the Keweenaw Land Trust that has over 300m of shoreline on the Portage Waterway (lat. 47° 10' 57.93"N, long. 88° 38' 0.63"W, Houghton County, MI). Much of this frontage was likely vegetated with coastal wetlands at the time of settlement and has been filled and converted to residential lawn over the past ~100 years. Currently, a narrow (1-2 m wide) band of degraded wetland vegetation occurs on the water's edge along much of the frontage. Reed

canarygrass (*Phalaris arundinacea*) and spearmint (*Mentha* x *spicata*) are common throughout much of this vegetative fringe (Table 1). Prior to restoration, the Marsin restoration site had a narrow (1 m wide) band of wetland and upland vegetation heavily infested with invasive reed canary grass and spearmint. The surface of the site was also raised above the current level of saturated soil by approximately 0.3 m, so we decided to remove the weedy vegetation with an excavator, to expose fresh soil and lower the soil surface to within 2.5 – 5 cm of the current level of soil saturation. Appropriate permits were applied for and received from U. S. Army Corp of Engineers (the Portage Waterway is a regulated U.S. water) and Michigan Department of Environmental Quality (MDEQ) in May of 2010. Individuals of reed canarygrass and tag alder were pulled and removed from the restoration site each summer during this project.

4.3.1.2 Sand Point

The Sand Point site is on the shoreline of a 2.2 hectare pond set in a matrix of stamp sands on Keweenaw Bay Indian Community (KBIC) property along Keweenaw Bay (46° 47' 21.54" N 88° 27' 49.65" W, Baraga County, MI). These stamp sands were recently (2008) capped with mineral subsoil as part of a U. S. EPA-funded Superfund Site restoration (Nankervis, 2012). Scattered clumps of wetland plants occur along the shoreline, primarily necklace sedge (*Carex projecta*), needle spikerush (*Eleocharis acicularis*), common rush (*Juncus effusus*) and other rushes (*Juncus* spp). High quality coastal fens occur immediately to the west and north of the pond, which was also likely an interdunal wetland/coastal fen prior to human alteration.

The soil cap on the stamp sands had previously been seeded with Eurasian pasture species including fescue (*Festuca arundinacea*), sheep fescue (*F. trachyphylla*), bird's-foot trefoil (*Lotus corniculatus*), black medic (*Medicago lupulina*), alfalfa (*M. sativa*) and clovers (*Trifolium* spp.) and these were growing in the upper third of the restoration site. Given the recent capping of the stamp sands, no attempt was made to lower the soil surface or scrape away the non-native vegetation. The site was selected based on low slope, the relative lack of vegetative cover and obvious signs it had recently been under water (drift line, scattered clumps of wetland vegetation, band of wetland spikerush (*Eleocharis flavescens*) along the former high water mark). To minimize cover by non-native upland species, all individuals of alfalfa, bird's-foot trefoil and black medic were cut off at soil surface during seed set and removed from the restoration area following vegetation data collection in late summer of 2010, 2011 and 2012.

4.3.2 Experimental Design

At each of the two sites selected for coastal restoration (Marsin and Sand Point), a 33 m long by 4 m wide sector of shoreline was selected and subdivided into three zones: emergent, wet meadow and shrub (Figure 4.2). The emergent and shrub zone fen meadow plots were of two, alternating types, those with an organic soil amendment (5 each per zone) and those without (5 each per zone). The organic soil amendment consisted of milled *Sphagnum* peat moss.

The emergent zones consisted of 10, 3 m long x 0.3 m diameter “coir logs”. Coir logs were made from a 3 x 3 meter section of coir matting (made from coconut husk

fibers - Bio D-Mat 70™ (Rolanka Corporation, Georgia, USA)) overlaid with a 1.5 x 3 meter section of jute matting (made from fibers of a plant in the family Malvaceae) and then rolled tightly, lengthwise, to form a cylindrical "log". For the peat-treated logs, a 5 cm layer of milled peat moss was applied over the jute matting prior to rolling. Seeds were placed inside the outermost layers of coir and jute matting on the top side of the log by placing logs with the final flap of fabric on top and then folded back allowing seeds to be placed inside the outermost layers. For peat-treated logs, seeds were scattered on top of the peat and the coir/jute matting then placed back over them. Logs were then put in a linear arrangement at the current waterline, with the seeded section up, and secured in place with 1.3 m pieces of rebar and wire.

The fen meadow zone was a 3 x 33 m area immediately inland and adjacent to the emergent zone and divided into 10, 3 x 3 m restoration plots, lining up with each of the emergent coir logs. Seeds were placed directly onto the soil and covered in a 3 x 33 m section of coir material, underlain with a 3 x 33 m layer of jute fiber matting. For the peat treated plots, 5 cm of peat was placed over the soil surface and seeds broadcast over the peat surface before being covered with geotextile layers. The shrub zone consisted of an additional row of 3 m x 0.3 m diameter coir logs constructed as in the emergent zone, and laid immediately upslope and adjacent to the wet meadow zone (Figures 4.3 and 4.4).

4.3.3 Seed Stock and Treatment

A total of 380 grams of seed from 47 species of wetland plants native to the Keweenaw Peninsula were collected for use in this project (Table 4.1). All seeds were

hand collected from August through October of 2009 and obtained within a 40 km radius of the restoration sites. Seeds of shrubs were retted and scrubbed through screens to remove all fruit pulp and to lightly scarify the seed coat. In the case of chokeberry (*Aronia melanocarpa*), we were unable to efficiently separate the seed from the fruit pulp, so the entire mix was sifted to the smallest possible grain size without damaging the seeds themselves. For planting purposes, *Aronia* seed/pulp mix was applied (at a rate of 30% seed per unit weight/volume). All other shrubs were planted as near pure live seed.

Carex spp., *Iris* and *Juncus* spp. were all planted as near pure cleaned seed. Iris had seed predation from the flag weevil (*Monomychus vulmeculus*) that approached 10%. Seed were hand cleaned to remove all living weevil larvae and pupae from the seed and remove much of the damaged seed. No insecticide was applied to avoid any future adverse effects on the developing plant and insect community once the restorations were planted and becoming established. Iris seed was applied at an increased rate to account for potential inclusion of damaged seed. With the Asteraceae, the pappus was left on the seeds in all species used. This facilitated mixing of seeds and the pappus retained minute seeds such as those of *Eleocharis, Scirpus* and *Juncus*, allowing for more even mixing and distribution of seed.

Following cleaning, sorting and weighing, seeds were stored cold and dry in a refrigerator for 6 months until April 15 of 2010, when cold stratification commenced. Identical seed mixes were weighed out for each of the treatment plots in each of the three zones at the two sites. The seeds were mixed with 946 cm^3 of dry Vermiculite, 250 ml of very warm (~43 degrees C) water and 10 ml of liquid fungicide (Dalconex). The seed,

vermiculite, water and fungicide were then thoroughly mixed in a one-gallon Ziploc bag and the bags sealed and placed warm in a cooler for 24 hours before being placed in a refrigerator at 3.3 degrees C for 3 months of cold stratification. This was done to maximize the saturation of hydrophobic *Carex* perigynia and thick seed coats in other species.

4.3.4 Zone Construction and Seeding

The coir "logs" used in this experimental planting differ from pre-made ones available from manufacturers. We made our own logs by tightly rolling 3 m square sectors of Bio D-Mat 70™ coir material, lined with a 3 m^2 piece of jute fiber matting, into a 3 m long by 0.3 m diameter, tubular, "log" in which seeds were then placed. For the logs with organic (peat) addition (hereafter referred to as "peat logs"), milled peat moss was spread over the 3-m square coir-jute mat to a depth of 5 cm prior to rolling. Seeds were placed inside the outer layers of matting prior to placement and the entire log was secured in place with 15-gauge wire and 1.3 m sectors of rebar, driven into the substrate. The 30 cm diameter seeded logs were placed so that the seeded portion was on the top and placed so they were partially submerged, with the tops approximately 15 cm above the waterline (at that time). Seeds from 19 species of emergent wetland plants were used in restoration of the emergent zone (Table 4.1).

As with the emergent zone, the fen meadow zone had alternating treatments of organic soil amendment vs no amendment. Seed from 36 species of wetland plants (Table 4.1) were hand-broadcast across each of the 3 m x 3 m wet meadow restoration

plots. For planting, the bags of seed mix were placed in a cooler for transport to the restoration site. Immediately prior to planting, a bag of seed/vermiculite mix was poured into a 7.56 liter plastic bucket and then further mixed by hand, to break up clumps of seed and make the mixture as homogeneous as possible. In the case of the coir logs, of a 0.5 m flap of coir-jute matting pulled back and the seed mix was then spread evenly over the top of the exposed sector of log. Following seed placement, the flap of matting was placed over the seeds and the log secured in place with rebar and wire. In the case of the logs with peat amendment, the seeds were placed on top of the milled peat moss and the flap of matting replaced as with the untreated logs. For the wet meadow zone, seed mix was broadcast evenly over each of the 3m x 3m restoration plots and, as with the coir logs, seed was placed on top of the milled peat moss. For the organic amendment plots (hereafter referred to as "peat plots"), seed was placed on top of the milled peat moss, prior to covering with the jute-coir mat layer. Immediately upslope from, and adjacent to the fen meadow, another linear arrangement of 3m long by 0.3 m diameter coir logs was used to form a shrub zone. Like the emergent zone, alternate logs in the shrub zone had peat added to them and were planted with seeds of 11 native wetland trees and shrubs (Table 4.1), using the same technique as for the emergent zone logs. For each set of emergent log, fen meadow plot and shrub zone log, they had matching treatments; the first set were all treated with peat, the second set no peat, the third set with peat and so on (Figure 4.2). Both sites were constructed and seeded in late June, 2010 (Figures 4.3, 4.4).

Given that it is a common component of coastal wetlands in the upper Great Lakes region, and was not included in our seed mix, 1,200 bare root *Carex stricta* culms

were planted, 600 in the wet meadow zones at each of the two restoration sites in May of 2011. Each wet meadow was subdivided into 3 “sectors” parallel to the water’s edge. The culms were planted in pairs, 10 pairs per sector in each plot at each site (200 culms total per sector, 600 culms total per site). Sectors were parallel to the emergent zone logs; 1.) “lakeside” (0.3 m from the emergent zone coir logs), 2.) “middle” (halfway between lake side and upper edges) and 3.) “upper” (0.3 m from upper edge of meadow plot). These sectors were also used for vegetation sampling from 2010 to 2013.

4.3.5 Vegetation Sampling

One-third square meter vegetation sampling plots (0.3 m^2) were made out of 1.25 cm diameter polyvinylchloride pipe and used to gather vegetation data on both the coir logs and wet meadow restoration plots (Figure 4.5). Sampling quadrats were placed every 0.6 m, starting 0.3 m in from the southern edge of each log/plot and ending 0.3 m before the north end/edge of each log/plot. Five subsamples were collected from each emergent zone and shrub zone coir log and data on vegetative cover and diversity were recorded on standardize data sheets. For the fen meadow plots, subsample collection was repeated 3 times, once in each of the three sectors (lakeside, middle and upper), for a total of 15 subsamples for each wet meadow restoration plot. Plants were identified to species whenever possible, although many vegetative sedges, grasses and young mosses could only be determined to genus. Voss’ three-volume “Michigan Flora” (Voss, 1972, 1985, 1996) was used for determinations and the most recent names of our flora were obtained

from Voss and Reznicek (2012) and the USDA PLANTS Database (USDA-NRCS, 2012).

Vegetative cover was estimated visually to the nearest percentage. Cover was assessed on a per-species or taxon basis and, given the multiple strata of plant growth, total vegetative cover for individual quadrats could exceeded 100% when values for individual species/taxa were tallied together. Data on species richness was collected at the subsample level for use in later analysis and consisted of tallies of taxa (usually identified to species) for each subsample. Subsample cover and species richness data were combined to give average values for individual logs and fen meadow sectors, treatments and plots. The subsample data were also combined to give cover and richness information for treatments (peat vs no peat) and entire zones (emergent, fen meadow, shrub meadow). *Carex stricta* survivorship was measured as at least 1 culm remaining green in the late summer of 2011.

4.3.6 Statistical Analysis

We compared total vegetative cover and species richness in the wet meadow zone between the 3 sectors (lakeside, middle and upper) and treatments (peat vs no peat). Percent cover of individual plant taxa was also compared among treatments and sectors. Analysis of variance (nested ANOVA) was used to determine whether there were significant differences in the variation of vegetative cover among the sectors and treatments. P-values ≤ 0.05 were considered statistically significant. SAS software (Proc-ANOVA, SAS Institute, Inc., Cary, NC) was used to calculate ANOVA’s.

4.4 RESULTS

4.4.1 Water Levels in Lake Superior

In the spring of 2010, mean water levels in Lake Superior (and thus the Portage Waterway and Lake maintained pond at Sand Point) were nearly 20 cm below the 154 year average of 183.3 m above mean sea level (msl). This trend continued from spring 2011 until July, 2013 (Figure 4.5). Water levels in Lake Superior typically cycle annually, with higher water levels in summer and lower in early spring (March-April; NOAA, 2015). However, during the spring 2011-2013 seasons, reduced snow pack and minimal spring rainfall intensified this cycle and some of the lowest spring water levels in the past 20 years occurred in 2011-2013. Increased rainfall in the summer of 2013 led to a rise in lake levels and abundant snowfall in the winter of 2013-2014 caused Lake Superior water levels to reach their long-term (154 year) average in summer of 2014 (Figure 4.5).

4.4.2 Marsin Center

4.4.2.1 Overview

The Marsin wetland restoration had a variable response to fluctuating water levels over the four years of this study. In 2010, there was extensive germination of wetland seeds in the emergent and wet meadow zones within 2 weeks of planting (Figures 4.6A and 4.6B), yet none in the shrub zone. Seedlings formed an extensive carpet of vegetation underneath the coir-jute matting in the fen meadow zone and on the tops of the emergent zone coir logs. However, the continued drought (and lake level drop) during

2011-2012 resulted in the death of the seedlings in the exposed emergent zone logs in 2011 (Figure 4.7A). Consequently, while seedling establishment in the shrub zone coir logs didn't occur, rainfall and wave action apparently washed seeds out of these logs and deposited them behind and underneath, where they germinated and shrubs became established. The soil in the wet meadow zone remained moist and resident vegetation was dense and diverse throughout the course of this study.

4.4.2.2 Vegetation - 2010

Seedlings were observed within 2 weeks following planting, resulting in a carpet of young plants under the coir-jute matting in the fen meadow zone by the end of summer (Figures 4.6A-C). The emergent zone logs also had a dense cover of young sedges, bulrushes and other monocots by late summer of 2010 (Figure 4.6A, Tables 4.3A, 4.4). The no peat logs had a slightly greater cover of vegetation (26% vs 19% on the peat logs, Tables 4.3A, 4.4) but richness was identical (6 species each treatment, Table 4.5). *Iris versicolor* had the greatest cover (16% no peat vs 10% peat, Table 4.5), followed by *Carex* spp. (4% each) and *Juncus* spp. (4% no peat vs 2% in the peat logs).

Vegetative cover within the fen meadow zone was well-established in all three sectors (lakeside, mid-plot and upslope). Total vegetative cover values ranged from 25% in the no peat lakeside sector, to 47% in the peat lakeside sector. The peat treated plots had the greatest vegetative cover in the lakeside sector (47%), while the no peat had the greatest cover in the middle sector (39%). Averaged across the three sectors, overall

vegetative cover was 43% in the peat plots and 34% in the no peat plots (Figure 4.9, Tables 4.3A, 4.4).

Wetland plant species richness was nearly identical among the two treatments, with 26 species in the peat plots and 25 species in the no peat, for a total of 28 wetland plant species in the fen meadow zone (Table 4.5). The emergent logs were also nearly identical in species presence, with 10 species total for the peat and 9 on the no peat logs (Table 4.5). In the fen meadow, *Carex* spp. had the greatest average cover (20% in the peat plots vs 14% in the no peat), followed by *Bidens frondosa* (6% vs 4%), *Juncus* spp. (4% vs 5%), forb seedlings (4% each), *Doellingeria umbellata* (2% vs 3%). *Iris versicolor* and *Scirpus* spp. provided 1% cover in each treatment, while *Asclepias incarnata*, *Lycopus* spp. and *Phalaris arundinacea* provided 1% cover in the peat plots, but less than 1% in the no peat (Table 4.4). Conversely, *Thalictrum dasycarpum* provided 1% cover in the no peat plots but less than 1% in the peat. All other species provided less than 1% cover across all plots. In the emergent logs, "*Iris versicolor*" (including at least some *Sparganium* spp. seedlings) had the greatest cover (10% in the peat logs, 16% in the no peat logs). This was followed by *Carex* spp. cover (4% each log type) and *Juncus* spp. (2% and 4%, respectively).

4.4.2.3 Vegetation – 2011

Continued lowering of Lake Superior water levels resulted in the death of all seedlings in the emergent zone logs at the Marsin site during the winter/spring of 2011 (Figures 4.7A, 4.8A). However, the soil in the fen meadow zone remained moist and the vegetation there continued to grow and increase from the 2010 levels (Figures 4.8C and 4.10, Tables 4.6A). In the fen meadow peat plots, mean vegetative cover was 98%, with a total of 44 species of wetland plants recorded, while in the no peat plots mean cover and species richness were less (78% and 39 species). The difference in cover was statistically significant between the peat and no peat research plots (p = 0.01; Table 4.7A). Among both treatments, the middle sector of the fen meadow zone had the greatest vegetative cover (102% in the peat plots and 87% in the no peat). In the peat plots, vegetative cover was lowest in the upper sector (83%), while in the no peat plots, vegetative cover was lowest in the lakeside sector (72%).

Among both treatments, *Carex* spp (39% peat vs 29% no peat), *Juncus* spp. (19% vs 16%) and *Doellingeria umbellata* (6% each) provided the greatest cover (Table 4.8). In the peat plots, the next greatest cover values were for *Iris versicolor* (6%), *Solidago uliginosa* (5%) and *Bidens frondosa* (4%). The invasive *Phalaris arundinacea* was still prevalent in the peat plots and cover had increased from 2010 (nearly 2.5% vs 1% in 2010). In the no peat plots, the next greatest cover values were for *Solidago uliginosa* and *Lycopus* spp. (4% each) and *Iris versicolor* and *Bidens frondosa* (nearly 3% each). *Phalaris arundinacea* was also present, but with a slightly lesser cover (~1.8%) than in the peat plots. Vegetative cover in the peat plots was still significant greater than in the

no peat ones in 2011 (Table 4.6A - 4.8). Plant diversity was also significantly different among both treatments and sectors, with the peat treated middle sectors having the greatest diversity of wetland plants (Table 4.9). *Carex stricta* survivorship varied between treatments, with the no peat plots having greater average survivorship across all sectors. Survivorship among the sectors were nearly identical in the non-treated plots, while the peat plots had greater average survivorship in the upper sector which was the same as the no peat plots (33, Table 4.10A).

4.4.2.4 Vegetation - 2013

Lake level rose markedly in 2013, increasing 40 cm from January through August (Figure 4.5), and completely inundating the coastal wetland restoration at Marsin (Figures 4.10, 4.11). Vegetative cover and species composition changed in response to the rise in lake level (Figure 4.11, Table 4.6A). The no peat plots had the greatest cover and richness of wetland plants (76% cover and 40 species vs 65% cover and 35 species in the peat plots). *Juncus* spp. remained the dominant cover, with 28% cover in the peat plots and 29% in the no peat. *Carex* spp. had the second greatest cover with 9% in the peat plots and 14% in the no peat, followed by *Iris versicolor* (7.3% vs 5.4%), *Solidago uliginosa* (3.4% vs 5.0%), *Doellingeria umbellata* (3.19% vs 4.91%), *Myrica gale* (3.7% vs 3.5%), *Lycopus* spp. (2.1% vs 4.1%), *Calamagrostis canadensis* (1.6% vs 1.9%) and *Eupatorium maculatum* (1.1% vs 1.7%).

Phalaris arundinacea was still prevalent, with 1.4% cover in the peat plots and 2.6% cover in the no peat. Plant diversity changed over time (Figure 4.13) and by 2013,

the peat plots had 13 wetland plant taxa with 1% cover or greater, while the no peat had 15 taxa with 1% cover or greater. Mean vegetative cover across the two treatments was 70% with an overall richness of 40 wetland plant taxa. There were statistically significant differences in vegetative cover between the two treatments, with the no peat plots having slightly greater cover. The no peat lakeside and upper sectors had the greatest vegetative cover (88% and 83% cover, respectively; Table 4.4).

4.4.3 Sand Point

4.4.3.1 Overview

Like the Marsin Center site, Sand Point showed a variable response in vegetation establishment among the experimental treatments – the emergent logs and wet meadow plantings grew fairly well, while those in the shrub zone did not. The dense cover of Ele*ocharis acicularis* and upland pasture species (already present on-site at planting time) may have impeded seedling establishment in some areas. Evidence of muskrat (*Ondatra zibethicus*) and Canada geese (*Branta canadensis*) grazing on plants in the restoration was evident in the first year and throughout this study. This became much more evident in 2013, when muskrats began tunneling under the coir matting, making large trenches in the planting area. Despite this, vegetation continued to grow and spread, although certain species disappeared as a result of continued grazing, particularly pickerelweed (*Pontederia cordata*) and broadleaf arrowhead (*Sagittaria latifolia*).

4.4.3.2 Vegetation - 2010

Seedlings became apparent within 2 weeks of planting and had covered the tops of the emergent logs and saturated portions of the wet meadow plots (Figure 4.5D). On the emergent logs, the peat treated plots had substantially greater vegetative cover than the no peat plots (58% vs 19%, respectively; Figure 4.8). In both the peat and no peat treated logs, *Carex* spp., (12% vs 5%), *Eleocharis* sp. (1% vs 2%), *Iris/Sparganium* (11% vs 8%) and *Scirpus* spp. (5% vs 1%) were the dominant plant taxa (Figure 4.8, Table 4.2B). *Iris* and *Sparganium* cover was combined because of difficulty differentiating young vegetative individuals in the field. We believe *Sparganium* only occurred in the emergent logs at Sand Point.

In the wet meadow zone, total wetland vegetation cover on the peat plots was 90% vs 80% in the no peat plots (Figure 4.7, Table 4.2B). In both treatments, wetland plant cover was greatest in the mid-plot sector, with 142% cover in the peat and 131% cover in the no peat plots. Wetland plant species richness was essentially identical between the two treatments, with 27 species in the peat plots and 26 species in the no peat. *Eleocharis acicularis* dominated both the peat and no peat plots, averaging 39% and 33% cover, respectively. Additional wetland plant species cover on both the peat and no peat plots was dominated by *Carex* spp. (10% vs 13%, respectively), undetermined grass spp. (9%, each), *Juncus* spp. (11%vs 13%), *Echinocloa crus-galli* (4% vs 3%), *Asclepias incarnata* (2% vs .24%) and *Bidens frondosus* (2.2% vs 2.5%). No seedlings were noted in the shrub zone logs.

4.4.3.3 Vegetation - 2011

The peat treated emergent logs continued to have greater vegetative cover (55% vs 33%) compared to the ones without peat (Figure 4.11, Table 4.3B). Conversely, the no peat emergent logs had a greater richness of wetland species (15) than the peat treated ones (11). In the wet meadow, vegetative cover was slightly higher in the no peat plots (79%) than the peat treated ones (71%). Wetland plant species richness was also slightly higher in the no peat plots (27 vs 23 species). *Juncus* spp. dominated the peat plots (23%), whereas *Eleocharis acicularis* still provided the greatest cover in the no peat plots with 27% cover (followed by *Juncus* spp. with 20% cover). *Carex* spp. continued to provide substantial cover, with 10% in the peat and 7% in the no peat plots. *Agrostis stolonifera* was also common in both treatments, with 7% cover in the peat and 10% cover in the no peat plots.

Bidens frondosa was still a major cover component (4% peat vs 3% no peat), followed by *Lycopus* spp. (1.7% vs 2.5%), *Doellingeria umbellata* (1.6% vs 1.1%), *Iris versicolor* (1.7% vs 0.6%), *Asclepias incarnata* (1.6% vs 0.4%) and *Thalictrum dasycarpum* (0.9% each). The peat treated plots had 12 wetland plant taxa providing greater than 1% cover, while the no peat plots had only 9 taxa providing greater than 1% cover. Statistically significant differences in vegetative cover and diversity were found between the two treatments (peat versus no peat) and sectors (Table 4.4). *Carex stricta* survivorship is given in Table 4.5.

4.4.3.4 Vegetation - 2013

Rising lake levels in 2013 resulted in inundation of much of the wetland restoration at Sand Point, killing off much of the upland vegetation growing on-site and encouraged the growth of wetland plants (Figures 4.10B, 4.11). The emergent logs were especially thick with vegetation, with 111% total cover on the peat logs and 89% cover on the no peat (Table 4.6B and Figure 4.12). Vegetative cover on the emergent logs was dominated by *Carex* species (67% on the peat logs, 51% on the no peat), with *Carex comosa/pseudocyperus* being the most prevalent (64% vs 57%). Many *Carex comosa and C. pseudocyperus* were in full fruit at the time of vegetation surveys. *Iris versicolor* (15% vs 14%), *Juncus* spp. (14% vs 8%), *Scirpus atrovirens* (9% vs 11%) and *Sparganium* spp. were the next most abundant cover species, followed by *Scirpus cyperinus* (4% vs 0.8%) and *Eleocharis palustris* (0.8% vs 1%). All other species provided less than 1% cover. Total wetland plant richness on the emergent logs (across the two treatments) was 17 species, with 13 species in each treatment (Figure 4.14).

As with the Marsin site, plant diversity at Sand Point changed over time (Figure 4.14). The wet meadow zone had good coverage by wetland plant species, with a total of 36 wetland plant taxa providing an average cover of 48% across the two treatment types (29 species providing 49% cover in the peat plots and 28 species with 46% cover in the no peat). *Juncus* spp. continued to provide the most cover of any wetland taxa, with ~20% cover in both treatments. *Carex* spp. provided the next greatest cover, with 6.7% across the two treatments (7.5% vs 5.8%, respectively). *Carex projecta* was the most

abundant (4.7% cover vs 5.1%) of these, followed by *Carex stricta* (1.5% cover vs .7%) and *Carex comosa* (0.3% cover vs 0%).

Additional common cover species included *Asclepias incarnata* (4.1% vs 1.7%), *Scirpus cyperinus* (2.4% vs 2.9%), *Eleocharis palustris* (2.6% vs 2.2%), *Lycopus americanus* (2.0% vs 2.1%), *Iris versicolor* (2.3% vs 1.4%), *Calamagrostis canadensis* (1.1% vs 1.8%), *Agrostis hyemale* (0.9% vs 1.3%) and *Scirpus atrovirens* (1.8% vs 0.0%). A notable species that appeared in the plots (but was not in the initial seed mix) was the ladies tresses orchid *Spiranthes cernuua*, which had a cover of 0.7% in the peat plots and 0.3% in the no peat. This fairly common, fall-flowering orchid was observed all around the pond at Sand Point, apparently resulting from seed being blown in from adjacent natural areas. All other plant species occurred at less than 1% cover. Analysis of Variance found there to still be statistically significant differences in vegetative cover and diversity between the two treatments (peat versus no peat) and sectors (Table 4.4). The peat treatment and middle sector plots had the greatest vegetative cover and diversity in both the 2011 and 2013 samples.

4.5 Discussion and Implications for Practice

Despite low lake water levels during much of this study, both restorations were successful in establishing wetland vegetation on two sites that had little prior wetland habitat. The sites selected for this study represent two common coastal situations in the Keweenaw Peninsula; filled, mowed lawns with a mix of wetland plants and non-native upland species as a fringe along the water's edge and stamp sands resulting from previous

copper mining activity. The fact that we were successful in establishing fairly diverse wetlands on both site types, in a fairly short period of time, is encouraging for other coastal wetland restoration projects in the region. The combination of using seeds and natural fiber geotextiles worked very well and appears to have been a novel approach, as we could find no other references detailing the use of seeds in establishing wetland vegetation in high wave action, coastal situations. We believe that the initial low water level greatly facilitated the success of these restorations and fluctuating water levels (in conjunction with resident seed banks) are known to be a strong driving force in the maintenance of healthy Great Lakes coastal wetlands (Keddy and Reznicek 1982-1986; Farney and Bookhout 1982; Herrick and Wolf, 2005; Frieswyk and Zedler 2007).

In comparison to the use of nursery stock, seeds can be a very economical alternative for certain coastal wetland restoration projects, especially where wet meadow/fen meadow and emergent vegetation is desired. Plantings during low water level periods would also benefit from the use of seed, mimicking the natural cycle of coastal wetland development and maintenance. For this project our total costs for seed and labor for planting totaled \$2,297.50. For a minimal density planting of nursery stock at 5 plants/0.3 m^2 (45 plants per m^2), we would have needed 4,550 plants per site or 9,100 plants total. At a cost of \$1.00/plant, this would have been \$9,100.00, not including delivery and handling. Labor costs would also have been high. At a fast planting rate of 120 plants per hour, this would have required 75.83 hours and, at an hourly rate of \$10.00, cost an additional \$758.30, for a total cost of \$9,858.30 (both sites included).

This is more than 4 times the cost of seeding and would have resulted in a less dense and less diverse wetland planting.

The addition of peat to half of the plots and geotextile logs had mixed effects on vegetative cover and plant species richness. In the wet meadow zones at both sites, the peat and no peat plots had very similar vegetative cover and wetland plant species richness values. However, in the emergent logs at Sand Point (the emergent logs at the Marsin site did not survive the drought), there was a marked difference in vegetative cover between the peat and no peat treatments, throughout the course of the study. The peat treated logs had a greater vegetative cover and this may have been purely mechanical (the peat held seeds in place), biological (the peat provided additional nutrients that encouraged plant growth) or some combination of the two.

Among the three sectors sampled in the wet meadow zone, the median sector had the greatest vegetative cover and plant species richness throughout the course of this study. This was likely a result of minimal wave action in this zone, which likely removed a substantial portion of seed and young seedlings from the lakeshore sectors at both sites. The upper sector at Marsin was similar in cover and diversity, likely because of the minimal slope at this site and the moist soil conditions throughout the study. The upper sector at Sand Point was fairly dry from 2010-2012, only becoming more moist in 2013 when Lake Superior water levels rose substantially. The lakeshore sector at Sand Point was heavily grazed by muskrats and Canada geese, which negatively affected plant species diversity and vegetative cover.

The emergent logs were successful in initially establishing vegetation at both sites, but the continued drought killed off the seedlings at the Marsin site. For future restorations using this technique, it is recommended that the logs be embedded into the substrate (if possible), to minimize desiccation during low water periods. The same recommendation goes for the shrub zone geotextile logs, as these remained dry at both sites throughout 2010-2012. Logs might not be acceptable for some sites where drying of the substrate is an issue. For sites with wetland herbivore populations, efforts to protect plantings (particularly emergent plantings) such as fencing or other obstructions are recommended to allow vegetation to establish and spread.

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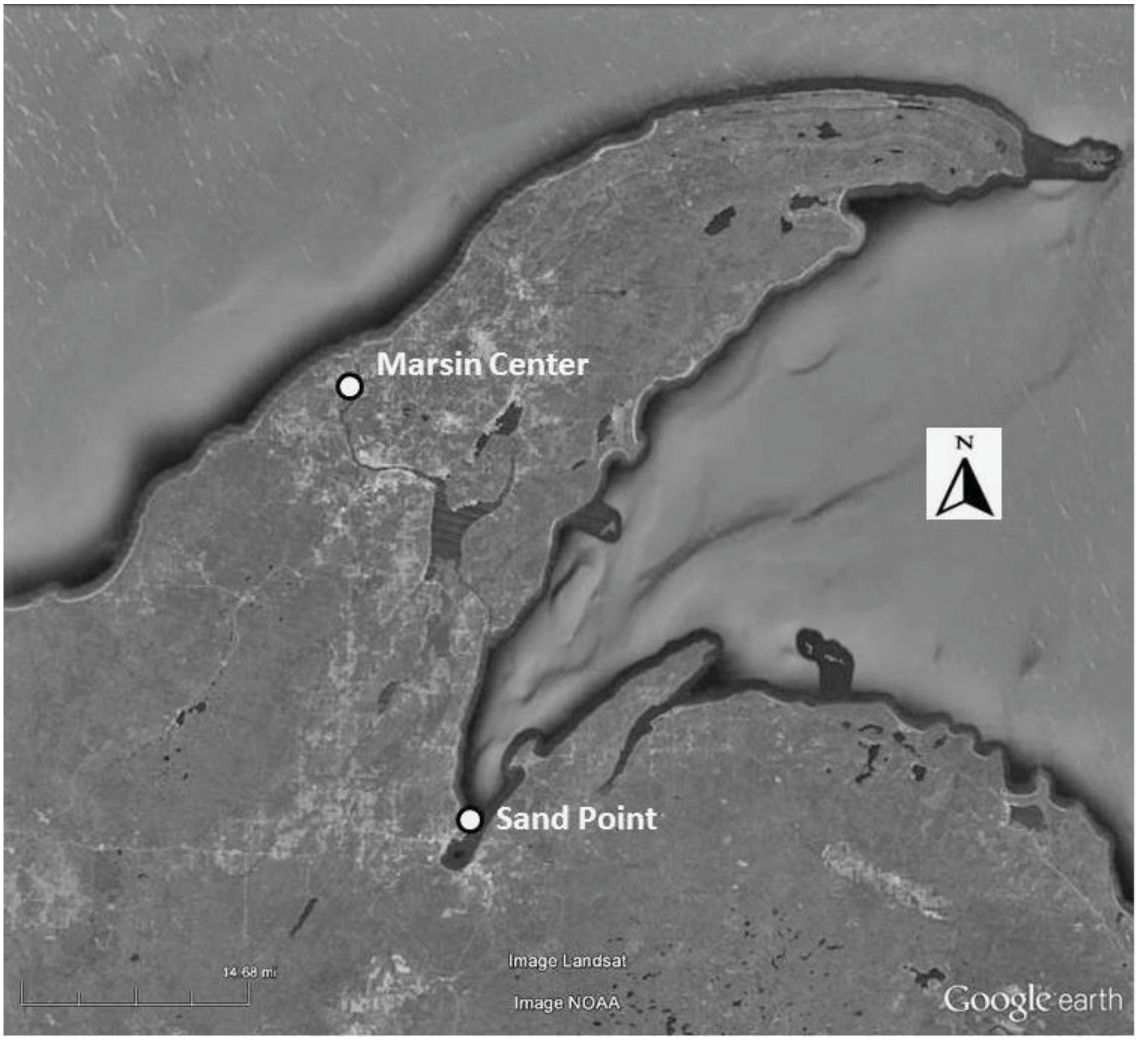

Figure 4.1. Map of the Keweenaw region of Michigan's western Upper Peninsula showing Marsin (upper) and Sand Point (lower) restoration sites. Source: "Keweenaw Peninsula." 47° 3'2.28" N and 88°19'15.68" W. **Google Earth**. August 2014. Accessed April 21, 2015.

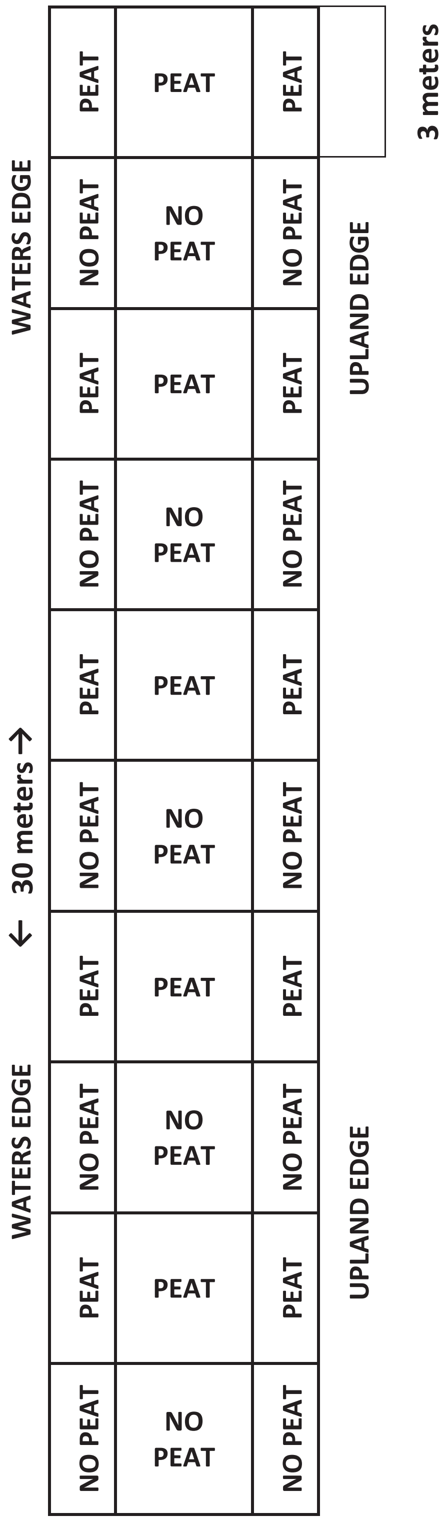

Figure 4.2. The experimental design used at the Marsin and Sand Point restoration sites in Michigan's western Upper Peninsula.

Figure 4.3. The Sand Point restoration site showing completed planting (June 28, 2010). Photograph by J. Bess.

Figure 4.4. The Marsin restoration site showing completed planting (June 26, 2010). Photograph by J. Bess.

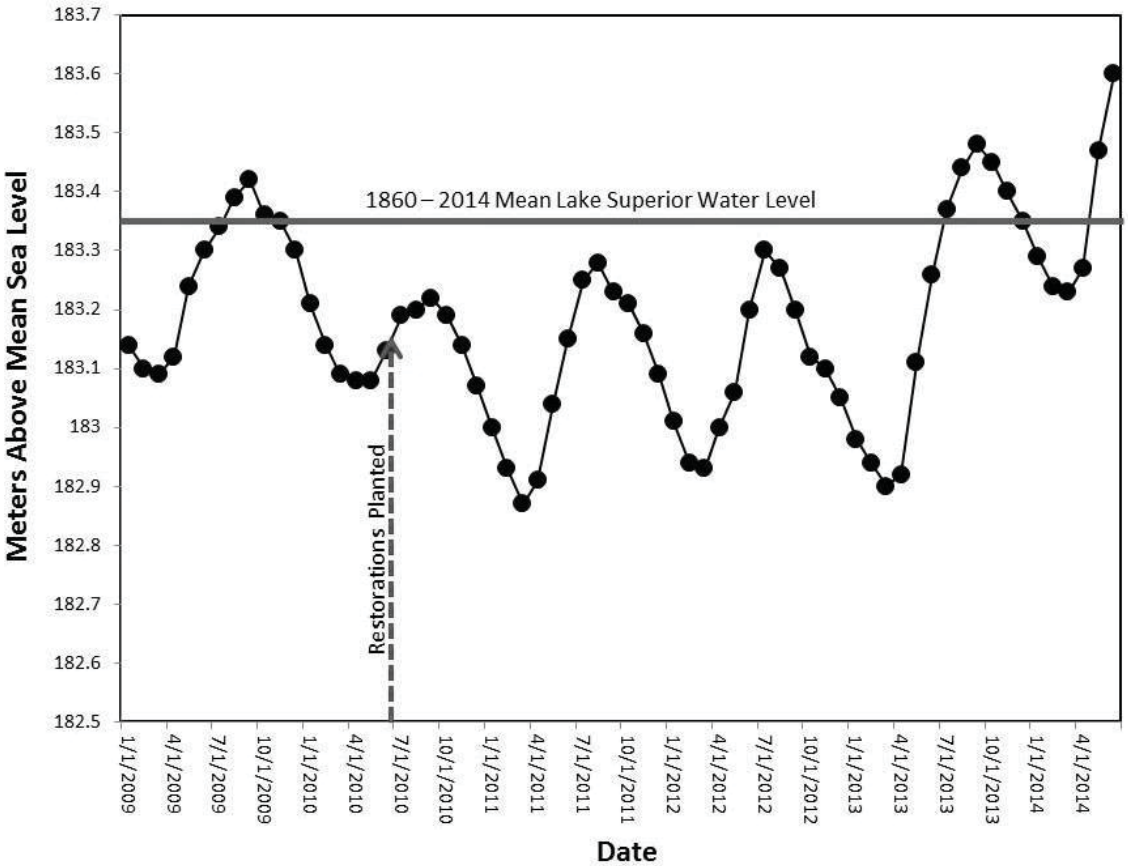

Figure 4.5. Lake Superior water levels 2009 - 2014 with 154 year mean water level and date of restoration plantings at Marsin and Sand Point. Data from NOAA.

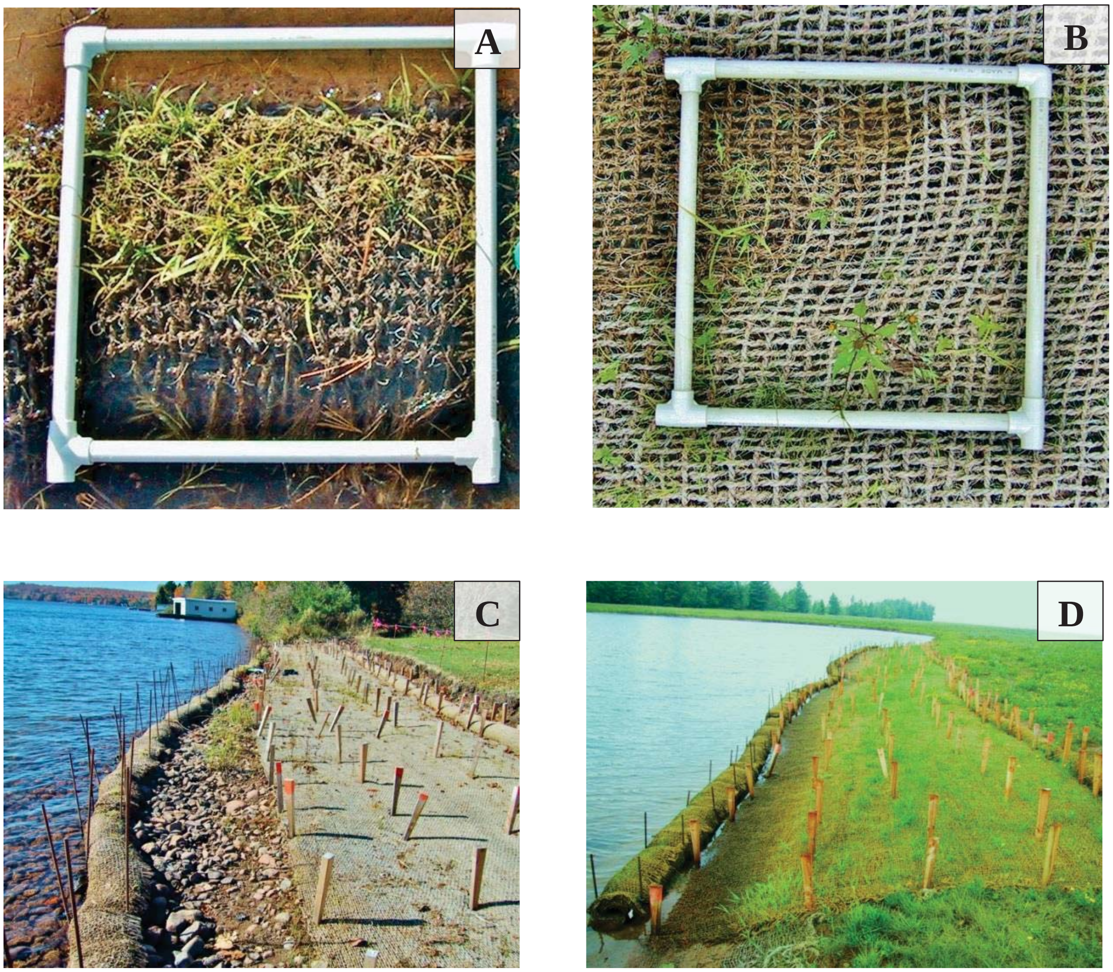

Figure 4.6A-D. Photos showing initial germination of seedlings at the Marsin and Sand Point restoration sites (2010). A.) Marsin Emergent Log – close up, B.) Marsin Fen Meadow – close up, C.) Marsin Center – entire restoration, D.) Sand Point – entire restoration. Photographs by J. Bess.

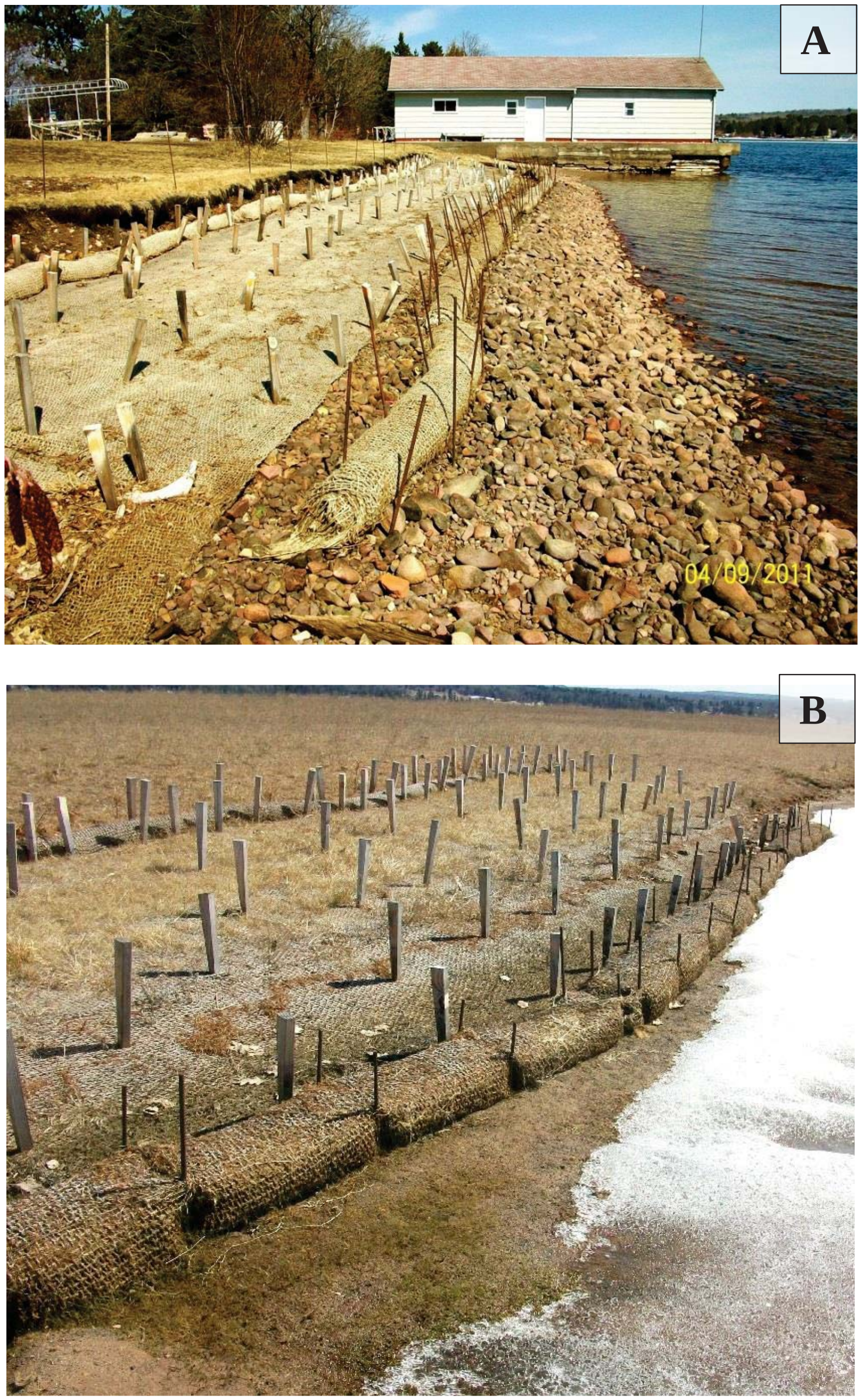

Figure 4.7A-B. The Marsin and Sand Point restoration sites showing low Lake Superior water levels in spring of 2011. A) Marsin wetland restoration site on April 9, 2011; B) Sand Point wetland restoration site on March 17, 2011. Photographs by J. Bess.

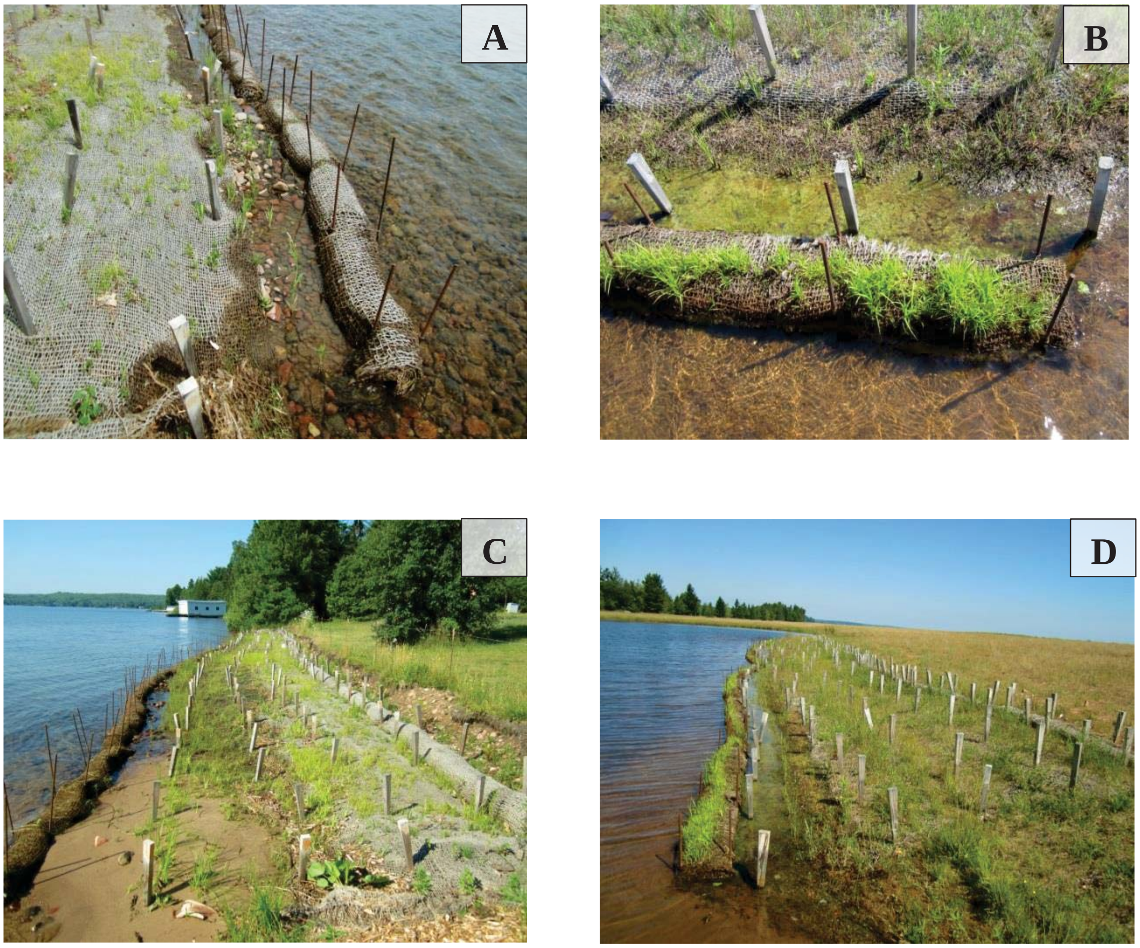

Figure 4.8A-D. Photographs showing condition of vegetation at the Marsin and Sand Point restoration sites in August, 2011. A.) Marsin site showing death of seedlings in emergent zone logs. B.) Sand Point site showing continued growth of seedlings in emergent logs. C.) Marsin site showing growth of wetland vegetation in wet meadow zone. D.) Sand Point site showing growth of vegetation in emergent logs and wet meadow zones. Photographs by J. Bess.

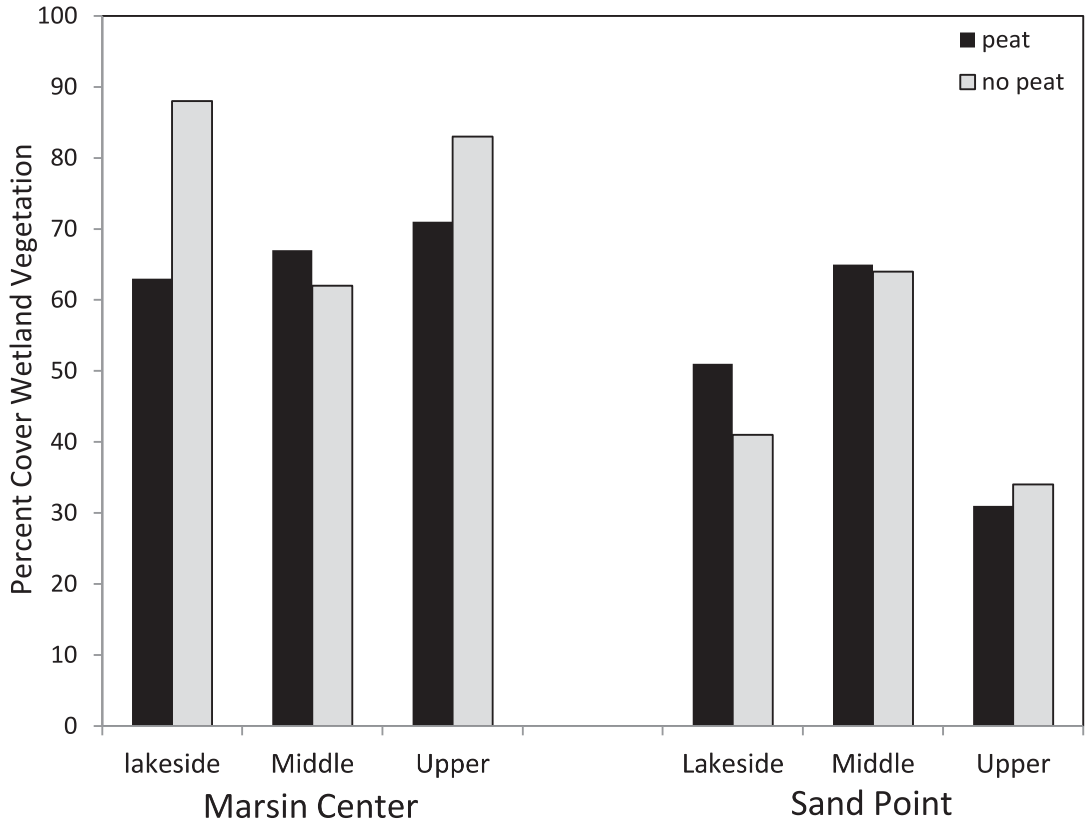

Figure 4.9. Average vegetative cover at the Marsin and Sand Point restoration sites 1 year post-planting (2010).

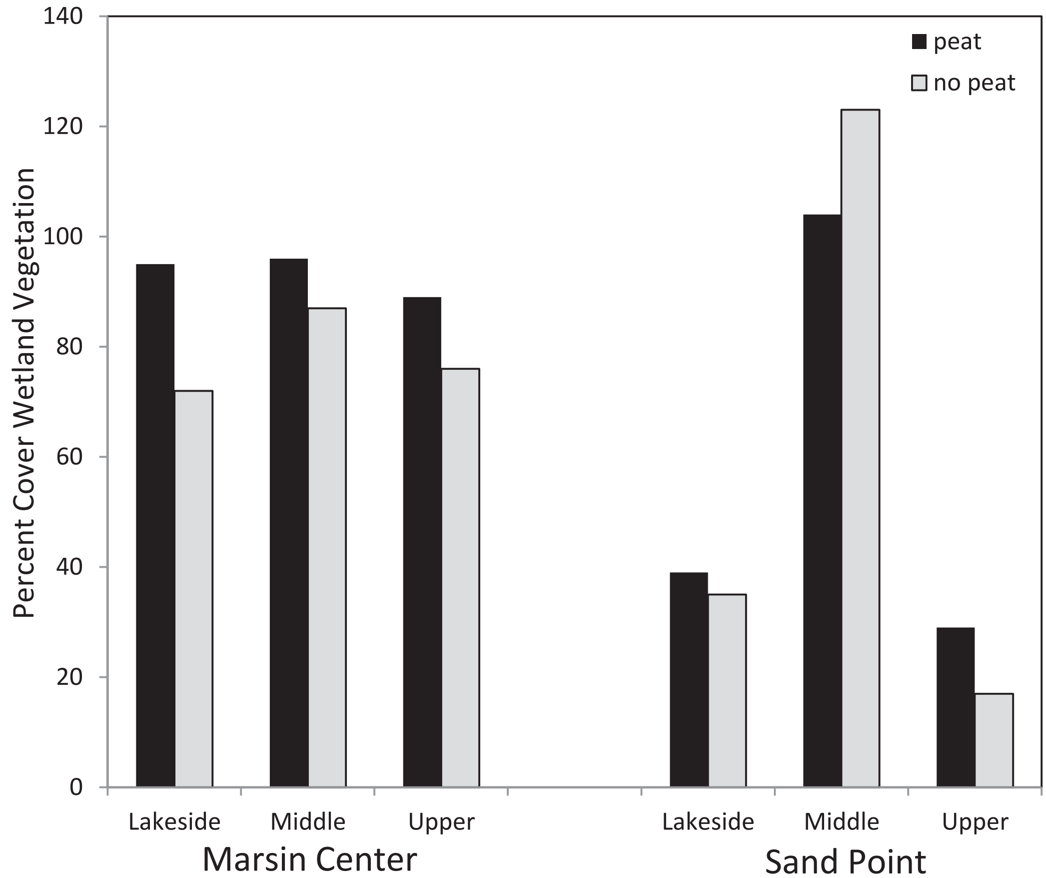

Figure 4.10. Average vegetative cover at the Marsin and Sand Point restoration sites 2 years post-planting (2011).

Figure 4.11A-B. Photos showing condition of vegetation and water levels at the Marsin and Sand Point restoration sites 3 years post-planting. A.) Marsin Center and B.) Sand Point in August, 2013. Photographs by J. Bess.

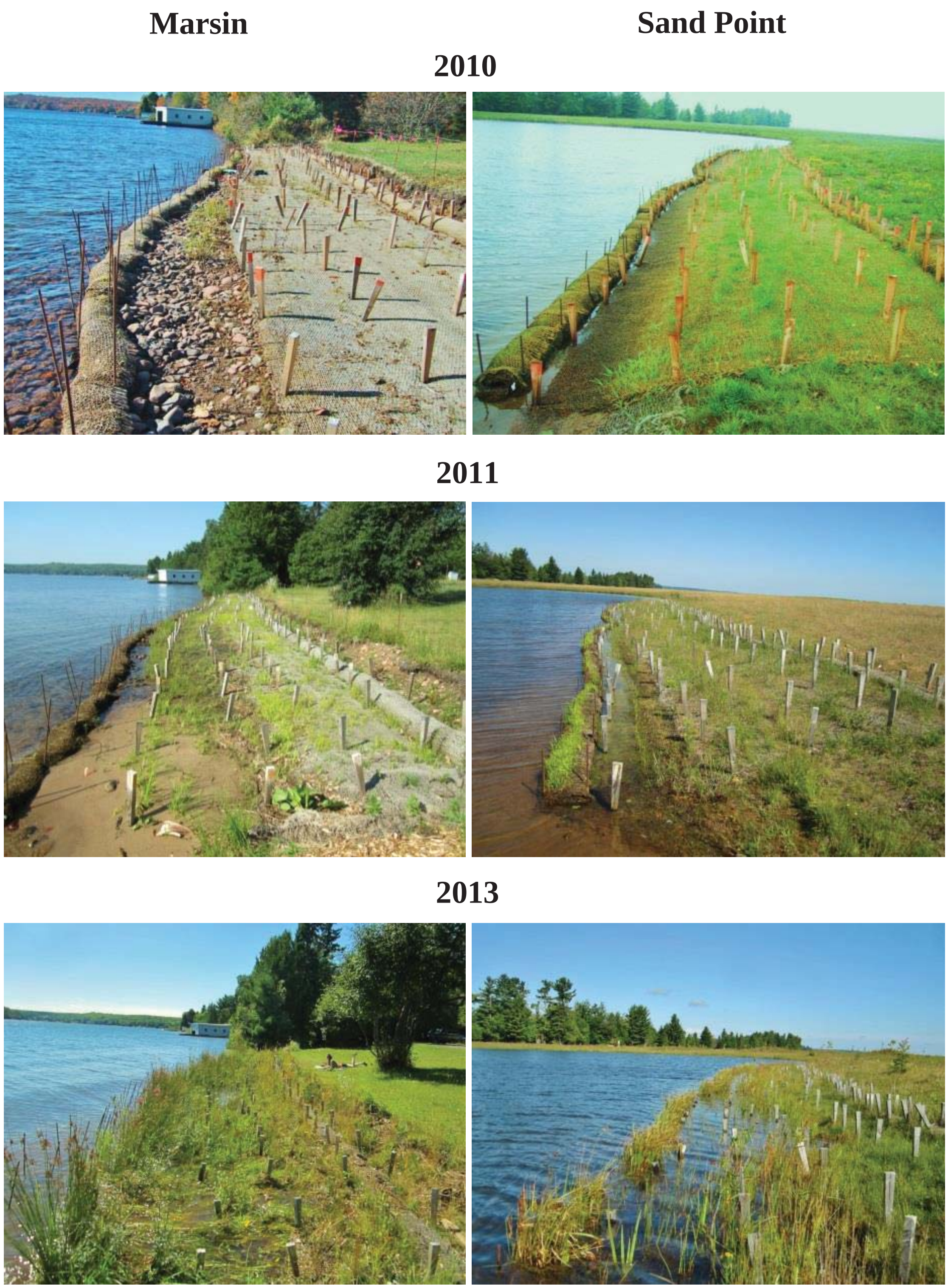

Figure 4.12. Time sequence photographs of Marsin and Sand Point restoration sites showing condition of vegetation and lake water levels (2010-2013). Photographs by J. Bess.

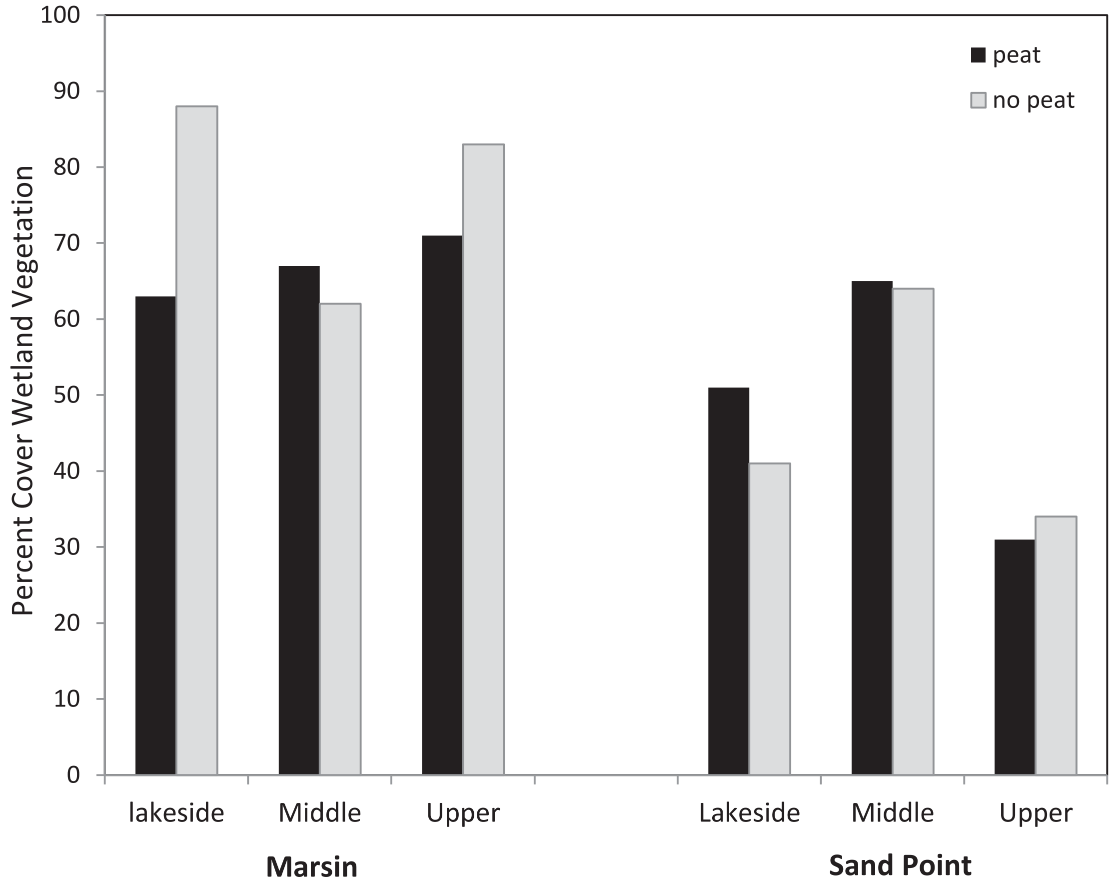

Figure 4.13. Vegetative cover at the Marsin and Sand Point restoration sites in 2013.

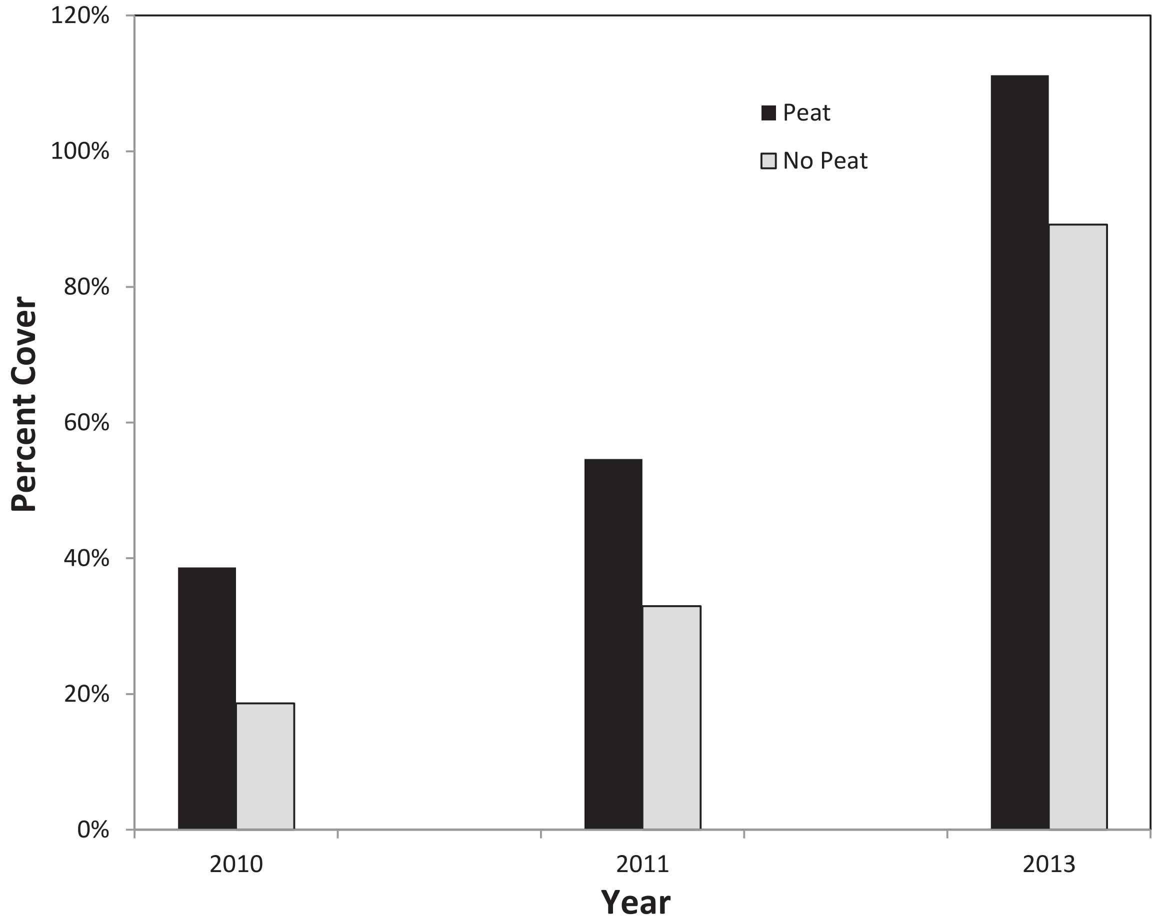

Figure 4.14. Vegetative cover on the emergent logs at the Sand Point restoration site 2010-2013.

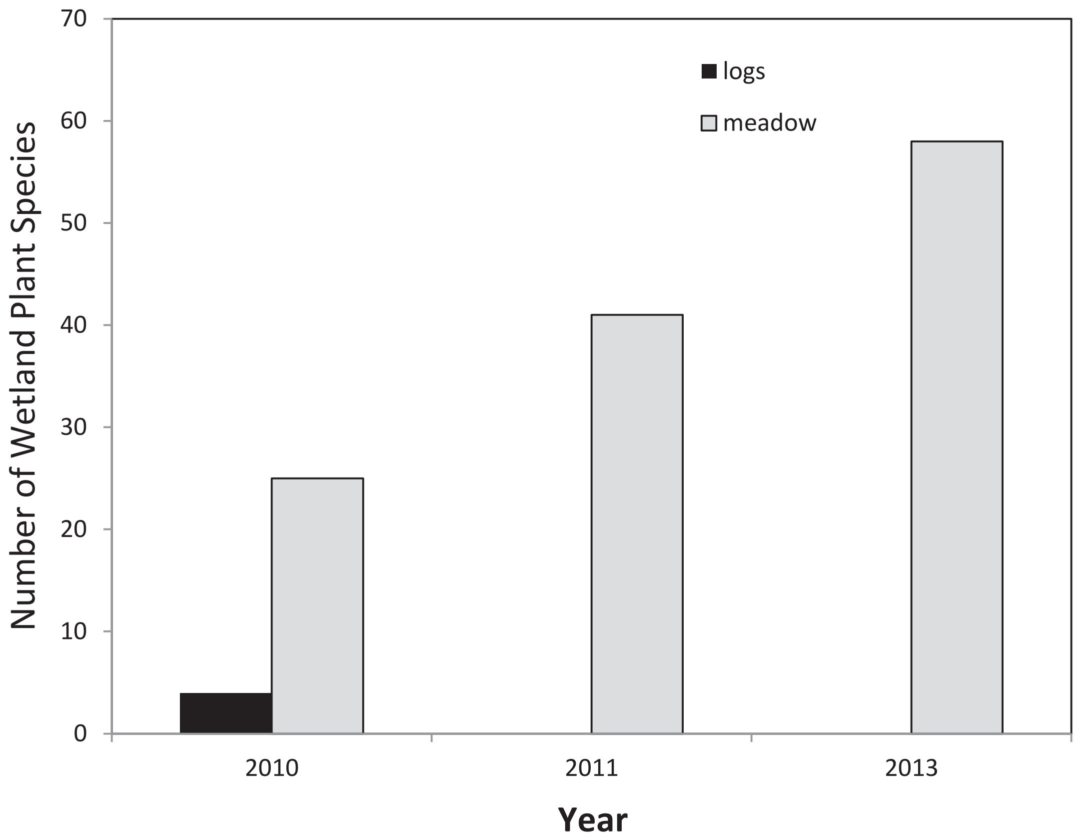

Figure 4.15. Wetland plant species diversity in the emergent logs and fen meadow plots at the Marsin restoration site (2010-2013).

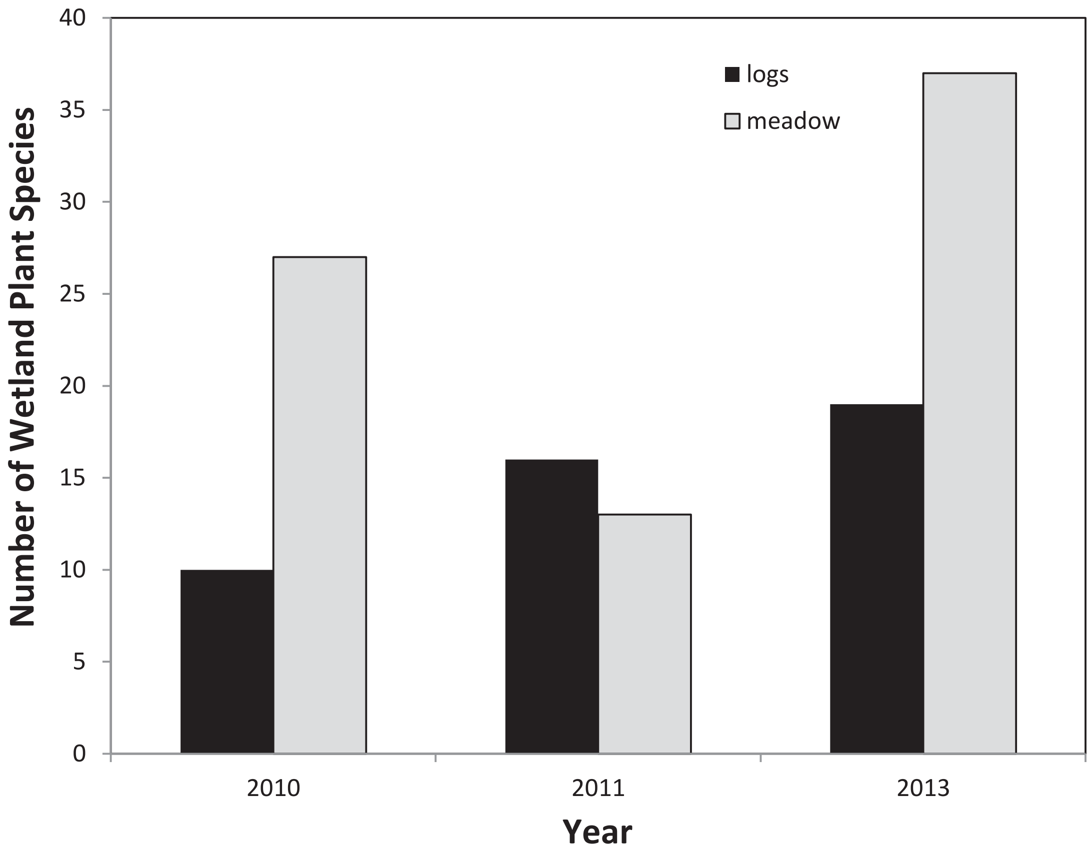

Figure 4.16. 2010-2013 wetland plant species diversity at the Sand Point restoration site.

Table 4.1. Vegetation cover by plant species at the Marsin Center site prior to clearing for restoration (2009).

Wetland Species

Plant Species	1	2	3	4	5	6	7	8	9	10	Mean Cover
Agrostis perennans									10		**1**
Alnus incana							22				**2.2**
Anemone canadensis				12		2			27		**4.1**
Calamagrostis canadensis			25	3	80		11	20	17	10	**17**
Carex stricta	35	18	65	80	60	20	15	40	35	5	**37**
Cornus stolonifera										25	**2.5**
Doellingeria umbellatus			4								**0.4**
Eupatorium maculatum				3							**0.3**
Euthamia graminifolia			2								**0.2**
Impatiens capensis						1		2	1		**0.4**
Lycopus uniflorus			1		1						**0.2**
Mentha x spicata	40	48	18	15	15	4	5	15	25	5	**19**
Myrica gale			3		25	70	65			40	**20**
Phalaris arundinacea	25	60	10	12	3	10	10	70	35	60	**29**
Physocarpus opulifolius						5					**0.5**
Salix spp.	5			1							**0.6**
Symphyotrichum puniceus			1	6	3						**1**
Symphyotrichum simplex	3			2	2			13		8	**2.8**
Totals:	**108**	**126**	**129**	**134**	**189**	**112**	**128**	**160**	**150**	**153**	**139**

Upland Species

Plant Species	1	2	3	4	5	6	7	8	9	10	Mean Cover
Agropyron repens									1	2	**0.3**
Dactylis glomerata				5							**0.5**
Danthonia spicata	7	3	8	2					6		**2.6**
Festuca sp.	2										**0.2**
Fragaria virginica				1			1				**0.2**
Gnaphalium obtusifolium							4				**0.4**
Hieracium sp.							2				**0.2**
Poa compressa						15	15		20		**5**
Solidago canadensis	12		2			3			1	3	**2.1**
Sonchus arvensis	5	5	4								**1.4**
Taraxicum officinale				1					1	1	**0.3**
Totals:	**26**	**8**	**14**	**9**	**0**	**18**	**22**	**0**	**29**	**6**	**13**

Table 4.2. Plant species used in the 2010 Marsin and Sand Point restoration plantings and seed amounts per log and plot.

Species	Seed amounts (grams) per Log/Plot			Species	Seed amounts (grams) per Log/Plot		
	Emergent	Meadow	Shrub		Emergent	Meadow	Shrub
Acorus calamus	4			*Juncus balticus*	0.5	2	
Aronia melanocarpa			0.5	*Juncus effusus*	3	2	
Asclepias incarnata	0.5	2		*Juncus* spp. mix	1.5	2	
Bidens mix		4		*Larix laricina*			0.9
Calamagrostis can.	0.5	2		*Lycopus* mix		1	
Carex comosa	4	4		*Myrica gale*			4.5
Carex crinita	4	5		*Physocarpus opul.*			1.5
Carex magellanica		2		*Pontederia cordata*	5	5	
Carex projecta		4		*Rosa palustris*			4
Carex pseudocyperus	2	1		*Sagittaria latifolia*	1	1	
Carex retrorsa		3		*Sambucus canadensis*			3
Carex scoparia		3		*Scirpus acutus*	2	2	
Carex vesicaria		0.8		*Scirpus atrovirens*		1	
Cladium mariscoides	5	5		*Scirpus cyperinus*	2	1	
Cornus stolonifera			4	*Solidago uliginosa*		2	
Doellingeria umb.		4		*Sparganium amer.*	5	4	
Eleocharis palustris	4	4		*Sparganium eury.*	5	4	
Eriocaulon aquaticum		0.5		*Thalictrum dasy.*		6	
Eupatorium mac.		2		*Thuja occidentalis*			4
Eupatorium perf.		0.5		*Triadenum fraseri*		2	
Euthamia gramnifolia		2		*Viburnum cassinoides*			2
Ilex verticillata			1.5	*Viburnum opulus*			2
Iris versicolor	5	4		**Totals per log/plot:**	**54**	**88**	**28**

Table 4.3. Average vegetative cover on the emergent log and fen meadow zones at the A) Marsin and B) Sand Point restoration sites in late summer 2010.

A. Marsin

	Peat Sectors/Logs						No Peat Sectors/Logs					
Zone/Sector	**1**	**2**	**3**	**4**	**5**	**Ave.**	**1**	**2**	**3**	**4**	**5**	**Ave.**
Emergent Logs	11	15	17	24	27	**19**	12	9	38	33	39	**26**
Wet Meadow												
Lakeside	31	46	71	46	41	**47**	29	30	27	16	24	**25**
Middle	37	68	63	61	52	**56**	18	37	54	38	51	**40**
Upper	40	62	68	25	46	**48**	25	41	31	37	49	**37**
Average	**36**	**59**	**67**	**44**	**46**	**50**	**24**	**36**	**37**	**30**	**41**	**34**

B. Sand Point

	Peat Sectors/Logs						No Peat Sectors/Logs					
Zone/Sector	**1**	**2**	**3**	**4**	**5**	**Ave.**	**1**	**2**	**3**	**4**	**5**	**Ave.**
Emergent Logs	38	35	41	32	47	**39**	21	28	12	15	16	**18**
Wet Meadow												
Lakeside	22	123	137	142	126	**110**	43	130	108	106	73	**92**
Middle	134	124	166	170	115	**142**	105	110	157	160	122	**131**
Upper	32	1	12	11	35	**18**	6	7	5	12	53	**17**
Average	**63**	**83**	**105**	**108**	**92**	**90**	**51**	**82**	**90**	**93**	**83**	**80**

Table 4.4. Percent cover for select wetland plant species in the emergent log and fen meadow zones at the Marsin and Sand Point restoration sites in late summer 2010.[1]

	Marsin 2010										Sand Point 2010									
	Emergent Logs		Fen Meadow Sectors: Lakeside		Middle		Upper		Meadow Totals		Emergent Logs		Fen Meadow Sectors: Lakeside		Middle		Upper		Meadow Totals	
Plant Species	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**
Agrostis hyemale															1%				**3%**	
Asclepias incarnata	1%	1%	1%		1%		1%		**1%**				0%		4%		3%		2%	
Aster umbellatus			2%	2%	3%	4%	3%	3%	**2%**	**3%**			0%	1%	1%	1%	0%		0%	1%
Bidens frondosa			9%	7%	5%	5%	3%	4%	**6%**	**5%**			2%	6%	4%	2%			2%	3%
Carex spp.	4%	4%	20%	9%	19%	16%	22%	17%	**20%**	**14%**	12%	5%	20%	29%	4%	6%	6%	3%	10%	13%
Echinocloa crus-galli													1%		11%	10%	1%		4%	3%
Eleocharis acicularis													52%	38%	66%	56%		6%	39%	33%
Eleocharis palustris											1%	2%								
Epilobium sp.															2%	2%			1%	1%
forb seedlings	1%		4%	3%	4%	5%	3%	3%	**4%**	**4%**			1%	1%	1%	3%	2%		1%	1%
Iris versicolor[2]	10%	16%	1%		2%	1%	1%	1%	**1%**	**1%**	11%	8%								
Juncus arcticus													1%		11%	10%	3%		5%	3%
Juncus effusus																4%		1%		2%
Juncus spp.	2%	4%	5%	2%	3%	6%	5%	6%	**4%**	**5%**	6%	1%	9%	7%	7%	10%		3%	6%	7%
Lycopus spp.			1%		1%	1%			**1%**	**0%**					2%	2%			1%	1%
Persicaria pensylvanica													1%	1%	1%	2%			1%	1%
Phalaris arundinacea			2%	1%	1%				**1%**											
Pontederia cordata											1%									
Sagittaria latifolia											2%	1%	5%	1%					2%	
Scirpus spp.			1%		1%	1%	1%	1%	**1%**	**1%**	5%	1%								
Thalictrum dasycarpum					1%	1%	1%	1%		**1%**										
Total Cover	**18%**	**25%**	**45%**	**22%**	**41%**	**38%**	**39%**	**35%**	**41%**	**32%**	**38%**	**18%**	**93%**	**84%**	**115%**	**108%**	**15%**	**13%**	**77%**	**69%**

1: Only wetland plant species with 1% total cover or greater are included. For species with 0.5 – 0.99% cover per zone, value was rounded up to 1%. P = peat plots/logs and N = no peat plots/logs.

2: The "*Iris*" seedling values for the emergent logs likely include some *Sparganium* seedlings as these were very difficult to tell apart in the field.

Table 4.5. Total plant species richness in the emergent log and fen meadow zones at the Marsin and Sand Point restoration sites in late summer 2010.[1]

	Marsin 2010										Sand Point 2010									
	Emergent Logs		Fen Meadow Sectors: Lakeside		Middle		Upper		Meadow Totals		Emergent Logs		Fen Meadow Sectors: Lakeside		Middle		Upper		Meadow Totals	
Plant Species	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**
Agrostis hyemale															1				**1**	
Anemone canadensis								1		**1**										
Aronia melanocarpa								1		**1**										
Asclepias incarnata	1	1	1	1	1	1	1	1	**1**	**1**	1		1	1	1	1	1		**1**	**1**
Bidens cernuus			1	1	1	1	1		**1**	**1**					1		1		**1**	
Bidens frondosa			1	1	1	1	1	1	**1**	**1**	1	1	1	1	1	1			**1**	**1**
Calamagrostis canadensis			1	1	1	1	1	1	**1**	**1**										
Carex lasiocarpa	1	1	1	1					**1**	**1**										
Carex stricta			1	1					**1**	**1**										
Carex spp.	1	1	1	1		1	1	1	**1**	**1**	1	1	1	1	1	1	1	1	**1**	**1**
Doellingeria umbellata			1	1		1		1	**1**	**1**			1	1	1	1	1		**1**	**1**
Echinocloa crus-galli													1	1	1	1	1	1	**1**	**1**
Eleocharis acicularis													1	1	1	1		1	**1**	**1**
Eleocharis palustris						1		1		**1**	1	1	1	1					**1**	**1**
Epilobium sp.														1	1	1		1	**1**	**1**
Equisetum sp.			1		1	1			**1**	**1**										
Eupatorium perfoliatum																1				**1**
Euthamia graminifolia								1		**1**						1				**1**
forb seedlings	1	1	1	1	1	1	1	1	**1**	**1**	1	1	1	1	1	1	1		**1**	**1**
Iris versicolor[2]	1	1	1	1	1	1	1	1	**1**	**1**	1	1	1	1	1	1			**1**	**1**
Juncus arcticus													1		1	1	1		**1**	**1**
Juncus effusus															1	1		1	**1**	**1**
Juncus spp.	1	1	1	1	1	1	1	1	**1**	**1**	1	1	1	1	1	1	1	1	**1**	**1**
Lycopus spp.			1	1	1	1	1	1	**1**	**1**			1	1	1	1			**1**	**1**
Mentha x *spicata*					1	1			**1**	**1**										
Persicaria pensylvanica			1		1				**1**				1	1	1	1			**1**	**1**
Phalaris arundinacea			1	1	1	1	1	1	**1**	**1**										
Physocarpus opulifolius					1				**1**											
Pontederia cordata											1	1							**1**	**1**
Potentilla norvegica															1	1			**1**	**1**
Rumex sp.			1						**1**											
Sagittaria latifolia											1	1	1	1					**1**	**1**
Scirpus spp.			1	1	1	1	1	1	**1**	**1**	1	1							**1**	**1**
Shrub seedlings														1	1				**1**	**1**
Solidago uliginosa															1	1			**1**	**1**
Spirea alba														1	1	1			**1**	**1**
Symphyotrichum simplex																1				
Thalictrum dasycarpum			1	1	1	1	1	1	**1**	**1**			1		1	1			**1**	**1**
Viola blanda															1				**1**	
Total Species	**6**	**6**	**18**	**15**	**15**	**16**	**12**	**16**	**20**	**21**	**10**	**9**	**15**	**16**	**22**	**21**	**8**	**6**	**26**	**25**

1: P = peat plots/logs and N = no peat plots/logs. In columns, 1 = present, blank = absent.

2: The "*Iris*" seedling values for the emergent logs likely include some *Sparganium* seedlings as these were very difficult to tell apart in the field.

Table 4.6. Vegetative cover on the emergent logs and in the emergent log and fen meadow zones at the A) Marsin and B) Sand Point restoration in late summer 2011. Peat plots/logs refers to the 5 replicates of each log/plot per treatment (peat or no peat).

A. Marsin

	Peat Plots/Logs						No Peat Plots/Logs					
Zone/Sector	**1**	**2**	**3**	**4**	**5**	**Ave.**	**1**	**2**	**3**	**4**	**5**	**Ave.**
Emergent Logs	0	0	0	0	0	**0**	0	0	0	0	0	**0**
Fen Meadow												
Lakeside	42	85	104	128	116	**95**	39	79	64	95	83	**72**
Middle	48	80	135	116	130	**102**	48	91	88	86	121	**87**
Upper	33	76	104	103	101	**83**	44	87	84	70	96	**76**
Average	**41**	**80**	**114**	**116**	**116**	**93**	**44**	**86**	**79**	**84**	**100**	**78**

B. Sand Point

	Peat Plots/Logs						No Peat Plots/Logs					
Zone/Sector	**1**	**2**	**3**	**4**	**5**	**Ave.**	**1**	**2**	**3**	**4**	**5**	**Ave.**
Emergent Logs	62	48	53	48	62	**55**	47	21	25	35	37	**33**
Fen Meadow												
Lakeside	28	30	40	39	57	**39**	54	42	24	20	35	**35**
Middle	42	107	124	144	100	**103**	78	120	138	144	134	**123**
Upper[1]	*	*	*	*	*	*	*	*	*	*	*	*
Average	**35**	**69**	**82**	**92**	**79**	**71**	**66**	**81**	**81**	**82**	**85**	**79**

1: These data were not collected in 2011 as the sector looked identical to 2010 and had little wetland plant growth.

Table 4.7. ANOVA results for comparison of treatment and sector effects in the fen meadow zone at the Marsin and Sand Point restoration sites in late summer 2011. Sector refers to the three sampling sectors; "lakeside", "middle" and "upper". Treat is treatment type - peat addition or no peat addition.

2011 Data

Site Restoration Parameter	Root MSE	y1 Mean	y1 F-stat	y1 P-value	Sector P-val	Treat P-val	R^2
Marsin							
Wetland Plant Vegetative Cover	36	86	3.7	0.013*	0.11	0.01*	0.07
Wetland Plant Diversity	2.5	9	4.5	0.005*	0.002*	0.35	0.09
Sand Point							
Wetland Plant Vegetative Cover	30	55	102	<.0001*	<.0001*	0.28	0.68
Wetland Plant Diversity	2	4	73	<.0001*	<.0001*	0.30	0.60

Table 4.8. Percent cover values for select wetland plant species in the emergent log and fen meadow zones at the Marsin and Sand Point restoration sites in late summer 2011.[1]

	Marsin 2011										Sand Point 2011									
	Emergent[2] Logs		Fen Meadow Sectors: Lakeside		Middle		Upper		Meadow Totals		Emergent Logs		Fen Meadow Sectors: Lakeside		Middle		Upper[3]		Meadow Totals	
Plant Species	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**
Agrostis perennans				1%	1%	2%		1%	**1%**	**1%**			2%	5%	13%	14%			**7%**	**8%**
Asclepias incarnata															3%				**2%**	
Bidens frondosa			6%	3%	4%	2%	2%	3%	**4%**	**3%**	2%	3%	4%	3%	4%	3%			**4%**	**3%**
Calamagrostis canadensis			1%	1%	2%	1%	2%		**2%**	**1%**			1%						**1%**	
Carex stricta			5%	3%	4%	4%	4%	6%	**5%**	**4%**			4%	4%	1%	1%			**2%**	**2%**
Cyperaceae spp.			34%	25%	37%	25%	32%	24%	**34%**	**25%**	36%	13%	8%	5%	7%	3%			**17%**	**7%**
Doellingeria umbellata			6%	4%	7%	8%	5%	7%	**6%**	**6%**					3%	2%			**2%**	**1%**
Eleocharis acicularis															23%	55%			**16%**	**27%**
Epilobium sp.			1%	1%		2%				**1%**										
Eupatorium perfoliatum																1%				**1%**
Euthamia graminifolia															2%				**1%**	
feather moss sp.																2%				**1%**
Iris versicolor[4]			5%	1%	7%	4%	5%	3%	**6%**	**3%**	11%	12%	1%	1%	3%				**2%**	**1%**
Juncus arcticus			2%						**1%**				2%	2%	12%	14%			**7%**	**8%**
Juncus effusus			6%	4%	1%		2%	1%	**3%**	**2%**						1%				**1%**
Juncus spp.			12%	14%	17%	14%	16%	15%	**15%**	**14%**	5%	2%	2%	6%	21%	16%			**16%**	**11%**
Lycopus spp.			2%	2%	2%	5%	2%	4%	**2%**	**4%**					3%	5%			**2%**	**3%**
Persicaria pensylvanica														1%						**1%**
Phalaris arundinacea			3%	2%	3%	2%	1%	1%	**2%**	**2%**										
Physocarpus opulifolius				2%	2%		1%	1%	**1%**	**1%**										
Potentilla norvegica			1%	1%	2%	4%	1%	1%	**1%**	**2%**										
Sagittaria latifolia													3%	1%					**2%**	**1%**
Solidago uliginosa			5%	4%	5%	5%	6%	5%	**5%**	**5%**										
Spirea alba															1%				**1%**	
Symphyotrichum puniceum			1%						**1%**					1%					**1%**	
Thalictrum dasycarpum			1%	2%	2%	2%	1%	1%	**1%**	**1%**					2%	2%			**1%**	**1%**
Total Cover			91%	70%	96%	80%	80%	73%	**90%**	**75%**	54%	30%	27%	29%	98%	119%	0%	0%	**84%**	**77%**

1: Only wetland plant species with 1% total cover or greater are included. For species with 0.5 – 0.99% cover per zone, value was rounded up to 1%. P = peat plots/logs and N = no peat plots/logs.

2: All vegetation on Marsin site emergent logs died in spring of 2011 due to low lake levels.

3: Data were not collected in upper sector at Sand Point in 2011 as the conditions looked the same as in 2010 with little wetland vegetation development.

4: The "*Iris*" seedling values for the emergent logs at Sand Point likely include some *Sparganium* seedlings as these were very difficult to tell apart in the field.

Table 4.9. Plant species richness in the emergent log and fen meadow zones at the Marsin and Sand Point restoration sites in late summer 2011.[1]

	Marsin 2011										Sand Point 2011									
	Emergent[2] Logs		Fen Meadow Sectors: Lakeside		Middle		Upper		Meadow Totals		Emergent Logs		Fen Meadow Sectors: Lakeside		Middle		Upper[3]		Meadow Totals	
Plant Species	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**
Agrostis perennans				1	1	1		1	**1**	**1**			1	1	1	1			**1**	**1**
Alnus incana						1		1		**1**										
Anemone canadensis						1		1		**1**										
Asclepias incarnata															1				**1**	
Bidens frondosa			1	1	1	1	1	1	**1**	**1**	1	1	1	1	1	1			**1**	**1**
Calamagrostis canadensis			1	1	1	1	1		**1**	**1**			1						**1**	
Carex lasiocarpa				1						**1**										
Carex stricta			1	1	1	1	1	1	**1**	**1**			1	1	1	1			**1**	**1**
Cyperaceae spp.[4]			1	1	1	1	1	1	**1**	**1**	1	1	1	1	1	1			**1**	**1**
Cuscuta sp.						1				**1**										
Doellingeria umbellata			1	1	1	1	1	1	**1**	**1**					1	1			**1**	**1**
Eleocharis acicularis															1	1			**1**	**1**
Epilobium sp.			1	1		1				**1**										
Eupatorium maculatum						1		1		**1**										
Eupatorium perfoliatum																1				**1**
Euthamia graminifolia						1		1		**1**					1				**1**	
feather moss sp.																1				**1**
Iris versicolor[5]			1	1	1	1	1	1	**1**	**1**	1	1	1	1	1				**1**	**1**
Juncus arcticus			1						**1**				1	1	1	1			**1**	**1**
Juncus effusus			1	1	1		1	1	**1**	**1**						1				**1**
Juncus spp.			1	1	1	1	1	1	**1**	**1**	1	1	1	1	1	1			**1**	**1**
Lycopus spp.			1	1	1	1	1	1	**1**	**1**					1	1			**1**	**1**
Persicaria pensylvanica														1						**1**
Phalaris arundinacea			1	1	1	1	1	1	**1**	**1**										
Physocarpus opulifolius				1	1		1	1	**1**	**1**										
Potentilla norvegica			1	1	1	1	1	1	**1**	**1**										
Sagittaria latifolia													1	1					**1**	**1**
Solidago uliginosa			1	1	1	1	1	1	**1**	**1**										
Spirea alba															1				**1**	
Symphyotrichum puniceum			1						**1**					1					**1**	
Thalictrum dasycarpum			1	1	1	1	1	1	**1**	**1**					1	1			**1**	**1**
Veronica beccabunga				1		1		1		**1**										
Total Cover			16	18	15	20	14	19	**17**	**23**	4	4	9	10	14	13	0	0	**17**	**16**

1: P = peat plots/logs and N = no peat plots/logs.

2: All vegetation on Marsin site emergent logs died in spring of 2011 due to low lake levels.

3: Data were not collected in upper sector at Sand Point in 2011 as the conditions looked the same as in 2010 with little wetland vegetation development.

4: This includes vegetative *Carex* and *Scirpus* spp.

5: The "*Iris*" seedling values for the emergent logs at Sand Point likely include some *Sparganium* seedlings as these were very difficult to tell apart in the field.

Table 4.10. *Carex stricta* survivorship in the fen meadow zone at the A) Marsin Center and B) Sand Point restoration sites in late summer 2011.

A. Marsin Center

	Block and Treatment										Treatment & Zone Totals	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
Zone	**Peat**	**No Peat**	**Peat**	**No Peat**	**Peat**	**No Peat**	**Peat**	**No Peat**	**Peat**	**No Peat**	**Peat**	**No Peat**
Lakeside	6	4	7	8	5	6	1	6	2	8	**21**	**32**
Mid-Plot	3	5	7	8	6	6	2	6	3	7	**21**	**32**
Upper	7	8	7	8	8	5	6	4	4	8	**32**	**33**
Block Totals:	**16**	**17**	**21**	**24**	**19**	**17**	**9**	**16**	**9**	**23**	**74**	**97**

B. Sand Point

	Block and Treatment										Treatment & Zone Totals	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
Zone	**Peat**	**No Peat**	**Peat**	**No Peat**	**Peat**	**No Peat**	**Peat**	**No Peat**	**Peat**	**No Peat**	**Peat**	**No Peat**
Lakeside	7	8	4	6	6	4	7	4	7	8	**31**	**30**
Mid-Plot	1	4	3	4	4	3	0	7	4	2	**12**	**20**
Upper	0	1	0	0	0	0	0	0	3	0	**3**	**1**
Block Totals:	**8**	**13**	**7**	**10**	**10**	**7**	**7**	**11**	**14**	**10**	**46**	**51**

Table 4.11. Percent cover values for select wetland plants in the emergent log and fen meadow zones at the Marsin and Sand Point restoration sites in late summer 2013.[1]

	Marsin 2013										Sand Point 2013									
	Emergent[2] Logs		Fen Meadow Sectors: Lakeside		Middle		Upper		Meadow Totals		Emergent Logs		Fen Meadow Sectors: Lakeside		Middle		Upper		Meadow Totals	
Plant Species	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**
Agrostis scabra															1%	2%	2%	2%	**1.0%**	**1.3%**
Agrostis perennans			1%	1%		1%			**0.3%**	**0.7%**						1%		2%	**0.0%**	**1.0%**
Asclepias incarnata			1%						**0.3%**				2%	1%	9%	4%	4%		**4.3%**	**1.7%**
Calamagrostis canadensis			2%	2%	1%	1%	2%	3%	**1.7%**	**2.0%**						1%	1%	5%	**0.3%**	**2.0%**
Carex comosa[3]			1%	2%	1%	2%		1%	**0.7%**	**1.7%**	**64%**	**50%**	1%	1%		5%			**21%**	**2.0%**
Carex lasiocarpa				1%						**0.3%**									**0.0%**	**0.0%**
Carex projecta			4%	6%	6%	1%	10%	11%	**6.7%**	**6.0%**			2%		4%	7%	5%	8%	**3.0%**	**5.0%**
Carex scoparia			1%	1%		9%	1%	1%	**0.7%**	**3.7%**	**1%**		3%				1%		**0.7%**	**0.0%**
Carex stipata			1%			2%			**0.3%**	**0.7%**									**0.0%**	**0.0%**
Carex stricta						1%	1%	1%	**0.3%**	**0.7%**	**2%**	**1%**	2%	2%	2%		1%		**1.7%**	**0.7%**
Carex spp.						1%			**3.0%**	**0.3%**									**0.0%**	**0.0%**
Doellingeria umbellata			2%	4%	2%	5%	5%	6%		**5.0%**					1%		1%		**0.7%**	**0.0%**
Eleocharis acicularis													1%	1%	1%	1%			**0.3%**	**0.7%**
Eleocharis palustris											**1%**	**1%**	7%	7%					**0.3%**	**2.3%**
Epilobium sp.									**0.3%**										**0.0%**	**0.0%**
Equisetum sp.							1%		**1.0%**										**0.0%**	**0.0%**
Eupatorium maculatum			3%	2%		2%		1%	**0.0%**	**1.7%**									**0.0%**	**0.0%**
Eupatorium perfoliatum									**1.0%**	**0.0%**									**0.0%**	**0.0%**
Euthamia graminifolia			1%		1%	1%	1%	1%		**0.7%**				1%	1%				**0.3%**	**0.3%**
Iris versicolor[4]			8%	7%	9%	5%	6%	4%	**2.0%**	**5.3%**	**15%**	**14%**	3%	1%	4%	3%			**6%**	**1.3%**
Juncus arcticus			4%	10%	2%	2%			**12%**	**4.0%**			2%	3%	11%	14%	9%	6%	**7%**	**7.7%**
Juncus effusus			26%	18%	6%	6%	3%	4%	**14%**	**9.3%**	**2%**		4%	1%	2%	2%		2%	**1.3%**	**1.7%**
Juncus spp.			13%	19%	16%	18%	13%	11%	**2.3%**	**16.0%**	**12%**	**7%**	18%	21%	14%	10%	2%	2%	**9%**	**11%**
Lycopus spp.			3%	6%	2%	3%	2%	3%	**3.7%**	**4.0%**			1%	1%	5%	5%		1%	**1.7%**	**2.3%**
Myrica gale			1%	2%	6%	4%	4%	5%		**3.7%**									**0.0%**	**0.0%**
Persicaria sagittata					1%				**1.3%**										**0.0%**	**0.0%**
Phalaris arundinacea			3%	3%	1%	4%		1%		**2.7%**									**0.0%**	**0.0%**
Sagittaria latifolia											**1%**								**0.3%**	**0.0%**
Scirpus atrovirens									**0.3%**		**9%**	**11%**	2%		1%		3%		**4.3%**	**0.0%**
Scirpus cyperinus			1%	1%					**3.3%**	**0.3%**	**4%**		2%		3%		2%		**3.0%**	**0.0%**
Solidago uliginosa			1%	2%	2%	5%	7%	9%		**5.3%**									**0.0%**	**0.0%**
Spiranthes cernua															1%	1%	1%		**0.7%**	**0.3%**
Spirea alba									**0.7%**						1%	1%			**0.3%**	**0.3%**
Symphyotrichum puniceum			1%				1%			**0.0%**					1%	1%			**0.3%**	**0.3%**
Triadenum frasieri																1%				**0.3%**
Total Cover			78%	87%	56%	73%	57%	62%	**56%**	**74%**	**111%**	**84%**	50%	40%	62%	59%	32%	28%	**68%**	**42%**

1: Only wetland plant species with 1% total cover or greater are included. For species with 0.5 – 0.99% cover per zone, value was rounded up to 1%. P = peat plots/logs and N = no peat plots/logs.

2: All vegetation on Marsin site emergent logs died in spring of 2011 due to low lake levels.

3: These values likely include *C. pseudocyperus* vegetation.

4: The "*Iris*" seedling values for the emergent logs at Sand Point likely include some *Sparganium* seedlings as these were very difficult to tell apart in the field.

Table 4.12. Total plant species richness in the emergent log and fen meadow zones at the Marsin and Sand Point restoration sites in late summer 2013.[1]

	Marsin 2013										Sand Point 2013									
	Emergent[2] Logs		Fen Meadow Sectors: Lakeside		Middle		Upper		Meadow Totals		Emergent Logs		Fen Meadow Sectors: Lakeside		Middle		Upper		Meadow Totals	
Plant Species	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**
Agrostis scabra															1	1	1	1	**1**	**1**
Agrostis perennans			1	1		1			**1**	**1**						1		1		**1**
Asclepias incarnata			1						**1**				1	1	1	1	1		**1**	**1**
Calamagrostis canadensis			1	1	1	1	1	1	**1**	**1**						1	1	1	**1**	**1**
Carex comosa[3]			1	1	1	1		1	**1**	**1**	**1**	**1**	1	1		1			**1**	**1**
Carex lasiocarpa				1						**1**										
Carex projecta			1	1	1	1	1	1	**1**	**1**			1		1	1	1	1	**1**	**1**
Carex scoparia			1	1		1	1	1	**1**	**1**	**1**		1				1		**1**	
Carex stipata			1			1			**1**	**1**										
Carex stricta						1	1	1	**1**	**1**	**1**	**1**	1	1	1		1		**1**	**1**
Carex spp.						1				**1**										
Doellingeria umbellata			1	1	1	1	1	1		**1**					1		1		**1**	
Eleocharis acicularis													1	1	1	1			**1**	**1**
Eleocharis palustris											**1**	**1**	1	1					**1**	**1**
Epilobium sp.									**1**											
Equisetum sp.							1		**1**											
Eupatorium maculatum			1	1		1		1	**1**	**1**										
Eupatorium perfoliatum									**1**	**1**										
Euthamia graminifolia			1		1	1	1	1		**1**				1	1				**1**	**1**
feather moss sp.									**1**											
Glyceria canadensis																1				**1**
Impatiens capensis			1						**1**											
Iris versicolor[4]			1	1	1	1	1	1	**1**	**1**	**1**	**1**	1	1	1	1			**1**	**1**
Juncus arcticus			1	1	1	1			**1**	**1**			1	1	1	1	1	1	**1**	**1**
Juncus effusus			1	1	1	1	1	1	**1**	**1**	**1**		1	1	1	1	1	1	**1**	**1**
Juncus spp.			1	1	1	1	1	1	**1**	**1**	**1**	**1**	1	1	1	1	1	1	**1**	**1**
Leersia oryzoides												**1**								
Lycopus spp.			1	1	1	1	1	1	**1**	**1**			1	1	1	1		1	**1**	**1**
Myrica gale			1	1	1	1	1	1		**1**										
Persicaria pensylvanica																				
Persicaria sagittata					1				**1**											
Phalaris arundinacea			1	1	1	1		1		**1**										
Sagittaria latifolia											**1**									
Scirpus atrovirens									**1**		**1**	**1**	1		1		1		**1**	**1**
Scirpus cyperinus			1	1					**1**	**1**	**1**		1		1		1		**1**	
Solidago uliginosa			1	1	1	1	1	1		**1**										
Spiranthes cernua															1	1	1		**1**	**1**
Spirea alba									**1**						1	1			**1**	**1**
Symphyotrichum puniceum			1				1			**1**					1	1			**1**	**1**
Triadenum frasieri																1				**1**
Total Cover			21	17	14	19	14	15	**22**	**23**	**10**	**7**	14	11	17	17	13	8	**13**	**12**

1: P = peat plots/logs and N = no peat plots/logs.

2: All vegetation on emergent logs at the Marsin site died in spring of 2011 due to low lake levels/extreme drying..

3: These values likely include *C. pseudocyperus* vegetation.

4: The "*Iris*" seedling values for the emergent logs at Sand Point likely include some *Sparganium* seedlings as these were very difficult to tell apart in the field.

Table 4.13. Vegetative cover in the emergent log and fen meadow zones at the A) Marsin and B) Sand Point restoration sites in late summer 2013.

A. Marsin

	Peat Plots/Logs						No Peat Plots/Logs					
Zone/Sector	**1**	**2**	**3**	**4**	**5**	**Ave.**	**1**	**2**	**3**	**4**	**5**	**Ave.**
Emergent	0	0	0	0	0	**0**	0	0	0	0	0	**0**
Wet Meadow												
Lakeside	91	78	66	46	32	**63**	129	74	68	84	84	**88**
Middle	53	83	68	53	76	**67**	58	78	47	55	73	**62**
Upper	69	56	94	56	81	**71**	73	65	73	96	110	**83**
Meadow Average	**71**	**72**	**76**	**52**	**63**	**67**	**87**	**72**	**63**	**78**	**89**	**78**

B. Sand Point

	Peat Plots/Logs						No Peat Plots/Logs					
Zone/Sector	**1**	**2**	**3**	**4**	**5**	**Ave.**	**1**	**2**	**3**	**4**	**5**	**Ave.**
Emergent	117	99	121	106	113	**111**	102	96	72	62	114	**89**
Wet Meadow												
Lakeside	39	34	80	31	71	**51**	28	51	51	36	39	**41**
Middle	63	78	65	66	55	**65**	56	66	52	78	68	**64**
Upper	6	23	16	47	65	**31**	6	41	25	55	42	**34**
Meadow Average	**36**	**45**	**54**	**48**	**64**	**49**	**30**	**53**	**43**	**56**	**50**	**46**

Table 4.14. ANOVA results for comparison of treatment and sector effects in the fen meadow zone at the Marsin and Sand Point restoration sites in late summer 2013. Sector refers to the three sampling sectors; "lakeside", "middle" and "upper". Treat is treatment type - peat addition or no peat addition.

2013 Marsin and Sand Point Vegetation ANOVA Results

Restoration Parameter	Root MSE	y1 Mean	y1 F-stat	y1 P-value	Sector P-val	Treat P-val	R^2
Marsin Vegetative Cover	25	71	8.3	<.0001*	0.0002*	0.009*	
Marsin Wetland Plant Diversity	2	6.7	2.4	0.07	0.03*	0.64	0.05
Sand Point Vegetative Cover	22	47	19	<.0001*	<.0001*	0.27	0.28
Sand Point Wetland Plant Diversity	1.6	3.5	23	<.0001*	<.0001*	0.72	0.32

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