Restoration of boreal peatland impacted by an in-situ oil sands well-pad 1: Vegetation response

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In this study, our goal was to adapt the moss layer transfer technique (MLTT), first developed to restore degraded Sphagnum-dominant peatland explicitly with a bryophyte layer, to a former in-situ oil sands well-pad constructed with nearby mineral fill in northwestern Alberta, Canada. Mineral fill was either completely removed or partially removed with residual fill buried under excavated and decompacted peat, followed by the transfer of donor moss collected from nearby linear features with different plant communities in peatlands. Three years after MLTT, peatland vegetation covers 63% of the site. Carex spp. dominate with 36% coverage, followed by mosses at 12%, including 3% Sphagnum spp. and 8% fen mosses, and shrubs at 8%. Different substrate adjustment treatments and types of donor moss had negligible impact on vegetation development although areas without MLTT remained devoid of mosses and had the lowest peatland species cover. Instead, surface elevation, moisture conditions, and substrate chemistry played important roles in shaping the vegetation communities. The prompt introduction and establishment of peatland donor species through MLTT was crucial to the overall re-establishment of peatland vegetation. This is the first full pad scale study to prove that a flat, moist peat surface created by the removal and/or burial of mineral fill can support peatland vegetation development, particularly ground layer bryophytes. Overall, the reclaimed well-pad appears to be on trajectory toward becoming a functional peatland and our approaches should be considered and tested in future well-pad reclamation trials.

Key words: in-situ oil sands, moss layer transfer technique, peatland restoration, vegetation, well-pad

Implications for Practice

- Decomposted peat after the removal and/or burial of mineral fill is a suitable organic substrate for peatland vegetation, particularly bryophyte development.
- Prompt introduction of donor material including plant spores, fragments, seeds, roots, and rhizomes is necessary and crucial.
- Regardless of the adjustment methods and donor sources, it is important to contour the reclaimed surface so that it is hydrologically connected with the surrounding areas and the peat surface is flat and moist to facilitate bryophyte establishment and development.
- Impact of buried mineral fill on hydrology, chemistry, and vegetation is limited but longer-term monitoring is needed.

Introduction

Peatlands are dominant landforms in Canada’s boreal and subarctic region, covering 12% of Canada’s land surface area. One of the major anthropogenic activities causing the degradation of peatlands and their associated ecosystem services is the extraction of gas and petroleum in the northern hemisphere, with deposits that often coincide with the main distribution of peatlands. About 30% of Alberta’s oil sands regions are covered by peatlands (Vitt et al. 2000). The majority (82%) of Alberta’s oil sands reserve, which makes up the third largest proven reserve in the world, is too deep to directly mine and must be extracted with in-situ recovery methods such as cyclic steam stimulation (CSS) and steam-assisted gravity drainage (SAGD) (Alberta Energy Regulator 2018). Unlike open-pit mining of near-surface bitumen, in-situ exploration and production relies on interconnected features and facilities, including exploratory and producing well-pads and their associated winter/access roads, pipelines, utility lines, central processing and reclamation facilities.
steam-electricity cogeneration facilities, resulting in a high density of small scale (relative to mining) disturbances in fragmented boreal forests (Mackenzie & Renkema 2013). As of April 30, 2020, there are 41,486 (https://www.aer.ca/providing-information/data-and-reports/activity-and-data/active-in-situ-schemeapproval-well-list.html) active in-situ scheme approval wells in Alberta. At the same time, for context, there are about 91,000 inactive wells and 73,000 abandoned wells in the entire province of Alberta (https://www.alberta.ca/upstream-oil-and-gas-liability-and-orphan-well-inventory.aspx). The cumulative impact of these tens of thousands of well-pads and their connecting features on the peatland rich boreal regions of Alberta is potentially significant, but difficult to quantify (Graf 2009). Given the considerable number of abandoned and inactive wells, new restoration technologies are essential to accelerate the quality and pace of reclamation, not only for anticipated future industry growth, but for the health of the boreal region in Alberta.

The main effects of resource extraction activities on peatlands are: (1) landscape fragmentation and habitat destruction; (2) altered hydrology by compaction, damming effect from infrastructure or drainage; (3) physical and chemical changes in soil and water properties; and (4) the ultimate loss of ecosystem function and service (Daly et al. 2012). Mineral fill from nearby upland sources is used in the construction of well-pads and access roads to provide all season access to the development area in peatland environments. Placement of mineral fill on peat surfaces buries vegetation present on the ground, consequently terminating CO₂ uptake via photosynthesis and the potential for continued carbon (C) uptake through peat formation. The weight of mineral fill causes peat compaction and reduces local hydraulic conductivity (Gillies 2011; Partington et al. 2016). Leaching of nutrients from mineral fill can also alter the soil and water chemistry of peatlands surrounding the well-pads and along the access roads (Plach et al., 2017), leading to changes in plant growth, community composition, and the eventual loss of C sequestration and storage in the adjacent areas (Miller et al. 2015; Bocking et al. 2017; Johansen et al. 2017). Padded well sites built with mineral fill on peatland are particularly challenging to reclaim, ecologically and logistically. Removal of mineral fill can be costly and requires proper sites (i.e. borrow pits) for disposal of removed material (Mackenzie & Renkema 2013). There are no proven solutions to effectively revegetate the disturbed sites with sustainable peatland vegetation but see Caners et al. 2014, 2019 and Lieffers et al. 2017 for suggested approaches for non-padded exploration features. Leaving mineral fill in place and revegetating with woody forest species or grass cover crops is not uncommon, but the results are highly variable and often undesirable due to limiting factors such as soil compaction, rooting limitation by geotextile, and low nutrient availability (Mackenzie & Renkema 2013; Government of Alberta 2018).

Peatland restoration ecology has developed greatly over the last 30 years (Bonn et al. 2016; Chimner et al. 2017). Generally speaking, the reintroduction of peatland vegetation (including bryophytes) with adequate moisture conditions leads to a peat-accumulating system in usually less than 15 years (Graf & Rochefort 2016; Nugent et al. 2018). Restoration of cutover peatlands has shown that blocking drainage ditches and raising water table alone is not enough to support natural recovery of peatland plants due to poor water holding capacity and low saturated hydraulic conductivity of highly decomposed peat (Graf et al. 2008). Introduction of peatland vegetation through the moss layer transfer technique (MLTT) (Quinty & Rochefort 2003) has proven effective to restore cutover bogs and to promote ground layer moss, particularly Sphagnum spp., development on rewetted peat substrate (González et al. 2013; González & Rochefort 2019). The MLTT involves collecting the top 10 cm vegetation from donor areas (e.g. a nearby natural peatland) and spreading the collected diasporas (plant fragments, spores, seeds, roots, and rhizomes) over a disturbed area at a 1:10 (collected areadisturbed area) ratio.

In contrast, research on restoring peatlands disturbed by in-situ extraction activities in the oil sands region of Canada has just begun and reclamation trials of in-situ facilities to peatlands are few in number and tenure (Vitt et al. 2011; Shumina et al. 2016; Gauthier et al. 2017). In principle, the restoration of boreal peatlands should aim to restore proper soil and moisture conditions and to introduce suitable vegetation species that could evolve toward a peat-forming state (Vitt & Bhatti 2012; Cumulative Environmental Management Association [CEMA] 2014; Dommain et al. 2016; Graf & Rochefort 2016). Establishing characteristic fen species on rewetted mineral substrate is feasible when most of the mineral fill is removed to restore a water table level similar to the surrounding peatland, followed by the plantation of Carex aquatilis and Salix lutea (Vitt et al. 2011). Seven years post-revegetation, the Vitt et al.'s study site had a vegetation community similar to a saline fen dominated by sedges and willows, as well as wetland species established by ingestion from the surrounding areas. Site hydrology and chemistry were the main drivers contributing to the development of a fen-like community with no effect of the addition of varied soil amendments (Vitt et al. 2011). But, most importantly, the site lacked a ground layer of peatland mosses, the main peat-forming species characteristic of boreal peatlands. Gauthier et al. (2017) took a modified approach by removing part of a mineral well-pad, lowering the surface elevation, and rewetting the substrate, followed by organic soil amendment and the transfer of a moss layer collected from nearby donor peatlands. They observed establishment of fen mosses on peat amended mineral substrate, demonstrating the feasibility of MLTT in this context. Borkenhagen and Cooper (2016) also conducted a field mesocosm study and concluded that establishment of fen moss species on mineral sediments could be a viable approach for reclaiming peatland in the oil sands region given good rewetting. As far as we know, the restoration of peatlands impacted by in-situ well-pads capped with geotextile and mineral fill has had limited success of establishing fen communities, particularly a bryophyte-dominated ground layer.

In this study, we set out to test the feasibility of establishing a peatland community, explicitly with a bryophyte layer, for restoring a peatland impacted by an in-situ oil sands well-pad. We intended to adapt the MLTT developed for cutover peatlands to this site impacted by a well-pad, therefore choosing to restore a peat surface substrate to favor the development and growth of a moss layer. The end goal was to restore both the hydrological connectivity and peat accumulating characteristics epitomizing those of the reference peatlands common in the
region, such as Sphagnum-dominated treed bogs/poor fens. One approach was the complete removal of the mineral pad and geotextile, decompaction and reprofiling the buried, compressed peat (Peat-Dec method) to create a suitable peat surface, followed by the application of MLTT. Operationally we also tested two other site adjustment approaches: the “burial under peat layer (BUPL)” method and the “mixed peat and mineral (Mixed-P-M)” method (see site adjustment and revegetation section for detail). Several revegetation strategies were applied to determine their applicability in promoting peatland vegetation development. This study was the very first to apply the MLTT over an entire well-pad (1.4 ha) and one of the first trials to expose buried peat by the complete removal and/or burial of the mineral fill.

In this paper, we focus on (1) three substrate adjustment treatments: the Peat-Dec (de-compacting the peat), the BUPL (burying mineral fill material under some peat layer), and the Mixed-P-M (mixing peat and mineral fill) and (2) several revegetation strategies and their effects on peatland vegetation establishment 3 years post restoration. Specifically, we want to answer the following questions:

1. Is mineral fill removal and/or burial a viable option to create suitable peat substrate quality necessary for MLTT application?
2. Is donor moss transfer necessary? Without donor material, can exposed peat that was previously buried facilitate spontaneous regeneration of peatland vegetation, particularly Sphagnum spp., either from plant diaspores that may be available on site or from natural ingress from nearby peatlands?
3. Does the presence of mineral fill under peat affect vegetation development?
4. Does the source of donor material matter for vegetation development?
5. Overall, what are the key factors (e.g. moisture, temperature, chemistry, elevation) driving the vegetation development?

Methods

Site Description

The IPAD (acronym referring to Well-Pad Inversion project) is located within a treed bog/fen complex about 50 km northeast of the town of Peace River (56.397°N, 116.890° W), Alberta. This area is characterized by a typical continental climate, with a mean temperature of 13.8°C and mean precipitation of 214 mm during growing season (June – September) between 1981 and 2010 (https://climate.weather.gc.ca/climate_normals/index_e.html). The moderate rich fen area to the north of the pad is dominated by Picea mariana, Larix laricina, Salix spp., Rhododendron groenlandicum, Vaccinium vitis-idaea, Carex spp., Sphagnum spp., Pleurozium schreberi, and limited Aulacomnium palustre and Tomentypnum nitens. It is lower in elevation and wetter than the bog area to the south-west side of the pad, which has similar species as the fen but lacks Carex spp., Salix spp., and L. laricina.

The 1.4 ha well-pad (120 m by 120 m) was constructed in December 2006 by laying down the woody vegetation, covering the area with a semi-permeable geotextile liner and introducing a 1.4 m thick mix of clay, silt, loam, sand, and gravel sourced from a nearby upland site. While detailed pre-construction vegetation information is unavailable, it is reasonable to assume similar community assemblage as the surrounding bog and fen areas given the locally small size of the disturbance. The padded site was then drilled but not actually operated (no oil was produced). Prior to reclamation in 2011, the mineral pad was mostly barren with scattered ruderal weeds (Fig. 1A).

Soil Adjustment and Revegetation Treatments

The well-pad was restored using a burial technique in which the underlying peat substrate was exposed either with or without the burial of some of the mineral fill. As the goal was to reestablish a peat accumulating plant community, the return of peat mosses was critical, and consequently, achieving the right level of rewetting was judged paramount to the success of the restoration project.

Site adjustment was done by excavators to remove mineral fill in strips running north–south. The removed mineral fill was returned to the same borrow pit used originally for the well-pad construction. In areas where peat under the pad was deep (>1 m), the remaining mineral fill and geotextile was completely removed and the buried peat (up to 1 m deep) was de-compacted with an excavator bucket (Fig. 1B). The peat surface was then gently smoothed with the back of the bucket (Fig. 1D) to achieve the targeted elevation for optimal contact of donor moss fragments with peat substrate. For simplicity, “Peat De-compaction (Peat-Dec)” will be used for this treatment.

In areas where compressed peat was shallow (less than 1 m) under the pad, the following was applied: (1) the remaining mineral fill (and associated geotextile liner) was excavated and put to one side of the excavator; (2) an equivalent peat thickness as the soil fill removed was excavated and put on the other side; (3) the set aside mineral fill, without the geotextile liner, was placed back in the now excavated hole (Fig. 1C); and (4) the set aside peat was put back on top of the buried mineral fill, resulting in an inverted soil profile. “BUPL” will be used for this treatment.

A faster method was tested, for less than 12% of the well-pad, where the excavator lifted the remaining mineral fill, geotextile liner, and underlying peat (up to 0.5 m) in one scoop and inverted it with a good shake in one step. This resulted in the mixing of mineral soil and exposed peat. “Mixed-P-M” will be used for this treatment.

In all cases (Peat-Dec, BUPL, Mixed-P-M), the result after site adjustment was the creation of a uniform, flat peaty surface with an elevation ~10 cm below the surrounding natural peatland hollows as measured at the four corners of the pad. The 10 cm difference was based on the assumption that the exposed peat would further expand and raise the surface elevation over time. Because absolute elevation naturally varied between these corners, the reclaimed surface was gently contoured to blend, resulting in an increase in elevation moving from northeast to southwest corner.

Revegetation started in June 2012 with treatment strips running east–west. As per the MLTT, moss fragments, along with roots,
rhizomes, seeds, and spores, were collected from three distinctive communities, Sphagnum-dominated, fen moss-dominated (mainly T. nitens and A. palustre), and a Polytrichum-enriched Sphagnum community from the surrounding seismic lines. Polytrichum strictum is an early successional species known to improve soil stability by reducing frost heaving, which favors the establishment of peat-forming moss carpets (Groeneveld et al. 2007). It is considered a nurse species as this also helps facilitate the colonization of other peatland species, including peatland mosses. The entire site was then fertilized with rock phosphate (0-13-0, 150 kg/ha) to promote the growth of the Polytrichum strictum.

At each donor site, the top 10 cm of the living moss was harvested with a rototiller, transported by helicopter and spread across the restored site with the aid of an all-terrain-vehicle (Argo) equipped with a small manure spreader (Fig. 1E), following the standard MLTT protocol. Two control areas with no moss introduction (non-MLTT areas including BARE and STRAW) serve to quantify the contrast between the use of donor materials (MLTT areas including Sphagnum-, Polytrichum-enriched, and fen moss-dominated areas) and lack of donor materials on peatland vegetation development. A small area also received donor Sphagnum moss but was not covered by straw mulch (NOSTRAW) to investigate the importance of adding mulch over newly transferred moss fragments. As such, we refer to the revegetation treatments as BARE, STRAW, NOSTRAW, SPHAGNUM, POLYTRICHUM, and FENMOSS (Fig. 2). See Supplement S1 for a brief description of donor harvest and spreading. Restoration work was completed at the beginning of July 2012, so that the 2015 survey assessed field conditions three years post-revegetation (Fig. 1F).

Vegetation Survey
In August 2015, we conducted a site wide vegetation survey using an 11 row by 10 column grid design (Fig. 2). The distance between each grid point was ~10 m. The 11th column was later excluded from data analysis as it was close to the east edge not representative of the rest of the site in terms of site adjustment treatment. At each survey point, a 50 cm by 50 cm quadrat was used to visually estimate the percent cover of major plant species/groups (≥1%). Three plots in the natural areas to the north of the well-pad were also surveyed.

At the time of survey, the well-pad was 3 years old since MLTT. Moss growth was slow and the young Sphagnum species were difficult to identify cover to the species level with certainty. Therefore, mosses were separated into Sphagnum spp., P. strictum, T. nitens, and A. palustre. The latter three species are collectively referred to as “fen mosses” in the following discussion. Mosses other than these four targeted species genera were broadly categorized into acrocarpous (e.g. Dicranum spp.) and pleurocarpous (e.g. Pleurozium schreberi) mosses. Lichens (Cladina spp. and Cladonia spp., Peltigera spp.), liverworts (Marchantia spp.), litter, and bare ground were also assessed during the survey. Shading (%) was estimated as the total vertical projection by field layer on the ground. Percent cover of juvenile vascular species was assessed to species level when possible and if not to the genus (e.g., Salix spp.) or functional group. Tree seedlings that germinated on-site, either from the donor material seedbank or seed rain, were included in the survey results. We did plant ~300 L. laricina and P. mariana seedlings in 2012 at the request of our industry partner; however, these were visually distinctive (20–40 cm tall) from
natural germinants (<5 cm tall) and not included in the assessment. See Table S1 for the list of species with abbreviations (codes) used in the analysis.

**Site Characteristics: Elevation, EC, pH, Soil Moisture, Soil Temperature**

Elevation of each grid point was measured against a fixed onsite permanent monument (reference) using a level laser (Spectra Precision Laser LL300). Relative elevation is the difference between E (reference) – E (grid point) and more negative values indicate lower elevation relative to the reference. Each grid point was matched with corresponding site adjustment and revegetation treatments (Fig. 2).

From each grid point, grab samples of peat (~125 mL) were collected from beneath the living moss layer at the time of the field survey in August 2015. Peat samples were transported in a cooler and stored at −4°C until analysis. Prior to analysis, pieces of wood and root were carefully removed from the peat. Saturated peat samples were prepared by adding deionized water in a 1:2 peat to water ratio (by volume) to create a peat slurry in a 250 mL Erlenmeyer flask and shaken for 2 minutes on a benchtop shaker. After 1 hour, the peat slurry was shaken again and left for another hour at room temperature. Then, electrical conductivity (EC, μS/cm) and pH were measured using an advanced electrochemistry meter (Thermo Scientific Orion VersaStar) (Carter & Gregorich 2006).

Weather data were compiled from an Environment Canada weather station in Peace River, Alberta. Depth to water table (more negative numbers corresponding with water table further below surface) was measured (seven times between May and September 2015) using a blow pipe in permanent water wells installed in different soil and revegetation treatment areas as well as the adjacent natural peatlands. Two sets of soil sensors were installed near the center of the pad in a low elevation and a high elevation location (~25 cm difference) at two depth (2 cm and 5 cm below surface) to continuously measure volumetric water content (VWC, m³/m³) and soil temperature (°C) over the 2015 growing season.

**Data Analysis**

To understand species distribution and community composition across the site, we conducted a non-metric multidimensional scaling (NMDS) using percent cover (relativized abundance) of each species (>1%) (response variable) with explanatory variables (EC, pH, Elevation, Shade, Soil adjustment and Revegetation treatments) overlaid in the ordination space using PC-ORD 7 (Wild Blueberry Media LLC.). Both soil adjustment and revegetation (categorical variables) were coded as binary.
quantitative variables. For example, there are three classes for the soil adjustment variable. Each class can be denoted by the combination of three new binary (0/1) variables. The BUPL is equal to 0 (Peat-Dec), 1 (BUPL), and 0 (Mixed-P-M) and Peat-Dec is equal to 1 (Peat-Dec), 0 (BUPL), and 0 (Mixed-P-M) (McCune & Mefford 2011). Similarly, the SPHAGNUM treatment is equal to 0 (BARE), 0 (STRAW), 0 (NOSTRAW), 1 (SPHAGNUM), 0 (POLYTRICHUM), and 0 (FENMOSS).

Table 1. Mean (standard error) site characteristics by soil adjustment and revegetation methods, compared to natural areas. Different letters indicate significant differences between groups following Tukey’s pairwise comparisons. Elevation: $F_{[5,10]} = 9.47, p < 0.001$; EC: $F_{[2,10]} = 5.14, p = 0.008$; WT: $F_{[2,8]} = 16.49, p < 0.001$. BUPL = burial under peat layer, Mixed-P-M = mixed peat and mineral, Peat-Dec = removal of mineral and decompacted peat; BARE = no moss, no straw, STRAW = no moss, only straw, NOSTRAW = moss transfer, no straw, SPHAGNUM = Sphagnum moss-dominated donor, POLYTRICHUM = Polytrichum moss-enriched donor, FENMOSS = fen mosses (Tomentypnum nitens and Aulacomnium palustre)-dominated donor.

| Method          | $T$ (°C) | Elevation (cm) | pH     | EC ($\mu$S/cm) | WT (cm) |
|-----------------|----------|----------------|--------|----------------|---------|
| Natural         | 4.3 (0.3)| n.d.           | 6.5 (0.2) | 450 (43)       | −15.7 (1) |
| Well-pad overall| −34.0 (1.5) | 5.4 (0.1)     | 583 (43)       | −25.1 (1.4) |
| BUPL            | −34.4 (2.9) | 5.3 (0.1)     | 746 (111) $^a$ | −29 (1.9) $^b$ |
| Mixed-P-M       | −36.9 (3.1) | 5.7 (0.2)     | 842 (116) $^a$ | −43.9 (3.6) $^c$ |
| Peat-Dec        | −33.1 (2)   | 5.4 (0.1)     | 466 (44) $^b$  | −20 (1.8) $^a$  |
| BARE            | 13.3 (0)    | −48.1 (2.2) $^c$ | 5.5 (0.1)     | 603 (116)       | −24.4 (2.9) |
| STRAW           | −46.1 (3.7) $^b$ | 5.3 (0.2)     | 868 (209)       | −23.2 (3.4) |
| NOSTRAW         | −38.2 (3.5) $^{abc}$ | 5.3 (0.2)     | 712 (105)       | −32.8 (3.3) |
| SPHAGNUM        | −36.1 (3.2) $^{ab}$ | 5.2 (0.1)     | 771 (96.6)      | n.d.     |
| POLYTRICHUM     | −30.9 (2.5) $^a$ | 5.5 (0.1)     | 602 (86)        | −27.5 (2.6) |
| FENMOSS         | −20.3 (2.2) $^a$ | 5.6 (0.1)     | 313 (45)        | −26.6 (2.6) |

Figure 3. Average daily soil conditions between two locations (high and low) with a ~25 cm elevation difference near the center of the pad. Horizontal lines are medians while circles with a cross are means. Data were non-normal and analyzed using Friedman test with time as a repeated factor. Different letters indicate significant differences of medians. A: Volumetric water content: $\chi^2 = 144.03, p < 0.001$; B: Soil temperature: $\chi^2 = 39.03, p < 0.001$; C: Electrical conductivity (EC): $\chi^2 = 45.43, p < 0.001$. 
All surveyed species were then grouped into functional groups: mosses, *Carex* spp., forbs/other graminoids, shrubs, and trees. Peatland typical species are capable of combining species found in peatlands as specified by the plant list in the Alberta Peatland Reclamation Criteria and the Plants of the Western Boreal Forest and Aspen Parkland field guide (bog, fen, peatland habitat) (Johnson et al. 1995; Alberta Environment and Parks 2017). All species include both peatland typical species and non-peatland species such as *Populus balsamifera*, *Typha latifolia*, *Rhinanthus minor*, and *Agrostis scabra* (Table S1). General linear models were used to test the fixed effects of site adjustments and revegetation treatments on EC, pH, surface elevation, and the percent coverage by functional groups. Data were visually assessed and confirmed for normality. The treatment effects were considered significant if \( p \leq 0.05 \) and Tukey pairwise comparisons were then performed to determine the difference among treatments. Statistics are reported considering type III errors and F-values generated by the general linear model. Non-normal data were analyzed using non-parametric Kruskal-Wallis tests. To compare soil conditions (moisture content, temperature, and electrical conductivity) between high and low elevation areas, the non-parametric Friedman test was conducted with time as a repeated factor. All statistical analysis was performed using Minitab 19 (Minitab LLC.). Graphs are produced using ArcGIS (ESRI), Minitab 19, and PC-ORD7.

To understand the controls on species abundance, a stepwise regression was carried out to analyze the strength and direction of relationship between percentage cover of plant species and non-peatland species such as *Carex* spp., forbs/other graminoids, shrubs, and trees. Peatland typical species are calculated by combining mosses, *Carex* spp., forbs/other graminoids, shrubs, and trees. Peatland typical species are calculated by combining mosses, *Carex* spp., forbs/other graminoids, shrubs, and trees. Peatland plants were then grouped into functional groups: mosses, *Carex* spp., forbs/other graminoids, shrubs, and trees. The restored well-pad had a mean soil temperature (5 cm below surface) of 13.3 °C, pH of 5.4 ± 0.1, EC of 583 ± 43 μS/cm, and mean water table of −25.1 ± 1.4 cm.

There was no significant difference in pH across either site adjustment or revegetation areas. There was, however, a significant difference in EC among site adjustment areas (Table 2).

### Results

#### Site Characteristics

The 2015 growing season was a dry summer in northern Alberta. The total precipitation measured on-site between June and September was 141.4 mm, 34% less than the 30-year average rainfall of 214.4 mm for the same period. The moderate rich fen’s seasonal average temperature, pH, EC, and water table were 4.3 ± 0.3°C, 6.5 ± 0.2, 450 ± 43.4 μS/cm, and −15.7 ± 1 cm, respectively (Table 1). The restored well-pad had a mean soil temperature (5 cm below surface) of 13.3 ± 0.0°C, pH of 5.4 ± 0.1, EC of 583 ± 43 μS/cm, and mean water table of −25.1 ± 1.4 cm.

There was no significant difference in pH across either site adjustment or revegetation areas. There was, however, a significant difference in EC among site adjustment areas (Table 2, \( F_{[2,10]} = 5.14, p = 0.008 \)). The Mixed-P-M area had much higher mean EC...
(842 ± 116 μS/cm) than the Peat-Dec area (466 ± 44 μS/cm), which was similar to the moderate rich fen’s EC (Table 1). The Mixed-P-M area also had significantly lower water table (−43.9 ± 3.6 cm) than both the BUPL area (−29.0 ± 1.9 cm) and the Peat-Dec area (−20.0 ± 1.8 cm) ($F_{[2,8]} = 16.49, p < 0.001$) (Table 1). There were significant elevation differences among different revegetation treatment areas ($F_{[5,10]} = 9.47, p < 0.001$), with the FENMOSS treatment area (−20.3 ± 2.2 cm) significantly higher than both the BARE (−48.1 ± 2.2 cm) and STRAW areas (−46.1 ± 3.7 cm) (Table 1). Near pad center, the high elevation area had significantly lower volumetric water content (median 0.45 m$^3$/m$^3$, $\chi^2 = 144.03, p < 0.001$), higher temperature (median 13.7°C) ($\chi^2 = 39.03, p < 0.001$), and lower EC (median 770.7 μS/cm) ($\chi^2 = 45.43, p < 0.001$) than the low elevation area (0.51 m$^3$/m$^3$, 14.3°C and 1,104.7 μS/cm) (Fig. 3).

**Vegetation**

Total vegetation cover of the restored well-pad was 65.1 ± 2.9%, comprising of 97% peatland species (i.e., peatland species cover 63.4 ± 2.9%). *Carex* spp. dominated the site with an overall...

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**Figure 4.** Non-metric multidimensional scaling (NMDS) with vector fitting (red line) showing association between vegetation and relative elevation and the bare peat treatment. Blue triangles are plots and black dots are species/functional groups. Plexus lines (blue) connect species commonly associated with each other. More negative values (contour lines) indicate lower surface elevation relative to the reference. Species abbreviation (code) is listed in Table S1.
coverage of 35.5 ± 2.4%, followed by mosses at 11.6 ± 1.0% (including Sphagnum spp. 3.3 ± 0.6% and fen mosses 8.3 ± 0.8%) (Table 2). Shrubs covered 8.2 ± 0.9% while forbs/other graminoids and trees accounted for 3.6 ± 0.4% and 0.4 ± 0.1% of the site, respectively (Table 2).

Soil adjustment and revegetation treatments had negligible effect on vegetation cover. The only significant difference was found in the forbs/other graminoid cover among different revegetation treatment areas (H<sub>S</sub>= 13.69, p = 0.018), with FEN-MOSS area had significantly higher cover (6 ± 1%) than the BARE (1.8 ± 0.5%) and STRAW area (1.6 ± 0.8%) (Table 2).

NMDS analysis showed that species distribution and composition were associated with surface elevation and the BARE vegetation treatment (Fig. 4). C. aquatilis and common fen mosses (T. nitens, A. palustre) were associated with low elevation areas while Equisetum spp., R. groenlandicum, P. strictum, and P. balsamifera were associated with the higher elevation areas. Most peatland species were found in between the low to intermediate elevations (~14.3 cm to 0.6 cm). The BARE area had higher wet fen species (C. aquatilis and fen mosses) cover while the rest of the site had a variety of herbs, shrubs, and trees. Ericaceous shrubs and Salix spp. were found with P. strictum, while P. mariana was commonly associated with other forbs and T. nitens.

Stepwise regression found significant effects of pH on the cover of Sphagnum spp., P. strictum, T. latifolia, C. aquatilis, fen mosses, and all mosses (Table S2). T. latifolia was the only species that responded positively to increasing pH while all other species decreased with increasing pH. EC was a significant contributor for the abundance of Sphagnum spp. and P. strictum, fen mosses, and all mosses, with decreasing cover as EC increased. None of the vascular plants responded to EC. Elevation had a significant effect on the abundance of P. strictum, T. nitens, pleurocarpous moss, T. latifolia, C. aquatilis, and Carex canescens. P. strictum, T. latifolia, and C. canescens responded positively to higher elevation while other species were more abundant at lower elevation (Table S2).

Discussion

Reclaiming in-situ oil sands well-pads built with borrowed mineral material on top of flattened and compressed peat presents a series of challenges to practitioners and peatland ecologists. Previous trials to establish fen communities on rewetted, lowered mineral surface had limited success to promote ground layer moss growth (Vitt et al. 2011). In most cases, species that performed well on the reclaimed mineral surface were those that typically grow in near-neutral pH and nutrient rich fens. Establishment of fen mosses was only possible when donor materials, collected from nearby sources matching on-site chemistry, were applied (Gauthier et al. 2017).

Our study is the first reclamation trial to explore the potential of exposing buried peat as a substrate to initiate peat forming vegetation development at a full well-pad scale in Alberta. In this study, we tested several adjustment approaches to remove the mineral fill and the geotextile, thus exposing and rehabilitating the buried peat as a medium to receive transferred donor moss according to the MLTT developed for harvested peatlands. Three years after revegetation, we found 63.4% of the restored well-pad was covered by peatland vegetation, including 11.6% mosses. Therefore, linking to our first research question, there is strong evidence to suggest that both Peat-Dec and BUPL can create a suitable peat substrate for MLTT revegetation, given the high cover of peatland plants established in the first 3 years. The vegetation cover observed in the present study is equal to, or greater than, that reported following MLTT on cut-over peatlands. For example, considering vegetation across 53 restored bogs in eastern Canada, Gonzalez and Rochefort (2014) observed outcomes at 3–4 years post-restitution ranging from bare-peat-dominated area with around 10% moss cover and 25% vascular plant cover to Sphagnum spp.- and P. strictum-dominated outcomes with 30–40% moss cover and 10–30% vascular plant cover; our observed outcomes fit well within this range.

Our second research question was related to the need for donor material for successful peatland plant community establishment. Simply removing the mineral pad and rewetting the exposed peat was not enough to revegetate the site with peatland species, as shown in our community analysis. The two areas (BARE and STRAW) that did not receive donor moss (non-MLTT) had the lowest peatland vegetation cover, dominated by T. latifolia and C. aquatilis, but almost completely devoid of mosses, shrubs, and trees. It is worth noting that the BARE, STRAW, and NOSTRAW treatments are placed toward the north end of the pad. This area is lower and wetter than the south end. Therefore, the vegetation treatment effect is confounded by differences in elevation and soil moisture. Despite this limitation, we suspect that even with similar moisture conditions as the rest of the vegetation treatments, the exposed peat would have had limited moss regeneration from remnant peat alone. Unlike peatlands drained for harvesting, in-situ well-pad construction usually does not remove the surface peat where viable seeds and spores exist. However, a recent study has found that under field condition peat buried under a mineral road had limited regeneration from either moss fragments or spores after the mineral fill was removed, even though moss regeneration was decent under ideal laboratory conditions (Shunina et al. 2016). Moss spores have surprisingly short longevity and burial for only a few years may severely damage their ability to germinate due to strict requirements for germination conditions (Clymo & Duckett 1986; Sundberg & Rydin 2000). Our result also agrees with other studies in cutover peatland where natural regeneration is a slow process and often not sufficient to restore peatland functions (Poulin et al. 2005; Rochefort & Lode 2006), because of highly decomposed peat with high water holding capacity but low saturated hydraulic conductivity, causing a disconnection between surface moss layer and moist underlying peat (McCarter & Price 2015). Therefore, many peatlands remained devoid of vegetation after decades of abandonment, even though the residual peat had abundant moss spores and seeds of various ericaceous shrubs and trees (González et al. 2013). Vascular plants usually can immigrate from nearby sources but the ingress rates vary greatly among
species and depend on site conditions (van der Valk et al. 1999; Campbell et al. 2003).

The burial of mineral fill underneath excavated peat was a potential concern as its presence may lead to prolonged impact on substrate chemistry and water flow patterns. Therefore, our third research question considered whether the burial of mineral under the peat would affect revegetation patterns. The relatively uniform mineral layer in the BULP areas did seem to maintain a higher water table in the peat on top, compared to the Peat-Dec areas (Engering 2018). However, the vegetation cover in the two areas with residual mineral (BULP and Mixed-P-M) was not significantly different from that in the Peat-Dec area, although the Mixed-P-M area had the lowest moss and peatland species cover. The Mixed-P-M area is near the center, covers only 12% of the well-pad, and not replicated as the other two treatments. This area had the lowest water table and highest EC of all treatment areas. In other words, the Mixed-P-M treatment effect was likely confounded by soil conditions and its position on the pad. Caution should be taken when interpreting the lower peatland vegetation growth response in this area. More thorough analysis of the water table and peat chemistry over time is needed to fully understand the impact of buried mineral on surface chemistry and hydrology. Additionally, phosphate rock was applied following moss transfer, further complicating determination of the direct chemical impact of buried mineral on surface peat and vegetation composition.

Revegetation through MLTT was successful to promote both the moss ground layer and a vascular layer of peatland sedges and shrubs, although the difference in vegetation by donor types was negligible. Therefore, in response to our fourth research question, the source of material had little effect in the present study. Given the right elevation and moisture conditions, transferred moss fragments and spores were able to grow and germinate, and the application of straw seemed to further enhance the moss growth. The MLTT has been proven successful and crucial if ground layer moss growth is a key goal in peatland restoration (González & Rochefort 2014). As mentioned above, germination and growth of mosses (11.6%) by the third year is comparable to similar trials on restored cutover peatland (González et al. 2013). We want to point out that the revegetation treatments are not replicated due to space and logistical constraints. Our conclusions are therefore only applicable in the current study. More field trials are needed to test different types of donor communities and proper controls (BARE, STRAW) on vegetation recovery.

Considering factors contributing to vegetation outcomes, our fifth research question, surface elevation was the overriding factor associated with on-site vegetation community composition and distribution. This indicates that proper site adjustment and the restoration of moisture condition is crucial for the establishment of peatland vegetation on exposed peat. Overall, the profiled peat surface followed the topographic gradient of the surrounding areas and no impediment to water flow was observed near the edges. Most peatland species were found in the low to intermediate elevation areas where the peat remained moist to flooded throughout the growing seasons. Non-peatland species were found on the higher portion of the pad that had low moisture and high EC. Our result was similar to other studies, where raising and maintaining a stable near-surface water table was key to the success of many restored cutover peatlands (González & Rochefort 2014; McCarter & Price 2015). A flat surface is more favorable for maintaining contact of moss fragments with moist peat (Price et al. 1998, 2002) but higher and dryer microsites (e.g. mounds or hummocks) should be targeted if tree growth and fast canopy closure are restoration goals.

In addition to elevation and moisture conditions, peat chemistry (EC and pH) also contributed to the development of different vegetation communities. Mosses were particularly sensitive to both pH and EC. Areas with lower pH and EC had consistently higher moss growth. In fact, pH and EC were stronger predictors than elevation for the cover of Sphagnum spp. and mosses in general. At the end of the third growing season, the mean on-site EC and pH was not much different than that of the nearby moderating rich fen. However, there were significant variations in the on-site EC and pH. Overall, the on-site conditions were favorable for the continued growth and expansion of various mosses. In fact, we have seen a significant increase in moss coverage (~40%) after a moist summer in 2016 (data not shown). T. latifolia and C. aquatilis were the only two vascular species that responded to pH. The site pH (5.2–5.7) was well within C. aquatilis’s natural tolerance range, so this species is likely to persist and grow over time. According to Rochefort et al. (2016), growth of C. aquatilis and other peatland field layer species will further help the growth of ground layer mosses. T. latifolia is commonly found in non-peat forming wetlands and disturbed peatland areas with elevated pH and eutrophic nutrient conditions leading to high decomposition rates and low peat accumulation potential (Cumulative Environmental Management Association [CEMA] 2014), although the genus can be carbon accumulating in some conditions (Strachan et al. 2015). We found a strong preference of T. latifolia for high pH in this study. This agrees with a previous study showing significant decline in T. latifolia abundance as the pH continued to drop, a favorable environment for the growth of C. aquatilis (Vitt et al. 2011). C. aquatilis is known to tolerate a wide range of soil conditions, particularly salinity, making it an ideal species in many fen reclamation projects (Koropchak et al. 2012; Mollard et al. 2012).

After 3 years, the reclaimed in-situ oil sands well-pad had excellent vegetation recovery, including ground layer bryophytes, particularly Sphagnum spp. We found that it is possible to initiate Sphagnum moss growth on exposed peat following the removal and/or burial of residual mineral fill. Regardless of site adjustment and revegetation methods, it was the surface elevation and moisture conditions that shaped the vegetation development. Buried mineral did not affect the site hydrology and vegetation growth although more studies are required on the long-term impact on chemistry and hydrology and connectivity with the surrounding landscape. The early introduction and establishment of peatland donor species through MLTT is crucial to the overall success since the BARE areas without MLTT had poor growth of peatland mosses and shrubs. Mosses prefer lower EC and pH conditions while C. aquatilis grew well within its tolerance range. T. latifolia was limited to high pH/moisture areas and is
expected to decline in cover over time as the site becomes more acidic and nutrient limited through the acidification of Sphagnum mosses (Rydin et al. 2006; Bansal et al. 2019). Peatland shrubs and trees were also growing well through natural regeneration and ingress from surrounding areas.

This study was the first entire well-pad scale trial attempting to establish a moss-dominated ground layer, with diverse strata of vascular peatland species. While the vegetation results are encouraging, the effectiveness of different treatments is hard to properly evaluate due to an unbalanced design and lack of replication. The selection and placement of different soil adjustment techniques was determined during field operation without the pre-construction information on peat depth, elevation, and level of peat compression under the pad. For example, the BUPL option was only needed where shallow compressed peat was present; therefore, it was only applied in three strips compared to the six strips where Peat-Dec was applied. Similarly, the Mixed-P-M was only applied in one area as a test trial toward the end of field operation after the other treatment strips had been completed. The horizontal layout of vegetation treatment was a workaround for summer application. Donor harvest and transfer usually takes place in frozen winter conditions with large equipment as per MLTT. In this study, there was no precedent on how to collect material from narrow linear features and limited equipment to choose from. There was a 7-month gap between site work and the donor transfer, and we had to operate in thawed summer conditions. This limited the maneuverability of the Argo on the saturated, soft peat surface. We would have risked re-disturbing the reclaimed peat surface and sinking equipment if multiple passes were needed to implement a completely randomized design. There were also inherent differences in elevation and moisture conditions across the site. These differences can further complicate the interpretation of results and findings from this study.

Despite the limitation and deficiencies discussed above, results from our case study provide valuable information on the feasibility of reclaiming a peat forming, moss-dominated vegetation community on a former well-pad by highlighting the importance of achieving target elevation and appropriate soil conditions for peatland vegetation establishment. It also provides direction for future studies to address important knowledge gaps we could not answer in this paper. More studies of both the BUPL and Mixed-P-M treatments are needed to fully understand their effectiveness before broad application. Similarly, more trials are needed to test the regenerative potential of remnant peat (BARE) and the effect of different treatments (STRAW and NOSTRAW) and donor types (SPHAGNUM, POLYTRICHUM, FENMOSS) on vegetation development.

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LITERATURE CITED

Alberta Energy Regulator (2018) ST98: 2018 - Alberta’s Energy Reserves & Supply/Demand Outlook - Executive Summary. 16
Alberta Environment and Parks (2017) Reclamation criteria for well sites and associated facilities for peatlands. Alberta Environment and Parks, Edmonton, Alberta, Canada
Bansal S, Lishawa S, Newman S, Wilcox D, Albert D, Ateau MJ, et al. (2019) Typha (cattail) invasion in north American wetlands: biology, regional problems, impacts, ecosystem services, and management. Wetlands 39: 645–684
Bocking E, Cooper DJ, Price J (2017) Using tree ring analysis to determine impacts of a road on a boreal peatland. Forest Ecology and Management 404:24–30
Bonn A, British Ecological Society, Locky D, Mawdsley N, McLaughlan M, Kumaran-Prentice S, Reed M, Swales V (2016) Peatland restoration and ecosystem services: science, policy, and practice. Cambridge University Press, Cambridge, United Kingdom
Borkenhagen A, Cooper DJ (2016) Creating fen initiation conditions: a new approach for peatland reclamation in the oil sands region of Alberta. Moreno Mateos, D, editor. Journal of Applied Ecology 53:550–558
Campbell DR, Rochefort L, Lavoie C (2003) Determining the immigration potential of plants colonizing disturbed environments: the case of milled peatlands in Quebec. Journal of Applied Ecology 40:78–91
Caners RT, Crisfield V, Lieffers VJ (2019) Habitat heterogeneity stimulates regeneration of bryophytes and vascular plants on disturbed minerotrophic peatlands. Canadian Journal of Forest Research 49(3):281–295
Caners RT, Lieffers VJ, Caners RT, Lieffers VJ (2014) Divergent pathways of successional recovery for in situ oil sands exploration drilling pads on wooded moderate-rich fens in Alberta, Canada. Restoration Ecology 22: 657–667
Carter MR, Gregorich EG (2006) Soil sampling and methods of analysis. 2nd edition. CRC Press, Boca Raton, FL
Chimner RA, Cooper DJ, Warster FC, Rochefort L (2017) An overview of peatland restoration in North America: where are we after 25 years? Restoration Ecology 25:283–292
Clymo RS, Duckett JG (1986) Regeneration of sphagnum. New Phytologist 102: 589–614
Cumulative Environmental Management Association (CEMA) (2014) Guidelines for Wetlands Establishment on Reclaimed Oil Sands Leases, Third Edition
Daly C, Price J, Rezazehad F, Pouliot R, Rochefort L, Graf M (2012) Initiatives in oil sand reclamation: considerations for building a fen peatland in a post-mined oil sands landscape | repository of the Athabasca River basin. Pages 179–201. In: Vitt D, Bhatti J (eds) Restoration and reclamation of boreal ecosystems: attaining sustainable development. Cambridge University Press, Cambridge, United Kingdom
Dommain R, Dittrich I, Giesen W, Joosten H, Rais DS, Silvius M, Wibisono ICT (2016) Ecosystem services, degradation and restoration of peat swamps in the south-east Asian tropics. Pages 253–288. In: Bonn A, Allott T, Evans M, Joosten H, Stoneman R (eds) Peatland restoration and ecosystem services: science, policy and practice. Cambridge University Press, Cambridge, United Kingdom
Engering A (2018) Carbon gas exchange, primary production and litter decomposition of a restored fen on a former oil well-pad. University of Waterloo, Waterloo, Ontario, Canada
Gauthier M-EE, Rochefort L, Nadeau L, Hugron S, Xu B (2017) Testing the moss layer transfer technique on mineral wet peatlands. Restoration Ecology 25:184–190

Gillies C (2011) Water management techniques for resource roads as a state of practice review. Prepared for ducks unlimited Canada. FPInnovations contract report no. CR-652

González E, Rochefort L (2010) Trophic strategies of Sphagnum peatland restoration: identifying outcomes from readily measurable vegetation descriptors. Mires and Peat 24:1–16

González E, Rochefort L, Poulin M (2013) Trajectories of plant recovery in block-cut peatlands 35 years after peat extraction. Applied Ecology and Environmental Research 11:385–406

Government of Alberta (2018) Alberta Wetland Mitigation Directive. 9

Graf MD, Rochefort L (2016a) A conceptual framework for ecosystem restoration applied to industrial peatlands. Pages 192–212. In: Bonn A, Allott T, Evans M, Joosten H, Stoneman R (eds) Peatland restoration and ecosystem services: science, policy and practice. Ecological Reviews of Cambridge University Press, Cambridge, United Kingdom

Graf MD (2009) Literature review on the restoration of Alberta’s boreal wetlands affected by oil, gas, and in situ oil sands development. Ducks Unlimited Canada

Graf MD, Rochefort L, Poulin M (2008) Spontaneous revegetation of cutaway peatlands of North America. Wetlands 28:28–39

Groeneveld EVG, Massé A, Rochefort L, Massé A, Rochefort L (2007) Polytrichum strictum as a nurse-plant in peatland restoration. Restoration Ecology 15:709–719

Johansen MD, Aker P, Klanderud K, Olsen SL, Skrindo AB (2017) Restoration of peatland by spontaneous revegetation after road construction. Applied Vegetation Science 20:631–640

Johnson D, Kershaw LJ, Mackinnon A (1995) Plants of the Western Boreal Forest and Aspen Parkland, 1st edition. Lone Pine Publishing, Edmonton, Canada

Koropchak S, Vitt D, Blouise R, Wieder R (2012) Fundamental paradigms, foundation species selection, and early plant responses to peatland initiation on mineral soils. Pages 76–100. In: Vitt D, Bhatti J (eds) Restoration and Reclamation of Boreal Ecosystems – Attaining Sustainable Development. Cambridge University Press, Cambridge, UK

Liefers VJ, Caners RT, Ge H (2017) Re-establishment of hummock topography promotes tree regeneration on highly disturbed moderate-rich fens. Journal of Environmental Management 197:258–264

Mackenzie D, Renkema K (2013) In-situ oil sands extraction reclamation and restoration practices and opportunities compilation

McCarter CPR, Price JS (2015) The hydrology of the bois-des-bel peatland restoration: Hydrophysical properties limiting connectivity between regenerated Sphagnum and remnant vacuum harvested peat deposit. Ecolhydrology 8:173–187

McCune B, Mefford MJ (2011) PC-ORD multivariate analysis of ecological data

Miller CA, Benscoter BW, Turetsky MR (2015) The effect of long-term drying associated with experimental drainage and road construction on vegetation composition and productivity in boreal fens. Wetlands Ecology and Management 23:845–854

Mollard FPO, Roy M-C, Frederick K, Foote L (2012) Growth of the dominant macrophyte Carex aquatilis is inhibited in oil sands affected wetlands in northern Alberta, Canada. Ecological Engineering 38:11–19

Nugent KA, Strachan IB, Strack M, Roulet NT, Rochefort L (2018) Multi-year net ecosystem carbon balance of a restored peatland reveals a return to carbon sink. Global Change Biology 24:5751–5768

Partington M, Gillies C, Gingras B, Smith CE & Morissette J (2016) Resource roads and wetlands: a guide for planning, construction and maintenance (Special publication, SP-530E)

Plach JM, Wood ME, Macare ML, Osko TJ, Petrone RM (2017) Effect of a semi-permanent road on N, P, and CO2 dynamics in a poor fen on the Western Boreal Plain, Canada. Ecolhydrology 10(7):e1874

Poulin M, Rochefort L, Quinty F, Lavoie C (2005) Spontaneous revegetation of mined peatlands in eastern Canada. 557:539–557

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

Price JS, Rochefort L, Campeau S (2002) Use of shallow basins to restore cutover peatlands: hydrology. Restoration Ecology 10:259–266

Quinty F, Rochefort L (2003) Peatland restoration guide

Rochefort L, Lode E (2006) Boreal peatland ecosystems: restoration of degraded boreal peatlands. Pages 1–43. In: Ecological studies. Vol 188. Springer, Berlin, Germany

Rochefort L, LeBlanc M-C, Bérubé V, Hugron S, Boudreau S, Pouliot R (2016) Reintroduction of fen plant communities on a degraded minerotrophic peatland. Botany 94(11):1041–1051

Rydin H, Gunnarsson U, Sundberg S (2006) The role of Sphagnum in peatland development and persistence. Pages 47–65. In: Vitt D, Wieder K (eds) Boreal Peatland Ecosystems. Ecological Studies (Analysis and Synthesis). Vol. 188. Springer, Berlin, Heidelberg

Shunina A, Osko TJ, Foote L, Bork EW (2016) Comparison of site preparation and revegetation strategies within a sphennum-dominated peatland following removal of an oil well pad. Ecological Restoration 34:225–235

Strachan IB, Nugent KA, Cromptie S, Bonneville M-C (2015) Carbon dioxide and methane exchange at a cool-temperate freshwater marsh. Environmental Research Letters 10(6):065006

Sundberg S, Rydin H (2000) Experimental evidence for a persistent spore bank in Sphagnum. New Phytologist 148:105–116

van der Valk AG, Bremholm TL, Gordon E (1999) The restoration of sedge meadows: seed viability, seed germination requirements, and seedling growth of Carex species. Wetlands 19:756–764

Vitt DH, Bhatti JS (2012) Restoration and reclamation of boreal ecosystems. Cambridge University Press, Cambridge, United Kingdom

Vitt DH, Halsey LA, Bauer IE, Campbell C (2000) Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. Canadian Journal of Earth Sciences 37:683–693

Vitt DH, Wieder RK, Xu B, Kaskie M, Koropchak S (2011) Peatland establishment on mineral soils: effects of water level, amendments, and species after two growing seasons. Ecological Engineering 37:354–363

Supporting Information
The following information may be found in the online version of this article:

Supplement S1: Detailed description of donor moss collection, transfer, and spreading.

Table S1: List of surveyed vegetation by functional groups and species if identifiable by species.

Table S2: Statistical results of stepwise regression by species.

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