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Creating fen initiation conditions: a new approach for peatland reclamation in the oil sands region of Alberta

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Summary

1. Reclaiming peatland ecosystems is challenging our understanding of how to rebuild functioning landscapes. Assisted succession may provide a practical approach to guide the reestablishment of peatlands in denuded landscapes. In Alberta, the majority of peatlands began as fens during the paludification process. This research focuses on creating fen initiation conditions to establish fen moss species on mineral sediment as an approach for peatland reclamation in the oil sands region.

2. In a field mesocosm experiment, we evaluated the establishment of five common fen mosses (*Drepanocladus aduncus, Ptychostomum (Bryum) pseudotriquetrum, Campylium stellatum, Tomentypnum nitens* and *Aulacomnium palustre*) introduced in equal proportions to clay loam. To determine the optimal hydrologic conditions for the establishment of each species, we tested four water levels (0, −10, −20 and −30 cm). We created vegetation types similar to those identified at the peat–mineral interface in peat profiles to determine the effect of herbaceous plant, low shrub and wood-strand mulch cover treatments on moss establishment.

3. Three seasons after introduction, total moss cover averaged 40% and was greatest under all cover treatments and at the 0 cm water level. Total moss biomass averaged 95·5 g m^{-2} in moss introduction mesocosms and was greatest under low shrubs and herbaceous plants and at the 0 and −30 cm water levels. Fen moss species distribution was significantly influenced by water-table depth. *Drepanocladus aduncus* and *Ptychostomum pseudotriquetrum* were most common at 0 cm and *Aulacomnium palustre* and *Tomentypnum nitens* at −30 cm.

4. In this approach, we created vegetation types similar to those found on mineral sediments at the base of Alberta peat cores and successfully established distinct fen moss communities along a water-table gradient and under shade cover. Introducing a suite of fen moss species that inhabit a range of hydrologic niches under low shrubs or herbaceous plants improves moss establishment.

5. *Synthesis and applications*. Our research shows that it is possible to create fen initiation conditions on clay loam sediment by introducing foundation moss and vascular plant species at optimal water levels. Restoring the community structure and biomass accumulation that occurs in the initial stages of fen development appears to be a suitable target for peatland reclamation. These methods introduce a practical strategy to reclaim peatlands in the heavily impacted oil sands region of Alberta.

Key-words: boreal, constructed fens, fen moss, hydrologic niches, mineral sediment, moss establishment, mulch cover, vascular plant cover, water-table gradient

Introduction

The global extent of peatlands continues to decline as degradation, conversion and removal occurs from human land-use activities and industrial practices (Zedler & Kercher 2005; Rydin & Jeglum 2013). Concern for these losses has stimulated an increase in compensation measures to restore some degree of the pre-existing community structure and function (Hobbs & Cramer 2008). For peatland ecosystems, this can include the recovery of species diversity, hydrologic regime and peat-accumulation processes (Rochefort & Lode 2006; Nwaishi *et al.* 2015). There are many successful examples and suggested guide-

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lines for restoring degraded peatland bogs (Bugnon, Rochefort & Price 1997; Rochefort *et al.* 2003) and fens (Cooper & MacDonald 2000; Cobbaert, Rochefort & Price 2004); however, reclamation methods that reconstruct a fully removed peatland do not exist.

Peatland reclamation solutions are particularly important in northern Alberta, Canada, where large areas of oil sand deposits are accessed by open-pit mining that removes extensive networks of forests and peatlands (OSWWG 2000). The magnitude of the need for reclamation methods is immense as peatlands comprise 62% of the over two million hectares of surface mineable oil sand deposit area (Rooney, Bayley & Schindler 2012). Fens are the most common peatland type in the region and are hypothesized to be an achievable reclamation target in a post-mining landscape (Price, McLaren & Rudolph 2010). To compensate for peatland losses that have occurred, highly engineered reclamation approaches using peat soils harvested from natural peatlands are being tested (Price, McLaren & Rudolph 2010; Daly *et al.* 2012; Wytrykush *et al.* 2012). However, viable strategies must ultimately be economical and practical for implementation at larger landscape scales (Fung *et al.* 2000). Integrating the principles of ecological succession (Odum 1969) could produce reclamation strategies that reduce cost and effort, introduce target community structure and create a self-sustaining functional ecosystem (Hobbs 2007; Vitt & Bhatti 2012). Instead of attempting to reconstruct mature ecosystems on peat soils, we tested the concept of establishing the initial stages of fen development on mineral sediments collected from beneath a natural peatland in the region.

Paludification is the most common process of peatland initiation, globally and regionally, and begins on mineral soil in terrestrial ecosystems (Nicholson & Vitt 1990; Rydin & Jeglum 2013). Cores taken from peatland complexes in Canada indicate that the mineral sediments found at the base of paludified peatlands is predominantly loam-type texture (Bloise 2007) and contains less than 25% organic matter (Bauer, Gignac & Vitt 2003). Macrofossil analyses of peat profiles show that vegetation types at the peat–mineral interface consist of herbaceous plants, woody material and fen mosses (Nicholson & Vitt 1990; Bauer, Gignac & Vitt 2003; Bloise 2007). Peatlands typically begin as fens that are true moss dominated and supplied by groundwater that has been in contact with mineral rich sediment. Fens can transition into ombrotrophic bogs as *Sphagnum* moss accumulates, and the connection to groundwater is lost (Sjörs 1950).

Rebuilding fens on surface mineral soils using vascular plants has been tested in Canada (Amon, Jacobson & Shelley 2005; Duval, Waddington & Branfireun 2010; Vitt *et al.* 2011); however, establishing mosses on subsurface mineral sediment has not been attempted. Mosses can be hard to establish in restored systems as they are restricted by water level (Li & Vitt 1995), soil and water pH (Chee & Vitt 1989), temperature, light (Fenton & Bergeron 2006), frost heaving (Chimner 2011), salinity (Pouliot, Rochefort & Graf 2013) and substrate type (Pharo & Beattie 2002). Despite these issues, mosses are a key component of boreal peatland communities, crucial peat formers (Vitt *et al.* 2009) and the dominant ground cover (Rydin & Jeglum 2013).

Fens have a high diversity of moss species due to their spatial and hydrologic heterogeneity (Li & Vitt 1995). Water-table levels within peatlands may vary due to hummock/hollow microtopography, peat physical properties and interannual variability of water fluxes (Rochefort *et al.* 2012). Mosses have adapted to this variation and developed distinct hydrologic niches (Gignac *et al.* 1991; Vitt 1994; Hájková & Hájek 2004). In restoration projects, moss survival and biomass growth is highest when the water-table is at or near the soil surface (Bugnon, Rochefort & Price 1997). Unfortunately, controlling the water level within reclamation projects is challenging due to land surface variation, soil subsidence or erosion, unpredictable flow paths and seasonal fluctuations (Fung *et al.* 2000). We propose introducing a mixture of fen moss species that occupy wet to dry habitats to allow the formation of distinct species assemblages along a water-table depth gradient that may develop in a reclamation site.

Shade is critical to moss establishment as it moderates light, temperature, relative humidity and soil moisture (Price, Rochefort & Quinty 1998; Graf & Rochefort 2010). In restoration experiments, mulch improved moss establishment in areas with deeper water-tables (Price, Rochefort & Quinty 1998; Rochefort *et al.* 2003). Agricultural straw mulch and to a lesser extent herbaceous plants have been used as a cover treatment for mosses in peatland restoration projects in eastern Canada (Rochefort *et al.* 2003; Graf & Rochefort 2010), but the effect of vascular plant and woody material cover on moss establishment on mineral sediment remains untested.

Based on ecological concepts of peatland development and restoration techniques, we hypothesize that it is possible to create fen initiation on mineral sediments by maintaining near-surface water-tables and introducing fen mosses under vascular plant and woody material cover. To test this hypothesis, we examined the establishment of five characteristic fen moss species that were mixed in equal portions and introduced onto mineral sediment. To evaluate optimal hydrologic conditions for establishment, we tested this species mixture at four water-table depths. To create vegetation types similar to those found during fen initiation and shade conditions for moss establishment, we tested the effect of herbaceous plants, low shrubs and wood-strand mulch cover. In this paper, we address four questions: (i) Can fen moss species establish from vegetative propagules on mineral sediment? (ii) How does depth to water-table affect moss establishment? (iii) How is moss establishment affected by vascular plant and wood-strand mulch cover, and can species establish without cover? (iv) Does moss community composition vary in response to fen moss introduction, water level or cover treatments?

Materials and methods

STUDY AREA

The study was conducted on an oil sands mine site, 35 km north of Fort McMurray, in Alberta, Canada (56° 43′ 35″ N, 111° 22′ 49″ W). Average annual precipitation is 419 mm, with approximately 316 mm of rainfall and 134 cm of snowfall. During the growing season (May to September), the mean daily temperature is 13·3 °C and there is 287 mm of rainfall (Environment Canada 2015). The experiment was conducted from 8 June 2012 through 24 September 2014. During the three surveyed growing seasons (8 June to 21 September 2012, 18 May to 26 September 2013 and 8 June to 24 September 2014), the average daily temperature was 17·4 °C, 16·1 °C and 16·5 °C with 280, 339 and 177 mm of rainfall precipitation, respectively.

The experiment was conducted in two trenches that were each 45-m long × 10-m wide × 3-m deep and constructed for wetland research in 1991. An outlet in each trench regulated the maximum water level. The water level was maintained at 0–10 cm below the outlet elevation for the entire study period by natural rainfall and manual filling with local fresh lake water. See Appendix S1 and Fig. S1 (Supporting information) for hydrologic details.

EXPERIMENTAL DESIGN AND TREATMENTS

The effect of four water level and five cover treatments were evaluated in mesocosms organized in a randomized split-plot design ($n = 4$). Mesocosms were created using plastic bins that were 61-cm long × 40-cm wide × 42-cm deep and had a planting surface area of 2418 cm^2. The mesocosms were placed on wooden structures in the trenches and filled with mineral sediment obtained from stockpiles at a peatland excavation site. The wooden structures elevated mesocosms to create four water level treatments, the whole-plot factor, at 0, −10, −20 and −30 cm from the soil surface. Holes were drilled in each mesocosm to allow lateral water flow and equilibration of the water-table. Five cover treatments, the split-plot factor, consisted of: (i) herbaceous plants (HP) and moss mixture, (ii) low shrubs (LS) and moss mixture, (iii) wood-strand mulch (WM) and moss mixture, (iv) a no-cover control (NC) and moss mixture and (v) a no-cover-no-moss control (C). Vascular plant seeds of desired species were locally collected and seedlings propagated in a greenhouse for 3 months. Seedlings were planted to create an average of 50% canopy cover in the herbaceous plant and low shrub treatments. The herbaceous plant cover treatment created a canopy >10 cm in height above the soil surface using four seedlings each of *Carex aquatilis* water sedge, *Calamagrostis stricta* narrow reed grass, *Juncus balticus* wire rush and *Triglochin maritima* seaside arrow grass. The low shrub cover treatment was <10 cm tall and planted with 10–12 seedlings each of *Oxycoccus microcarpus* small bog cranberry and *Vaccinium vitis-idaea* lingonberry. Wood-strand mulch cover treatment (WoodStraw® ECM) was spread to 50% cover over the moss mixture.

FEN MOSS SPECIES MIXTURE

Five moss species tested in this experiment were as follows: *Drepanocladus aduncus* (Hedw.) Warnst., *Ptychostomum (Bryum) pseudotriquetrum* (Hedw.) D.T.Holyoak et N.Pedersen, *Campylium stellatum* (Hedw.) C.Jens., *Tomentypnum nitens* (Hedw.) Loeske and *Aulacomnium palustre* (Hedw.) Schwaegr. These species are abundant in the rich fens of Alberta (Chee & Vitt 1989), occur at or near the peat–mineral interface in peat profiles (Bauer, Gignac & Vitt 2003; Koropchak *et al.* 2012) and occupy distinct niches along a hydrologic gradient (Gignac *et al.* 1991; Hájková & Hájek 2004). Each species was harvested from a natural donor site (56° 56′ 13″ N, 111° 33′ 18″ W and 56° 57′ 14″ N, 111° 31′ 09″ W) by cutting the top 3 cm of live moss from monospecific patches (95% of one species) that ranged in size from 5 to 10 cm in diameter. The moss patches were cut into 1–2 cm fragments and combined to create a five-species moss mixture. The amount required for introduction was determined on an area basis using a 1:10 ratio of harvested material to planting area (Rochefort *et al.* 2003). On 8 June 2012, the mixture was evenly spread onto the soil surface. Moss planting was completed within 3 days of collection.

SAMPLING

To quantify moss establishment, the percentage cover of live (green) regenerated moss shoots was visually estimated by species on 24 September 2014. Total moss biomass was also collected using randomly placed cores with a surface area of 78·5 cm^2, from which live moss shoots were removed with tweezers, dried at 60 °C for 48 h and burned at 550 °C for 6 h to determine percentage organic matter (OM) content and remove any residual mineral sediment (Soil Survey Staff 2009).

Hydrologic and microclimate conditions at the soil surface were monitored throughout the experiment. An AquaTROLL 200 logger (InSitu, Inc., Fort Collins, CO, USA) was installed in each trench each summer, to record hourly water level in 2012–2014 (Fig. S1) and specific conductivity in 2012–2013. Over the study period, the water conductivity in both trenches averaged 658 μS cm^{-1} (SD = 202·75). The average water-table depth was calculated using baro-corrected logger data and hand measurements of each mesocosm in September each year. In September 2013, gravimetric water content of the top 5 cm of soil in each mesocosm was determined by removing soil cores and drying at 70 °C for 48 h (Soil Survey Staff 2009). The temperature difference between the soil surface and at 5-cm depth was measured using a handheld thermometer on a sunny afternoon in September each year. Accumulated litter percentage cover was visually estimated in September 2013 and 2014. Three times each season, wind-dispersed vascular plants that established in the mesocosms were trimmed at the base to limit their influence on the experimental treatments.

Soil properties were evaluated by collecting a sample core from the top 5 cm of each mesocosm in September 2012. The soil was dried at 105 °C for 72 h and burned at 550 °C for 5 h to determine percentage OM (Soil Survey Staff 2009).

MINERAL SEDIMENT CHARACTERIZATION

The sediment used for the experiment averaged 15% (SD = 0·009 n = 80) OM, which is approximately 7·8% organic carbon (OC; Vitt *et al.* 2000). The mineral fraction particle size distribution was 41% sand, 31% silt and 28% clay, and had a specific conductivity value of 3·3 mS cm^{-1} (SD = 1·2). The sediment is classified as a weakly saline clay loam (Soil Classification Working Group 1998; Soil Survey Staff 2010; Purdy, Macdonald & Lieffers 2005) of fair rating for reclamation use in the Northern Forest Region of Alberta (Alberta Soils Advisory Committee 1987). For additional sediment sample analyses results, see Appendix S1 and Table S1.1.

DATA ANALYSIS

To evaluate differences between the effects of treatments, we used linear mixed effect models with water level and cover as fixed factors and water level within replicate as random factors for the split-plot error. Repeated measures mixed models were run for litter, temperature difference and average water level using a 1st order ante-dependence covariance structure. A Tukey-adjusted least squares means test was applied to determine statistical significance ($\alpha = 0{\cdot}05$) between the marginal means. All mixed model analyses were performed in SAS using proc MIXED (Version 9.3, Cary, NC, USA). Heteroscedasticity and normality were evaluated, and non-normal data were logit or square root transformed *prior to* analysis. An outlier test confirmed *a priori* observations that two mesocosms (one of each 0 and −30 cm) had deviated from their water level treatment as their wooden structure had collapsed and they were removed from subsequent analyses. Three additional mesocosms in the 0 cm water level treatment were also removed from analysis because the plant cover was destroyed by a burrowing mammal.

A distance ordination analyses were performed to visualize differences in moss species community composition in response to measured environment variables. A non-metric multidimensional scaling (NMDS; Minchin 1987) was conducted using a Bray–Curtis dissimilarity matrix (Bray & Curtis 1957) of relativized moss abundance data of the 11 taxa. A distance-based permutational multivariate analysis of variance (PERMANOVA; Anderson, Gorley & Clarke 2008) was used to test whether moss species community composition differed in response to water level and cover treatments. Due to an unequal sample size and small number of unique values under permutation in the pairwise tests, we used type III sums of squares and a Monte Carlo asymptotic distribution method to obtain an empirical *P* value (Anderson & Robinson 2003). All multivariate analyses were performed using PRIMER 6+ (Clarke & Gorley 2006; Anderson, Gorley & Clarke 2008). An indicator species analysis was performed in R 3.0.2 (R-Development Core Team 2014) to identify moss species associated with certain treatments (Cáceres & Legendre 2009).

Results

WATER LEVEL AND COVER TREATMENT EFFECT

The water level treatment significantly affected hydrologic conditions in the mesocosms (Tables S1.2 and S1.3). The depth to water in the four treatments differed over the course of the experiment ($F_{3,8{\cdot}5} = 354{\cdot}4$, $P < 0{\cdot}0001$; Table 1). In September 2013, the gravimetric water content was greatest in the 0 cm treatment and decreased with water level treatment ($F_{3,13{\cdot}5} = 16{\cdot}1$, $P < 0{\cdot}0001$).

The five cover treatments created different environmental conditions throughout the course of the experiment (Tables S1.2, S1.3 and S1.4). The percentage cover of litter was significantly greater in the herbaceous plant treatment than all other cover and non-cover treatments ($F_{3,45{\cdot}1} = 487{\cdot}9$, $P < 0{\cdot}0001$; Table 2). The high litter cover likely produced a smaller temperature difference between the soil surface and 5-cm depth, whereas the no-cover and no-moss controls had the largest temperature difference and highest soil surface temperatures ($F_{4,78{\cdot}9} = 5{\cdot}05$, $P = 0{\cdot}0011$). Gravimetric water content in the top 5 cm of soil was lower in the wood-strand mulch and no-moss controls compared to low shrub and no-cover treatments, but similar to the herbaceous plant treatment ($F_{4,43{\cdot}8} = 3{\cdot}30$, $P = 0{\cdot}019$).

Table 1. Water level depth and gravimetric water content achieved over the three season study period following water level treatments

Water level treatment, cm	Depth from soil surface to water level (cm) Mean (SE, *n*)	Gravimetric water content Mean (SE, *n*)
0	−4·4 a (0·70, 19)	0·99 a (0·03, 19)
−10	−11·5 b (0·70, 20)	0·86 b (0·03, 20)
−20	−21·0 c (0·70, 20)	0·76 c (0·03, 19)
−30	−32·0 d (0·71, 17)	0·70 cd (0·03, 15)

Means with different letters are significantly different (Tukey-adjusted comparison of least squares means, $P < 0{\cdot}05$).

MOSS ESTABLISHMENT ON MINERAL SEDIMENT

The five fen mosses introduced by vegetative propagules successfully established on the mineral sediment after three seasons of growth. Their relative abundance varied along the water-table depth gradient (Fig. 1b) and when introduced without a cover (Fig. 2b) treatment.

When introduced, *Tomentypnum nitens* was the most successful fen moss species to establish, averaging 11% across treatments and with the highest cover in the −30 cm water level (mean 18%) and lowest without shade cover (mean 4%). *Campylium stellatum* was the second most abundant species, averaging 9% across treatments and with the highest cover at the 0 cm water level (mean 16%) and lowest in the −30 cm water level (mean 7%). *Ptychostomum pseudotriquetrum* was more variable with an overall average cover of 8% and highest cover in the 0 cm water level (mean 24%), but lowest in the −30 cm water level (mean 3%). *Drepanocladus aduncus* had a limited range, attaining 4% cover overall, with the highest cover in the 0 cm water level (mean 11%), but only 1–2% in the deeper water levels and without shade cover. *Aulacomnium palustre* was also limited by water level and cover, attaining an overall cover of 2%, with 5% in the −30 cm water level and only trace amounts without shade cover.

In year three, six additional species considered to be 'opportunistic mosses' were identified in the mesocosms. These include two less common peatland species *Drepanocladus polygamous* and *Helodium blandowii*, and *Leptobryum pyriforme* that is a ruderal species on disturbed mineral and organic soils (BFNA 2014; Vitt & House

Table 2. Percentage cover of litter, temperature difference between the soil surface and 5-cm depth, and gravimetric water content achieved during the three season study period in response to cover treatments

Cover treatment	Litter cover (%) Mean (SE, *n*)	Temperature difference (°C) Mean (SE, *n*)	Gravimetric water content Mean (SE, *n*)
No-moss control	3 a (0·07, 14)	1·8 a (0·07, 14)	0·81 a (0·03, 13)
Herbaceous plants	61 b (0·06, 16)	1·0 b (0·07, 15)	0·84 ab (0·03, 15)
Low shrubs	6 c (0·06, 16)	1·5 abc (0·07, 16)	0·88 b (0·03, 15)
Wood-strand mulch	4 a (0·06, 16)	1·1 b (0·07, 16)	0·77 a (0·03, 16)
No-cover control	4 a (0·06, 15)	1·7 ac (0·07, 15)	0·87 b (0·03, 14)

Means with different letters are significantly different (Tukey-adjusted comparison of least squares means, $P < 0{\cdot}05$).

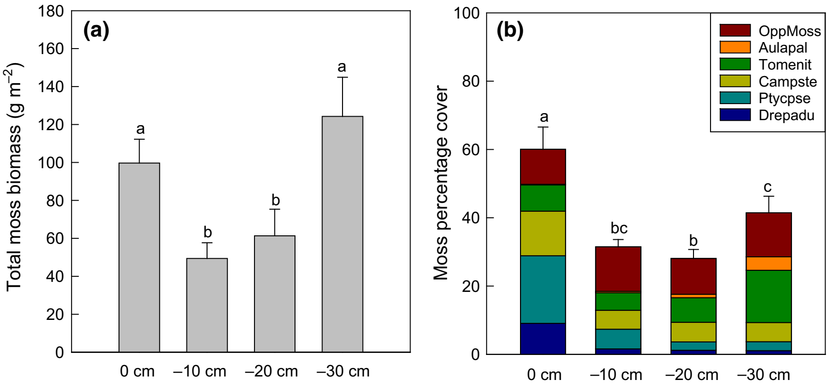

Fig. 1. Effect of water level treatments after three seasons of growth on: (a) mean total moss biomass and (b) percentage cover of total opportunistic and five introduced moss species. Bars represent mean values with +1 standard error. Biomass and total moss cover means with different letters are significantly different (Tukey-adjusted comparison of least squares means, $P < 0{\cdot}05$; 0 cm, $n = 16$; −30 cm, $n = 19$; −10 cm and −20 cm, $n = 16$).

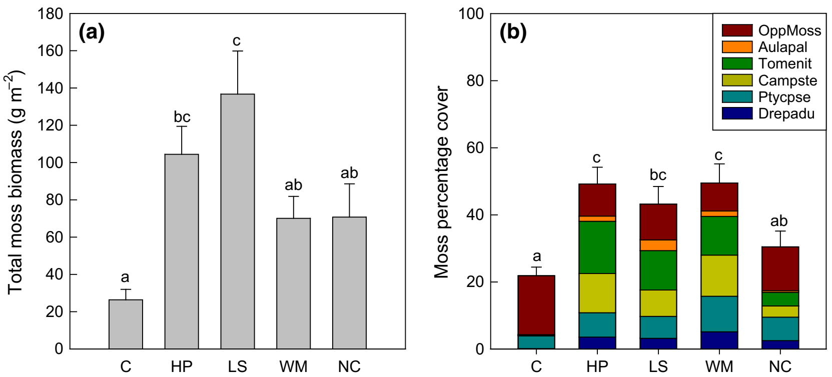

Fig. 2. Effect of the cover treatments: no-moss control (C), herbaceous plants (HP), low shrubs (LS), wood-strand mulch (WM) and no-cover control (NC) after three seasons of growth on: (a) total moss biomass and (b) percentage cover of total opportunistic and five introduced moss species. Bars represent mean values with +1 standard error. Biomass and total moss cover means with different letters are significantly different (Tukey-adjusted comparison of least squares means, $P < 0{\cdot}05$; C, $n = 14$; SWP, WM and NC, $n = 15$; HP, $n = 16$).

2015). Fragments of these taxa may have been introduced with the harvested target fen mosses. Also present were *Barbula unguiculata*, *Dicranella varia* and *Funaria hygrometrica* that are known to be high-dispersal ruderals that colonize bare ground but are uncommon in North American peatlands (BFNA 2007; Vitt 2014). Opportunistic moss percentage cover averaged 42% of the total moss cover in the no-cover control and 80% of the total moss cover when fen mosses were not introduced (no-moss control).

MOSS ESTABLISHMENT ALONG A HYDROLOGIC GRADIENT

Total moss biomass accumulation after three seasons of growth differed between water level treatments ($F_{3,47} = 6{\cdot}2$, $P = 0{\cdot}0012$; Fig. 1a), with biomass being greatest in treatments with the shallowest and deepest water levels (0 and −30 cm) and lowest in the intermediate water levels (−10 and −20 cm). Total moss cover was also affected by water level ($F_{3,11{\cdot}2} = 10{\cdot}1$, $P = 0{\cdot}0016$; Fig. 1b), with the greatest cover in the 0 cm treatment and least in the −20 cm treatment. *Drepanocladus aduncus* and *Ptychostomum pseudotriquetrum* were most common in the 0 cm treatment and *Tomentypnum nitens* and *Aulacomnium palustre* in the −30 cm treatment. Opportunistic moss establishment was not significantly influenced by water level and averaged 10–13% cover across treatments ($F_{3,9{\cdot}1} = 1{\cdot}6$, $P = 0{\cdot}2551$).

MOSS ESTABLISHMENT UNDER HERBACEOUS PLANT, LOW SHRUB AND WOOD-STRAND MULCH COVER

Cover treatment had a significant effect on total moss biomass accumulation ($F_{4,46{\cdot}6} = 8{\cdot}44$, $P < 0{\cdot}001$; Fig. 2a).

The greatest total moss biomass occurred under low shrub and herbaceous plant cover. Moss biomass did not differ between herbaceous plants, wood-strand mulch and no-cover treatments. In the no-moss control, moss biomass was 19–38% of what accumulated when fen mosses were introduced. Total moss cover was also affected by cover treatments ($F_{3,44}$ = 18·13, P < 0·001; Fig. 2b) and was greatest under all cover treatment types compared to no-cover controls. Opportunistic moss cover also differed by cover treatment ($F_{4,44\cdot4}$ = 7·34, P = 0·0001), averaging 17% when fen mosses were not introduced (C), and 13% in the no-cover control.

MOSS COMMUNITY COMPOSITION

Multivariate analyses of the species relative cover indicated that several treatments had a significant effect on community structure (Fig. 3). A solution for the NMDS ordination was reached in 2 dimensions after 22 tries with a stress value of 0·13. Based on the R^2 between ordination distance and Bray–Curtis dissimilarity distance, the non-metric fit of the NMDS ordination explained 98·3% of the variance in species composition. The continuous environmental variables that significantly explained variation in the data set were depth to water level, percentage soil organic matter, and percentage cover of wood-strand mulch, herbaceous plants and low shrubs (Table S1.5). The multivariate PERMANOVA analysis confirmed this pattern and indicated that community variation was significantly affected by water level and cover treatment, the interaction and pairwise between certain treatments (Table S1.6). The indicator species analysis of water level and cover treatment groups showed clear differentiation between wet and dry habitat moss species in the 0 and −30 cm water levels and opportunistic mosses in the no-moss controls (Table S1.7).

Discussion

MOSS ESTABLISHMENT ON MINERAL SEDIMENT

The five moss species tested in this experiment typically grow on organic soils (Vitt 1990); however, we demonstrated that they can establish and grow on clay loam with low organic matter content. The average fen moss cover achieved was similar to moss cover in a 2-year-old restored fen with peat soils and *Scirpus* sp. cover (Graf & Rochefort 2010). Where fen moss was introduced, moss production of regenerated shoots after three seasons of growth averaged 42 g m^{-2} yr^{-1}. This is on the lower end of the variance in natural fens where moss layer production averages 116 g m^{-2} yr^{-1} (SD = 66) (Campbell *et al.* 2000) and ranges from 36 g m^{-2} yr^{-1} in extreme and moderately-rich fen lawns (Moore 1989; Vitt 1990) to 303 g m^{-2} yr^{-1} in a wooded poor fen hummock (Rochefort, Vitt & Bayley 1990). In mesocosms without fen moss introduction, opportunistic mosses colonized and moss production averaged 11 g m^{-2} yr^{-1}. These opportunistic mosses grow in tufts, have a short life span and are not peat-accumulating (Glime 2013).

Tomentypnum nitens was the most successful moss species tested, attained the highest overall cover and was not

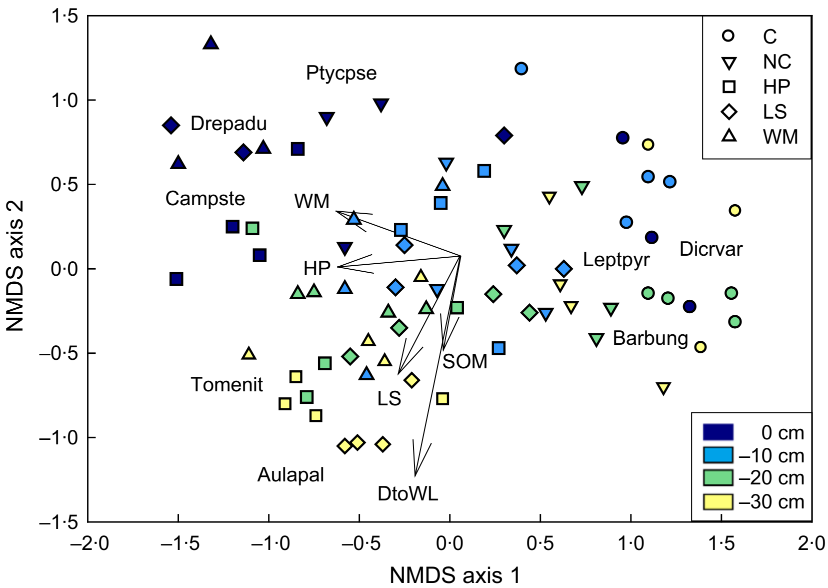

Fig. 3. Non-metric multidimensional scaling (NMDS) ordination of mesocosms and indicator species of introduced fen mosses and control treatment. Symbols represent cover treatment, and colours indicate water level treatment. Environmental variables that are significantly correlated to ordination axes are represented as vectors scaled by their squared correlation coefficient (P < 0·05). C, no-moss control; NC, no-cover control; HP, herbaceous plants; LS, low shrubs; WM, wood-strand mulch; DtoWL, depth to water level; SOM, soil organic matter; Aulapal, *Aulacomnium palustre*; Barbung, *Barbula unguiculata*; Campste, *Campylium stellatum*; Dicrvar, *Dicranella varia*; Drepadu, *Drepanocladus aduncus*; Leptpyr, *Leptobryum pyriforme*; Ptycpse, *Ptychostomum pseudotriquetrum*; Tomenit, *Tomentypnum nitens*.

water limited in the range of treatments. In natural rich fens, it is a dominant hummock former with high biomass production (Vitt 1990; Goetz & Price 2015a). The second most abundant moss, *Ptychostomum (Bryum) pseudotriquetrum,* established in all water level and cover treatments, as well as in the no-moss no-cover control. It is one of the most common species of Bryaceae and inhabits a variety of substrates, but is slender, unbranched erect, grows intermixed with other mosses in rich fens and produces low biomass (BFNA 2014).

MOSS ESTABLISHMENT ALONG A HYDROLOGIC GRADIENT

Moss cover was greatest at the 0 cm water level, but total moss biomass did not differ between the 0 and −30 cm treatments. This trend can also occur in natural fens where areas with intermediate water-tables (−10 to −15 cm) may have lower production rates than hollows and hummocks (Vitt 1990). Proximity to water-table is known to improve moss establishment (Bugnon, Rochefort & Price 1997), but when water-tables were deeper in our experiment, the high moss biomass was due to the compacted growth form of *Tomentypnum nitens*. This is hypothesized to be a desiccation-tolerance strategy as compact cushions are slower to dry out (Proctor *et al.* 2007; Goetz & Price 2015b) and could increase moss survival and bulk density (biomass) in drier habitats (Bauer *et al.* 2007).

Moss establishment on mineral sediment was lowest in the −10 and −20 cm intermediate water levels. Clay soils are prone to soil structure decline caused by slow infiltration, surface swelling and particle dispersion during wetting. As the soils dry, particle hardsetting causes surface crusting, tightening and soluble salt precipitation (Mullins *et al.* 1990). The clay loam used in this experiment could have retained enough moisture to promote some moss establishment but reduced regenerating shoot survival during drying events and surface hardsetting. Water levels that are subject to repeated wetting and drying events may take longer to colonize with moss species unless individuals develop drought-tolerant growth forms, as observed for *Tomentypnum nitens* in the −30 cm water level treatment.

MOSS ESTABLISHMENT UNDER HERBACEOUS PLANT, LOW SHRUB AND WOOD-STRAND MULCH COVER

The most common macrofossils at the base of peat bodies in east-central Alberta are herbaceous plants, woody material and fen mosses (Bauer, Gignac & Vitt 2003; Bloise 2007). We replicated this vegetation in our experiment and found that moss establishment was greatest when fen mosses were introduced with low shrubs or herbaceous plants. The vascular plant cover also produced the lowest soil temperature compared to controls, but high soil water content under low shrubs may have contributed to the higher moss biomass. An herbaceous plant canopy has been shown to increase fen moss species establishment in field restoration (Graf & Rochefort 2010) and reclamation (Vitt & House 2015) experiments. However, low shrubs with lower evapotranspiration rates and near-surface canopy cover could further increase moss biomass. Without shade cover, total fen moss cover decreased, opportunistic moss species cover increased and biomass was significantly lower.

MOSS COMMUNITY COMPOSITION

Shade cover, water level treatments and the introduction of fen mosses all significantly influenced moss community composition. However, depth to water-table was the most important factor influencing fen moss species establishment and after three seasons of growth it was clear that certain species has a distinct hydrologic niche (Manukjanová, Štechová & Kucera 2014). *Drepanocladus aduncus* and *Ptychostomum pseudotriquetrum* were most common in the wettest treatments and *Tomentypnum nitens* and *Aulacomnium palustre* in the driest, whereas *Campylium stellatum* grew along the entire hydrologic gradient. Opportunistic moss species were common where fen mosses were grown without shade cover and dominant when fen mosses were not introduced.

APPLICATIONS

Creating the environmental and biotic conditions for peatland initiation may provide an effective successional strategy for fen reclamation in Alberta's oil sands region. In field mesocosms, we successfully established diverse fen moss communities on mineral sediment along a water-table gradient and under shade cover. This experiment tested a new approach for peatland reclamation and could be implemented in a larger-scale project as an economical and practical strategy for initiating fen ecosystems.

The introduction of peat-forming fen moss species initiated rapid biomass accumulation within three seasons of growth. Without the introductions, it could take much longer for desirable fen mosses to invade hydrologically suitable mineral soil habitats. Shade cover treatments facilitated moss establishment and herbaceous plant and low shrub cover treatments improved moss biomass accumulation. Near-surface water-tables supported the highest moss cover and biomass, but biomass was also high in mesocosms with deeper water-tables due to the dense growth form of *Tomentypnum nitens*. Prioritizing moss species to those with higher production could improve establishment outcomes and biomass accumulation targets. Additionally, introducing a suite of fen moss species that inhabit a range of hydrologic niches will allow for differentiation along a hydrologic gradient in the reclaimed site and achievement of target total moss cover.

Oil sands producers are mandated by Alberta Environment to reclaim disturbed lands to a state of 'equivalent land capability' (OSWWG 2000). After years of upland forest and open water wetland reclamation producers are now focused on peatland reclamation initiatives (CEMA 2014). Extensive peatland loss could result from open-pit mining (Rooney, Bayley & Schindler 2012) if the current reclamation practices of replacing peatlands with marsh wetlands and uplands continue. This land conversion from reclamation may be unnecessary because creating the foundations for the early successional stages of fens on clay loam sediment appears to be possible.

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Data accessibility

Data on moss per cent cover and biomass and measured abiotic parameters in response to water level and cover treatments are available from the Dryad Digital Repository doi:10.5061/dryad.534ng (Borkenhagen & Cooper 2015).

References

Alberta Soils Advisory Committee (1987) Soil Quality Criteria Relative to Disturbance and Reclamation (Revised). Alberta Agriculture. Available at http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag9469

Anderson, M.J., Gorley, R.N. & Clarke, K.R. (2008) *PERMANOVA + for PRIMER: Guide to Software and Statistical Methods*. Primer-E, Plymouth, UK.

Anderson, M., Gorley, R.N. & Clarke, R.K. (2008) *Permanova+ for Primer: Guide to Software and Statistical Methods*.

Anderson, M.J. & Robinson, J. (2003) Generalized discriminant analysis based on distances. *Australian & New Zealand Journal of Statistics*, **45**, 301–318.

Bauer, I.E., Gignac, L.D. & Vitt, D.H. (2003) Development of a peatland complex in boreal western Canada: lateral site expansion and local variability in vegetation succession and long-term peat accumulation. *Canadian Journal of Botany*, **81**, 833–847.

Bauer, I.E., Tirlea, D., Bhatti, J.S. & Errington, R.C. (2007) Environmental and biotic controls on bryophyte productivity along forest to peatland ecotones. *Botany-Botanique*, **85**, 463–475.

BFNA (2007, 2014). *Flora of North America North of Mexico*, Volume 27 Bryophyta, part 1 (2007), Volume 28 Bryophyta, part 2 (2014). Oxford University Press, New York.

Bloise, R. (2007). *Initiation and Early Development of Boreal Peatlands*. M.Sc. Thesis, Southern Illinois University, Carbondale, IL, USA.

Borkenhagen, A. & Cooper, D.J. (2015) Data from: creating fen initiation conditions: a new approach for peatland reclamation in the oil sands region of Alberta. *Dryad Digital Repository*, http://dx.doi.org/10.5061/dryad.534ng.

Bray, J.R. & Curtis, J.T. (1957) An ordination of the upland forest communities of southern Wisconsin. *Ecological Monographs*, **27**, 325–349.

Bugnon, J.L., Rochefort, L. & Price, J.S. (1997) Field experiment of Sphagnum reintroduction on a dry abandoned peatland in eastern Canada. *Wetlands*, **17**, 513–517.

Cáceres, M.D. & Legendre, P. (2009) Associations between species and groups of sites: indices and statistical inference. *Ecology*, **90**, 3566–3574.

Campbell, C., Vitt, D.H., Halsey, L.A., Campbell, I.D., Thormann, M.N. & Bayley, S.E. (2000) *Net Primary Production and Standing Biomass in Northern Continental Wetlands*. Information Report-Northern Forestry Centre, Canadian Forest Service, Alberta, Canada.

CEMA (2014) *Guideline for Wetland Establishment on Reclaimed Oil Sands Leases*, 3rd edn. Prepared by the Wetlands and Aquatics Subgroup of the Reclamation Working Group of the Cumulative Environmental Management Association, Alberta, Canada.

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

Chimner, R. (2011) Restoring sedges and mosses into frost heaving iron fens, San Juan Mountains, Colorado. *Mires and Peat*, **8**, 7.

Clarke, K.R. & Gorley, R.N. (2006) *PRIMER v6*, 6th edn. PRIMER-E, Plymouth, UK.

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

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

Daly, C., Price, J.S., Rezanezhad, 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. *Restoration and Reclamation of Boreal Ecosystems: Attaining Sustainable Development* (eds D.H. Vitt & J. Bhatti), pp. 179–201. Cambridge University Press, Cambridge, UK.

Duval, T.P., Waddington, J.M. & Branfireun, B.A. (2010) Towards calcareous wetland creation in flooded abandoned aggregate quarries: a 3-year field mesocosm study. *Ecological Engineering*, **36**, 586–595.

Environment Canada (2015) *Canadian climate normals 1981–2010*. Meteorological service of Canada. Available at http://climate.weather.gc.ca/climate_normals/index_e.html.

Fenton, N.J. & Bergeron, Y. (2006) Facilitative succession in a boreal bryophyte community driven by changes in available moisture and light. *Journal of Vegetation Science*, **17**, 65–76.

Fung, M.Y., Macyk, T.M., Barnhisel, R., Darmody, R. & Daniels, W. (2000) *Reclamation of oil sands mining areas*. Reclamation of Drastically Disturbed Lands, pp. 755–774.

Gignac, L.D., Vitt, D.H., Zoltai, S.C. & Bayley, S.E. (1991) Bryophyte response surfaces along climatic, chemical, and physical gradients in peatlands of western Canada. *Nova Hedwigia*, **53**, 27–71.

Glime, J.M. (2013) Adaptive strategies: life cycles. Chapt. 4-6. *Bryophyte Ecology. Volume 1. 4-5-1 Physiological Ecology* (ed. J.M. Glime). Ebook sponsored by Michigan Technological University and the International Association of Bryologists. Last updated August 2013. Available at www.bryoecol.mtu.edu.

Goetz, J.D. & Price, J.S. (2015a) Ecohydrological controls on water distribution and productivity of moss communities in western boreal peatlands, Canada. *Ecohydrology*, doi:10.1002/eco.1620.

Goetz, J.D. & Price, J.S. (2015b) Role of morphological structure and layering of Sphagnum and Tomenthypnum mosses on moss productivity and evaporation rates. *Canadian Journal of Soil Science*, **95**, 109–124.

Graf, M.D. & Rochefort, L. (2010) Moss regeneration for fen restoration: field and greenhouse experiments. *Restoration Ecology*, **18**, 121–130.

Hájková, P. & Hájek, M. (2004) Sphagnum-mediated successional pattern in the mixed mire in the Muránská planina Mts. (Western Carpathians, Slovakia). *Biologia-Bratislava*, **59**, 65–74.

Hobbs, R.J. (2007) Setting effective and realistic restoration goals: key directions for research. *Restoration Ecology*, **15**, 354–357.

Hobbs, R.J. & Cramer, V.A. (2008) Restoration ecology: interventionist approaches for restoring and maintaining ecosystem function in the face of rapid environmental change. *Annual Review of Environment and Resources*, **33**, 39–61.

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

Li, Y. & Vitt, D.H. (1995) The dynamics of moss establishment: temporal responses to a moisture gradient. *Journal of Bryology*, **18**, 677–687.

Manukjanová, A.T., Štechová, T. & Kucera, J. (2014) Drought survival test of eight fen moss species. *Cryptogamie, Bryologie*, **35**, 397–403.

Minchin, P.R. (1987) An evaluation of the relative robustness of techniques for ecological ordination. *Vegetatio*, **69**, 89–107.

Moore, T.R. (1989) Growth and net production of Sphagnum at five fen sites, subarctic eastern Canada. *Canadian Journal of Botany*, **67**, 1203–1207.

Mullins, C.E., MacLeod, D.A., Northcote, K.H., Tidall, J.M. & Young, I.M. (1990) Hardsetting soils: behaviour, occurrence and management. *Advances in Soil Science*, **11**, 37–99.

Nicholson, B.J. & Vitt, D.H. (1990) The paleoecology of a peatland complex in continental western Canada. *Canadian Journal of Botany*, **68**, 121–138.

Nwaishi, F., Petrone, R.M., Price, J.S. & Andersen, R. (2015) Towards developing a functional-based approach for constructed peatlands evaluation in the Alberta oil sands region, Canada. *Wetlands*, **35**, 211–225.

Odum, E.P. (1969) The strategy of ecosystem development. *Science*, **164**, 262–270.

OSWWG (Oil Sands Wetlands Working Group) (2000) *Guidelines for Wetland Establishment on Reclaimed oil Sands Leases* (ed N. Chymko). Rep. ESD/LM/00-1, Alberta Environment, Environmental Services Publication No. T/517.

Pharo, E.J. & Beattie, A.J. (2002) The association between substrate variability and bryophyte and lichen diversity in eastern Australian forests. *The Bryologist*, **105**, 11–26.

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

Price, J.S., McLaren, R.G. & Rudolph, D.L. (2010) Landscape restoration after oil sands mining: conceptual design and hydrological modelling for fen reconstruction. *International Journal of Mining, Reclamation and Environment*, **24**, 109–123.

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

Proctor, M.C., Oliver, M.J., Wood, A.J., Alpert, P., Stark, L.R., Cleavitt, N.L. & Mishler, B.D. (2007) Desiccation-tolerance in bryophytes: a review. *The Bryologist*, **110**, 595–621.

Purdy, B.G., Macdonald, E.S. & Lieffers, V.J. (2005) Naturally saline boreal communities as models for reclamation of saline oil sand tailings. *Restoration Ecology*, **13**, 667–677.

R-Development Core Team (2014) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Rochefort, L. & Lode, E. (2006) Restoration of degraded boreal peatlands. *Boreal Peatland Ecosystems*. *Ecological Studies*, Vol. 188. (eds R.K. Wieder & D.H. Vitt), pp. 381–426. Springer-Verlag, Berlin, Germany.

Rochefort, L., Vitt, D.H. & Bayley, S.E. (1990) Growth, production, and decomposition dynamics of Sphagnum under natural and experimentally acidified conditions. *Ecology*, **71**, 1986–2000.

Rochefort, L., Quinty, F., Campeau, S., Johnson, K. & Malterer, T. (2003) North American approach to the restoration of Sphagnum dominated peatlands. *Wetlands Ecology and Management*, **11**, 3–20.

Rochefort, L., Strack, M., Poulin, M., Price, J.S., Graf, M., Desrochers, A. & Lavole, C. (2012) Northern peatlands. *Wetland Habitats of North America: Ecology and Conservation Concerns* (eds D.R. Batzer & A.H. Baldwin), pp. 119–134. University of California Press, Los Angeles.

Rooney, R.C., Bayley, S.E. & Schindler, D.W. (2012) Oil sands mining and reclamation cause massive loss of peatland and stored carbon. *Proceedings of the National Academy of Sciences*, **109**, 4933–4937.

Rydin, H. & Jeglum, J.K. (2013) *The Biology of Peatlands*, 2nd edn. Oxford University Press, Oxford, UK.

Sjörs, H. (1950) Regional studies in North Swedish mire vegetation. *Botaniska Notiser*, **2**, 173–222.

Soil Classification Working Group (1998) *The Canadian System of Soil Classification*. National Research Council Canada and Canada. Agriculture and Agri-Food Canada. Research Branch and Canadian Agricultural Services Coordinating Committee. NRC Research Press, Ontario, Canada.

Soil Survey Staff (2010) *Keys to Soil Taxonomy*, 11th edn. USDA Natural Resources Conversation Service, Washington, DC, USA.

Soil Survey Staff (2009) *Soil survey laboratory methods manual*. Soil Survey Investigations Report No. 51, Version 1.0. (ed R. Burt). U.S. Department of Agriculture, Natural Resources Conservation Science.

Vitt, D.H. (1990) Growth and production dynamics of boreal mosses over climatic, chemical and topographic gradients. *Botanical Journal of the Linnean Society*, **104**, 35–59.

Vitt, D.H. (1994) An overview of factors that influence the development of Canadian peatlands. *Memoirs of the Entomological Society of Canada*, **126**, 7–20.

Vitt, D.H. (2014) A key and review of bryophytes common in North American peatlands. *Evansia*, **31**, 121–158.

Vitt, D.H. & Bhatti, J.S. (2012) The changing boreal forest: incorporating ecological theroy into restoration planning. *Restoration and Reclamation of Boreal Ecosystems: Attaining Sustainable Development* (eds D.H. Vitt & J. Bhatti), pp. 3–12. Cambridge University Press, Cambridge, UK.

Vitt, D.H. & House, M. (2015) Establishment of bryophytes from indigenous sources after disturbance from oil sands mining. *The Bryologist*, **118**, 123–129.

Vitt, D.H., Halsey, L.A., Bauer, I.E. & 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, D.H., Wieder, R.W., Scott, K.D. & Faller, S. (2009) Decomposition and peat accumulation in rich fens of boreal Alberta, Canada. *Ecosystems*, **12**, 360–373.

Vitt, D.H., Wieder, R.K., 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.

Wytrykush, C., Vitt, D., Mckenna, G. & Vassov, R. (2012) Designing landscapes to support peatland development on soft tailings deposits. *Restoration and Reclamation of Boreal Ecosystems: Attaining Sustainable Development* (eds D.H. Vitt & J. Bhatti), pp. 161–178. Cambridge University Press, Cambridge, UK.

Zedler, J.B. & Kercher, S. (2005) Wetland resources: status, trends, ecosystem services, and restorability. *Annual Review of Environment and Resources*, **30**, 39–74.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. Full description of water level treatment, sediment analysis results and model results from linear mixed effect models and PERMANOVA on biotic and abiotic variables.

Table S1.1. Chemical analysis of the clay loam soil.

Table S1.2. Model results from linear mixed effect model on abiotic and biotic variables in response to water level and cover treatments.

Table S1.3. Comparison of a Tukey-adjusted least squares means test on abiotic and biotic variables with no significant interaction in response to water level and cover treatments.

Table S1.4. Comparison of a Tukey-adjusted least squares means test on abiotic and biotic variables with significant interactions in response to water level and cover treatments.

Table S1.5. Fit of continuous environmental variable vectors to the NMDS ordination.

Table S1.6. Model results from the PERMANOVA of differences in species abundance between water level and cover treatments.

Table S1.7. Indicator species significantly associated with water level and cover treatments.

Fig. S1. Hydrograph of water level and rainfall and fill event inputs into Trench 8 and 9 during the study periods of 2012 to 2014.