THESIS

RECREATING PEATLAND INITIATION CONDITIONS: METHODS FOR RECLAIMING PEATLANDS IN ALBERTA'S OIL SANDS REGION

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ABSTRACT

RECREATING PEATLAND INITIATION CONDITIONS: METHODS FOR RECLAIMING PEATLANDS IN ALBERTA’S OIL SANDS REGION

Northern Alberta’s oil sands deposit is the largest in the world and mining operations remove vast areas of upland forests and peatland ecosystems. Reclaiming peatland ecosystems is challenging as it takes thousands of years to reestablish peat soils to pre-disturbance extents. Practical approaches that are easy to implement are required to reclaim the tens of thousands of peatland hectares that have been lost to mining activities. My research focuses on developing reclamation methods that recreate peatland initiation conditions on mineral soil and apply assisted succession techniques by introducing mosses, plants and woody cover. I evaluated the regenerative abilities of five common fen mosses introduced in a 1:10 mixture to clay loam mineral soil. To evaluate optimal hydrologic conditions for moss species establishment, I tested four water levels below the soil surface (0, -10, -20, and -30 cm). I recreated plant communities and microclimates similar to those found during peatland initiation to determine those that increased moss species establishment by comparing cover treatments of herbaceous plants, woody plants, and WoodStraw® (wood-strand) mulch. After two seasons of growth, fen mosses established and grew to an average of 20 percent cover on mineral soils. Total moss cover was not significantly different between 0cm and -30 cm water levels but species distribution was as depth to the water table was the most important factor influencing establishment. *Drepanocladus aduncus* was most common when the water level was 0 cm and *Aulacomnium palustre* was most common in the -30 cm water level. *Tomentypnum nitens* had five times greater cover than any other moss. Moss species cover and height was greatest under herbaceous plants and at 0 cm water level. Wood-strand mulch reduced the cover of salt that precipitated on the soil surface, which also increased as the water table deepened. Implications to peatland reclamation include selecting a mixture of mosses to adapt to chemical and hydrologic variations and planting herbaceous plants and or applying wood-strand mulch to improve moss establishment on mineral soil. Peatlands may take thousands of years to develop, but reclaiming a carbon-accumulating ecosystem and establishing the foundations for peatland succession is possible. The applications described here provide economical and practical strategies to reconstruct pre-existing peatland ecosystems in Alberta’s oil sands region.

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1. INTRODUCTION

One of the largest crude oil reserves in the world lies beneath 140,200 km^2 of boreal forest in northern Alberta, Canada (Alberta Energy 2013). Open-pit mines access near-surface oil sands by first removing extensive networks of upland forests and peatlands. The Alberta Government and Regulatory Agencies require oil sands operators to reclaim disturbed lands to an equivalent land capacity (OSWWG 2000). This requires topographic reconstruction, re-establishing hydrologic regimes, integrating post-mining materials, replacing topsoil, and re-introducing native vegetation (Fung et al. 2000). Reclamation of upland forest and open water wetlands has been occurring for years (Rooney et al. 2012) but the recreation of peatlands, the dominant ecosystem (Vitt and Chee 1990), is just beginning.

The peatlands in the region took hundreds to thousands of years to develop (Bloise 2007). Highly engineered and costly peatland reconstruction approaches are now being tested (Price et al. 2010, Daly et al. 2012, Wytrykush et al. 2012) but reclamation strategies must be improved so that more economical and practical approaches can be developed (Macdonald et al. 2012). Integrating ecological succession principles (Odum 1969) into reclamation techniques may minimize costs and efforts, improve the certainty of achieving the target ecosystem, inform species selection, and create a self-sufficient ecosystem (Hobbs 2007). Defining peatland initiation as the starting point of reclamation and assembling a biotic community of plants and mosses that inhabit niche gradients could provide ecosystem resilience and assist successional trajectories towards a mature peatland.

Paludification is the most common process, globally and locally, for peatland initiation and occurs on mineral soil in terrestrial ecosystems (Heinselman 1963, Nicholson and Vitt 1990, Rydin and Jeglum 2013). A shift in climate or disturbance regimes allows fine textured mineral soils to retain water (Gorham and Janssens 1992, Halsey et al. 1998). Anaerobic conditions develop that support the colonization of hydrophilic vegetation (Taylor and Smith 1980, Halsey et al. 1998). As decomposition rates and soil temperature decrease under saturated conditions and from insulating biotic cover (Benninghoff 1952, Taylor et al. 1988), organic matter accumulates and a peatland can develop. Peatlands typically begin as fens due to the supply of groundwater that has been in contact with mineral rich sediment. Fens can transition into bogs as peat accumulates beyond surficial access to groundwater (Kuhry and Turunen 2006).

The early stages of peatland development occur when the water table is within 10 cm of the soil surface (Gorham and Janssens 1992). However, water table levels within mature peatlands vary seasonally and spatially by up to 0.75 m due to hummock/hollow microtopography, peat properties and inter-annual variability in water fluxes (precipitation/evapotranspiration; Rochefort 2012). Moss species have adapted to the variation and have hydrologic niches preferences (Gignac et al. 1991, Vitt 1994, Hájková and Hájek 2004). This is particularly true in fens, which can have high moss species diversity in response to spatial and hydrologic heterogeneity (Li and Vitt 1995). In restoration projects, moss survival and biomass growth is reported to be highest when the water table is within 0-5 cm of the soil surface (Bugnon et al. 1997, Malson and Rydin 2007). However, introducing a mixture of moss species known to occupy both wetter and dryer environments may allow one mixture to facilitate the formation of different communities along the water table depth gradient, while supporting similar total moss covers.

Moss establishment is a key step in reassembling boreal peatland communities as they are crucial peat-formers (Rochefort 2000) and are a dominant ground cover (Goffinet and Shaw 2009). Mosses reproduce both sexually and vegetatively (Giles 1971, Poschlod and Schrag 1990, Li and Vitt 1994, Goffinet and Shaw 2009) and have been successfully reestablished in harvested bogs (Quinty and Rochefort 2003, Rochefort et al. 2003) and hydrologically restored fens (Cobbaert et al. 2004, Malson and Rydin 2007, Graf and Rochefort 2010) using vegetative reproduction. Dispersal is limited in post-mining landscaped (Battaglia et al. 2008) and to assist successional trajectories reclamation professionals must increase the available species pool (Poulin et al. 1999, Novák and Prach 2003) and establish moss species that dominate regional peatlands.

Paleoecological analyses have demonstrated that early paludified peatland communities consist of herbaceous plants or woody species and few fen mosses (Janssens 1990, Nicholson and Vitt 1990, Gorham and Janssens 1992, Bauer et al. 2003). Herbaceous peat, woody peat and herbaceous peat with wood are common basal layers found in peat profiles as dry forests transitioned to swamps and wooded fens (Nicholson and Vitt 1990, Bauer et al. 2003). These plants also provide shade that is critical to moss establishment, due to microclimate moderation of temperature, light, relative humidity and soil moisture (Price et al. 1998, Graf and Rochefort 2010). In restoration experiments, mulch improved moss establishment in areas with a deeper water table (Quinty 1997), and may be more important to moss survival than water table depth (Price 1996). Agricultural straw mulch and to a lesser extent herbaceous vegetation have successfully been used as a cover treatment for mosses in peatland restoration (Quinty and Rochefort 2003, Groeneveld et al. 2007, Graf and Rochefort 2010), but recreating herbaceous and woody plant or wood shade covers common in initial peatland communities and the effect of the covers proximity to the soil surface warrants further investigation.

To simulate peatland initiation conditions and assist successional trajectories, I examined the regeneration ability of five common fen mosses mixed in equal portions and introduced onto a mineral soil. To evaluate optimal hydrologic conditions for establishment, I subjected this species mix to four depth to water levels. To create a plant community and shade conditions similar to those found during peatland initiation, I tested the effect of herbaceous and woody plants at two heights above the soil surface as well as WoodStraw® (wood-strand) mulch. In a factorial field experiment I address the following questions:

1) Can fen moss species regenerate vegetatively on mineral soil?

2) Do fen moss species exhibit niche differentiation at the establishment phase along a hydrologic gradient?
3) How is fen moss species establishment affected by herbaceous and woody plants and wood-strand mulch cover and can species establish without cover?

2. MATERIALS AND METHODS

2.1 STUDY AREA

I worked in the oil sands region on the Suncor Millennium Mine, 35 km north of Fort McMurray, Alberta (56° 43′ 35″ N, 111° 22′ 49″ W) (Figure 1). The site is at 369 m above sea level. Average total annual precipitation is 455 mm, with most occurring from May to September. Daily mean temperatures are -18.8^{o} C in January with an average annual snowfall of approximately 156 cm. During the growing season, daily mean July temperatures are 16.8^{o} C with a total average rainfall of 336 mm (from 1971-2000; Government of Canada 2014). My experiment was conducted from June 2012 through September 2013. Temperature and rainfall were near the means for the summer of 2012, but 10^{o} C warmer and nearly 80 mm more rainfall then the historical means in 2013 (Dyke 2W; Daly 2013).

2.2 MESOCOSMS

Mesocosms were created in plastic bins, 40 cm tall and a surface area of 2418 cm^{2}, which were filled with a local mineral soil. Soil used in this experiment had 28% organic matter (OM), or approximately 14.6% organic carbon (OC), based on 52% of OM being OC in peatlands in continental western Canada (Vitt et al. 2000). Mineral soils in Canada contain 17 % or less organic carbon by weight (Soil Classification Working Group 1998). Therefore, based upon particle size distribution (Bouyoucos 1962), the soil I used was a clay loam with 41% sand, 31% silt, and 28% clay. Chemical analysis of nutrients, soluble parameters, soil properties, and elements show high levels of soluble sulfate and available sulfur (Table A1). Soil analysis methods are described in Appendix 1.

2.3 MOSS SPECIES MIXTURE

I selected five moss species that are abundant in Alberta rich fens (Chee and Vitt 1989), are known to have occurred in developing peatland communities (Bauer et al. 2003, Koropchak et al. 2012), niche differentiation along a hydrologic gradient (Gignac et al. 1991, Hájková and Hájek 2004) (Table 1), and ability to survive exposure to high salt concentrations (greenhouse studies; Pouliot et al. 2013). The species I included were *Drepanocladus aduncus* (Hedw.) Warnst., *Bryum pseudotriquetrum* (Hedw.) Gaetn., *Campylium stellatum* (Hedw.) C. Jens., *Tomenthypnum nitens* (Hedw.) Loeske, and *Aulacomnium palustre* (Hedw.) Schwaegr. Moss nomenclature follows Crum and Anderson (1981). I identified relatively homogenous patches in a natural donor fen, harvested the top 5 cm with a handsaw, and created a moss mixture where all 5 species were equally represented. In June 2012, I evenly spread and gently appressed the moss mixture to the mesocosm soil surface at a ratio of 1:10, with 1 m^2 of field collected moss to 10 m^2 of planting area (Quinty and Rochefort 2003), . Moss harvest was completed no more than 3 days prior to planting onto the mesocosms.

2.4 EXPERIMENTAL DESIGN AND SAMPLING

The experiment was conducted in two trenches designed for wetland research (Nix and Gunter 1993, Bishay 1998, Crowe 1999, Crowe et al. 2001, Swisterski and Beierling 2006, Hornung 2007, Frederick 2011) (Figure 1). Each trench was 45 m long, 10 m wide and 3 m deep, lined with waterproof polyethylene and capped with 0.45 m of sand. An outlet in each trench guaranteed that a maximum water level was never exceeded. The outlet elevation was set at 0 cm, and the water level in the trenches was maintained between 0 and 10 cm below the outlet elevation in 2012 and in 2013 by rainfall events and manual filling with local lake water.

Plots were organized in a randomized split-plot design (n = 4) with four water level and five cover treatments in mesocosms. Wood structures were built to elevate 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 treatment mesocosms, which were used as the split plot factor, were nested in each water level and container: (1) herbaceous plants and moss mixture, (2) woody plants and moss mixture,

(3) wood-strand mulch and moss mixture, (4) a no-cover control and moss mixture, and (5) a no-cover-no-moss control. Plants were introduced to create an average of 50% cover in herbaceous plant or woody plant mixtures of different species. The herbaceous plant cover treatment created a plant canopy >10 cm above the soil surface and was planted with four seedlings each of water sedge (*Carex aquatilis*), northern reed grass (*Calamagrostis inexpansa*), wire rush (*Juncus balticus*), and seaside arrow-grass (*Triglochin maritima*). The woody plant cover treatment was 5 – 10 cm tall and planted with 10 – 12 seedlings each of small bog cranberry (*Oxycoccus microcarpus*) and bog cranberry (*Vaccinium vitis-idaea*). Vascular plant nomenclature follows the Flora of North America (Flora of North America 1993). Wood-strand mulch cover treatment (WoodStraw® ECM 2012) was spread at 50% cover to a maximum height of 5 cm from the soil surface. WoodStraw® mulch is made of low grade veneer, soaked and split into strands that are 16 to 6.4 cm long, 0.5 cm wide, and 0.1 cm thick.

Data on moss cover by species was collected on three dates: establishment during the first season was estimated in late September 2012, over-winter survival on May 18, 2013, and second season cover in late September 2013. Species percent cover of live (green) individuals was visually estimated. Moss height was measured from soil surface to the tip of the moss adjacent to a pin ruler placed in 10 randomly selected locations in each mesocosm. Height was visually assessed along a level plane parallel to the peat surface to minimize potential error from an incline view.

For both summers, an AquaTROLL 200 logger (InSitu, Inc., Fort Collins, CO) was installed in each trench to record hourly water level, water temperature, and specific conductivity in micro siemens (μS) temperature compensated to 25°C. In September 2013, gravimetric water content of the top 5 cm was calculated by removing cylinders of soil, weighing, drying at 79^{o} C for 48 hours, and reweighing. Depth from soil surface to water was also measured at each survey date.

The microclimate created by the cover treatments were evaluated by collecting data on estimates of percent cover of salt on the soil surface and accumulated litter, and difference in temperature between the soil surface to 5 cm depth. Three times each season, invasive vascular plants were trimmed at the base to limit their influence (contribution to shade or litter) as a cover on moss establishment.

2.5 DATA ANALYSES

Total and individual species' moss establishment was evaluated using a linear mixed effects model with water level and cover as fixed factors and cover, water level, and replicate as random factors. A Tukey-adjusted least squares means test was applied post hoc to determine statistical significant ($\alpha = 0.05$) between the marginal means. Percent cover data was transformed using the empirical logistic transform approach (Collett 2002) which adds a small value (e) to the numerator and denominator of the logit transform (log(y+e /1-y+e)) that was equal to the smallest non-zero observation in the dataset (Warton and Hui 2011). Height data was natural-log transformed to satisfy assumptions of normality. A subsequent two-way mixed linear effects model with random effects for trench and replicate was conducted to test for differences in effects of water level and cover on both total and individual species percent cover and total moss height after two seasons of growth (September 2013). Using an outlier test confirmed *a-priori* observations that three mesocosms that had sunk and deviated from the water level treatment so they were removed from subsequent analyses. All analyses were done in using the nlme 3.1-113 package (Pinheiro et al. 2013) and the lsmeans 1.10-4 package (Lenth 2014) in R 3.0.2 (R Development Core Team 2013).

3. RESULTS

3.1 EFFECT OF WATER TABLE DEPTH

Water level in each trench was maintained within the target range of 0 to 10 cm below the outlet elevation in both summers (Figure 2). In 2012, Trench 9 averaged -7.2 cm (*sd* 4.9; max = 4.0 cm, min = -19.0 cm) with and Trench 8 -5.4 cm (*sd* 4.0; max = 3.8 cm, min = -14.9 cm) below the outlet elevation. Only Trench 8 received water on the third water addition event in 2012 resulting in a summer mean 2 cm higher than Trench 9. In 2013, Trench 9 averaged -5.5 cm (*sd* 5.6; max = 3.7 cm, min = -23.6 cm) and Trench 8 averaged -6.6 cm (*sd* 6.2; max = 3.4 cm, min = -25.7 cm). At the beginning of the season, the water level dropped to -23.6 cm in Trench 9 and -25.7 cm in Trench 8, but high summer rainfall kept the water level within the treatment range. In 2012, the mean specific conductivity of water in the trenches (Trench 9: mean = 841.51 µS (*sd* 111.04), max = 1055.21 µS, min = 638.42 µS; Trench 8: mean = 889.77 µS (*sd* 66.45). max = 1005.94 µS, min = 739.90 µS) was 42% higher than the average in 2013 (Trench 9 2013: mean = 466.62 µS (*sd* 39.37), max = 562.17 µS, min = 344.92 µS; Trench 8: mean = 516.01 µS (*sd* 79.11), max = 651.82 µS, min = 389.66 µS), which was within the range of regional extreme rich fens (Axys 2008). The water's specific conductivity varied temporally due to rainfall and manual freshwater fill events lowering the EC, and evaporation increasing EC (Figure 2).

The four water level treatments differed over the course of the experiment ($F_{3,33}$ = 1326.59, $P <$ 0.0001, all comparisons) and averaged -4.1 cm (*se* 0.3, *n* 20) in 0 cm, -11.2 cm (*se* 0.4, *n* 20) in -10 cm, -21.0 cm (*se* 0.4, *n* 20) in -20 cm, and -32.8 cm (*se* 0.7, *n* 17) in -30 cm (Figure 3A). Gravimetric water content of the top 5 cm of soil differed between the 0, -10, and -30 cm water levels ($F_{3,9}$ = 17.52, $P <$ 0.01), whereas -20 cm was similar to -10 and -30 cm ($F_{3,9}$ = 17.52, 10-20 cm: P = 0.11, 20-30 cm: P = 0.37) (Figure 3B). In September 2013, the gravimetric water content in the 0 cm water level was 99 % (*se* 3, *n* 19), in the 10 cm was 86 % (*se* 3, *n* 20), 20 cm was 76 % (*se* 1, *n* 19), and 30 cm was 73 % (*se* 3, *n* 19).

The percent cover of salt on the soil surface was different with depth to water table ($F_{3,48}$ = 58.90, $P <$ 0.0001, all comparisons) and was 11 times greater in -30 cm water level than 0 cm water level plots (Figure 3C).

Four months after planting in 2012, total most cover did not differ between water level treatments ($F_{3,9}$ = 0.44, P = 0.73, all comparisons) and averaged 23 % cover (*se* 1.8, *n* 62) (Figure 4). In May 2013, total moss cover in -10, -20 and -30 cm water levels averaged 13 % (*se* 0.9, *n* 46) of the September 2012 cover, except in the 0 cm water level, which had increased to 26 % cover (*se* 2.3, *n* 16) ($F_{3,9}$ = 16.74, $P <$ 0.001, all comparisons). By September 2013, total moss cover in the 0 and -30 cm water levels did not differ ($F_{3,9}$ = 5.65, P = 0.70) and averaged 27% (*se* 3.4, *n* 16) and 23% (*se* 3.4, *n* 14) respectively. Total moss cover in the -20 cm water level was 19 % (*se* 2.6, *n* 16) and 15 % (*se* 1.4, *n* 16) in the -10 cm water level, which was less than the 0 and -30 cm water levels ($P <$ 0.05). Total moss cover included the percent cover of moss species that were not planted, which averaged 0% in September 2012, 0.1 % (*se* 0.1, *n* 62) in May 2013, and 3.5 % (*se* 0.4, *n* 62) in September 2013.

Total moss height was also affected by water level ($F_{3,9}$ = 9.62, $P <$ 0.005, all comparisons) (Figure 5). After two seasons of growth, average moss height in the 0 cm water level was 1 cm (*se* 0.1, *n* 16), compared 0.5 cm (*se* 0.1, *n* 16) in -10 cm, 0.6 cm (*se* 0.1, *n* 16) in -20 cm, and 0.5 cm (*se* 0.1, *n* 14) in -30 cm.

3.2 INFLUENCE OF COVER

Fen mosses did not establish in the no-moss-no-cover control mesocosms. The no-moss-no-cover control was omitted from further analyses that evaluated fen moss cover and moss height responses to treatments.

Percent of soil surface covered by salt differed between cover treatments ($F_{4,53}$ = 4.15, P < 0.01, all comparisons; Fig. 6). The cover of salt on the soil surface was lowest under wood-strand mulch compared to the woody plant treatment and controls and similar to soil salt cover under herbaceous plants ($P < 0.05$) (Figure 6A). Gravimetric water content of the top 5 cm of soil was lower under wood-strand mulch than under woody plants and no-cover treatments ($F_{4,53} = 3.86$, $P < 0.05$), but similar to herbaceous plants and no-moss-no-cover ($P > 0.1$) (Figure 6B). The percent cover of litter averaged 52 % (*se* 4.7, *n* 15) under herbaceous plants compared to 4 % (*se* 0.3, *n* 46) under other cover treatments and controls ($F_{4,53} = 64.98$, $P < 0.0001$, all comparisons) (Figure 6C). The temperature difference from the soil surface to 5 cm depth was 1.5^{o} C (*se* 0.2, *n* 15) under herbaceous plants compared to 2.6^{o} C (*se* 0.3, *n* 16) under woody plants and 3.0^{o} C (*se* 0.3, *n* 30) in the controls ($F_{4,53} = 12.77$, $P < 0.05$). Wood-strand mulch also reduced the difference in temperature to 2.1^{o} C (*se* 0.2, *n* 16) ($P < 0.01$) (Figure 6D).

In September 2012, total moss cover under herbaceous plants was 11 % (*se* 1.4, *n* 15, $F_{3,43} = 30.15$, $P < 0.0001$) compared to 30 % cover (*se* 2.5, *n* 32; $F_{3,43} = 30.15$, $P = 0.36$) under wood-strand mulch and woody plants (Figure 7). In September 2013, total moss cover was differed between cover treatments (herbaceous and woody plants and wood-strand mulch), which had a mean cover of 24 % (*se* 1.7, *n* 47), and the no-cover control, which supported a mean cover of 9 % (*se* 2.1, *n* 15) ($F_{3,43} = 10.47$, $P < 0.0001$, all comparisons). Total moss cover values include the percent cover of invasive mosses, which averaged 0% in September 2012, 0.1 % (*se* 0.1, *n* 62) in May 2013, and 3.5 % (*se* 0.4, *n* 62) in September 2013.

After two seasons of growth, the moss height under herbaceous plants averaged 0.8 cm (*se* 0.1, *n* 15), compared 0.6 cm (*se* 0.1, *n* 16) under woody plants and 0.4 cm (*se* 0.1, *n* 15) with no-cover ($F_{3,43} = 12.54$, $P < 0.0001$, all comparisons). Total moss height under wood-strand mulch averaged 0.7 cm (*se* 0.1, *n* 16) and did not differ from herbaceous or woody plants ($P > 0.2$) but was 61 % taller than individuals with no-cover ($P < 0.0001$) (Figure 5).

3.3 SPECIES PERFORMANCE

At the end of the second summer, moss cover differed across water levels and cover treatments, but there was no interaction (Figures 8 and 9). *Drepanocladus aduncus* cover was greater in the 0 cm water level, averaging 4.8 % (*se* 0.6, *n* 16), than its mean cover of 0.8 % (*se* 0.1, *n* 46) in the -10, -20, and -30 water levels ($F_{3,9} = 52.50$, $P < 0.0001$). *Drepanocladus aduncus* cover was greater under herbaceous plants and wood-strand mulch, averaging 2.5 % (*se* 0.6, *n* 15) and 1.7 % (*se* 0.5, *n* 16), compared to woody plants and no-cover, where it averaged 1.4 % (*se* 0.4, *n* 14) and 0.8 % (*se* 0.7, *n* 15) ($F_{3,43} = 3.951$, $P < 0.05$).

Bryum pseudotriquetrum cover was greater in the 0 cm water level, averaging 3.2 % (*se* 0.5, *n* 16), compared to its average of 2.2 % (*se* 0.3, *n* 16) in the -10 cm ($P < 0.05$). Both 0 and -10 cm water levels supported greater cover of *B. pseudotriquetrum* ($P < 0.05$) then the -20 and -30 cm water levels ($P = 0.26$), which averaged 1 % cover (*se* 0.1, *n* 30) ($F_{3,9} = 25.69$, $P < 0.0001$, all comparisons). *Bryum* cover was greater under herbaceous plants and wood-strand mulch averaging 2.7 % (*se* 0.3, *n* 31), compared to woody plants and no-cover, where it averaged 1 % (*se* 0.1, *n* 31) ($F_{3,43} = 21.14$, $P < 0.0001$, all comparisons).

Campylium stellatum cover did not differ between water level treatments and averaged 3 % (*se* 0.2, *n* 62) ($F_{3,9} = 1.10$, $P = 0.40$, all comparisons). However, its cover was greater under herbaceous plants and wood-strand mulch, averaging 4.3 % (*se* 0.3, *n* 31), compared to woody plants and no-cover, where it averaged 1.8 % (*se* 0.2, *n* 31) ($F_{3,43} = 26.10$, $P < 0.0001$, all comparisons).

Tomenthypnum nitens cover was greater in the 0, -20, and -30 cm water levels, averaging 11.2 % (*se* 1.3, *n* 46), compared to the average cover of 4 % (*se* 0.6, *n* 16) in the -10 cm ($F_{3,9} = 6.60$, $P < 0.05$, all comparisons). Its cover was greater under herbaceous and woody plants and wood-strand mulch with an average of 11 % (*se* 1.3, *n* 47), compared to no-cover, where it averaged 4.1 % (*se* 1.2, *n* 15) ($F_{3,43} = 9.41$, $P < 0.001$, all comparisons).

Aulacomnium palustre cover was greater in the -30 cm water level, averaging 3 % (*se* 0.4, *n* 14), compared to its average cover of 1.7 % (*se* 0.2, *n* 16) in the -20 cm ($P < 0.005$). Both -30 and -20 cm water levels supported greater cover of *A. palustre* ($P < 0.0001$) then the -10 and 0 cm water levels, where it averaged near 0 % ($F_{3,9} = 83.39$, $P < 0.0001$, all comparisons). Its cover was greater under herbaceous and woody plants and wood-strand mulch with an average of 1.5 % (*se* 0.2, *n* 47), compared to no-cover, where it averaged 0.6 % (*se* 0.2, *n* 15) ($F_{3,43} = 6.89$, $P < 0.001$, all comparisons).

Total cover of the invasive moss species *Pohlia wahlenbergii* and *Leptobryum pyriforme* was greater in the -10, -20 and -30 cm water levels, averaging 3.9 % (*se* 0.2, *n* 46), compared to a mean cover of 2.2 % (*se* 0.4, *n* 16) in the 0 cm water level ($F_{3,9} = 8.03$, $P < 0.01$). Total cover of invasive moss was greater under herbaceous and woody plants with an average of 4.4 % (*se* 0.3, *n* 31), and no-cover with an average of 3.4 % (*se* 0.4, *n* 15), compared to under wood-strand mulch, which averaged 1.7 % (*se* 0.2, *n* 16) ($F_{3,43} = 26.32$, $P < 0.0001$, all comparisons).

4. DISCUSSION

After two seasons of growth, fen moss communities were establishing by vegetative reproduction on mineral soils. The best performance occurred under herbaceous plants and wood-strand mulch cover treatments. The five moss species established in different proportions at water levels between 0 to -30 cm below soil surface resulting in distinct trajectories of moss community formation yet no difference in total moss cover. Intermediate water levels supported the lowest total moss cover though all species were present and in relatively equal proportions. Only invasive mosses establish on mineral soil if fen mosses are not introduced.

4.1 MOSS ESTABLISHMENT ON MINERAL SOILS

The main properties that limit moss establishment on a substrate are the substrates longevity, chemical properties, and water holding capacity (During 1979, 1992, Bates 1998). Clay loam soils are common at the base of peatlands and wetlands in Alberta's oil sands region (Tattrie 2011, Koropchak et al. 2012). Although fen moss species typically are found growing on fen peat soils (Vitt 1990), clay loam soils have some similarities as they are mineral rich, have a high cation exchange capacity, and can release high concentrations of ions and salts into surrounding water (Soffe 2011). The clay loam used in the experiment had lower available nitrogen and phosphorous than fen peats in the region (Wind-Mulder et al. 1996). Clay loam has lower water retention capacity, saturated water content, residual water content, and hydraulic conductivity compared to peat in Fort McMurray region fens (Rawls et al. 1982, Price and Whitehead 2001, Rezanezhad et al. 2012). Despite the differences in substrate properties, my experimental results demonstrated that fen mosses can establish and grow on mineral soil with a clay loam particle size distribution.

Under herbaceous and woody plants or wood-strand mulch, average total moss cover on mineral soils was similar to moss cover on peat soils under *Scirpus* sp. cover after two years in a fen restoration (Graf and Rochefort 2010). Some moss dieback occurred in the -10, -20, and -30 cm water levels, likely from the stress of winter (Grime 1977, Glime 2007). The dieback was mitigated when the water level was at the surface, the environment where mosses are least water stressed (Grime 1977).

Sodium sulfate is abundant in Alberta soils (VanderPluym and Harron 1992) and sodium and sulfate were the dominant ions in the soils used in my experiment. Despite the high levels, the soil is rated as 'fair for use' in reclamation (Alberta Soils Advisory Committee 1987). Soil hydraulic conductivity, available water, and evapotranspiration influenced the amount and rate that soluble salts move through soil (Finlayson 1993) by leaching and capillary action (Addiscott and Wagenet 1985, Richards 2004). In my experiment the percent cover of salt on the soil surface varied with depth to water, and bins with the water table closer to the soil surface had the lowest salt deposition. Although there was no interactive effect with water table, wood-strand mulch and herbaceous plants lowered soil salt cover. Salts in solution were transported by capillary water where they precipitated on wood strands or plant tissue reducing soil salt accumulation at the soil surface where mosses were growing.

High salinity in soil water and on the soil surface can affect the growth of many moss species by impeding their rate of photosynthesis (Bates et al. 2009) and decreasing their desiccation tolerance (Bates 1976, 2000, Proctor et al. 2007). Due to the nature of the mineral soils and the potential for salt precipitation on the soil surface when water tables are 20-30 cm deep, selecting moss species that tolerate elevated salinity levels may facilitate establishment (Purdy et al. 2005, Trites and Bayley 2009, Pouliot et al. 2012, 2013).

4.2 ESTABLISHMENT ALONG A HYDROLOGIC GRADIENT

Depth to the water table was the most important factor influencing growth of each species. Total moss cover was greatest when the water level was 0 and -30 cm below the soil surface. This corresponded to higher production rates in fens when the water table is at the peat surface and in hummocks (> -15 cm) compared to areas with intermediate water tables (-10 to -15 cm) (Vitt 1990). This was due to niche differentiation and the development of distinct moss communities. Some species are able to establish along the entire hydrologic gradient, while others are limited to a particular hydrologic niche (Li and Vitt 1995). *Drepanocladus aduncus* and *Aulacomnium palustre* have limited hydrologic tolerances (Price and Whitehead 2001) with *D. aduncus* abundant only in the 0 cm water level and *A. palustre* only in the -30 cm water level. This resulted in comparable total moss cover in the 0 cm and -30 cm water levels due to niche differentiation and the development of distinct communities.

While species can survive outside their habitat niche, growth rates may be severely reduced (Busby and Whitfield 1978, Busby et al. 1978). Metabolic activity in mosses correlates with hydrologic conditions, rapidly increasing when water is available and decreasing or completely ceasing during droughts (Anderson 1974). The increase may have occurred in the 0 cm water level where total moss height was greater than in other water levels.

Total moss cover was lower in the -10 cm water level, which has been observed to be the optimal water level for moss regenerating in previous greenhouse studies of single species (Graf and Rochefort 2010). Despite lower total moss cover, all fen and invasive moss species established in relatively equal amounts. This may have resulted in hydrologic niche overlap and greater interspecific competition for available water (Okland 1990, Slack 1990, Gignac 1992, Rydin 1997). Interspecific competition can reduce relative growth rates when species are not initially establishment limited (Li and Vitt 1995, Glime 2007).

Another possible limiting factor in moss establishment in intermediate water levels is nutrient concentration within soil water. Bryophytes prefer low nutrient concentrations for optimal growth and can be stunted or killed in high concentrations (Voth 1943, Glime 2007, Goffinet and Shaw 2009). The intermediate water levels had moderately saturated soil conditions, potentially causing higher available nutrient concentrations compared with diluted concentrations in the 0 cm water level due to leaching and lower concentrations in the -30 cm water level due to lower soil water and less movement of nutrients in solution.

4.3 EFFECT OF PLANT AND WOODSTRAW® MULCH COVER

Moss cover and height was lower in plots without a shade treatment. The cover of most moss species increased under herbaceous plants and wood-strand mulch. The herbaceous plants and wood-strand mulch treatments moderated microclimate conditions by reducing soil temperature variation compared to woody plants and the controls. Total moss cover was similar under all cover treatments, but moss height was greatest under herbaceous plant cover. Mosses survived better over winter under herbaceous plants and continued to grow in the second season. Herbaceous plant cover was also shown to increase the regeneration of fen moss species in a field restoration (Graf and Rochefort 2010). Using herbaceous plants and or wood-strand mulch as a cover will provide the microclimatic conditions to support moss establishment. The height of the plants was did not seem to affect moss establishment as much of the type of plant cover. The microclimate under the woody plants was similar to no cover treatments and did not produce the protective plant and wood litter layer that encouraged most moss species and total moss height under herbaceous plants and wood-strand mulch cover.

Invasive moss species cover was highest under herbaceous and woody plant cover treatments suggesting that these moss species may have originated on greenhouse grown seedlings. However, their establishment was impeded by wood-strand mulch cover, a trend also seen in the use of woody debris for upland reclamation (Brown and Naeth 2014), and in the 0 cm water level.

4.4 REGENERATION ABILITY OF SELECTED FEN MOSSES

The species that most successfully established to date was *Tomenthypnum nitens*, which grew along the entire experimental water level gradient. *T. nitens* cover was five times greater than other planted species and influenced the overall trends in total moss cover. Average *T. nitens* cover was similar to a two year old fen restoration on peat soils in Quebec, where atmospheric humidity is much higher (Graf and Rochefort 2010). *T. nitens* is a dominant hummock former in rich fens (Vitt 1990) and has a wide ecological amplitude (Nicholson and Gignac 1995).

Moss species that inhabit different hydrological niches, such as *Drepanocladus aduncus* and *Aulacomnium palustre,* are important in helping to form the development of distinct communities. Desiccation resistance is lower in moss species that occupy wetter habitats (Proctor et al. 2007), as observed for *D. aduncus* and *Bryum pseudotriquetrum* that were less common in the -10, -20, and -30 cm water levels. Relative growth rates of peatland species can be limited by evaporative stress when transplanted to habitats without adequate available water (Busby et al. 1978). *Aulacomnium palustre* occurs on drier hummock tops and thrived in the -30 cm water level because it has greater desiccation tolerance, but it also could have benefited from lower interspecific competition (Li and Vitt 1995).

5. CONCLUSION

Creating ecosystem initiation conditions and integrating assisted successional strategies can provide a cost-effective process for building peat forming landscapes. Peatlands initiate on mineral soils with a combination of fen mosses, plants and woody debris. This study demonstrated that it is possible to recreate those conditions and establish fen moss species on mineral soil. The moss species segregated along a hydrologic gradient. A shade cover treatment facilitated moss establishment and herbaceous plants and WoodStraw® (wood-strand) mulch treatments improve moss cover and height growth. Water levels at or near the soil surface increased moss cover and height, although moss species were able to establish on soil with deeper water tables. Lower moss covers in the intermediate water levels may be due to interspecific competition or detrimental nutrient concentrations from the clay loam.

Oil sands producers are mandated by Alberta Environment to reclaim disturbed lands to a state of equivalent capability (OSWWG 2000). After years of upland forest and open water wetland reclamation (OSVRC 1998, Fung et al. 2000, Stolte et al. 2000, Rowland et al. 2009) producers are now focused on peatland reclamation initiatives (Daly et al. 2012). This experiment provides the basis for new methods for initiating reclamation of peatlands to mitigate losses in Alberta’s oil sands region. It has been estimated that 29,500 ha of peatland loss could result from open-pit mining (Rooney et al. 2012). Peatland development from mineral soil to maturity may take thousands of years (Bloise 2007), but creating a carbon-accumulating ecosystem and establishing the foundations for successional stages is possible. The applications described here can be tested in larger-scale projects to provide economical and practical strategies to reconstruct pre-existing peatland ecosystems.

6. TABLES AND FIGURES

Table 1. Hydrologic niche preferences of moss species as observed in natural fens in Alberta. Adapted from Gignac et al. (1991)[1] and Hájková and Hájek (2004)[2].

Height Below Soil Surface (cm)	**Moss Species**
0 to -10	*Campylium stellatum*[1] *Drepanocladus aduncus*[1]
-10 to -20	*Aulacomnium palustre*[2] *Bryum pseudotriquetrum*[2] *Campylium stellatum*[1,2] *Drepanocladus aduncus*[1]
-20 to -30	*Aulacomnium palustre*[1,2] *Campylium stellatum*[1] *Drepanocladus aduncus*[1] *Tomenthypnum nitens*[1]

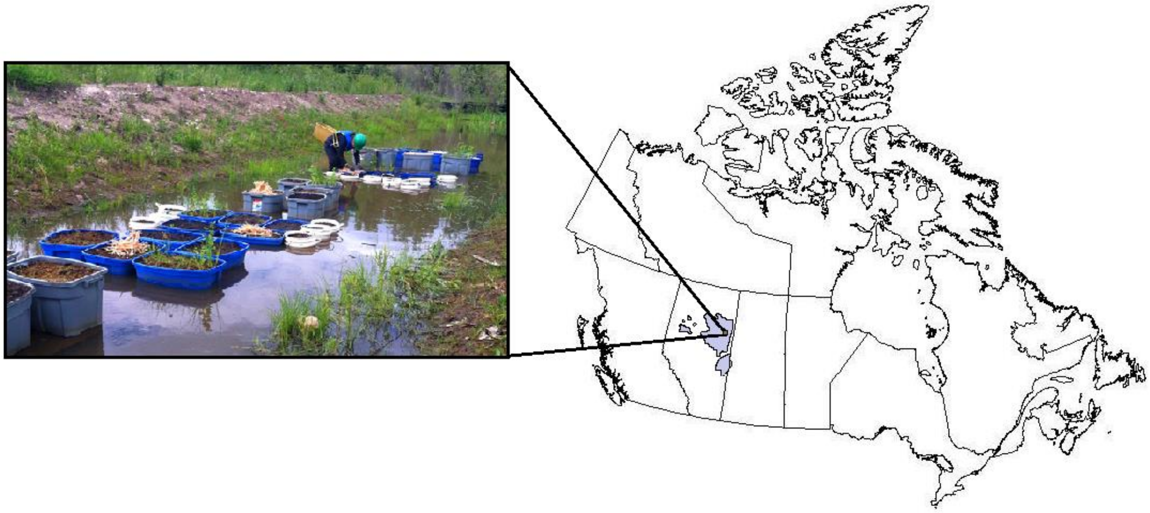

Figure 1. Inset image of trenches where the moss establishment experiment was conducted. Bins are mesocosms filled with mineral soil with shade cover treatments nested in water level treatments in a randomized split-plot design. The trenches are located on the Suncor Millennium Mine, north of Fort McMurray in the oil sands region (in grey) of Alberta, Canada.

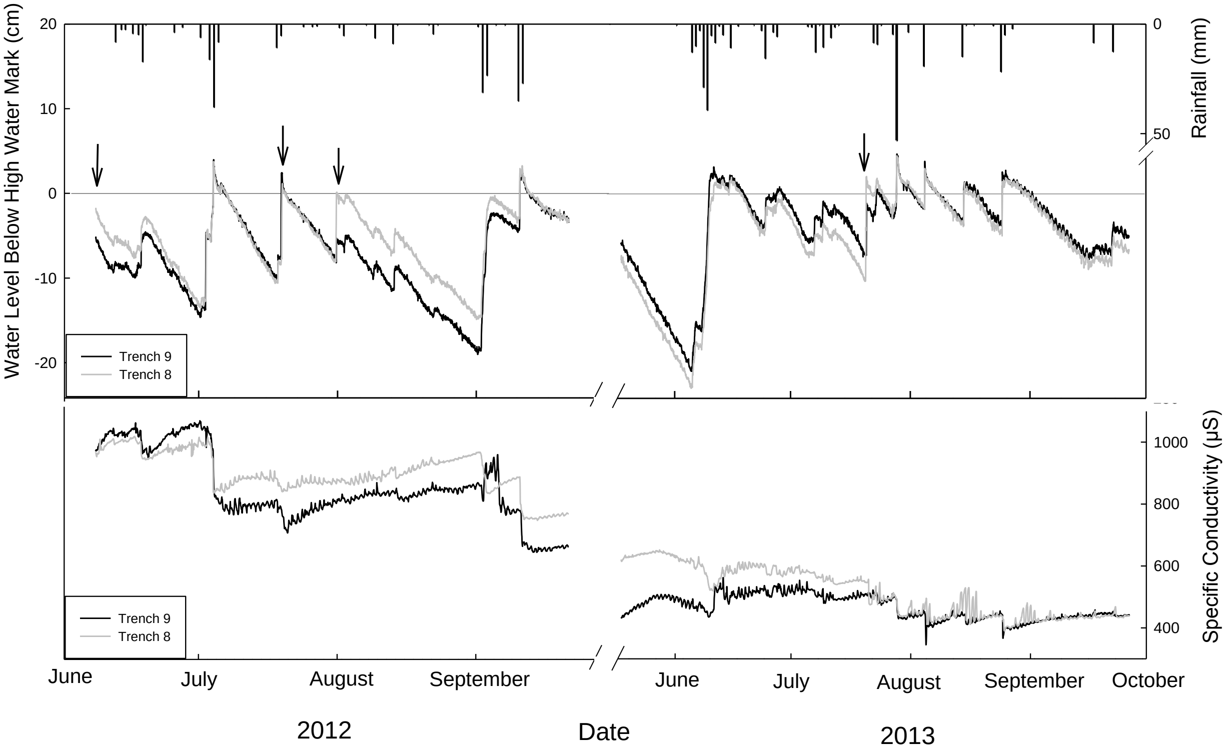

Figure 2. To evaluate moss establishment along a hydrologic gradient, water level was maintained in two trenches between the high water mark (0 cm) and -10 cm. Water was added through precipitation, shown as vertical bars of daily rainfall events in millimeters, and manual fills with fresh lake water, represented by black arrows. Water level below the high water mark (0 cm) is shown in the middle of the graph with Trench 9 in black and Trench 8 in grey. Specific conductivity is shown in the bottom of the graph with Trench 9 in black and Trench 8 in grey. Water level, specific conductivity and rainfall data was collected from June 8th to September 21, 2012 and from May 18 to September 26, 2013.

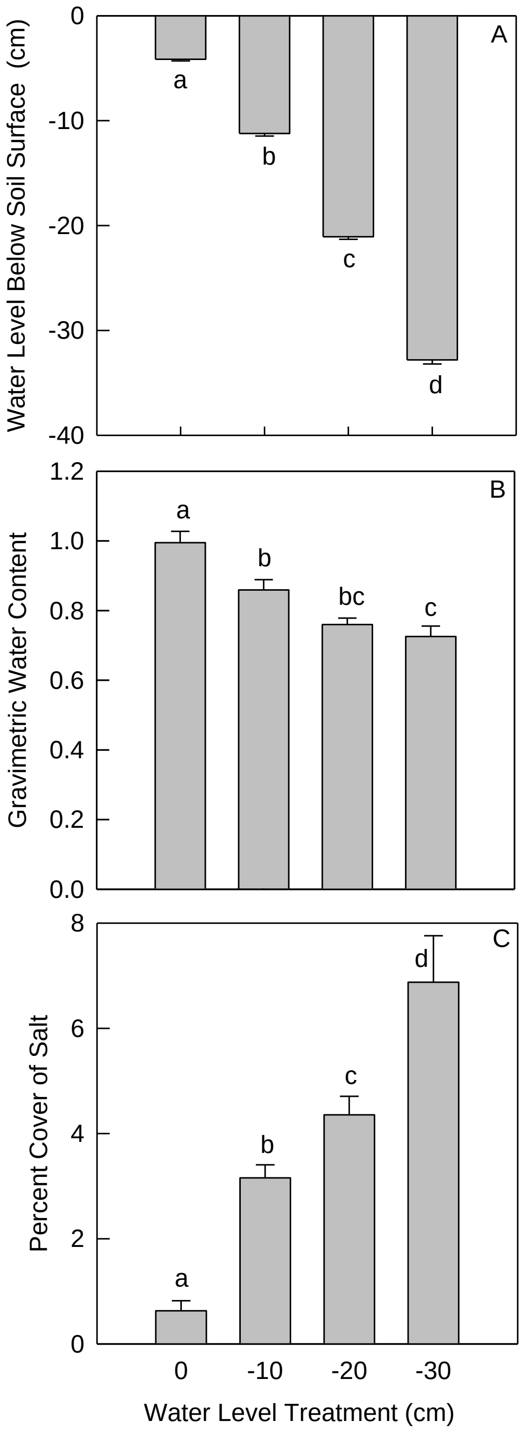

Figure 3. Effect of water level treatments 0, -10 -20, and -30 cm on; A) average water level below the soil surface from June 7- September 21, 2012 and May 18-September 26, 2013; B) gravimetric water content of top 5 cm of soil in September 2013; and, C) percent cover of salt on soil surface in September 2013. Bars represent mean values with standard errors. Means with different letters are significantly different (Tukey-adjusted comparison of least squares means, $P < 0.05$; 0 cm to -20 cm = n 16; -30 cm = n 14).

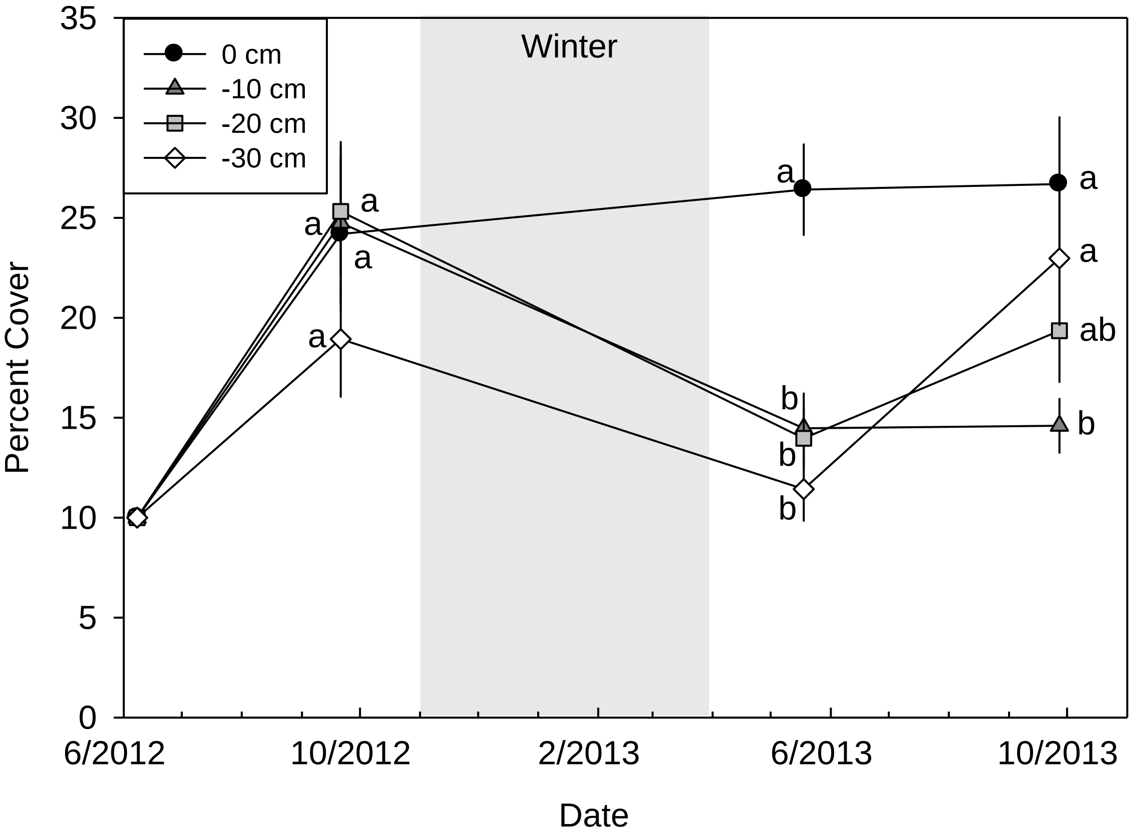

Figure 4. Effect of water level treatment on total moss cover at the end of the first growing season and beginning and end of the second growing season. Water level treatments are 0, -10, -20, and -30 cm below the soil surface. Mean values are shown as points with standard error bars. Mean values with different letters are significantly different from the other means at that date (Tukey-adjusted comparison of least squares means, $P < 0.05$; 0 cm to -20 cm = n 16; -30 cm = n 14).

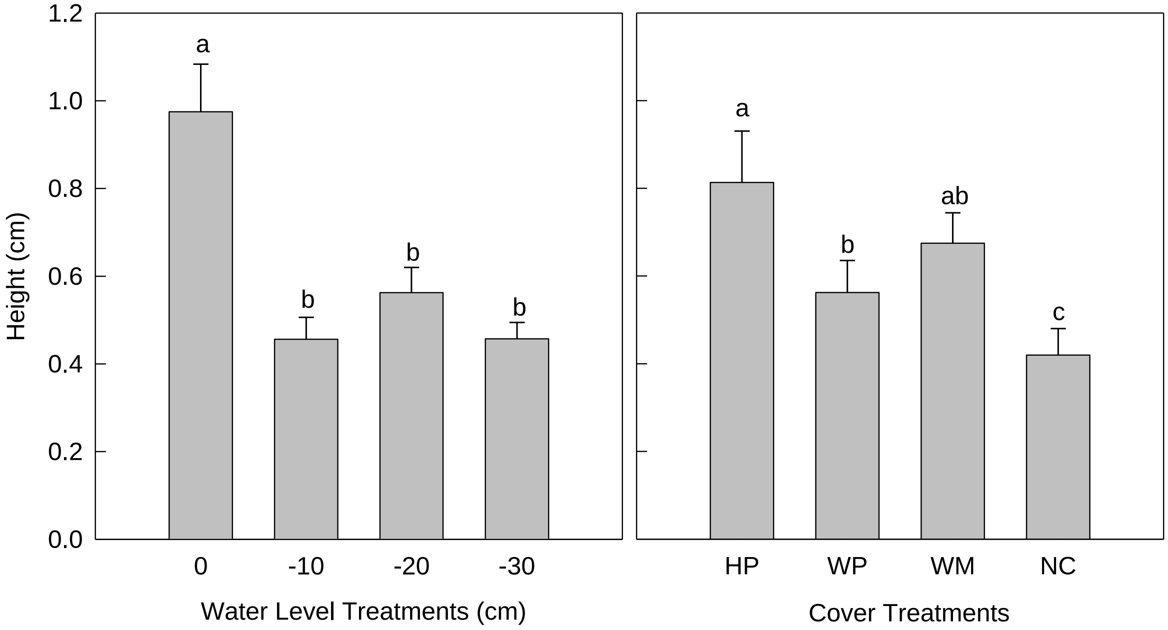

Figure 5. Effect of water level and cover treatments on moss height after two seasons of growth. Left panel shows moss height as influenced by water level treatment, which were 0 cm, -10 cm, -20 cm, and -30 cm below the soil surface. Right panel shows moss height as influenced by cover treatment, which were herbaceous plants (HP), woody plants (WP), wood-strand mulch (WM), and no-cover (NC). Bars represent mean values with standard errors. Means with different letters are significantly different (Tukey-adjusted comparison of least squares means, $P < 0.05$; herbaceous plants and no-cover = n 15; 0 cm to -20 cm, woody plants and wood-strand mulch = n 16; -30 cm = n 14).

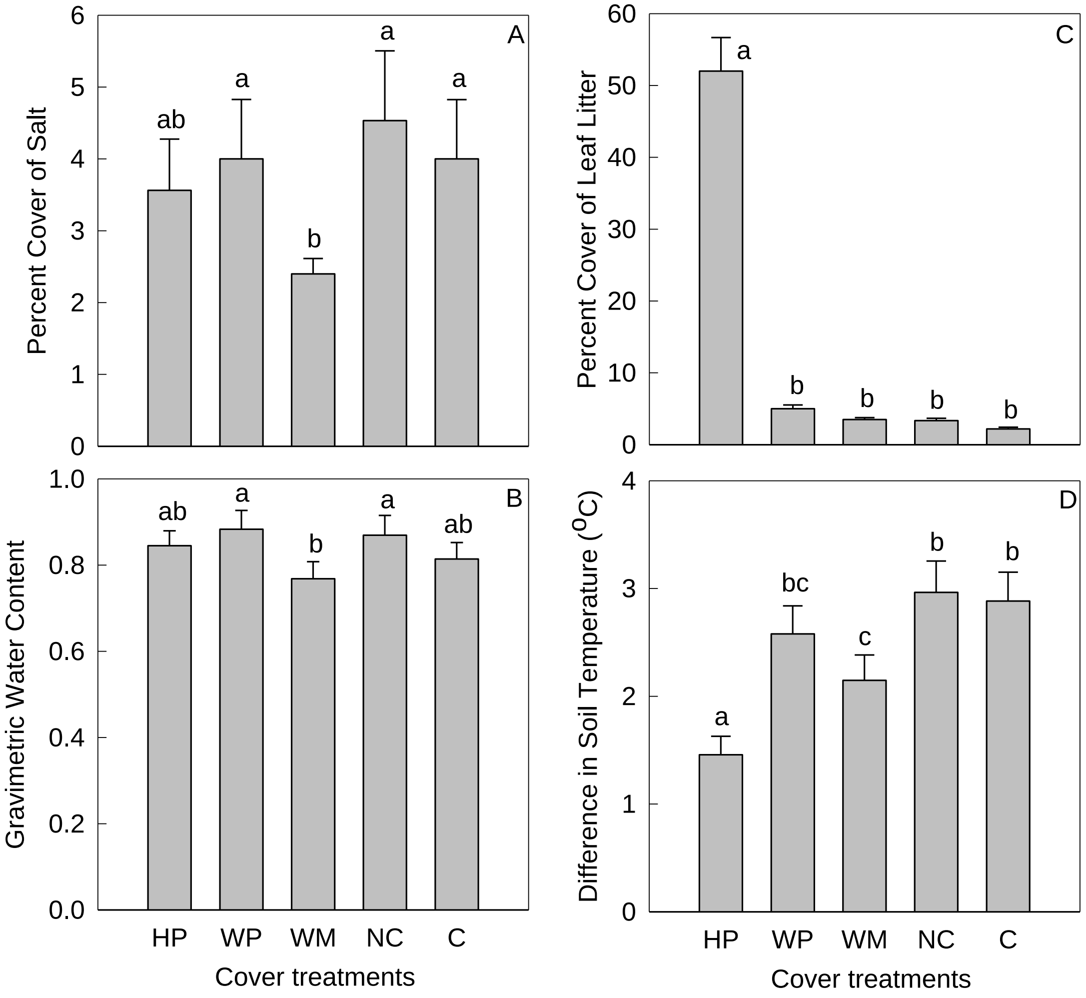

Figure 6. Effect of cover treatments herbaceous plants + moss (HP), woody plants + moss (WP), wood-strand mulch + moss (WM), no-cover + moss (NC), and no-cover-no-moss (C) on; A) percent cover of salt crusts on the soil surface in September 2013; B) gravimetric water content of top 5 cm of soil in September 2013; C) percent cover of litter accumulated after two growing season in September 2013; and, D) difference in temperature from soil surface to 5 cm depth averaged across survey dates. Bars represent mean values with standard errors. Means with different letters are significantly different (Tukey-adjusted comparison of least squares means, $P < 0.05$; herbaceous plants and no -cover = n 15; woody plants and wood-strand mulch = n 16)

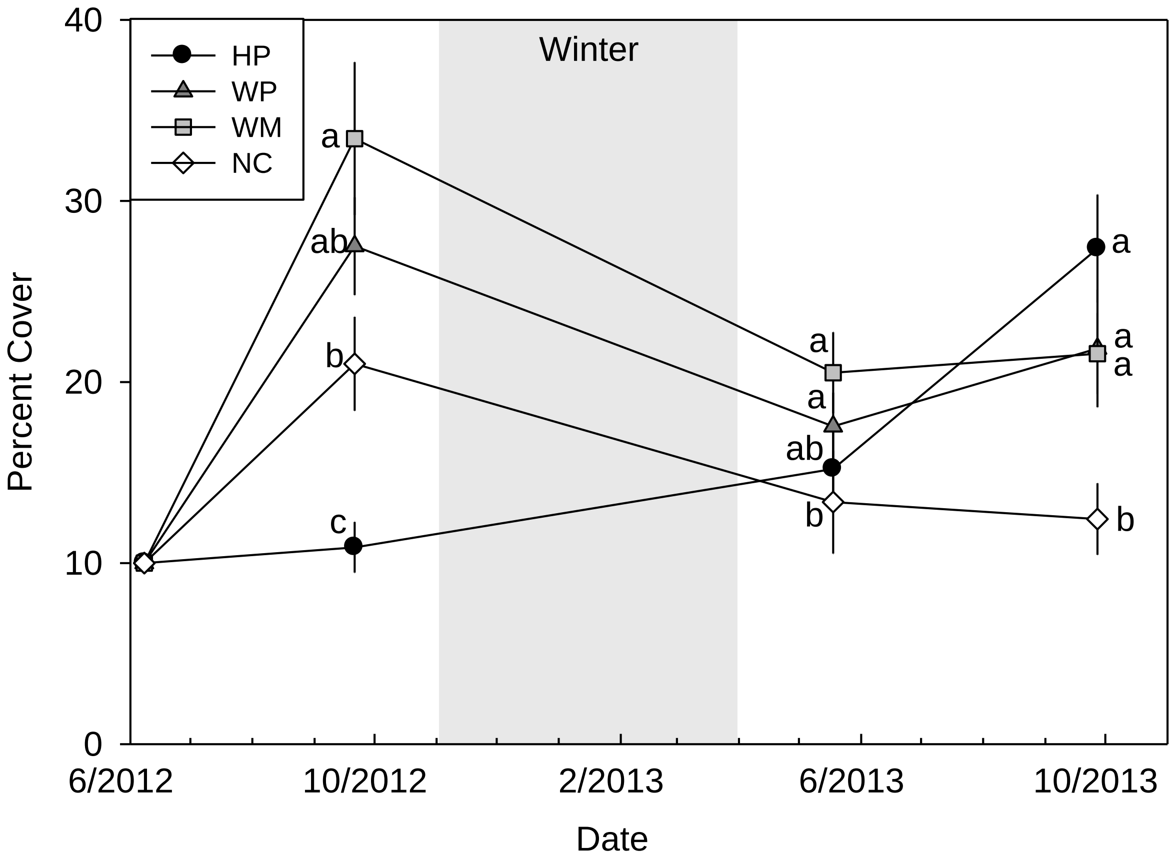

Figure 7. Effect of cover treatment on total moss cover at the end of the first growing season and beginning and end of the second growing season. Cover treatment include herbaceous plants (HP), woody plants (WP), wood-strand mulch (WM), and no-cover (NC). The mean value is shown as points with standard error bars. Mean values with different letters are significantly different from the other means at that date (Tukey-adjusted comparison of least squares means, $P < 0.05$; herbaceous plants and no -cover = n 15; woody plants and wood-strand mulch = n 16).

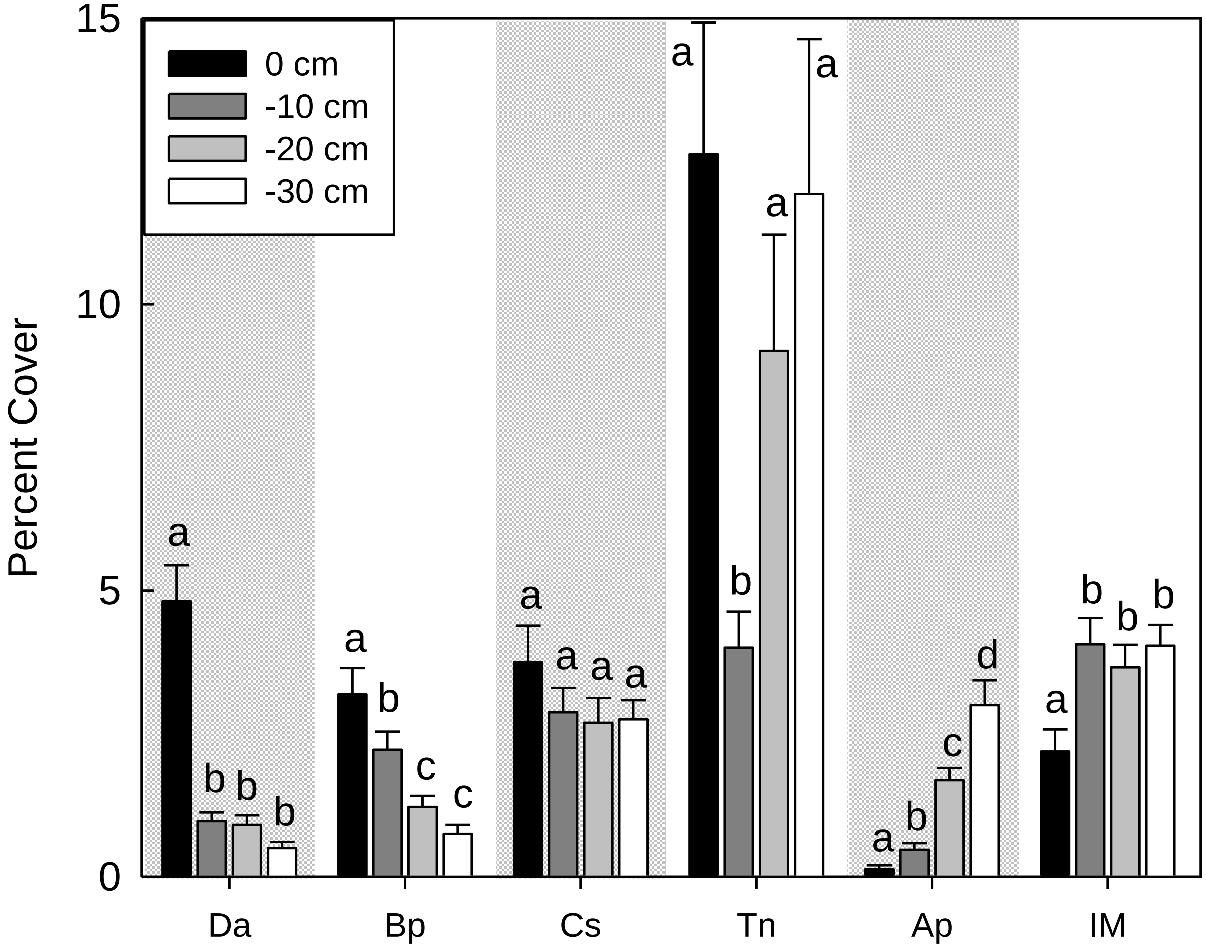

Figure 8. Effect of water level treatment on cover of *Drepanocladus aduncus* (Da), *Bryum pseudotriquetrum* (Bp), *Campylium stellatum* (Cs), *Tomenthypnum nitens* (Tn), *Aulacomnium palustre* (Ap), and invasive moss species (IM) after two growing seasons. Water level treatments were 0, -10, -20, and -30 cm below the soil surface. Bars represent mean values with standard errors. Means with different letters are significantly different from other means within that species or total moss values (Tukey-adjusted comparison of least squares means, $P < 0.05$; 0 cm to -20 cm = n 16; -30 cm = n 14).

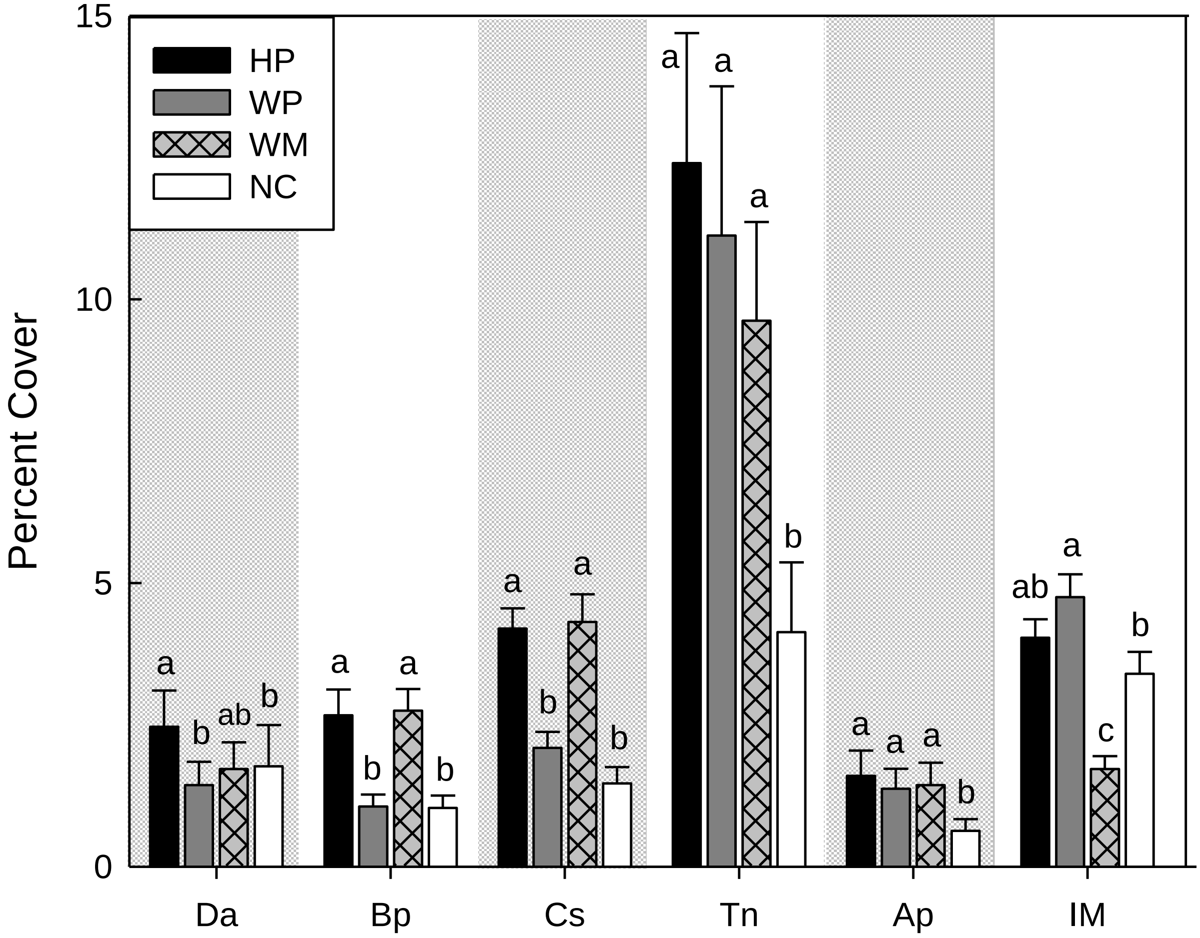

Figure 9. Effect of cover treatment on cover of *Drepanocladus aduncus* (Da), *Bryum pseudotriquetrum* (Bp), *Campylium stellatum* (Cs), *Tomenthypnum nitens* (Tn), *Aulacomnium palustre* (Ap), and invasive moss species (IM) after two growing seasons. Cover treatments include herbaceous plants (HP), woody plants (WP), wood-strand mulch (WM), and no-cover (NC). Bars represent mean values with standard errors. Means with different letters are significantly different from other means within that species or total moss values (Tukey-adjusted comparison of least squares means, $P < 0.05$; herbaceous plants and no-cover = n 15; woody plants and wood-strand mulch= n 16).

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APPENDIX 1

SOIL ANALYSIS METHODS AND RESULTS

Soil samples were collected in June 2012 to measure percent organic matter content and particle size distribution. Organic content was determined by hydrogen peroxide (30% solution) method (Huang et al. 2009) and particle sizes of mineral soils by hydrometer method (Bouyoucos 1962). Three soil samples were also analyzed (Table 1.1) for available nitrogen (Rice 2012), available phosphorus (Martin et al. 1995), available potassium (Martin et al. 1995), available sulphur (Martin et al. 1995), available ammonia (O'Dell 1993), soluble orthophosphate (Clesceri et al. 2005), soluble calcium (Carter and Gregorich 2008), soluble magnesium (Carter and Gregorich 2008), soluble sodium (Carter and Gregorich 2008), soluble potassium (Carter and Gregorich 2008), soluble sulfate (Carter and Gregorich 2008), calcium carbonate equivalent (Carter and Gregorich 2008), and boron (Martin et al. 1995). Physical parameters tested included soluble conductivity, sodium absorption ratio, and soluble ($CaCl_2$) pH (Carter and Gregorich 2008).

Table 1.1. Chemical analysis of available nutrients, soluble parameters, soil properties, and elements in the clay loam mineral soil used in the moss establishment experiment. The mean is from three samples with standard deviations (*sd*).

	UNITS	Mean
Available Nutrients		
Nitrogen (N)	mg/kg	54 (*sd* 42.9)
Phosphorus (P)	mg/kg	11 (*sd* 4.8)
Potassium (K)	mg/kg	74 (*sd* 32.3)
Sulphur (S)	mg/kg	1383 (*sd* 809.8)
Ammonia (N)	mg/kg	8 (*sd* 6.8)
Soluble Parameters		
Specific Conductivity	dS/m	3.3 (*sd* 1.2)
Orthophosphate (P)	mg/L	0.7 (*sd* 1.3)
pH	N/A	5.6 (*sd* 0.9)
Sodium Adsorption Ratio	N/A	4.8 (*sd* 3.7)
Calcium (Ca)	mg/L	333.3 (*sd* 140.5)
Magnesium (Mg)	mg/L	81 (*sd* 45)
Sodium (Na)	mg/L	350 (*sd* 227.2)
Potassium (K)	mg/L	11.4 (*sd* 5.6)
Sulfate (SO4)	mg/L	1220 (*sd* 1124.8)
Soil Properties		
Calcium Carbonate Equivalent	%	2.2 (*sd* 0.5)
Elements		
Total Boron (B)	mg/kg	20 (*sd* 11.2)