Restoring Peatland Plant Communities on Mineral Well Pads

Mémoire

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Résumé

Les tourbières sont largement représentées dans la région boréale de l'Alberta, mais peu est connu sur la restauration de plates-formes de forage localisées en milieux tourbeux. Deux expériences de terrain ont testées la provenance du matériel végétal (bog, écotone bog-peupleraie, fen dominé par saules-Cyperacées, riche fen arbustif, riche fen forestier) à réintroduire sur différents substrats (sciure, loam argileux, mélange sciure-loam, tourbe, microtopographie) sur d’anciennes plates-formes. Nos résultats montrent que les communautés de tourbières peuvent s’établir sur un sol minéral après transfert d’une couche muscinale. Le type de communauté végétale où les propagules sont récoltées est un facteur déterminant au succès des bryophytes à s’établir. Un amendement en tourbe facilite l’établissement des plantes. La technique de transfert de mousse est une approche prometteuse pour la restauration de fens sur plateformes pétrolières. Nous recommandons une mise à l’échelle pour tester la validité de ces méthodes de réintroduction de végétation de manière mécanisée.

Abstract

Peatlands are largely represented in the boreal region of Alberta but little is known about their restoration on well sites. The goal of this study is to compare plant communities and substrates in order to recover peatland vegetation. Two field experiments tested which plant communities (bog, bog-aspen ecotone, willow-sedge fen, shrubby rich fen, treed rich fen) would best regenerate on different substrate (sawdust, clay loam, mix sawdust-clay, peat, surface roughness). We found that peatland communities can establish on mineral soil after propagules transfer using the moss layer transfer technique (MLTT). The choice of plant community, where the propagules are harvested is key to bryophytes establishment. Peat amendment facilitated the plants establishment. The MLTT is a promising approach to restore fen plants on well sites. We recommend a scale-up experiment for a whole well site to test the validity of MLTT within pad removal techniques.

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Dédicace

À Benjamin.

1. Problem Definition

Wetlands represent 18 % of the Alberta land base (Environmental and Sustainable Resource Development 2013). In the Boreal Natural Region, this proportion reaches nearly 50 %, of which more than 90 % are peatlands (Vitt *et al.* 1996). Peatlands are recognized for the many ecosystem services they performed, most particularly long-term carbon storage through peat accumulation. The boreal biome is the world's largest carbon storehouse (Anielski 2010).

The three Alberta oil sands deposits (Fig 1.1) are mainly located in the Boreal region, and altogether they cover an important portion of the landscape (142 000 km^2; Gov. of Alberta 2010). The oil sands reservoir (171 billion barrels) is at 80 % recoverable by in situ methods only, as opposed to open mining (Gov. of Alberta

Note: 1 km^2 = 1 square kilometre = 0.39 square miles

Figure 1.1 Alberta's oil sands reservoirs in the Boreal region

2010). The disturbances related to in situ extraction include the construction of well pads and connected linear features (pipelines, exploration seismic lines, access roads, winter roads; Graf 2009, Osko 2010). Despite a legal obligation to return disturbed lands to ecosystems supporting an equivalent productivity (*equivalent land capability*; Gov. of Alberta 2009), the actual practice is to reclaim former peatlands into forested uplands (Ball 2012). Peatland loss is responsible for the emission of millions of metric tons of carbon per year (C/y), due both to land use changes and the reduction of carbon sequestration potential (Rooney *et al.* 2012). To this day, no well site has been returned to pre-disturbance functioning peatland. The absence of clear expectations from regulators did not encourage peatland restoration. There is a need to elaborate on criteria required to restore peatland ecosystem.

Reintroducing peatland vegetation on decommissioned well sites is an important step toward peatland restoration. Plant material reintroduction, dominated by bryophytes, along with adequate hydrological conditions, is likely to evolve toward a peat-accumulating system (Rochefort 2000, Waddington *et al.* 2010). However, decommissioned well sites offer harsh growing conditions for peatland plants. Well pads are compacted mineral platforms of 1 to 2 m thick. Well sites are thereby artificially elevated above the surrounding peatlands and are hydrologically completely disconnected from lateral water flows; their only input of water is through precipitation. The peat under the imported clay is compacted down under the weight of the pad. For restoration, the peat layer could be exposed anew but only if complete pad removal operations were undertaken, in which case the level of the peat would stand below natural surface of peatland, because of the compaction. One solution is to shave the pad down to the level of surrounding peatlands, although the mineral substrate left behind could be limiting to peatland restoration but this is unknown.

2. Background

2.1 Perspective on the Energy Sector

Definitions

The term “oil sands” refers to the type of reservoir found in the province of Alberta. Oil sands are a mixture of heavy oil (bitumen), sand clay and water. The bitumen has to be separated from sand and water, before being upgraded to crude oil or other products. It does not flow as conventional oil does unless heated or diluted. There are two ways to recover the oil located in the oil sands deposits: open mines or in situ extraction. If the bitumen is deeper than 75 m, it cannot be mined and has to be extracted using in situ techniques, such as Cyclic Steam Stimulation (CSS) and Steam Assisted Gravity Drainage (SAGD). According to the government of Alberta, 80 % of the oil sands reservoir is recoverable with in situ methods only (2010). The minable resource is limited to the Athabasca deposit, near Fort McMurray, and occupies 4 800 km^2. The in situ oil sands development is expected to exceed the production of mining exploitation by 2017 (Moorhouse *et al.* 2010) and to be responsible for 50 times more land disturbances in the Boreal region than the mining oil sands (Schneider & Dyer 2006).

Site-specific Constraints

Most in situ facilities located in peatlands require the construction of a stable platform to support the appropriate equipment throughout the recovery processes: the well pads. Traditional pads are on average 1 ha but the newest best management practices (BMPs) have led to the construction of pads up to 3 ha accommodating several wells. When constructed in peatlands, the peat layer of the natural system usually remains on site and a geotextile sheet is used to cover it. Borrow fill material is imported in layers and compacted. The fill is normally a fine-grained material, imported from surrounding uplands, such as clay loams, clays and silt clays. The platform created varies between 1 m to 2 m thick. This operation is referred to as ”capping”, and the platform, as “clay cap”. The chemical profile on the pad will vary depending on the borrow fill provenance. In many cases, the clay cap comes from solonetzics and luvisols, which are widely found in the Mixedwood Region (Natural Region Committee 2006). Higher salinity is often observed on pads (Shell pers. com.), and may results from capping with solonetzic soils or from contamination with salt water during drilling and extracting operations. After site closure, the equipment is moved away, the cores are closed and the compacted mineral layer is left on site, so the site remains above natural ground level.

Well pads and associated facilities are linked with access roads within extraction complexes. At the landscape level, the disturbances created by in situ extraction of oil include the well sites themselves and likewise central facilities, exploration wells, pipelines, seismic lines and access roads (Schneider & Dyer 2006, Osko 2010). Well pads and linear features are often discussed as a same topic in the literature since they share similarities. They are both raised with compacted borrow material above the ground level and they are both to creating major disturbances of hydrological systems, vegetation communities and habitat resulting often in forest fragmentation (Schneider & Dyer 2006).

Legislative Framework

In Alberta, 12 legislative acts, policies and regulations are in effect for wetland management (Short 2012). Under the *Environmental Protection and Enhancement Act* (EPEA), disturbed lands must be reclaimed and returned to an *equivalent capability*, which is *the ability of the land to support various land uses after conservation and reclamation is similar to the ability that existed prior to an activity being conducted on the land, but that the individual land uses will not necessarily be identical.* (Gov. of Alberta 2009). The 2010 Reclamation Criteria for Well Sites (Alberta Environment 2010a, Alberta Environment 2010b, Alberta Environment 2010c) describe the requirements of reclamation certification for three land types: forested, grassland and cultivated. Peatland reclamation criteria are being developed but are not available yet. Upon approval, a land type can be changed to another land type during the certification process, meaning that an upland forest can be reclaimed on a well site built in peatlands. This practice is widely observed in the industry: well pads are left in place and forest, agriculture or grassland species are reintroduced directly on the pad. More than the absence of regulations, it is the absence of clear expectations and detailed criteria to evaluate success that are missing in the existing regulatory framework (Ball 2012).

2.2 Peatland Definitions

Wetlands are ecosystems saturated with water and they sustain aquatic processes such as poor drainage, hydrophyte vegetation and specific biological activities (National Wetland Working Group 1997). They are organized in five classes in the Canadian Wetlands Classification System (CWCS): open waters, marshes, swamps, bogs and fens. Wetlands are frequently encountered in large complexes where more than one class can be found. Each class is organized in forms and sub-forms, according to the surface relief and pattern, basin topography, and proximity to water bodies. Several complementary wetland classification systems are available in the Alberta Boreal region. The *Alberta Wetland Inventory* (Hasley *et al.* 2003) and the *Field guide to Ecosites of Northern Alberta* (Beckingham & Archibald 1996) further divide wetlands in sub-classes and in ecosites.

Peatlands are peat-accumulating wetlands displaying an accumulated peat layer equal to or higher than 40 cm (National Wetland Working Group 1997). They are typically classified based on three criteria: chemistry, hydrology and vegetation (NWWG 1997, Vitt & Zoltai 1995) and are divided into two main groups: bogs and fens.

Bogs are ombrogenous ecosystems with pH range of 3.5-4.2 (Gorham & Janssens 1992). They receive water from precipitation only. The water table is typically found at 40-60 cm below ground with low seasonal variations. Bogs are poor in base cations and are dominated by species of *Sphagnum* and ericaceous shrubs. Bogs are strictly treed with *Picea mariana* in western Canada (Vitt *et al.* 1994). They are amongst the poorest ecosystems in plant diversity of the Boreal zone.

Fens are geogenous ecosystems where the pH ranges between 4.6 and 7.5. The mineral content is higher than in bogs because fens receive water inputs from precipitation but also from runoffs. The water table is fluctuating near the surface and slow water flows can occur. Mosses of the Amblystegiaceae family and vascular plants of the Cyperaceae, Gramineae and Poaceae families dominate the vegetation. Fens are among the most diverse ecosystems in terms of flora in the Boreal zone.

2.3 Peatland Distribution, Threats and Ecological Values

Peatlands are an important component of northern landscapes in Canada, both for their repartition and the numerous goods and services they provide. Peatlands occupy nearly 123 millions of hectares in Canada (Tarnocai 2000) of which 97 % are found in the Boreal and the Subarctic regions (Tarnocai 2006). In Alberta, wetlands occupy 18 % (103 000 km^2) of the province land base, of which 90 % are peatlands. (Vitt et al. 1996). In the oil sand region, the proportion of peatland varies between 25 and 45 %, depending on the Natural Region (Natural Region Committee 2006).

Peatlands are defined by their capacity to store carbon through their peat-accumulating function. This is an important characteristic since a fifth of the world's carbon is stored in peatlands (Gorham 1991). In Canada, 147 Gt of soil carbon in stored in peatlands. They contribute to preserve biodiversity by providing habitat for flora and fauna species. Peatland also play an important role in the water cycle such as water filtration and stabilization. The thick peat deposits found in peatland is a valuable resource and is harvested for fuel and for horticultural purposes (Chapman et al. 2003).

Despite their ecological importance and their high incidence in the Boreal landscape, peatlands are being damaged and destroyed by anthropogenic activities. Worldwide, 0.1 % of all global peatlands are destroyed every year, mainly due to agriculture, forestry and peat mining activities (Joosten & Clarke 2002). Climate change is also a real threat to Canadian peatlands. The increased of air temperature will affect the permafrost of the arctic ecosystems and dry out the Boreal ones (Tarnocai 2000). In Alberta, there is no accurate estimate of the total disturbances related the energy industry. In the surface mining area (Fig. 1.1), the actual peatland loss related to active mines is evaluated at 1 600 ha (Turetsky *et al*. 2002). If all leases granted by the province were been exploited, this number would be up to 29 500 ha of net peatland loss (Rooney *et al.* 2011). These estimates do not include the land disturbed by the 300 000 wells drilled since 1900 in the province (AESRD 2014) or the associated disturbances including access roads, pipelines, seismic lines and facilities. The province estimates that a total of 1 000 000 ha have been disturbed since the beginning of the oil sands activities. The reclamation industry has focused on unpland ecosystems, while to this day, there has been no peatland certified reclaimed in the province.

2.4 Restoration Goals

Setting restoration goals is a very important step in a restoration project. It orientates all decisions that will be made during the course of the operations. Goals are also indispensable to measure the success of the project. It is recommended to set both general goals and specific objectives that are easily measurable (Hobbs 2003).

In the oil sands region, overall goals for peatland and wetland restoration are found in the many pieces of legislation available on wetland management. Returning the land to an *equivalent capability* is ultimately what is expected from the industry. However, it is partly the absence of specific and measurable objectives, the reclamation criteria on peatland that is refraining the industry from being more proactive in restoring peatlands. It is to be expected that hydrology, vegetation and soil components will be part of the new reclamation criteria for peatland restoration (Ball 2012).

The long-term goal many peatland restoration projects is to restore the peat-accumulating function, which is what define peatlands above all. It can take decades (20-50 years) after restoration started to restore that function (Samaritani *et al.* 2010, Lucchese *et al.* 2010, Bortoluzzi *et al.* 2006) but this is still being measured on whole restored ecosystem sites (Rochefort, comm. pers.). Gorham & Rochefort (2003) suggest that the short-term goal for restoration projects should be to re-establish key vegetation species. In the present case study, key species include bryophyte species, because they are an important component peatland accumulation function. Another key species is black spruce, as it dominates most of the peatlands of the area, providing habitat for wildlife. Recovering a closed canopy would insure a continuum with the surrounding forest and solve the fragmentation problems.

2.5 Revegetation Strategies for Pealtand Plant Communities

Several revegetation techniques have shown success in reestablishing peatland vegetation on disturbed areas. Rewetting, hay transfer, seedling transplants, seed dispersal, mature plant transfer and seed bank transfer have been shown to be effective (van Duren *et al.* 1998, Pfadenhauer & Grootjans 1999, Patzelt *et al.* 2001, Amon *et al.* 2005, Vitt *et al.* 2011, Rochefort *et al.* 2003).

Seed bank transfer using the moss layer transfer technique (MLTT) was successful in restoring bog vegetation on cutaway peatlands (Rochefort *et al.* 2003; Gonzalez & Rochefort 2014). It is also showing promising result in restoring fen vegetation on minerotrophic peat (Leblanc *et al.* 2012).

The MLTT technique consists of transferring a seed bank from a targeted community onto the surface to be restored. The technique involves harvesting the top 10 cm of a natural peatland (donor site) and to spread it over the disturbed area, respecting a 1:10 areal ratio. The harvested material (donor material) is a mixture of different types of diaspores including bryophyte fragments, rhizomes, roots, seeds and spores. Phosphorus fertilization is applied using rock phosphate to facilitate the growth of *Polytrichum* mosses and the restored area is covered with straw mulch to create a protective humid microclimate. One interesting aspect of the MLTT is that it can be mechanically harvested and use at an industrial level (Rochefort *et al.* 2003). It is used in the peat industry to restore sites after exploitation. It is relatively cost effective for large areas ($1, 000/ha; Quinty & Rochefort 2003).

2.6 Restoring Minerotrophic Peatlands Communities

Bog restoration has been the target of many peatland restoration projects in Canada, both experimental and industrial. However, when the exposed substrate of a site is more minerotrophic, the reintroduction of fen plant communities is suggested (Wind-Mulder *et al.* 1996, Wind-Mulder & Vitt 2000). This applies for peat deposits when the extraction process reached deeper layers of sedge peat with minerotrophic characteristics. The use of fen plant communities as donor material could therefore be more successful for the establishment of peatland vegetation on the clay surface of a well pad.

Fen restoration has recently been the topic of several research projects (Cooper & MacDonald 2000, Cobbaert *et al.* 2004, Amon *et al.* 2005, Graf & Rochefort 2008b, Vitt *et al.* 2011). The use of the MLTT has shown positive results in reestablishing fen bryophytes on minerotrophic substrate (Graf & Rochefort 2008a, Graf & Rochefort 2008b). Fen bryophytes are a key component of restoration processes because of their low decomposition rate (Graf & Rochefort 2009). They also have a lower evapo-transpiration rate (Lafleur & Roulet 1992) and regenerate well from fragmented gametophytes (Mälson & Rydin 2007, Graf & Rochefort 2008a), if the water table remains close to the surface. Hydrological restoration is highly beneficial for fen vegetation (Mälson *et al.* 2008).

Fen vascular plants have also been successfully reintroduced on mineral soils using various methods: the MLTT, planting of greenhouse seedlings, transfer of mature plugs and direct seeding (Cobbaert *et al.* 2004, Leblanc 2012, Amon *et al.* 2005, Vitt *et al.* 2011). A challenge of working on minerotrophic surfaces is that spontaneous colonization of non-desirable plants can be important (Mahmood & Strack 2011) and create aggressive competition with desired species.

2.7 Surface Modifications

The reintroduction of peatland vegetation on mineral well sites can constitute many challenges. The well pad is a compacted clay surface artificially elevated, thus disconnected from surrounding water flows. One option to restore water conditions suitable for plant growth is to level the pad surface down to the surrounding level. But even if pad removal is operated, the water availability might still be reduced due to the clay physical properties: clay has a lower water retention capacity than peat and a higher bulk density (Siegel & Glaser 2006, Fetter 2001). Its chemistry is close to neutrality, mineral availability is higher and salinity may be slightly elevated due its provenance.

Substrate amendments and modifications are often used in restoration when the conditions are not ideal for the achievement of the restoration goals. For example, peat amendment has shown successful results when reintroducing moss diaspores on mineral substrate (Hugron *et al.* 2013).

Wood residues such as sawdust have frequently been used in restoration projects (Morgan 1994, Bulmer 2000, Averett *et al.* 2004, Staubli 2004, Eldridge *et al*. 2011). Sawdust or wood chips offer many advantages: affordable, available in large quantities in some regions, improve soil texture, increase soil organic matters, increase soil water content. However, sawdust has a very high C: N ratio that can tie up the soil nitrogen that microbes use up to decompose wood products (Cooperband 2002). Deliberately impoverishing the soil, also referred to as reverse fertilization, can reduce the competition of invasive ruderal species (Morgan 1994, Averett *et al.* 2004). In the context of restoring peatlands on minerotrophic substrate, this could be an effective approach to reduce the colonization on non-desirable species, while amending the soil with organic components.

Surface roughness is another substrate modification that can help the targeted species to establish (Eldridge *et al*. 2011). It creates pits and enhances the availability of microhabitats (Whisenant 1999, Bainbridge 2007). It can also increase vascular plants colonization (Davis 1990, Switalski *et al.* 2004). It has been successfully used in forestry to initiate the natural recovery process of highly disturbed sites (Polster 2009). However, for the reintroduction of peatland vegetation using the MLTT, surface roughness has shown a negative effect on *Sphagnum* cover (Campeau *et al.* 2004).

3. Hypothesis and Objectives

In the course of this project, we want to determine if peatland plant communities can establish on recontoured well sites using the transfer of plant fragments (diaspores) following a moss layer transfer method. More specifically we will evaluate if the mineral material left on the well site, a clay loam, has to be modified or amended to allow peatland plants establishment. Specific objectives are stated below:

1. Can peatland plants establish directly on the mineral surface of the well site following propagules transfer?
2. Which substrate (clay loam, decompacted clay loam, sawdust, mix sawdust and clay, decompacted mix and peat) offers the best medium for peatland plant communities to establish?
3. Which type of peatland plant communities (bog, bog-aspen ecotone, willow-sedge fen, shrubby-rich fen, treed-rich fen) established best on amended mineral pad substrate?

Because the growing conditions are challenging on abandoned well sites, we are formulating the hypothesis that organic amendments and substrate modifications will be beneficial to peatland plants establishment. Our second hypothesis is that the choice of plant communities plays a major role in the restoration success of well sites. We believe that donor sites with minerotrophic characteristics will have more success than ombrotrophic communities.

4. Material and Method

4.1 Site Description

The experimental sites were the same in both field experiments and were located at the Shell Canada Peace River complex (56°22‘N, 116°47’W), at 55 km northeast of Peace River, Alberta. They were located in a transition vegetation zone between the Central Mixedwood Subregion and the Dry Mixedwood Subregion (Natural Regions Committee 2006). The first growing season (2010), was dry with temperatures close to normal (Table 4.1). The second growing season was much wetter receiving more than double the amount of precipitation from the year 2010, with a summer cooler than average.

Table 4.1 Precipitation and average temperature for Peace River (Environment Canada).

	Normal	2010	2011
Total precipitation (mm)			
Growing season (May to August)	215.4	129.7	351.9
Annual mean	402.2	213.7	572.1
Average temperature (°C)			
Growing season (May to August)	13.9	13.8	13.7
Annual mean	1.2	1.8	0.8

The ecological restoration experiments were carried out within a peatland complex and the two well pads were constructed by importing borrow fill material in compacted layers. The fill was a clay loam, imported from surrounding borrow pits. The well pads varied between 1 m to 2 m in thickness, over 1 ha. One of the sites was built but never exploited and the other one was under production nearly 30 years before being decommissioned (Shell, pers. comm.). In both cases the clay layer was left on site.

In order to restore suitable hydrological conditions for peatland plant regeneration, the well pads had to be reprofiled. The clay loam of a whole side portion (10 m in width) of the pads was mechanically shaved off (Appendix 1). Excavators were used to bring the surface down to the average height of surrounding water table (Fig. 4.1). The surrounding peatlands were poor to moderate rich fen pockets in a large bog complex and the water levels were close the surface. After leveling the pad, the residual peat from the original peatland below the pad was not exposed because of the subsidence created by the weight of the pad. A superficial layer of 20 cm of clay remained above the original peat surface.

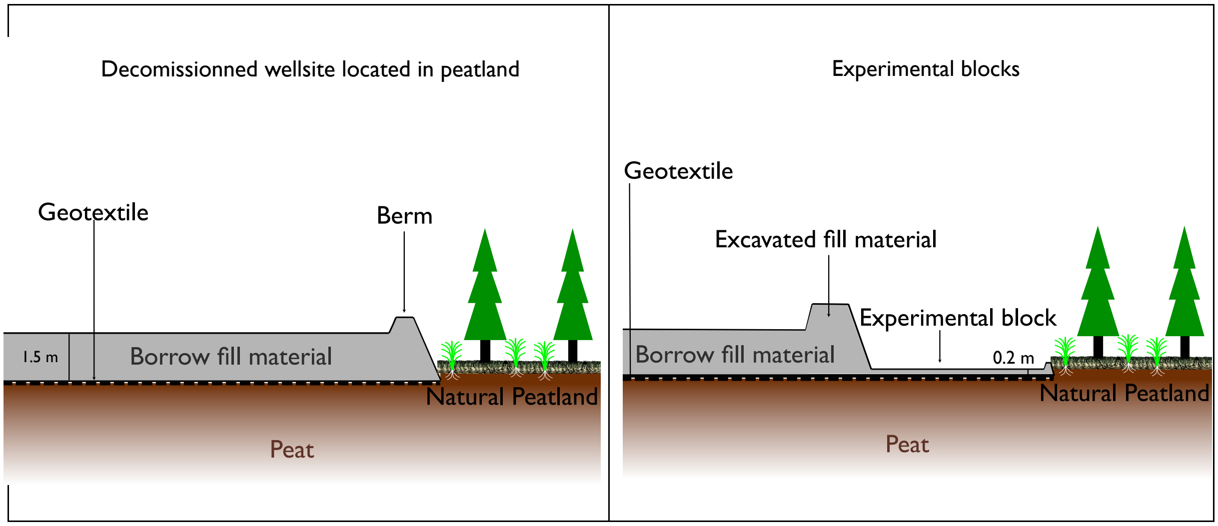


Figure 4.1 Well pad before (left) and after partially removing the fill material (right) to create experimental blocks.

4.2 Mechanically-harvested Diaspores Restoration Experiment

Experimental Design

The effect of substrate and peatland plant community reintroduction were tested in a factorial design repeated four times over two decommissioned well pads. The four experimental blocks of 36 m x 7 m were created in March 2009. The restoration trials were set up immediately following the earthwork.

The experimental design had two factors: the substrates were 1) clay loam, 2) peat, 3) aspen sawdust and 4) spruce sawdust and the chosen plant communities as reintroduction material were 1) bog, 2) willow-sedge and 3) shrub-*Sphagnum*). Each experimental unit measured 3 m x 7 m.

Substrate treatments

The clay loam treatment was the construction pad material left on site after the levelling of the pad. The peat substrate was harvested in a nearby peatland. A local sawmill provided both types of sawdust: aspen and spruce. Peat and sawdust treatments were spread in a 10 cm layer over the clay loam.

Reintroduction materials

The three donor sites were within 20 km of the experimental sites. A complete description of the vegetation communities used for the mechanically-harvested diaspores experiment is found in Table 4.1

Table 4.1 Description of peatland plant communities used as source of propagules (donors sites) for the mechanically-harvested diaspores experiment on plant establishment.

	Bog	**Willow-Sedge Fen**	**Bog-Aspen Ecotone**
pH	3.8	6.3	5.1
Tree layer dominant *spp.*	*Picea mariana*	-	-
Shrubs layer dominant *spp.*	*Ledum groendlandicum* *Vaccinium Vitis-idea*	*Salix spp*	*Alnus tenuifolia* *Salix spp.*
Herb layer dominant *spp.*	-	*Carex aquatilis* *Carex canescens*	*Equisetum arvense*
Moss layer	*Sphagum fuscum*	*Sphagum angustifolium* *Drepannocladus spp.*	*Sphagnum spp.*
Coordinates	56°14‘46”N 117°01’57W”	56°14‘42”N 117°02’01”W	56°14‘40”N 117°01’57”W

All experimental units received mechanically harvested diaspores, following the moss layer transfer protocol used in bog restoration (Rochefort & Lode 2006). After amending the plots with experimental substrates, the donor material was spread manually and evenly on the surface of all experimental units. All treatments were covered with straw mulch (3000 kg/ha) to protect the propagule against desiccation and to create a microclimate favourable to plants regeneration.

Data Collection

Vegetation surveys on all experimental units were performed in August 2011, 16 months after the reintroduction of diaspores. The survey followed a spatial systematic plan, with 3 plots of 25 cm x 25 cm per experimental unit (7 m x 3 m). Each plot was placed 150 cm away from the edges and 150 cm apart from each other. The total percent cover of each vascular plant and bryophyte species was evaluated. Species were thereafter classified according to their preferential habitat following the categories used by Poulin *et al.* (2012): 1-peatland specialists (found mainly in peatlands), 2-wetland specialists (found only in wetlands but not strictly in peatlands), 3-wetland non-specialists (usually found in wetlands but not exclusively) and 4-ruderal (typically found in disturbed environment). Classification into those categories was based on Payette & Rochefort (2001), Moss (1983) and Johnson *et al.* (1995). A complete list of species and their assignment to each group can be found in Appendix 2. Water levels in observation wells were recorded every week using a dipstick in each experimental block for one complete growing season (2011). Water pH was also measured once a week from water samples collected in observation wells (pHMS-1, Nutradip, Kelowna, BC).

Data Analyses

Vegetation data were analyzed with two-way analysis of variance (ANOVA). Plant community and substrate amendments were the fixed factors. Total cover of bryophytes and total cover of vascular plants were the dependent variables. Two substrates (aspen sawdust and spruce sawdust) were not included in the analysis because no growth was observed. The total moss group was square rooted to achieve normality. The significance level was set at 0.05. Fisher’s Least Significant

Difference (LSD) comparisons were performed when the ANOVA results were significant. Analyses were completed using STATA 11 (Statacorp LP, College Station, Texas, USA) and R 2.15.3 (Statistical Procedures for Agricultural Research. R package version 1.1-3, http://CRAN.R-project.org/package=agricolae).

4.2 Manually-harvested Diaspores Restoration Experiment

Experimental Design

The effect of substrate and peatland plant community reintroduced were tested in a factorial design repeated four times over two decommissioned well pads. The profiling of the four experimental blocks of 30 m x 3 m was carried out in March 2009. The restoration trials were set up in August 2010. Each experimental unit measured 3 m x 3 m.

The substrate treatments were 1) clay loam, 2) decompacted clay loam, 3) sawdust-clay mix, 4) decompacted sawdust-clay mix and 5) peat from a natural bog) and fen plant communities were 1) poor fen and 2) moderate-rich fen. The decompacted treatment was meant to roughen the substrate surface as to create surface microtopography. The decompaction was carried out with a horticultural tool (long-handled garden claw), within the first 5 cm of the surface. It created an amalgam of micro depressions (3 cm^2) and micro mounds (6 cm^2). The spruce sawdust was delivered on site 18 months prior to use. It was spread directly on the experimental units in a 2-3 cm layer in both mixed treatments. An equal layer of clay loam (2-3 cm) was spread over the sawdust layer. The clay material was collected on site, in the area surrounding the experiment. In the sawdust-clay mix treatment, the layers were left undisturbed. In the decompacted sawdust-clay mix treatment, layers were mixed by the result of the decompaction work. The peat was harvested from a natural bog found within 16 km of the restored experimental sites.

Moss Layer Transfer Technique

After all substrate treatments were implemented, all units received manually-harvested diaspores, following the moss layer transfer protocol used in bog restoration (Rochefort & Lode 2006). The donor material was spread manually and evenly onto the experimental units. All treatments were covered with straw mulch (3000 kg/ha) and a protective netting (fishing net, 4 inches multi nylon netting, Lakefish net & twine ltd., Winnipeg) following plant propagules reintroduction. The purpose of the net is to ensure that the straw mulch stays in place if ever units were to flood. One control plot per block did not receive any diaspores (not factorial) and was used to identify the spontaneous regeneration on the mineral soil. It was not used in the statistical model.

Reintroduction material

The donor sites were located within 2 km of the experimental area. They were disturbed by prospection operations in the past and were chosen for their fen-like plant communities and water chemistry (Table 4.2).

Table 4.2 Description of peatland plant communities used as source of propagules (donors sites) for the manually-harvested diaspores experiment on the regeneration of fen plants.

	Treed Rich Fen	**Shrubby Rich Fen**
pH	5.7	6.9
EC (uS cm^{-1})	190	98
Ca (mg l^{-1})	17	12
Depth to water table (*n* = 5)	-22.0 ± 3.2	-7.0 ± 3.0
Tree layer dominant *spp.* (%)	*Picea mariana*	-

Shrubs layer dominant *spp.* (%)	*Vaccinium Vitis-idea* *Larix laricina* *Chamaedaphne calyculata* *Empetrum nigrum* *Ledum groendlandicum* *Salix spp.*	*Salix spp.* *Betula glandulosa*
Herb layer dominant *spp.* (%)	*Carex aquatilis* *Carex tenuiflora*	*Carex aquatilis* *Potentilla palustris* *Carex paupercula*
Moss layer dominant *spp.* (%)	*Sphagum fuscum* *Aulocomnium palustre*	*Tomenthypnum nitens* *Aulocomnium palustre* *Sphagum angustifolium*
Coordinates	56°23‘03”N 116°46’40”W	56°22‘31”N 116°46’37”W

Data Collection

The establishment of all species was evaluated in September and October 2011, 12 months after treatment installation. The sequence of surveys was randomly chosen for each experimental unit. Within each unit, 16 quadrats of 25 x 25 cm were placed by dividing systematically each unit into 4 lines of 4 quadrats. A buffer zone of 50 cm around the edges was not included in the survey. Each quadrat was 50 cm apart from one another. The percent cover for each vascular plant and bryophyte species was calculated using a point intercept technique with a grid of 100 points. The total on 100 points was converted to a percent cover. Species were thereafter classified according to their preferential habitat following grouping in a similar way as used by Poulin *et al.* (2012): 1-peatland specialists (found mainly in peatlands), 2-wetland specialists (found only in wetlands but not strictly in peatlands), 3-wetland non-specialists (usually found in wetlands but not exclusively) and 4-ruderal (typically found in disturbed environment). Classification into those categories was based on Payette & Rochefort (2001), Moss (1983) and Johnson *et al.* (1995).

Reference ecosystems

A comparative reference ecosystem was built for each donor site. Data were collected in August 2011 and a complete list of species can be found in Appendix 3. Four natural peatlands were inventoried per donor site, for a total of eight. For each reference site, a transect proportional to the size of the site was outlined. Along each transect, 10 equidistant circular plots were sampled. Each plot was 1 m^2. The percent cover of all plant species was estimated, as well as the presence of surface water and litter.

Abiotic conditions

The thickness of the residual pad material down to the underlying peat was evaluated within each transect line (thus 4 times per experimental unit). To do so, a threaded steal rode was inserted in the pad until the geotextile or underlying gravel layer was reached. Water levels and water pH were recorded every week for each donor site, experimental site and adjacent peatland. A submersion index was estimated to quantify the presence of surface water in each unit. The submersion index was assessed in classes approximating the portion of the experimental unit covered with water: 1 = 0 %, 2 = 1-5 %, 3 = 6-25 %, 4 = 26-75 % and 5 = >75 %. This index was recorded as often as possible, sometimes every day. The final data analyzed were averages per unit of all indexes recorded in the course of the growing season (*n* = 45). Soil analyses for all experimental units was done in October 2011 for the following elements: EC, pH, Ca, Na, Mg, SO_4 and Cl.

Data Analyses

Data were analyzed with two-way analysis of covariance (ANCOVA). Plant communities and substrate modifications were the fixed factors. Dominant species of bryophytes, total cover of bryophytes and total cover of vascular plants were the dependent variables. The submersion index was used as co-variable. The total vascular plants and *Sphagnum spp.* were log transformed prior to performing the model*; Drepanocaldus spp.* and *T. nitens* cover values were square rooted. The significance level for statistical tests was set at 0.05. Post-hoc LSD comparisons were performed when ANCOVA results were significant. Analyses were completed using STATA 11 (Statacorp LP, College Station, Texas, USA) and R 2.15.3 (Statistical Procedures for Agricultural Research. R package version 1.1-3, http://CRAN.R-project.org/package=agricolae.

5. Results

5.1 Mechanically-harvested Diaspores Restoration Experiment

Vegetation Structure and Composition

Moss establishment was equivalent on both substrate treatments, peat and clay ($p = 0.6$; Table 5.1) but had an overall a low cover (an average of 10 %; Fig. 5.1). The willow-sedge fen community, dominated by *S. angustifolium* and *Drepanocladus spp*. and the bog-aspen ecotone community, dominated by *Sphagnum spp.* established better than the more acidic bog community dominated by *Sphagnum fuscum* ($p > 0.02$).

The most successful moss to establish was *Leptobryum pyriforme* (Hedw.) Wilson, a ruderal species (Fig. 5.2). *L. pyriforme* represented at least 70 % of the willow-sedge fen and the bog-aspen ecotone (Appendix 2). It is clear that *Sphagnum* species do not establish well directly on the clay loam treatment, regardless of the donor site. *Sphagnum* recovered with low values, varying from 0.3 % to 1 %.

The substrate had no impact for impeding or not, the establishment of ruderal species. Although peatland bryophytes establishment was low (0.5 to 2.6 %) they grew and spread better on peat surface than on mineral. The list of all bryophytes can be found in Appendix 2.

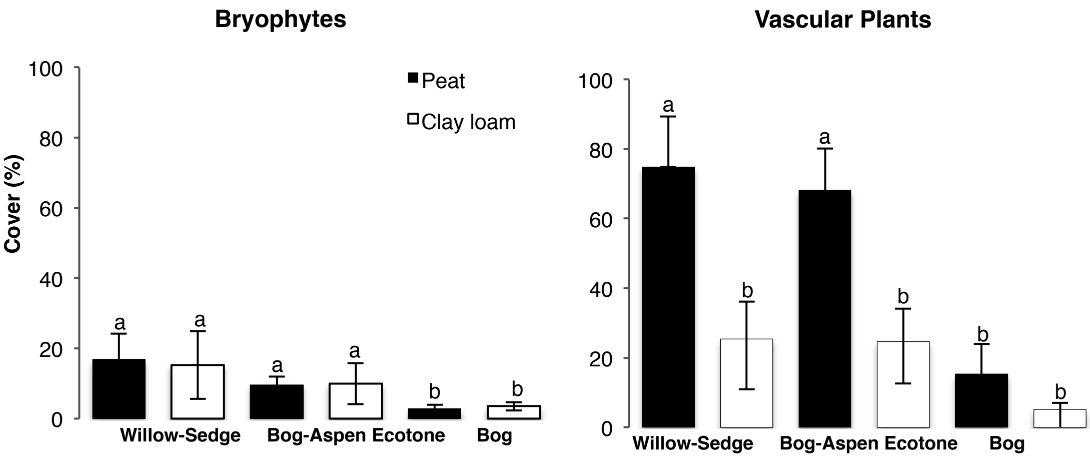


Figure 5.1 Establishment of bryophytes and vascular plants after two growing seasons in mechanically-harvested diaspores experiment. Treatments with the same letter are not significantly different as revealed by LSD test (α = 0.05)

Table 5.1 ANOVAs outcomes performed on bryophytes and vascular plants data of the mechanically-harvested diaspores experiment testing the effect of three types of plant community (willow-sedge fen, bog-aspen forest ecotone, bog) and two types of substrate (clay loam and peat) as per their preferential habitat. Two sawdust treatments were excluded from the statistical analysis since no vegetation grew on them. Significant values = bold.

		Total Bryophytes		**Total Vascular Plants**	
Source	**df**	***F***	***P***	***F***	***P***
Block	3	2.7		2.17	
Communities	2	4.9	**0.02**	12.35	**<0.01**
Substrate	1	0.26	0.61	21.82	**<0.01**
Subs*Comm	2	0.02	0.97	2.77	0.09
Residuals	15				
Total	23				

The vascular plants of the willow-sedge fen commnunity and the bog-aspen ecotone community regenerated better on peat than on mineral soil (substrate term significant at $p < 0.01$) whereas the bog community only tended to establish better on peat (non significant post-hoc LSD comparisons set a $p < 0.05$, Table 5.1; Fig. 5.1). The establishment of the willow-sedge fen commnunity (75 % ± 14 (mean ± SE) and the bog-aspen ecotone community (68 % ± 12) on peat were twice the covers compare to the mineral substrate. The worst combination of treatments was trying to transfer bog plant community onto mineral substrate (< 10 %).

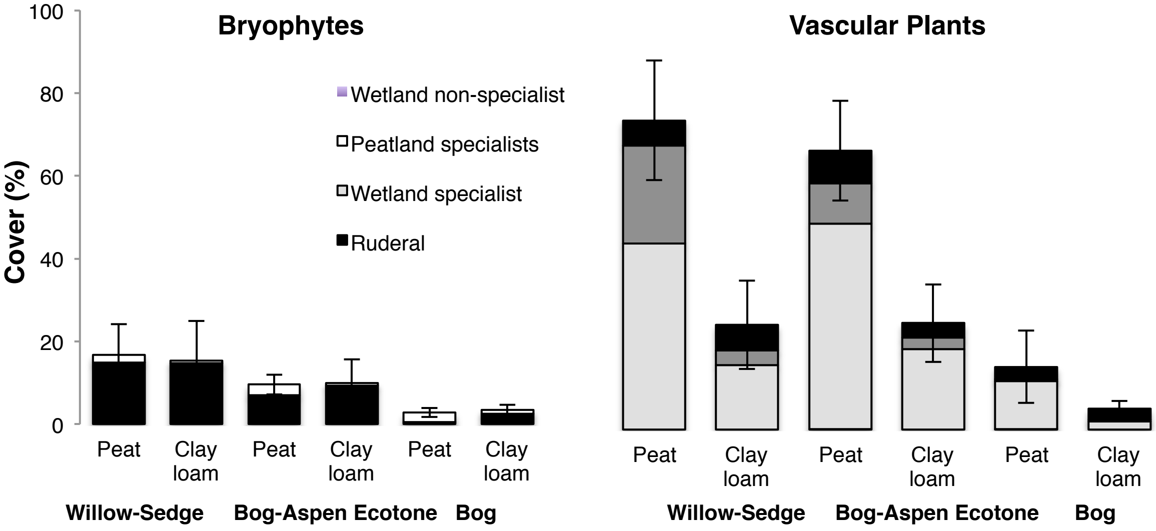


Figure 5.2 Establishment of bryophytes and vascular plants as per their preferential habitat after two growing seasons in mechanically-harvested diaspores experiment.

Wetland specialists and wetland non-specialists were the two dominant groups amongst the vascualr plants (Fig. 5.2). *Carex canesecens* and *Carex aquatilis* dominated the wetland specialists group and were found on all treatments. *C. canescens* had cover values of between 1.5 % and 49 % and *C. aquatilis* up to 6 %. *Salix* species and *Typha latifolia* were also found with covergae values below 1

%. For the wetland non-specialists, species found across all treatment include *Agrostis scabra*, *Equisetum arvense* and *Hordeum jubatum*.

Ruderal species were also found across all treatements and represented 6 % of the willow-sedge plants, 5 % of the bog-aspen forest ecotone plants and 3 % of the bog plants. The species with the highest cover for the ruderal group was *Trifolium hybridum* (overall average 3 %). Other species considerd weedy were *Cirsium arvense, Hordeum jubatum, Melilotus alba, Melilotus officinalis, Potentilla norvegica, Sonchus arvensis* and *Taraxecum officinalis.* No peatland specialist were found. The list of all vascular species can be found in Appendix 2.

Abiotic Factors

Water table fluctuations occurred principally below ground level during the 2011 growing season for most blocks, varying between 0 and -15 cm (Fig. 5.3), with a seasonal average of -7 ± 5.1 cm (mean ± sd, *n* = 80). Most blocks encountered two brief submersion events, in August and in September. The driest block had a depth to water table (DWT) of -16 cm on average. The wettest block had an average of -2 cm. Three out of four blocks had a seasonal water fluctuation similar to the natural peatland surrounding the pad called “Aspen”.

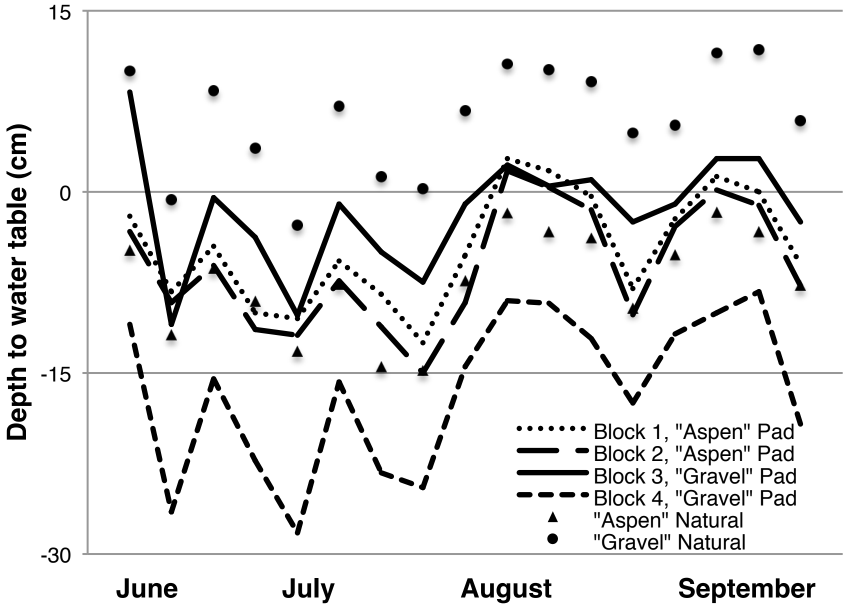


Figure 5.3 Water table fluctuations of four experimental blocks and the natural surroundings during the 2011 growing season. Values are averages ($n = 2$).

5.2 Manually-harvested Diaspores Restoration Experiment

Vegetation Structure

Bryophytes Response

After one growing season, the shrubby rich fen bryophytes established with greater success than the treed rich fen plant bryophytes (Fig. 5.4). The overall bryophyte cover was 30 ± 8 % for the treed rich fen and 57 ± 8 % for the shrubby rich fen. The total bryophyte cover found in the natural comparative peatlands was respectively 84 ± 14 % for the treed rich fens and 72 ± 21 % for the shrubby rich fens.

The different conditionings of the decommissioned pad substrate did not influence significantly the bryophytes establishment (Table 5.2). Neither the addition of sawdust nor the decompaction factor had an impact. However there was a tendency observed for the treed rich fen species to do better on peat than on all the other substrates. The degree of wetness also had no impact on bryophyte establishment ($p = 0.25$ for the submersion index).

In units where standing water was present for most of the summer, mosses grew as floating mats, with no connection to the ground, and remained in place due to the presence of a protective netting installed to keep the mulch from washing away.

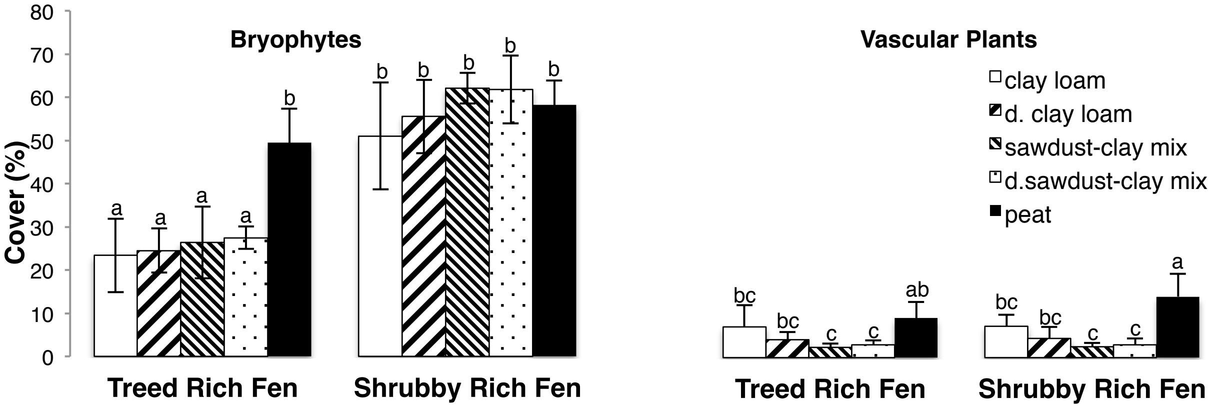


Figure 5.4 Establishment of bryophytes and vascular plants in the manually-harvested diaspores experiment after one growing season. Treatments = two types of donor site: a treed rich fen and a shrubby rich fen, reintroduced on five substrates (mean ± SE). Results of with the same letter are not significantly different as revealed by LSD (*α*=0.05).

Table 5.2 ANCOVAs outcomes performed on bryophytes and vascular plants data of manually-harvested diaspores restoration experiment are after one growing season. Treatments count two communities and five conditioning substrates within a factorial design. A submersion index was used for co-variable.

		Bryophytes		**Vascular plants**	
	df	***F***	***P***	***F***	***P***
Block	3	4.05		3.59	
Donor site	1	44.98	**<0.01**	2.48	0.13
Substrate	4	0.96	0.44	13.1	**<0.01**
Substrate*Donor site	4	1.52	0.23	0.24	0.91
Submersion	1	1.39	0.24	7.28	**0.01**
Residuals	26				
Total	39				

Vascular Plants Response

After one growing season, the vascular plants establishment varied significantly between the substrates tested ($p < 0.01$; Table 5.2) but not between the two reintroduced plant communities ($p = 0.13$). Peat yielded higher plant covers comparable to all other substrates. The treed rich fen and the shrubby rich fen established better on peat than on all other treatments (15 % and 9 % versus < 7 % for all other treatments). The second most successful substrate to be colonized was the clay loam (decompacted or not). The decompacted soil treatment had no significant effect on either of the introduced plant communities. After one growing season, the vascular plant cover was ranging between 2.9 ± 0.7 % (mean ± SE) and 14.2 ± 5.6 %, which is comparable to the values found in the natural peatlands, where the herb layer occupies on average 11 % of the treed rich fens and 16 % of the shrubby rich fens

Very little trees and shrubs were present on all experimental units. *Picea mariana* seedlings were found on all experimental substrates, with covers always < 1 %. In comparison, *P. mariana* reached covers of 4.5 % in the treed rich fens and 2.6 % the shrubby rich fens.

Shrub species were slightly more abundant than tree species. *Ledum groendlandicum*, *Ribes spp*. and *Salix spp*. were occasionally present in the treatments, never exceeding 1 %. This was a big contrast with the natural sites, were the shrub layer occupied 37 ± 15 % of the treed rich fens and 27 ± 15 % of the shrubby rich fens.

No statistical analysis was performed with the trees and shrubs data. The total percent cover for each stratum with each treatment compared with the natural peatlands is presented in Figure 5.5.

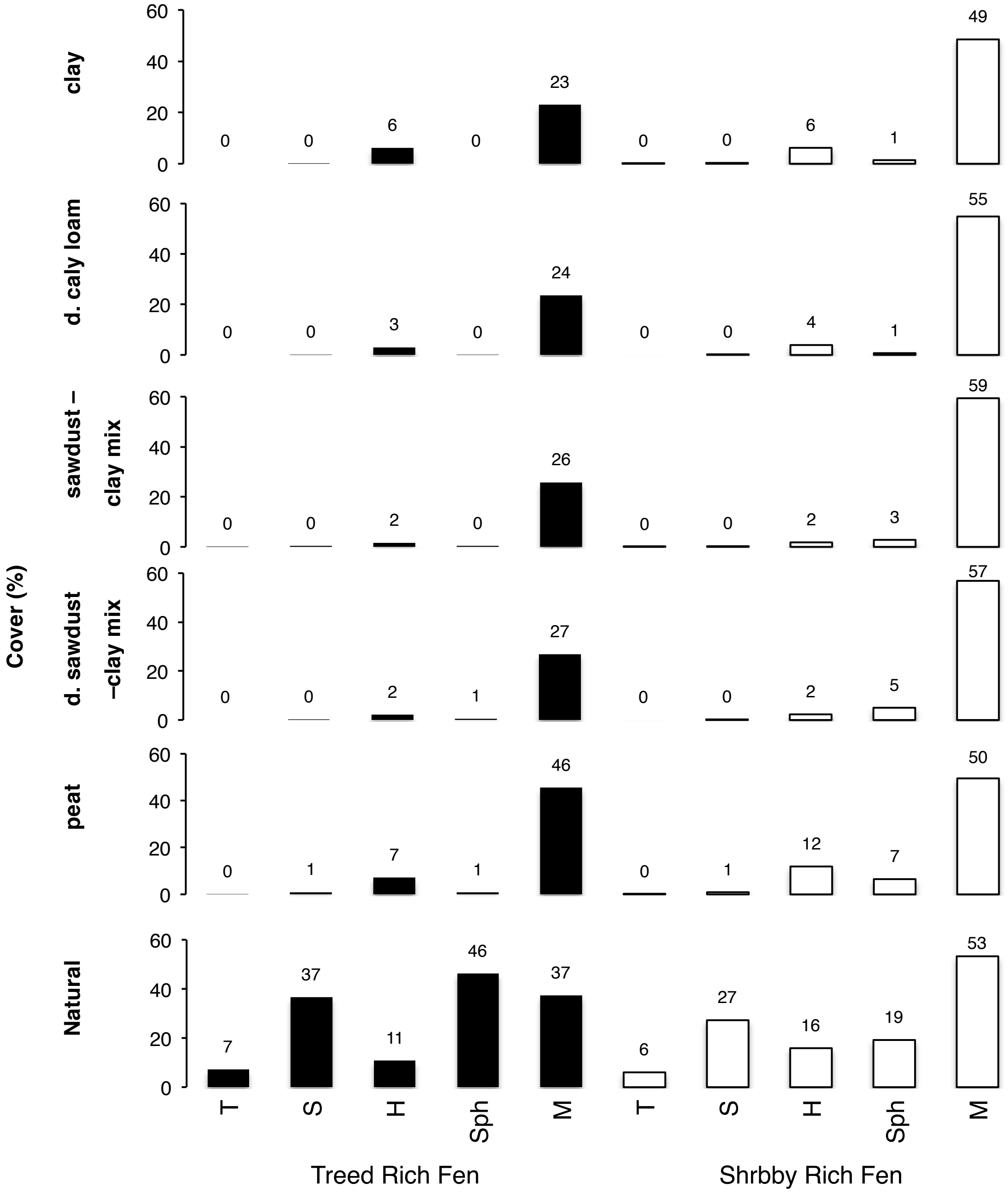


Figure 5.5 Reference ecosystem values per vegetation stratum compared to vegetation data from the manually-harvested diaspores experiment. T= tree, S = shrubs, H = herbs, Sph = sphagnum M = other moss; clay = clay loam d. clay loam = decompacted clay loam, sawdust-clay mix = combination of sawdust and clay loam, d. sawdust–clay mix = decompacted combination of sawdust and clay loam, peat = natural bog peat).

Vegetation Composition

Bryophytes response

The moss layer was dominated by peatland species (Fig. 5.6). They represented a proportion of at least 50 % of the total moss cover on every treatment and up to 95 % for some treatments. Wetland specialists were the second most represented group, with a maximum fraction of 32 %. The other groups represented a very small portion of the total moss cover.

Four main bryophyte species were found with distinctively higher ground cover: *Tomenthypnum nitens*, *Aulocomnium palustre* and the *Drepanocladus* group (sensu lato). *Sphagnum* species was included as a comparison, since it was dominant in the reference ecosystem. They all had significantly higher cover values when coming from the shrubby fen then when coming from the treed rich fen (Fig. 5.7; Appendix 4 *p* for all < 0.01). *Aulocomnium palustre* and *Sphagnum* species were the only bryophytes to be significantly influenced by the type of substrate. *A. palustre* was significantly more successful on peat; *Sphagnum species* on peat and on the mix of sawdust and clay treatment (Appendix 4).

Sphagnum species had relatively low cover values, between 0 and 6.5 %. In the natural peatlands, *Sphagnum* occupied 46 % of the treed rich fens and 19 % of the shrubby rich fens. Species from *Drepanocladus* group (sensu lato) displayed the highest ground cover values reaching a maximum of 35 %, but here again in the natural peatlands surveyed, the percent cover for *Drepanocladus* species was below 2 %. For most treatments, *T. nitens* and *A. palustre* had cover values similar to what was found in the reference ecosystem (Appendix 3).

No bryophyte grew on control plots, where no propagule was reintroduced. The entire list of bryophytes can be found in Appendix 3.

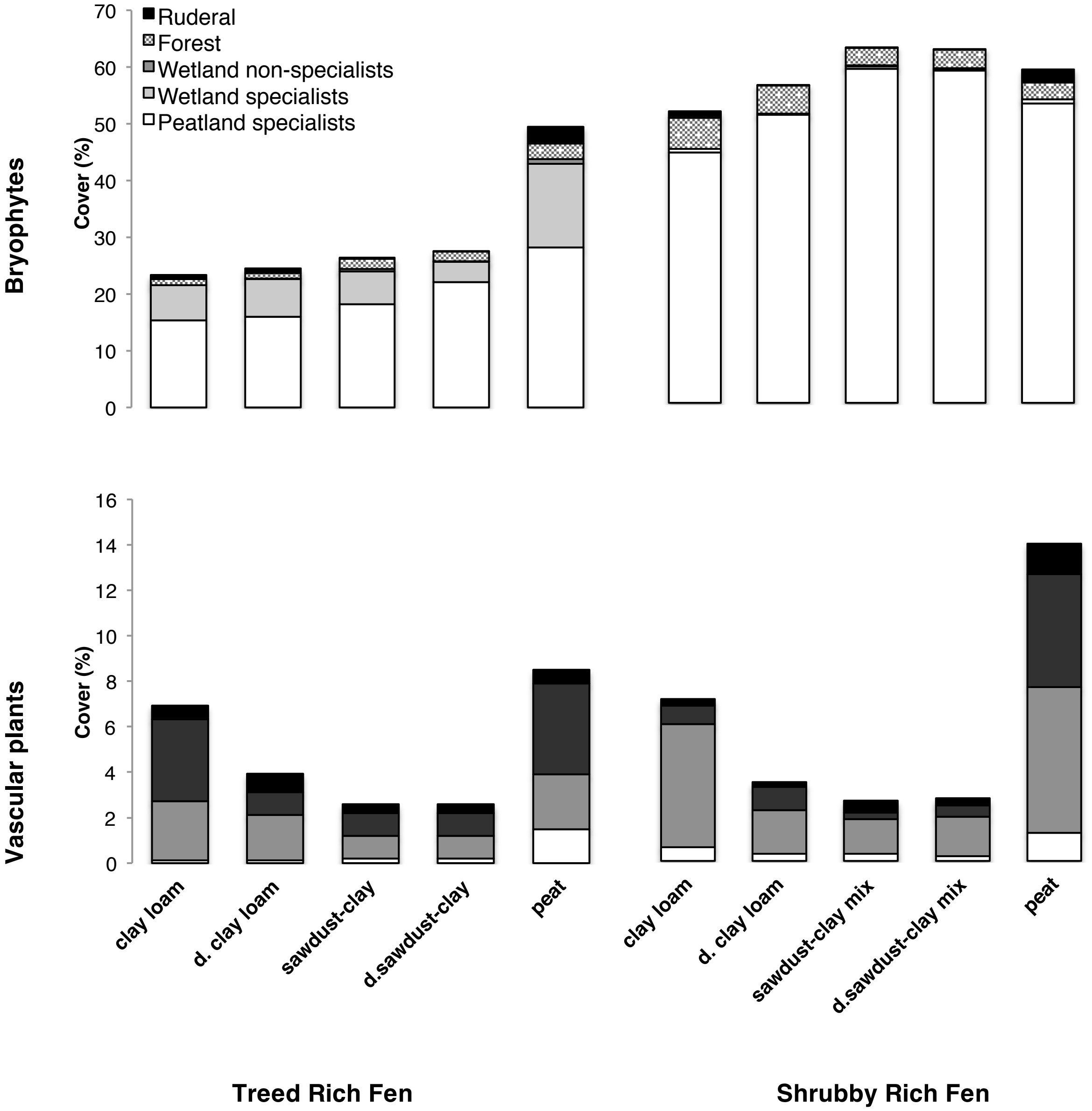


Figure 5.6 Establishment of bryophytes and vascular plants as per the preferential habitat after one growing season in manually-harvested diaspores experiment.

Vascular plants response

Wetland specialists (*Carex aquatilis* and *Carex canescens*) and wetland non-specialists (*Agrostis scabra*, *Juncus bufonius* and *Equisetum arvense*) dominated the vascular plant layer. Together they constituated more than 75 % of all treatments (Fig. 5.6), but they were not found in the natural fens surveyed.

Peatland specialists (mainly *Oxycoccus microcarpus* and *Potentilla palustris*) had a disctinct preference for peat (Fig. 5.6) but were present in small proportion (< 1.5%).

Ruderal species were found across all treatements and represented less than 2 % of all vascular plants. The main ruderal species were *T. officiale*, *T. hybridum*, *S. arvensis* and *Hordeum jubatum*.

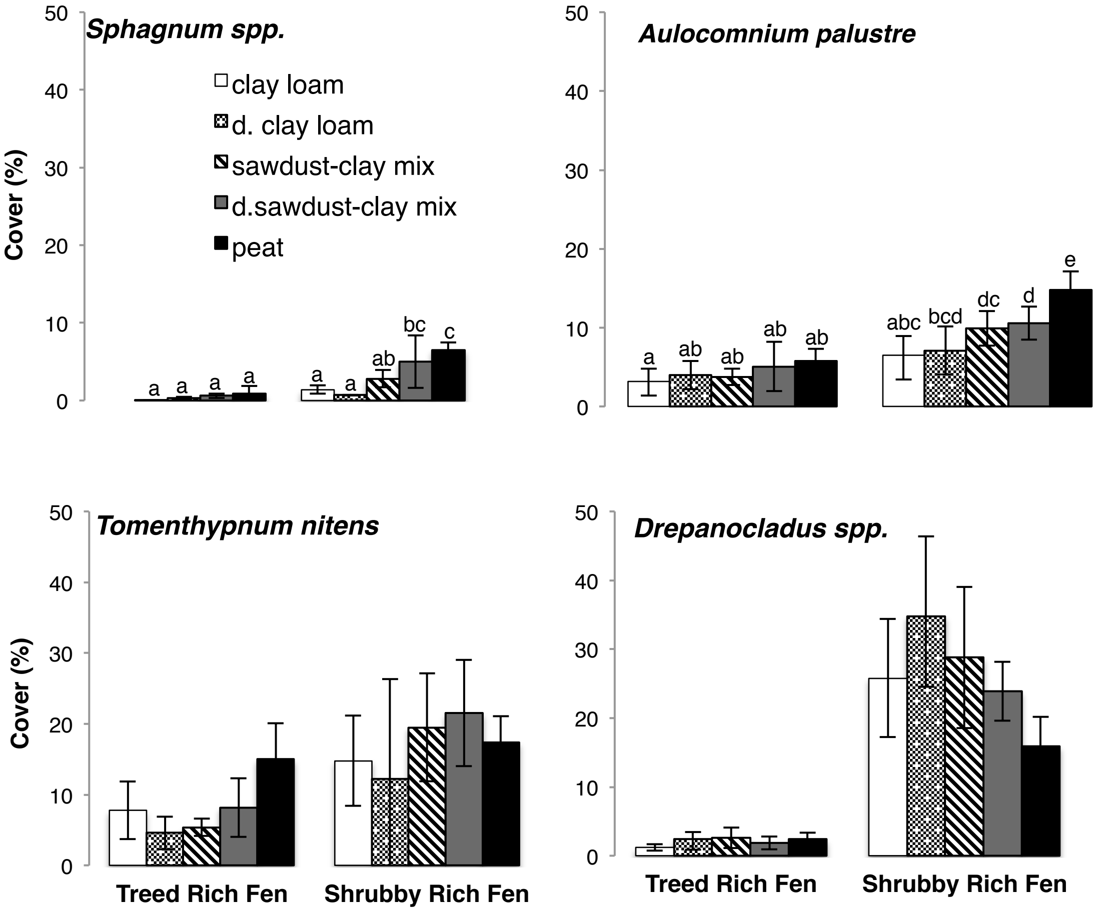


Figure 5.7 Establishment of four bryophytes from two types of donor site community reintroduced on five substrate treatments after one growing season (mean ± SE). Treatments with the same letter are not significantly different as revealed by LSD (*a* = 0.05).

Abiotic Factors

The experiment was installed in September of 2010, which was overall a very dry year (total precipitation: 215 mm), considerably below normal (annual mean: 402 mm; Table 4.1). The second growing season (2011) received substantially more precipitation, particularly during the summer: normal were exceeded by over 130 mm.

The water table fluctuated between 15 cm above ground and 15 cm below ground level (Fig 5.8), with a seasonal average of 1.6 ± 3.8 cm (mean ± sd, *n* = 80). Blocks 3 and 4 were submersed for most of the 2011 growing season while block 2 remained water free. Block 1 went through several wetting and rewetting cycles. The experimental sites were wetter than the natural peatlands where the diaspores were harvested.

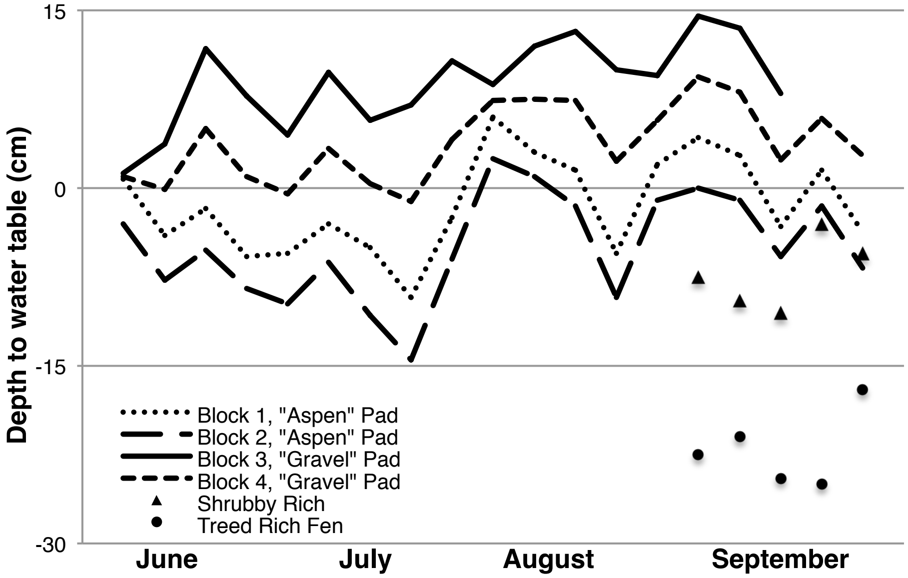


Figure 5.8 Water table fluctuations of four experimental blocks and two donor sites during the 2011 growing season. Values are averages (*n* = 2).

The experimental substrates varied significantly in concentration of Ca, Mg and Cl^- and in eC values (Table 5.3). Peat displayed the highest values of Ca, Mg, Na and Cl. $S0_4$ was comparably found in most substrates. The soil eC was significantly higher for the two treatments with strictly clay loam (clay loam and d. clay loam). Soil pH was comparable between treatments.

Water pH had a seasonal average of 6.88 ± 0. 21 (mean ± sd, *n* = 80).

Table 5.3 Soil chemistry of experimental substrates used in manually-harvested experiment. *n* = 5, mean (SE). Bold values indicate significant difference at $p < 0.05$.

	pH	**eC** [μS cm^{-1}]	**Ca^{2+}** [mg kg-^{1}]	**Mg^{2+}** [mg kg-^{1}]	**Na^{+}** [mg kg-^{1}]	**Cl^{-}** [mg kg-^{1}]	**S04^{2-}** [mg kg-^{1}]
Clay loam	6.69 (0.24)	1571.8 (223.2)	3450 (200)	580 (120)	45.5 (23.4)	35.4 (7.6)	1170 (420)
D.clay loam	6.53 (0.21)	1655.8 (245.9)	3400 (270)	560 (160)	49.4 (29.4)	35.1 (14.8)	1510 (520)
Sawdust clay mix	6.96 (0.18)	951.3 (317.0)	3200 (180)	660 (150)	72.4 (48.3)	43.7 (7.95)	730 (460)
D. sawdust-clay mix	6.80 (0.22)	1181.0 (145.1)	3330 (160)	550 (80)	46.9 (24.9)	43.2 (7.5)	630 (320)
Peat	6.87 (0.20)	1167.1 (228.2)	**10660** (2840)	**1660** (560)	**183.3** (127.9)	**88.7** (22.2)	1560 (680)

6.Discussion

6.1 Substrate Modifications

Bryophytes Response

The two restoration experiments carried out on decommissioned well pads allow us to conclude that using a moss layer transfer technique (Rochefort & Lode 2006) does favour the establishment of peatland plant-dominated communities on most substrates tested, even on mineral based ones. There was a clear difference in how bryophytes and vascular plants responded to the treatments tested so each group is discussed separately.

Fen bryophytes established particularly well in the manually-harvested diaspores experiment. The average cover value, all treatments considered, was 44 % after one growing season. This result is relatively high compare to similar studies which barely reached 20 % in moss cover after 2 growing seasons and confirms the efficient moss layer transfer technique (the transfer of surface soil along with the accompanying living plants) to reestablish a moss carpet (Rochefort & Isselin-Nondedeu 2013, Chirino *et al*. 2006).

Contrary to our initial hypothesis, decompaction or mixing in organic based sawdust with mineral soil did not improve bryophyte establishment. In both field experiments (mechanically-harvested diaspores and manually-harvested diaspores), the bryophyte cover was not influenced by the type of substrate, except for the treed rich fen community (Fig. 5.4), where peat clearly facilitated moss establishment. Peat amendment enhanced bryophyte species establishment on mineral soil in similar studies (Hugron *et al.* 2013). In the light of our results, it is clear that a peat amendment would favour a broader range of bryophyte communities. As mentioned by Bates (2009), substrate chemistry is amongst the most important factors for moss colonization. The chemistry of the peat substrate was surprising because of its high concentration in Ca, Mg and Na compared to the other substrates. The peat used in the experiment was harvested in a bog and had originally low concentrations of base cations. *Sphagnum* plants have a high cation exchange capacity (CEC) because of the uranic acids present in the cellular membrane (Clymo 1963). Hydrogen cations from the carbonyl group are released in the environment in exchange of other cations, often Na, Ca or Mg. This could explain the values observed on peat substrate were so high in base cations compared to the other substrates. Hence, peat is an interesting substrate to use in fen restoration because of its capacity to retain cations found in the environment, thus creating richer conditions for fen plants to establish.

In a restoration context, *Sphagnum* species and certain brown mosses have been observed to regenerate better when the water table was close to the surface, no further than -24 cm (Busby & Whitfield 1977, Price & Whitehead 2001, Mälson & Rydin 2007, Graf & Rochefort 2008a). In the present study, we can assume that the hydrological conditions were adequate for bryophytes establishment; summer average of -7.0 cm for the mechanically-harvested diaspores experiment and 1.6 cm for the manually-harvested diaspores experiment. It would be interesting to monitor the evolution of the established communities to verify if the environmental conditions created in the experimental settings would allow them to be sustainable.

In the mechanically-harvested diaspores experiment, the treatments with only sawdust completely inhibited bryophytes growth, probably because it was applied in a layer too thick (10 cm) and that sawdust, contrarily to peat, does not have a good water holding capacity. Hence, even with water levels relatively high, specific substrate characteristics are determinant for bryophyte establishment.

Vascular Plants Response

The vascular plants had a clear preference for the peat amendment, which also support the first hypothesis that peatland plants regenerate better with substrate modifications. Most communities tested showed a tendency to do better on peat than on the other treatments (Fig. 5.1 and Fig 5.4). This result differs from a similar study on peatland initiation where peat substrate has been observed to make no difference in plant establishment (Vitt *et al.* 2011). With the moss layer transfer technique, vascular plants regenerate mainly from the seeds contained in the donor site material than from fragmented rhizomes. In the peatland initiation project (Vitt *et al.* 2011), plants were introduced as natural transplants or greenhouse seedlings. This leads us to believe that peat offers a better ground for seed germination, but that some targeted mature individuals can survive indifferently on peat or on mineral soil.

The use of sawdust applied on the surface or mixed with 2 cm of surface clay reduced the vascular plants establishment in the manually-harvested diaspores experiment and inhibited all growth in the mechanically-harvested diaspores experiment. One of the reasons for this is probably the thickness of the amendment, which created conditions too dry for peatland plants to establish. In the mechanically-harvested diaspores experiment, the sawdust was applied in a 10 cm layer, which inhibited plant growth completely. In the second experiment, the sawdust was applied in a 2-3 cm layer, which did allow some plant growth but reduced the cover values compare to the other substrates. Sawdust is known to reduce the nitrogen availability for plants, which could explain the reduced success of vascular plants on treatment with 2 cm of sawdust.

6.2 Choosing a Donor Site

In both field experiments, the choice of plant communities for source of propagules was a determining factor for the successful establishment of peatland plants. Those results allow us to support the second hypothesis of this study stating that the type of donor site is determining for the establishment of peatland plants. The water and soil chemistry analysis could explain part of this variation. Andersen *et al.* (2011) have concluded that water pH, amongst others, is a good indicator for the evaluation of restoration success. In our case, the soil pH on all blocks (6.8) was more similar to the pH of the shrubby rich fen (6.9) than the pH of the treed rich fen (5.7). The same pattern was observed for the depth to the water table (DWT): the average DWT on all experimental blocks (1.6 cm) was more similar to the DWT of the shrubby rich fen (-7.0 cm) than the DWT of the treed rich fen (-22.0 cm).

Our hypothesis also stated that minerotrophic communities would have more success than bog communities, which is supported by both plant groups response in the mechanically-harvested diaspores experiment. All substrates considered, the vascular plants from the willow-sedge and the bog-aspen forest ecotone had considerably higher cover values after two growing seasons (50 % and 46 %) than the vascular from the bog (10 %). The same trend is observed for the bryophytes: the willow-sedge and the bog-aspen forest ecotone had considerably higher ground cover values after two growing seasons (16 % and 10 %) than the vascular from the bog (3 %). Our finding is that restoring minerotrophic communities seems to be more successful when the substrate to be restored presents minerotrophic conditions. This practice has been suggested by Wind-Mulder *et al.* (1996) and Wind-Mulder & Vitt (2000). The present study is in accordance with those recommendations.

6.3 Vegetation Composition

Bryophytes Response

The dominance of *T. nitens*, *A. palustre* and *Drepanocladus spp*. in the manually-harvested experiment was surprisingly high after one growing season, with values comparable to those from the reference ecosystems, and even higher for *Drepanocladus*. These three species are indicators of dryer fens or continental fens (Gignal *et al.* 1991), which is interesting since we did observed water levels close to the surface and periods of submersion in many units. The superficial clay layer left on site after partial pad removal operations (Fig 4.1) could explain these results. It is possible that even with a relatively high water table, the vertical water movements were reduced due to the poor hydraulic conductivity of clay. Nevertheless, these results suggest that brown mosses, notably *T. nitens*, are promising species for fen restoration, which was also observed in Pouliot *et al.* 2013).

Sphagnum cover was unexpectedly low in both field experiments (≤ 2 %). Campeau *et al.* (2004) found a *Sphagnum* cover considerably higher (15-20 %) in a similar study. *Sphagnum* mosses are limited in their distribution by many environmental factors: concentration of base cations, pH values and eC amongst others. The majority of *Sphagnum* species do not generally occur above pH 6, (Gignac *et al*. 1991) and high values of cations (Ca = 19-22 mg/l for example) usually indicate rich fens conditions where *Tomenthypnum nitens* and *Campylium stellatum* are found (Gignac *et al*. 1991; Vitt & Chee 1989). *Sphagnum* species are also extremely sensitive to salt, even in small concentrations (Wilcox 1984). The eC values of all experimental substrates were much higher than what is found in rich fens (Vitt & Chee 1989), and could have impeded *Sphagnum* establishment. Richer substrates conditions with elevated values of eC, pH and higher concentration of cations can reduce significantly *Sphagnum* establishment when reintroduced with other species as part of the donor site material.

The presence of a pioneer species such as *Leptobryum pyriforme* in the mechanically-harvested experiment was not unexpected; it does colonize disturbed soil (Mills & Macdonald 2005, Grime *et al.* 1990) in the area and is often well established on forest soils (Caners *et al.* 2009). Colonization of pioneer mosses could be beneficial to the establishment of *Sphagnum* species. *Polytrichum strictum*, a pioneer species, is believed to act as a nursing plant in facilitating the establishment of peatland mosses (Groeneveld & Rochefort 2005, Benscoter 2006). A recent study has however suggested that if the initial coverage of *P. strictum* species is too important (> 30 %), it can negatively affect the succession toward a *Sphagnum*-dominated moss carpet and be detrimental to a restoration project (González *et al.* 2013).

Vascular Plants Response

Most units were dominated by *Agrostis scabra* and *Carex* species, mainly *Carex aquatilis* and *Carex canescens*. *Carex aquatilis* has been observed to be quite successful in recolonizing recontoured well sites after mature plants transfer (Vitt *et al.* 2011). *C. aquatilis* occupies a wide range of ecological niches, with important variations of abiotic factors (Gignac *et al.* 2004). In northern Alberta, it was found in wetlands containing between 1 % and 100 % of organic matter, with wide range of pH (3.1-9.2), conductivity (36-8820 µS/cm) and a depth to water table (-80 to -30 cm; Koropchak *et al.* 2012). The example of *Carex aquatilis* leads us to believe that, with the MLLT, species with wide ecological niches might establish better than other species presents in the propagules mix.

The most successful vascular plant group to establish on the experimental substrates was the wetland specialists. Wetland specialists are strictly found in wetlands but are also found in peatlands. Most of the wetland specialists found on the experimental sites are also found in peatlands: *Carex aquatilis* and *Carex canescens*. The proportion in which they are present in the restored species pool is an important consideration. *Carex* species were not found dominant in the donor sites or in undisturbed peatlands of the area, which means that important shifts in the dominance can occur in similar species pool after reintroduction of propagules. Another example related to the dominance of a wetland specialist species is described by Poulin *et al.* (2012): *Typha latifolia*, a wetland specialist, is typically not found in bogs but has been a concern because of its successful colonization in a bog restoration project. The presence of wetland specialists is overall a good sign that the conditions created are suitable for those plants, of which many are also common in peatlands.

Peatland specialists were nearly absent in this restoration study. This is an expected result, since the restoration sites are still greatly disturbed and ecologically far from natural peatlands. The environmental conditions created by importing mineral substrate on exploitation pads are not favourable to the establishment of peatland plants and the natural chemistry found in natural peatland is greatly disturbed. In the light of our results, the use of a peat amendment could be a successful way to restore environmental conditions and peatland plant communities that will evolve toward a functioning peat-accumulating ecosystem.

Weed

The presence of ruderal species was limited on most experimental units. The species categorized as ruderal were abundantly found on the unshaved sections of the pad and heavily colonized the margin of the experimental blocks. The fact that we found 6 % and less of ruderal species in both experiments all treatments considered could reflect that the hydric conditions created in the experimental blocks were limiting to the colonization of species such as *Cirsium arvense*, *Sonchus arvensis*, *Melilotus spp*. and *Taraxecum officinalis*. It is plausible that wetland and peatland species transferred with the MLTT occupied the ground relatively quickly and that impeded the arrival of ruderal species by competition. As an observation, the most water tolerant invasive species seemed to be *Trifolium hybridum*.

Weedy species are a major concern in the province of Alberta. The *Weed Control Act* (Gov. of Alberta 2008) describes the requirements for handling weedy species considered noxious. Restoration practices need to be compliant with those requirements. Developing techniques that do not facilitate the colonization of noxious species is essential. The fact that very little noxious plants colonized the experimental blocks (only one species: Cirsium arvense < 1% in mechanically-harvested diaspores experiment only) is showing that levelling the pad along with the MLTT has the potential to restore peatland species, while limiting the ones considered noxious.

6.4 Mechanically-harvested Diaspores Versus Manually-harvested Diaspores

The mechanically-harvested diaspores approach seemed to favour the establishment of vascular plants. The mean cover values in the mechanically-harvested diaspores experiment was on average 35 % while the mean cover values in the manually-harvested diaspores experiment was on average 6 %. The peat used as experimental substrate in the mechanically-harvested diaspores experiment could explain the vascular plants success. The lower acrotelm of each donor site (collected below the first 10 cm) was harvested to use as amendment, which means that the peat was specific to each donor site. The seed bank in that lower portion of the acrotelm could have participated to the species pool by carrying a considerable amount of *Carex* seeds and other vascular plants in the propagule mix. Those results are important since restoring *Carex* species can be challenging when using the moss layer transfer technique in restoration projects. Investigating the potential of using the lower acrotelm as a source of *Carex* seeds could provide valuable answers on the regeneration of sedges in a restoration context.

6.5 Repercussion of Findings for Industry

Restoring peatlands on well pads is a major challenge for the energy sector. Peatlands perform several ecosystem services including habitat, support for biodiversity, water balance and carbon storage. These functions will not be recovered if the industry does not change its current practises of restoring upland ecosystems on well pads located in peatlands.

The Alberta regulatory framework does not yet include peatlands in its reclamation criteria. They have been under development for several years and are expected to be released soon. It is widely acknowledged that restoring a system identical to what was present in the landscape before disturbances is not realistic (SER 2004). Peatland restoration is just starting in the energy sector and there is much to learn before achieving the restoration of an independent and functioning ecosystem. It is however reasonable to expect that soil, hydrology and vegetation will be core components of the upcoming criteria (Ball 2012).

In our study, we have explored two of the three components: vegetation and soil. We have found that active reintroduction of propagules using a moss layer transfer technique (MLTT) was promising to reestablish peatland plant communities dominated by bryophytes. The establishment success of peatland plants is a crucial component for successful peatland restoration on well sites. The reestablishment of bryophytes is essential to the return of peat-accumulating function, because they contribute more than other vegetation groups to the peat-accumulation processes (Graf & Rochefort 2009). The MLTT is relatively new in the energy sector and there are many operational details to be experimented in order to mechanized all steps of this technique.

Finally, once the pad material is almost entirely removed from site, the exposed substrate is a clay loam. Reestablishing peatland plants on clay is achievable but might not be sustainable. Ideally, plants would be reintroduced on a thick peat substrate. As shown in this study, peat substrate maximizes the regeneration of both vascular plants and bryophytes. Because it delays the transport of contaminants, peat can be beneficial to peatland plants growing in contaminated conditions (Rezanezhad *et al*. 2012), which could be ideal for decommissioned well sites with disturbed chemistry. Choosing a restoration substrate that would be optimum for peatland plants while accommodating operational constraints remains a challenge for the restoration of peatlands on well pads.

7. Conclusion

This project was looking at different substrate treatments and plant communities to restore peatland plants on decommissioned well sites in Northern Alberta using a moss layer transfer technique (MLTT). In response to the substrate treatments, both mosses and vascular plants had a clear preference for the peat amendment. The use of sawdust had a negative impact on plant growth, especially if applied in a thick layer. The site chosen for the collection of propagules (donor site) was an important factor to the establishment of plants; bog plants were found with the lowest cover values while rich fen plants were the most abundant. Our findings support the restoration of minerotrophic communities on decommissioned well pads rather than bog communities if the site preparation is done in a similar fashion as in this study.

This project is one of the pioneer studies in peatland restoration on well pads in the boreal region of Alberta. There are a lot of unknowns related to the restoration of peatlands on artificially raised and compacted mineral sites. The results of our field experiments after one and two growing seasons clearly showed that the moss layer transfer technique (MLLT) is a promising approach to restore peatland plants on mineral well sites. Implementing a large-scale restoration project using peat amendment could have major implications for the restoration of well pads in the Boreal region of Alberta.

8. References

Alberta Environment, 2010a. 2010 Reclamation Criteria for Wellsites and Associated Facilities for Cultivated Lands Alberta Environment, Edmonton, Alberta. 117 p.

Alberta Environment, 2010b. 2010 Reclamation Criteria for Wellsites and Associated Facilities for Forested lands. Alberta Environment, Edmonton, Alberta. 99 p.

Alberta Environment, 2010c. 2010 Reclamation Criteria for Wellsites and Associated Facilities for Native Grassland. Alberta Environment, Edmonton, Alberta. 77 p.

Alberta Environment and Sustainable Resource Development, 2014. URL http://esrd.alberta.ca/lands-forests/land-industrial/education/industrial-land-use/oil-and-gas/default.aspx [accessed 07 May 2014].

Amon, J.P., Jacobson, C.S. & M.L. Shelley, 2005. Construction of fens with and without hydric soils. Ecological Engineering, 24: 341-357.

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

Anielski, M. & S. Wilson, 2010. Real Wealth of the McKenzie Region: Assessing the Natural Capital Values of a Northern Boreal Ecosystem. Canadian Boreal Initiative, Ottawa, Canada.

Averett, J.M., Robert, A.K., Lucas, N.E., Frey, S.D. & P. Curtis, 2004. Effects of Soil Carbon Amendment on Nitrogen Availability and Plant Growth in an Experimental Tallgrass Prairie Restoration. Restoration Ecology, 12: 568-574.

Bainbridge, D.A., 2007. A guide for desert and dryland restoration: new hope for arid lands. Island Press, Washington D.C., United States.

Ball, K., 2012. Peatland reclamation and criteria development. [PDF document]. Presented at the Peatland Restoration for Practitioners, Peace River, Alberta. September 5-7, 2012. URL http://www.nait.ca/70709.htm [accessed 25 September 2013].

Bates, J.W., 2009. Mineral nutrition and substratum ecology. Pages 300-356 in Goffinet, B. & A.J. Shaw (eds.). Bryophyte biology, 2nd edition. Cambridge University Press, Cambridge, United Kingdom.

Beckingham, J.D. & J.H. Archibald, 1996. Field guide to ecosites of Northern Alberta. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. Special Report 5.

Belyea, L. R., 2004. Beyond ecological filters: feedback networks in the assembly and restoration of community structure. Pages 115–131 in Temperton, V. M., Hobbs, R., Nuttle, T. and S. Halle, editors. Assembly rules and restoration ecology: bridging the gap between theory and practice. Island Press, Washington, DC.

Benscoter, B.W., 2006. Post-fire bryophyte establishment in a continental bog. Journal of Vegetation Sciences, 17: 647-652.

Bortoluzzi, E., Epron, D., Siegenthaler, A., Gilbert, D. & A. Buttler, 2006. Carbon balance of a European mountain bog at contrasting stages of regeneration. New Phytologist, 172: 708-718.

Bulmer, C., 2000. Reclamation of forest soils with excavator tillage and organic amendments. Forest Ecology Management, 33: 157-163.

Busby, J.R. & W.A. Whitfied, 1977. Water potential, water content and net assimilation of some boreal forest bryophytes. Canadian Journal of Botany, 56: 1551-1558.

Campeau, S., Rochefort, L. & J. Price, 2004. On the use of shallow basin to restore cutover peatlands: Plant Establishment. Restoration Ecology, 12: 471-482.

Caners, R.T., Macdonald, E.S. & R.J. Belland, 2009. Recollonization potential of bryophyte diaspores banks in harvested boreal mixed-wood forest. Plant Ecology, 204: 55-68.

Chapman, S., Buttler, A., Francez, A., Laggoun-Defrage, F., Vasander, H. and M. Scholter, 2003. Exploitation of northern peatlands and biodiversity maintenance: a conflict between economy and ecology. Frontiers in Ecology and the Environment, 1(10): 525-532.

Chee, W.L & D.H Vitt, 1989. The vegetation, surface water chemistry and peat-chemistry of moderate-rich fens in central Alberta, Canada. Wetlands, 9(2): 227-261.

Chirino, C., Campeau, S. & L. Rochefort, 2006. Sphagnum establishment on bare peat: The importance of climatic variability and Sphagnum species richness. Applied Vegetation Science, 9: 285-294.

Clymo, R.S., 1963. Ion exchange in Sphagnum and its relation to bog ecology. *Annals of Botany*, *27*(2): 309-324.

Cobbaert, D., Rochefort, L. & J.S. Price, 2004. Experimental restoration of a fen plant community after peat mining. Applied Vegetation Science, 7: 209-220.

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

Cooperband, L., 2002. Building Soil Organic Matter with Organic Amendments. Center for Integrated Agricultural Systems (CIAS), College of Agricultural and Life Sciences, University of Wisconsin-Madison, Madison, USA.

Davis, S., 1990. Effectiveness of a winged subsoiler in ameliorating a compacted clayey forest soil. Western Journal of Applied Forestry, 5: 138-39.

Eldridge, J.D., Redente, E.D & M. Pasche, 2011. The Use of Seedbed Modifications and Wood Chips to Accelerate Restoration of Well Pad Sites in Western Colorado, U.S.A. Restoration Ecology, doi: 10.1111/j.1526-100X.2011.00783.x

Environment Canada, 2012. URL http://climate.weatheroffice.gc.ca/climate_normals/ [accessed 21 July 2012].

Environmental and Sustainable Resource Development, 2013. Alberta Wetland Policy. Edmonton, Alberta. 25 p.

Fetter, C. M., 2001. Applied Hydrogeology 4th ed. Prentice Hall, Upper Saddle River, New Jersey. 589 p.

Hobbs, R.J., 2003. Ecological management and restoration: Assessment, setting goals and measuring success. Ecological Management #38; Restoration 4: S2-S3.

Gorham, E. & J.A. Janssens, 1992. Concepts of fen and bog re-examined in relation to bryophyte cover and the acidity of surface waters. Acta Societatis Botanicorum Poloniae, 61: 7-20.

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

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

Government of Alberta, 2008. Weed Control Act, Statutes of Alberta, 2008 Chapter W-5.1 Current as of October 1, 2011. Alberta Queen's Printer.

Government of Alberta, 2009. Environmental Protection and Enhacement Act, Revised Statutues of Alberta 2000. Chapter E-12. Current as of October 1, 2009. Alberta Queen's Printer.

Government of Alberta, 2010. Alberta's Oil Sands, Facts and stats. URL http://oilsands.alberta.ca [accessed 13 June 2010].

Graf, M.D., 2009. Literature review on the Restoration of Alberta's Boreal Wetlands: Affected By Oil, Gas and In Situ Oil Sands Development. Report prepared for Ducks Unlimited Canada. 59 p.

Graf, M.D. & L. Rochefort, 2008a. Moss regeneration for fen restoration: Fields and greenhouse experiments. Restoration Ecology, 18: 121-130.

Graf, M.D. & L. Rochefort, 2008b. Techniques for restoring fen communities on cut-away peatlands in North America. Applied Vegetation Science, 11: 521-528.

Graf, M.D. & Rochefort, L. 2009. Examining the peat-accumulating potential of fen vegetation in the context of fen restoration of harvested peatlands. Écoscience, 16: 158-166.

Grime, J.P., Rincon, E.R. & B.E. Wickerson, 1990. Bryophytes and plant strategy theory. Botanical Journal of the Linnean Society, 104: 175-186.

Groeneveld, E.V.G. & L. Rochefort, 2005. Polytrichum strictum as a solution to frost heaving in disturbed ecosystems: a case study with milled peatlands. Restoration Ecology, 13: 74-82.

Halsey, L.H., Vitt, D.H., Beilman, D., Crow, S., Mehelcic, S. & R. Wells, 2003. Alberta Wetland Inventory Standards 2.0. Alberta Sustainable Resource Development. Edmonton, Canada.

Hugron, S., Poulin, M. & L. Rochefort, 2013. Organic matter amendment enhances establishment of reintroduced bryophytes and lichens in borrow pits located in boreal forest highlands. Boreal Environment Research, 18: 317-328.

Johnson, D., Kershaw, L., MacKinnon, A. & J. Pojar, 1995. Plants of the western boreal forest & Aspen Parkland. Lone Pine Publishing, Edmonton, Canada.

Joosten, H. and D. Clarke, 2002. Wise use of mires and peatlands - Background and principles including a framework for decision-making, International Mire Conservation Group and International Peat Society. 304 p.

Koropchak, S., Vitt, D.H., Bloise, R. & R.K. Wieder, 2012. Fundamental paradigms, foundation species selection and early plant responses to peatland initiation on mineral soils. Pages 76-100 in Vitt, D.H. and J.S. Bhatti (eds.) Restoration and Reclamation of Boreal Ecosystems; Attaining Sustainable Development. Cambridge University Press, Cambridge, United Kingdom.

Lafleur P.M. & N.T. Roulet, 1992. A comparison of evaporation rates from two fens of the Hudson Bay Lowland. Aquatic Botany, 44: 59-69.

LeBlanc, M.-C., Malloy, S., Price, J.S., & L. Rochefort, 2012. Moss layer transfer technique: From bog to fen restoration. No 201/208. Proceedings of the 14th International Peat Congress: Peatland in balance, Stockholm, Sweden, June 3-8, 2012. International Peat Society. 4 p.

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

Mahmood, Md. S. & M. Strack, 2011. Methane dynamics of recolonized cutover minerotrophic peatland: Implications for restoration. Ecological Engineering, 37: 1859-1868.

Mälson, K. & H. Rydin, 2007. The regeneration capabilities of bryophytes for rich fen restoration. Biological Conservation, 135: 435-442.

Mälson, K., Backéus, I. & H. Rydin, 2008. Long-term effects of drainage and initial effects of hydrological restoration on rich fen vegetation. Applied Vegetation Science, 11: 99-106.

McNeil, P. & M. Waddington, 2003. Moisture controls on Sphagnum growth and Co2 exchange on cutover bog. Journal of Applied Ecology, 40: 354-367.

Mills, S.E. & S.E. Macdonald, 2005. Factors influencing bryophyte assemblage at different scales in the western Canadian boreal forest. Bryologist, 108: 86-100.

Moorhouse, J., Huot, M. & S. Dyer, 2010. Drilling deeper: The in situ oils sands report card. The Pembina Institute. www.pembina.org.

Morgan, J.P., 1994. Soil impoverishment: a little-known technique holds potential for establishing prairie. Restoration and Management Notes, 12: 55-56.

Moss, E.H., 1983. Flora of Alberta, 2nd edition. University of Toronto Press Incorporated, Toronto, Canada.

National Wetlands Working Group, 1997. The Canadian Wetland Classification System, 2nd Edition. B.G. Warner and C.D.A. Rubec (eds). University of Waterloo, Waterloo, Ontario.

Natural Regions Committee, 2006. Natural Regions and Subregions of Alberta. Compiled by D.J. Downing & W.W. Pettapiece. Government of Alberta, Pub. No. T/852.

Osko, T., 2010. Gap Analysis of Wetland Reclamation Knowledge and Practices in Northern Alberta. Prepared by Circle T Consulting, Inc. CEMA Contract No. 2008-0024.

Patzelt, A., Wild, U. & J. Pfadenhauer, 2001. Restoration of Wet Fen Meadows by Topsoil Removal: Vegetation Development and Germination Biology of Fen Species. Restoration Ecology, 9: 127-136.

Payette, S. & L. Rochefort, editors. 2001. Écologie des tourbières du Québec-Labrador. Les Presses de l'Université Laval, Sainte-Foy, Canada.

Pfadenhauer, J. & A. Grootjans, 1999. Wetland restoration in Central Europe: aims and methods. Applied Vegetation Science, 2: 95-106.

Polster, D.F., 2009. Natural Processes: The Application of Natural Systems for the Reclamation of Drastically Disturbed Sites. paper presented at the B.C. Technical and Research Committee on Reclamation, BC Mine Reclamation Symposium. Cranbrook, B.C. September 14-17, 2009.

Pouliot, R., Rochefort, L. and M.D. Graf, 2013. Fen mosses can tolerate some saline conditions found in oil sands process water. Environmental and Experimental Botany 89: 44-50,

Poulin, M., Andersen, R. & L. Rochefort, 2012. A new approach for tracking vegetation change after restoration: A case study with peatlands. Restoration Ecology, 21: 363-371.

Price J.S. & G.S. Whitehead, 2001. Developing hydrological thresholds for Sphagnum recolonization on an abandoned cutover bog. Wetlands, 21: 32-42.

Quinty, F. & L. Rochefort, 2003. Peatland restoration guide, 2nd ed. Canadian Sphagnum Peat Moss Association and New Brunswick Department of Natural Resources and Energy. Québec, Québec.

Rezanezhad, F., Andersen, R., Pouliot, R., Price, J.S., Rochefort, L. & M.D. Graf, 2012. How fen vegetation structure affects the transport of oil sands process-affected waters. Wetlands, 32: 557-570.

Rochefort, L., 2000. Sphagnum - A keystone genus in habitat restoration. The Bryologist, 103: 503-508.

Rochefort, L. & E. Lode, 2006. Restoration of degraded boreal peatlands. Pages 382-423 in Wieder, R.K. & D.H. Vitt (eds.). Boreal Peatlands Ecosystems, Ecological Studies Series, vol. 188. Springer-Verlag, Berlin.

Rochefort, L., Isselin-Nondedeu, F., Boudreau, S. & M. Poulin, 2013. Comparing survey methods for monitoring vegetation change through time in a restored peatland. Wetlands Ecology and Management 21: 71-85.

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

Rooney, R.C., Bayley, S.E. & D. Schindler, 2012. Oil sands mining and reclamation cause massive loss peatland and stored carbon. Proceedings of National Academy of Science. Early edition, 5p.

Samaritani, E., Siegenthaler, A., Yli-Pet¨ays, M., Buttler, A., Christin, P.A. & E.A.D. Mitchell, 2010. Seasonal Net Ecosystem Carbon Exchange of a Regenerating Cutaway Bog: How Long Does it Take to Restore the C-Sequestration Function? Restoration Ecology, 19: 480-489.

Schneider, R. & S. Dyer, 2006. Death by a thousand cuts: Impact of in situ oil sands development on Alberta's boreal forest. The Pembina Institute. URL www.pembina.org.

Siegel, D.I. & P. Glaser, 2006. Ecological Studies: The hydrology of peatlands. Springer Verlag Berlin Heidelberg, 188: 289-311.

Short, P., 2012. Strategy for responsible peat management. [PDF document]. Presented at the Peatland Restoration for Practitioners, Peace River, Alberta. September 5-7, 2012. URL http://www.nait.ca/70709.htm [accessed 25 September 2013].

Society for Ecological Restoration, International Science and Policy Working Group, 2004. The SER International Primer on Ecological Restoration. Available online at : www.ser.org

Staubli, P., 2004. Regeneration von Hochmooren im Kanton Zug. Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich, 149: 75-81.

Switalski, T.A., Bissonnette, J.A., DeLuca, T.H., Luce, C.H. & M.A. Madej, 2004. Benefits and impacts of road removal. Frontiers in the Ecology and Environment, 2: 21-28.

Tarnocai, C., Kettles, I.M., and B. Lacelle, 2000. Peatlands of Canada. Geological Survey of Canada, Ottawa, Ont. Open File 3152 (map).

Tarnacai, C., 2006. The effect of climate change in Canadian peatlands. Global and Planetary Change, 53: 222-232.

Van Duren, I.C., Strykstra, R.J., Grootjans, A.P., Heerdt, G.N.J. & D.M. Pegtel, 1998. A multidisciplinary evaluation of restoration measures in a degraded *Cirsio-Molinietum* fen meadow. Applied Vegetation Science, 1: 115-130.

Vitt, D.H., Halsey, L.A. & S.C. Zoltai, 1994. The bog landforms of continental Canada in relation to climate and permafrost patterns. Arctic and Alpine Research, 26: 1-13.

Vitt, D.H. & S.C. Zoltai, 1995. Canadian wetlands: Environmental gradients and classification. Vegetatio, 118: 131-137.

Vitt, D.H., Halsey, L.A., Thormann, M.N. & T. Martin, 1996. Peatland Inventory of Alberta. Prepared for the Alberta Peat Task Force, National Center of Excellence in Sustainable Forest Management, University of Alberta, Edmonton.

Vitt, D.H., Wieder, R. K., Xu, B., Kaksie, M. & S. Koropchak, 2011. Peatland establishment on mineral soils: Effects of water level, amendments, and species after two growing seasons. Ecological Engineering, 37: 354-363.

Waddington, J.M., Strack, M. & M.J. Greenwood, 2010. Toward restoring the net carbon sink function of degraded peatlands: short term response in CO2 exchange to ecosystem-scale restoration. Journal of Geophysical Research 115, G01008, doi:10.1029/2009JG001090.

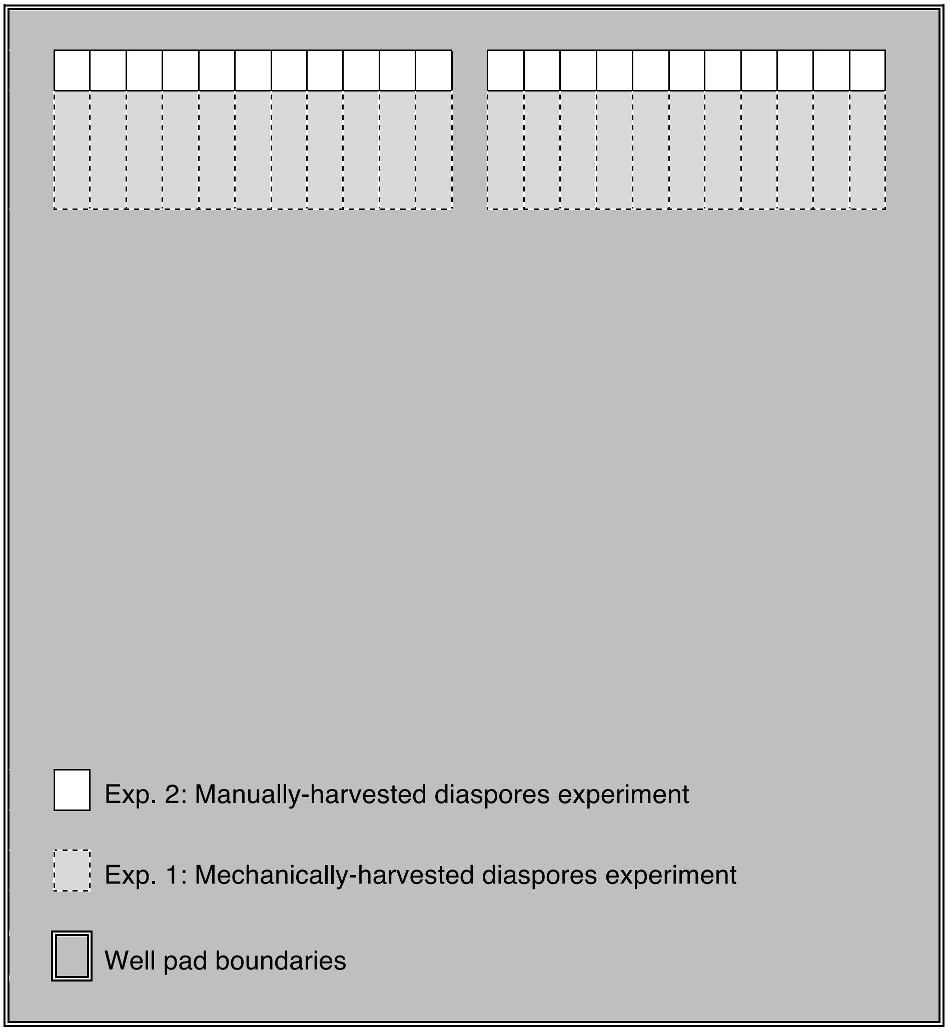
Whisenant, S.G., 1999. Repairing damaged wildlands: a process-oriented, landscape-scale approach. Cambridge University Press, Cambridge, United Kingdom.

Wind-Mulder, H.L., Rochefort, L. & D.H. Vitt, 1996. Water and peat chemistry comparisons of natural and post-harvested peatlands across Canada and their relevance to peatland restoration. Ecological Engineering, 7: 161-181.

Wind-Mulder, H.L. & D.H. Vitt, 2000. Comparisons of water and peat chemistries of a post-harvested and undisturbed peatland with relevance to restoration. Wetlands, 20: 616- 628.

Wilcox, D.A.,1984. The effects of NaCl deicing salts on Sphagnum recurvum P. beauv. Environmental and Experimental Botany, 24(4): 295-304.

Appendix 1. Schema of two experimental blocks located on the same well pad



Appendix 2. Species (mean) recorded in manually-harvested diaspores experiment after one growing season. * = presence. Gr: P= Peatland specialists WS= Wetland specialists WN= Wetland non-specialists F= Forest species, R= Ruderal, O= Others.

		PEAT			**CLAY**		
Species	**Gr**	**Willow-Sedge Fen**	**Aspen-Bog Forest Ecotone**	**Bog**	**Willow-Sedge Fen**	**Aspen-Bog Forest Ecotone**	**Bog**
Agrostis glabra Willd	WN	22.3±7.6	7.3±3.9	0.3±0.4	2.6±2.6	2.3±2.3	0.3±0.4
Calamagrostis canadensis (Michx)	WS	0	p	0	0	0	0
Carex aquatilis Wahl.	WS	0.3±0.3	0.4±0.8	0.4±0.8	3.5±4.4	5.7±6.5	0
Carex canescens L.	WS	44.5±24.3	49.1±25.5	10.9±16.1	11.8±18.4	13.4±15.3	1.5±0.8
Cirsium arvense (L.) Scop.	R	*	*	0	0.2±0.3	0	0
Epilobium angustifolium L.	R	0	*	0	0	0	0
Equisetum arvense L.	WN	0	0	0	*	0.4±0.8	*
Galium sp.	WN	0.2±0.4	0.3±0.3	0	0	0	0
Hieracium umbellatum L.	R	0.1±0.3	*	0	*	0.2±0.3	0.1±0.3
Hordeum jubatum L.	R	1.8±3.3	1.7±2.1	*	0.5±0.8	0.5±0.6	0.2±0.2
Hordeum vulgare L.	0	0.02±0.06	0	0.04±0.08	0.01±0.05	0.03±0.06	0.02±0.06
Juncus buffonius L.	WN	0	0	0	*	0	0
Ledum groenlandicum Oeder	P	0	*	*	0	0	0
Melilotus officinalis (L.) Lam.	R	*	*	0	0.1±0.07	*	*
Picea mariana Mill.	F	0	*	0.2±0.2	*	0	*
Plantago major L.	R	*	0	0	*	*	*
Populus sp.	F	*	0	0	0	*	0
Potentilla norvegica L.	R	0.8±0.7	0.2±0.1	0	0.6±1.1	0	0
Ribes spp. L.	WN	0.2±0.1	2.0±1.4	*	*	0	0
Rumex occidentalis	WN	0.1±0.08	0	0	0	0	0
Salix sp.	WS	0.2±0.3	0	0	*	0.2±0.3	0.3±0.3
Sonchus arvensis L.	R	0.2±0.3	*	*	*	0.1±0.3	*
Stellaria longifolia Muhl.	WN	0.9±0.5	0.2±0.2	*	0.7±0.6	0	0
Taraxacum officiale Weber.	R	0.5±0.2	0.5±0.6	0.5±0.2	0.9±1.2	0.4±0.5	0.5±0.1
Trifolium hybridum L.	R	2.5±1.5	5.1±4.6	2.4±2.8	3.7±4.6	2.0±4.0	1.5±2.3
Typha latifolia L.	WS	0	0	*	0.2±0.3	*	0.2±0.2
Bryophytes							
Aulocomnium palustre (Hedw.)	P	0.1±0.3	1.2±2.1	*	0	*	*
Bryum sp.	O	0.5±0.8	0.6±0.4	1.8±1.3	0.5±0.1	0.5±0.5	*
Dicranum undulatum Brid.	WN	*	0	*	0	0	0
Leptobryum pyriforme (Hedw.)Wilson	R	14.9±12.9	7.0±3.8	0.4±0.3	14.8±19.4	9.4±12.1	2.5±2.2
Pleurozium schreberi (Brid.)Mitt.	F	0	0	*	0	0	*
Polytichum strictum Brid.	WN	*	*	*	0	0	0
Sphagnum spp.	P	1.1±1.3	0.8±0.4	0.3±0.5	0	0	0

Appendix 3. Species (mean) recorded in manually-harvested diaspores experiment after one growing season. * = presence, Gr: P= Peatland specialists, WS= Wetland specialists, WN= Wetland non-specialists, F= Forest species.

	Species	**Gr**	**Treed Rich Fen**						**Shrubby Rich Fen**					
			clay	d.clay	mix	d.mix	p	Natural	cla	d.clay	mix	d.mix	p	Natural
Vascular plants	*Agrostis scabra* Willd	WN	2.8	0.8	0.3	0.3	2.6	*	0.7	0.2	0.3	0.1	3.7	0
	Apocym androsaemifolium L.	WN	0.1	*	0	0	*	0	*	0	0	0	0	0
	Carex aquatilis Wahl.	WS	0.2	0.1	0	0	0.1	5.3	2.5	0.4	0.2	0.4	2.9	7.8
	Carex canescens L.	WS	0.8	0.5	0.3	0.2	0.2	*	1.5	0.7	0	0	0.4	0
	Carex spp.	WN	1.4	1.3	0.4	0.7	1.4	2.5	1.0	0.5	1.2	1.0	1.9	0.6
	Drosera rotundifolia L.	P	0	0	*	0	0	*	0	0	0	0	0	*
	Epilobium palustre L.	P	*	*	*	*	0.9	*	0.1	0.2	0.1	0.2	0.7	*
	Equisetum arvense L.	WN	*	0	0.3	0.7	1.0	0	0.1	1.3	0	0.4	0.2	0
	Hordeum jubatum L.	R	0.2	0.2	*	0	0.1	0	0.2	*	0	0	0.2	0
	Hordeum vulgare L	O	0	*	0	*	0.2	0	0	*	0	0	0	0
	Juncus bufonius L.	WN	0.6	0.1	*	0	0.4	0	*	0.4	0	0	0.7	0
	Ledum groenlandicum Oeder	P	0	0	*	0	*	12.0	0	0	0	0	0	5.8
	Oxycoccus microcarpus L. Turcz.	P	0.1	0.1	0.2	0.2	0.6	0.9	0.1	*	0.2	0.1	0.5	0.4
	Parnassia palustris L.	P	*	0	*	0	*	0	0	0	0	0	0	*
	Picea mariana (Mill.) BSP	WS	0	0	*	0	0	4.5	*	0	*	0	*	2.6
	Potentilla palustris (L.) Scop.	P	0	0	0	0	0	0.7	*	0.1	0	*	0.1	0.7
	Ribes spp.	WN	0	0	0	0	*	0	0	0	0	0	0	*
	Salix spp.	WS	0	*	0.1	0.1	0.4	2.8	0.2	*	*	0.1	0.4	11.9
	Sonchus arvensis L.	R	*	*	*	*	0.2	0	0	0	0.1	*	0.2	0
	Stellaria longifolia Muhl.	WN	0.1	0	0	0	0	*	*	*	*	0	0.3	0
	Taraxacum officiale Weber.	R	0.2	0.5	0.1	0.1	0.2	*	0.1	0.1	0.2	0.1	0.4	0
	Trifolium hybridum L.	R	0.2	*	0.1	0.3	0.1	*	0	0	0.2	0.2	0.6	0
	Triglochin maritima L.	P	0	0	0	0	0	*	0	0	0	0	0	2.2
	Typha latifolia L.	WS	0.2	0.1	0.2	0.2	0.4	0	0.2	0.2	0.1	0.1	0.8	0
	Vaccinium vitis-idea L.	P	0	0	0	*	*	0.8	0	0	0	0	0	0.6

Appendix 3. (continued) Species (mean) recorded in manually-harvested diaspores experiment after one growing season. * = presence, Gr: P= Peatland specialists, WS= Wetland specialists, WN= Wetland non-specialists, F= Forest species.

Bryophytes

Species	**Gr.**	**Treed Rich Fen**						**Shrubby Rich Fen**					
		clay	d.clay	mix	d.mix	p	Natural	clay	d.clay	mix	d.mix	p	Natural
Aulocomnium palustre (Hedw.) Schwaegr.	P	3.2	4.0	3.8	5.1	5.7	6.6	6.5	7.1	9.8	10.6	14.8	9.4
Bryum pseudotriquetrum (Hedw.) Gaertn. eal..	W	0.7	1.1	0.3	0.4	1.8	0.2	0.5	0.1	0.2	0.2	0.5	0.6
Calliergon stramineum (dickson ex Bridel) Kindberg	P	3.9	4.8	6.5	6.7	4.7	3.1	0.2	0.3	0.4	0.2	0.2	0.6
Drepanolcadus aduncus (Hedw.) Warnst.	P	0.3	0.6	0.3	0.5	0.2	0.2	8.5	20.6	10.7	11.0	6.4	0
Drepanocladus uncinatus (Hedw.) Warnst.	F	0.7	0.7	1.2	1.2	0.9	*	5.3	4.9	2.9	3.2	2.7	1.3
Dicranum undulatum Brid.	P	0	0	0	0	0	*	0	0	*	0	*	0.5
Cinclidium stygium Sw. in Schrad	P	0.2	0.2	0.2	0.1	0.7	*	*	*	*	*	*	1.6
Helodium blandii (Web. & Mohr.) Warnst.	P	0.2	0.5	0.3	0.2	0.5	0.1	0.5	0.1	0.1	0.2	*	0.8
Hylocomnium splendens (Hedw.) Schimp.	F	0	0	*	*	0	1,8	0	0	0	0	0	2.3
Hypnum linbergii Mitt.	W	5.4	5.5	5.5	3.1	13.0	0.2	*	0.1	0.2	*	0.2	1.9
Pleurozium Schreberi (Brid.) Mitt.	F	0.3	0.3	0.5	0.7	0.8	6.0	0.1	0.1	0.1	0.1	0.2	1.3
Pholia nutans (Hedw.) Lindb.	WN	0.1	0.1	0.4	0.2	0.8	0.8	0	0	*	*	*	0.4
Leptobryum pyriforme (Hedw.) Wilson	R	0.8	0.9	0.2	0.1	3.0	0	1.2	*	*	*	2.3	*
Polytrichum strictum Brid.	P	*	0.1	0.2	0.1	0.1	0.3	*	*	0.1	0.1	0.1	0.2
Sphagnum spp.	P	0	*	0.3	0.6	0.9	46.3	1.4	0.7	2.8	5.0	6.5	19.2
Tomenthypnum nitens (Hedw.) Loeske	P	7.8	4.6	5.4	8.2	15.0	15.8	14.8	12.2	19.5	21.5	17.4	23.7
Warnstorfia fluitans (Hedw.) Loeske	P	0.3	1.0	1.1	0.5	0.3	1.2	12.0	9.3	15.2	9.8	6.8	0

Appendix 4 ANCOVAs outcomes performed on establishment data for four dominant bryophytes in the manually-harvested diaspores experiment. A submersion index was used for co-variable.

		T. nitens		***A. palustre***		***Drepanocladus* *spp.***		***Sphagnum* *spp.***	
	df	***F***	***P***	***F***	***P***	***F***	***P***	***F***	***P***
Block	3	1.73		20.3		4.62		5.9	
Donor site	1	7.95	**<0.01**	41.6	**<0.01**	96.7	**<0.01**	86.0	**<0.01**
Substrate	4	0.67	0.62	5.2	**<0.01**	0.77	0.55	7.4	**<0.01**
Substrate*Donor site	4	0.36	0.83	1.0	0.45	0.77	0.56	0.6	0.69
Submersion	1	0.01	0.93	0.9	0.34	0.42	0.52	0.47	0.50
Residuals	26								
Total	39								