Characterizing controls on plot-scale evapotranspiration and soil water dynamics of a constructed fen in the Athabasca Oil Sands Region, Alberta

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

In the Athabasca oil sands region of the Western Boreal Plains (WBP) mining companies now recognize the importance of reclaiming peatlands, as they cover > 50% of the pre-mined regional landscape. Open-pit mining operations require the removal of overburden, which is the surficial soil and vegetation overlying the oil-bearing formation. As a result, mining processes leave an unnatural, undulating landscape, which promotes the establishment of ecosystems non-native to the region. To date, oil sands wetland reclamation efforts have focused on marsh and open water wetlands. However, these wetland systems are not abundant in the sub-humid climate of the WBP due to high evaporative demand from free water surfaces. Despite their abundance on the landscape, the re-establishment of peatland ecosystems had not been previously tested due to their complexity and long successional development. However, the importance of these ecosystems was recognized by Alberta's Environmental Protection and Enhancement Act (EPEA), which mandated mining companies to test peatland reclamation. As a result Suncor's Nikanotee Fen, an experimental fen and watershed constructed as part of the landscape reclamation, was completed in 2013 and engineered with the intent to support natural fen vegetation and hydrologic processes.

During the initial years post-construction, the influence of the experimental planting design on the fen's hydrology is unknown. Therefore, plot-scale evapotranspiration (*ET*) and soil water dynamics were monitored at various mulched and unmulched vegetation plots (control, moss, seedlings; n = 31) across the fen, including ponds. Treatments types were found to influence available energy and thus *ET*, with highest rates over open water (4.4 mm/day) and lowest rates over moss-mulch plots (2.4 mm/day). Mulch reduced *ET* by lowering the vapour pressure deficit within the mulch layer, thus providing a favorable microclimate for moss establishment by elevating near-surface relative humidity and reducing air and soil temperatures by ~2°C. Plot-scale *ET* trends followed ponds (331 mm) > seedlings (294 mm) > seedling-mulch (273 mm) > control (246 mm) > moss (212 mm) > moss-mulch (179 mm), where cumulative seasonal *ET* exceeded cumulative precipitation (132 mm) in all plots.

While plot type was found to influence *ET* losses, it did not show a significant control on soil water dynamics in this study. While there were slight water deficits (*P-ET*) and lower soil moisture contents in mulched plots, probably caused by precipitation interception, the specific

effects of mulch on plot soil water dynamics are difficult to elucidate due to significant differences in plot water table levels ($p < 0.05$). Water table variability was directly related to surface elevation, which differed between plots by ~ 24 cm. Despite a relatively small range in elevations, plot water table positions varied > 20 cm bgs, where plots located at higher elevations had consistently lower and more variable water tables. Furthermore, the salvage and placement methods of the peat created highly heterogeneous peat properties across the fen, which significantly differed with location across the fen ($p < 0.05$). Therefore, the high variability in the hydrophysical properties and surface elevations, thus water table position, likely masked the effects of vegetation and treatment type on plot hydrology.

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Note: Sections 2.0 and 3.0 of this thesis are written as independent manuscripts to be submitted for publication. As a result some of the content within the manuscripts repeats previously stated information.

1.0 Introduction

In Alberta's Western Boreal Plains (WBP), oil sand deposits cover >140,000 km^2, where 4,800 km^2 is surface minable in the area north of Fort McMurray (Alberta Government, 2014). Open-pit mining operations require the removal of overburden, which is the surficial soil and vegetation overlying the oil-bearing formation. As of 2012, 844 km^2 had been disturbed by oil sands mining activities (Alberta Government, 2014). Given the extent of the oil sands impacted area, regulations require oil sands companies to return post-mined landscapes to land of "equivalent capability" (OSWWG, 2000), including wetlands which cover > 50% of the WBP (Vitt *et al*, 1996). In the oil sands development region surrounding Fort McMurray, 95% of these wetlands are fen peatlands (Suncor Energy Inc., 2005). Peatlands are not only dominant but functionally important landforms in the WBP, due to their ability to retain and regulate water on the landscape (Ferone & Devito, 2004; Devito *et al*., 2005; Rydin & Jeglum, 2006), act as long-term carbon stores (Strack, 2008; Bradshaw & Warkentin, 2015) and support diverse flora and fauna (Johnson *et al*., 1995; Lachance *et al*., 2005). However, the re-establishment of peatland ecosystems in the post-mined oil sands landscape has not previously been attempted due to their hydrological complexity and long successional development (Price *et al.,* 2010). Their importance was recognized by Alberta's Environmental Protection and Enhancement Act (EPEA), which mandated mining companies to test peatland reclamation (CEMA, 2014). The Nikanotee Fen, a pilot fen creation project on the Suncor Energy Inc. lease, was constructed based on the conceptual and numerical model proposed by Price *et al.* (2010), where peat stripped for accessing oil-bearing deposits was placed in a constructed watershed designed to provide the requisite groundwater supply. The design aimed to create a self-sustaining, carbon-accumulating ecosystem, capable of supporting representative fen species and resilient to normal stresses (Daly *et al*., 2012).

Prior to the pilot fen project, marshes and open water wetlands were the focus of wetland reclamation efforts, as they are able to spontaneously develop in poorly drained landscapes and are hydrologically simpler than peatlands (Harris, 2007). However, these wetland systems are not abundant in the sub-humid climate of the WBP due to large moisture losses though evapotranspiration (*ET*) compared to local peatlands (Petrone *et al.*, 2007). In the WBP potential *ET* normally exceeds precipitation in most years (Devito *et al*., 2005), where *ET* from natural peatlands can exceed 300 mm over the growing season (Thompson *et al*., 2014; Petrone *et al.,* 2007). As fens with dense vascular cover dominate the landscape (Chee & Vitt, 1989; Vitt *et al.,* 2000) *ET* rates are increased by vascular plant transpiration (Romanov, 1968; Takagi *et al*., 1999; Farrick & Price, 2009). Therefore, considering the dry climate of the WBP, *ET* plays an important role in the hydrological function of these peatlands.

Peatland hydrology is also dependent on soil water dynamics and ecohydrological processes. As peatland reclamation is a newly tested concept, the soil water dynamics of an constructed fen is currently unknown, specifically the effects of disturbed, placed peat and vegetation treatments on the soil water dynamics. Peatland hydrology is highly dependent on the peat properties (Boelter & Verry, 1978; Price, 2003), vegetation water requirements (Kim & Verma, 1996) and meteorological controls (Petrone *et al.,* 2004). The peat used in the construction of this fen had been highly disturbed through the salvage and placement processes and therefore does not have a natural structure or stratigraphy (Price *et al.,* 2010). There were limited studies on the hydrophysical properties of peat used in reclamation. Nwaishi *et al*. (2015) presented the physical properties and saturated hydraulic conductivity of the constructed fen peat in comparison to those of the dewatered donor site and a local natural fen. The potential ecohydrological impacts of the placed peat properties are discussed, however, direct measurement of spatial variability, the influence of different plot types and unsaturated zone hydrology were not considered.

While the construction of peatlands has previously been untested, peatland restoration is now a common practice following drainage for land-use change or horticultural peat extraction (e.g. Price, 1997; Schlotzhauer & Price, 1999; Petrone *et al.,* 2004; Holden *et al.*, 2011; Ketcheson & Price, 2011; McCarter & Price, 2013; Haapalehto *et al*., 2014; Strack *et al.,* 2014) which creates a landscape similar in some respects to that of a constructed peatland. Cutover harvested peatlands have had their vegetation and upper peat profiles removed to expose deeper, more decomposed layers (Price *et al.,* 2003), similar to the peat used in the constructed fen. However, although compacted, the natural structure of the unused deeper peat profiles remain intact in harvested sites, unlike the placed peat of the constructed fen which has lost its natural structure. Yet, despite differences in peat structure, the restoration of harvested peatlands may be the closest analogue for oil sands peatland reclamation. Both practices leave dewatered, highly decomposed peat, resulting in smaller pore sizes, decreased hydraulic conductivity and higher soil water retention (McCarter & Price, 2014). These properties are uncharacteristic of natural surface peat profiles and create complications in the reclamation process, such as vegetation establishment. McCarter and Price (2014) observed a capillary barrier between the surface of a cutover peatland and the regenerated moss, creating a hydrologic disconnect between the two layers. This barrier could occur in the constructed fen as a result of the highly decomposed nature of the placed peat. However, the unsaturated processes of the peat are currently unknown. Knowledge of unsaturated zone hydrologic processes is required to estimate moisture availability for vegetation, specifically mosses, as they do not have internal water conducting mechanisms such as vascular species and rely on capillary transport from the underlying peat.

Rochefort *et al.* (2003) outlined restoration practices for North American peatlands, however; these focus on *Sphagnum* dominated bogs in temperate climates. Although these methods (i.e. moss-transfer, mulching) have been previously tested at harvested sites (e.g. Bugnon *et al.,* 1997; Price *et al*., 1998; McCarter & Price, 2013; Malloy & Price, 2014), they have not been applied in a post-mined oil sands landscape. Alberta's oil sands region receives less than half the precipitation of eastern Canada (Environment Canada, 2010) and moderate-rich fens dominate the landscape (Chee & Vitt, 1989; Vitt *et al.,* 2000). Transpiration from vascular plants affects the soil water dynamics of peatlands, drying the near surface and lowering the water table (Takagi *et al.*, 1999; Farrick & Price, 2009; Rezanezhad *et al.,* 2012). Previous studies of moisture and energy dynamics of restored (i.e. not constructed) peatlands identify the importance of vegetation composition and mulch cover, where mulch has been proven to retain moisture at the peat surface and create a microclimate favorable for vegetation establishment (Price *et al*., 1998; Petrone et al., 2004). However, these practices have not been tested in the dry sub-humid climate of the WBP, where potential evapotranspiration typically exceeds precipitation (Devito *et al*., 2005).

1.2 Objectives

While numerous studies of peatland restoration post horticultural extraction in Quebec and eastern Canada have been accomplished, there are no published studies evaluating the hydrology of reclaimed peatlands in a post-mined oil sands landscape. It is unclear how the differences in climate, peatland type and peat substrate will affect the reclamation process and how tested restoration practices will function in the WBP. The influences of different vegetation and treatment types on the fen's hydrological processes are currently unknown, however this information is necessary to estimate the trajectory and success of the Nikanotee Fen. Therefore, the objectives of this thesis are to:

1. Quantify the differences in plot-scale surface energy fluxes and determine controls on evapotranspiration from different cover types
2. Characterize plot-scale soil water dynamics with respect to the influences of vegetation type and mulch
3. Characterize and quantify the variability of the placed peat hydrophysical properties and determine their effect on the fen's hydrological processes

1.3 General Approach and Project Role

My role within the larger project was primarily an investigation into hydrological processes at the plot-scale. I was responsible for designing, implementing and conducting field and laboratory work, as well as writing both manuscripts. This thesis is composed of two independent yet complementary manuscripts. The first manuscript assesses controls on plot-scale evapotranspiration and changes in energy fluxes with plot type. Influences of vegetation type and mulch cover on evapotranspiration were isolated by repeated measures of water table, soil moisture, temperature and relative humidity at 31 study plots. A roaming meteorological station moved over studied cover types to measure differences in available energy. The second manuscript expands upon plot-scale hydrology, investigating controls on soil water dynamics and the spatial variability of placed peat hydrophysical properties (i.e. bulk density, porosity, specific yield, mineral content, saturated hydraulic conductivity). The influence of these properties on the unsaturated hydrology (i.e. unsaturated hydraulic conductivity, moisture retention) is also explored. Combined, these manuscripts provide an assessment of plot-scale hydrology of the Nikanotee Fen and provide recommendations for future peatland reclamation projects in Alberta's oil sands.

2.0 Manuscript 1: Controls on plot-scale evapotranspiration from a constructed fen, Fort McMurray Alberta

2.1 Introduction

Oil sands mining activities impact more than 844 km^2 in northeastern Alberta (Alberta Government, 2014), including wetlands which cover > 50% of the Western Boreal Plain (WBP) (Vitt *et al.*, 1996), of which most are fen peatlands (Suncor Energy Inc., 2005). Until recently marshes and open water wetlands have been the focus of reclamation efforts, as they are able to spontaneously develop in poorly drained landscapes and are hydrologically simpler than peatlands (Harris, 2007). However, these wetland systems are not abundant in the sub-humid climate of the WBP due to large moisture losses though evapotranspiration (*ET*) compared to local peatlands (Petrone *et al.*, 2007). Peatlands are natural moisture regulators on the landscape (Rydin & Jeglum, 2006) and able to mitigate high evaporative demand (Devito *et al.*, 2005). However, the re-establishment of peatland ecosystems has not previously been attempted due to their hydrological complexity and long successional development (Price *et al.,* 2010). Their importance was recognized by Alberta's Environmental Protection and Enhancement Act (EPEA), which mandated mining companies to test peatland reclamation (CEMA, 2014). The Nikanotee Fen, a pilot fen creation project on the Suncor Energy Inc. lease, was constructed based on the conceptual and numerical model proposed by Price *et al.* (2010). The fen was designed with the goal of being a self-sustaining ecosystem, resilient to the normal moisture stresses of the WBP (Daly *et al*., 2012).

The WBP exists in a sub-humid climate where potential *ET* exceeds precipitation in most years (Devito *et al*., 2005; Petrone *et al.,* 2007; Thompson *et al*., 2014). In this typically dry climate, implementing effective reclamation practices must consider evaporative stress. Previous studies of moisture and energy dynamics of restored (i.e. not constructed) peatlands identify the importance of vegetation composition and mulch cover (Price *et al*., 1998; Petrone et al., 2004), where mulch created a microclimate favorable for vegetation establishment and reduced moisture stress. Hares and Novak (1992) and Novak *et al.* (2000) documented reduced net radiation and atmospheric mixing over mulched covered surface, therefore reducing available energy and the vapour pressure deficit and thus *ET*. *Sphagnum* mosses do not have roots or an internal water conducting mechanism and instead depend on capillary rise from the underlying peat (Rydin & Jeglum, 2006). As a result, *ET* from *Sphagnum*-dominated peatlands is typically lower than that from fens (Romanov, 1968), due to limited vertical water movement in mosses (Price, 1997; Goetz & Price, 2015). Conversely, WBP fens can have a dense vascular cover (Chee & Vitt, 1989), which increases *ET* through vascular transpiration (Romanov, 1968; Takagi *et al*., 1999; Farrick & Price, 2009). Considering the sub-humid climate of the WBP, transpiration plays an important role in the water balance of these peatlands. Therefore, differences in climate and peatland type must be considered when assessing reclamation strategies, as they can substantially influence the hydrological and thermal behavior of reclaimed peatlands.

While the construction of peatlands is previously untested, peatland restoration is now a common practice following drainage for land-use change and horticultural peat extraction in North America (e.g. Ketcheson & Price, 2011; McCarter & Price, 2013; Strack *et al.,* 2014, Taylor & Price, 2015) and Europe (Holden *et al.,* 2011; Haapalehto *et al*., 2014). Many of these studies are focused on *Sphagnum*-dominated peatlands in temperate climates and therefore, there exists extensive literature on restoration practices in these settings (e.g. Price *et al.,* 1998; Rochefort *et al*., 2003). However, Alberta's oil sands region is located in a dry sub-humid climate where moderate-rich fens dominate the landscape (Chee & Vitt, 1989; Vitt *et al.,* 2000).

As peatland reclamation has only recently been attempted in the Alberta oil sands region, reclamation practices have not yet been well tested and have relied on knowledge from other study areas where peatland types and climate are dissimilar. On the Nikanotee fen different vegetation plots were created as part of a factorial design to help evaluate the most appropriate re-vegetation strategy. The influence of these strategies on the hydrology of the fen is unknown. Therefore, this study aims to better understand the influences of various vegetation and treatment types on the energy balance and evaporative demand of a reclaimed fen in the WBP. Specifically, the objectives are to 1) quantify the differences in plot-scale surface energy fluxes, 2) determine controls on evapotranspiration from different plot types and 3) develop recommendations for future oil sands reclamation projects to reduce evaporative stress and aid in the establishment of a functioning fen ecosystem.

2.2 Study Site

The Nikanotee Fen (56.932° N, 111.417° W; Figure 2.1) is a 2.9 ha pilot fen creation project that sits in a larger 32 ha constructed watershed on the Suncor Energy Inc. lease, 20 km north of Fort

McMurray, Alberta. In this region of the WBP average temperatures (1981-2010) range from -17.4°C (January) to 17.1°C (July) and average annual precipitation is 419 mm, of which ~76% is rainfall (measured at the Fort McMurray Airport ~ 33 km south of the study; Environment Canada, 2010). Construction of the fen was completed in January 2013 and planted in June 2013. The peat used in the construction of this site was extracted from a natural fen on the lease, where the top ~ 30 cm of peat was discarded to exclude viable seeds, roots and rhizomes. The peat was placed to a depth of approximately 2 m on the constructed site.

The experimental planting was based on a factorial design that was divided into replicates of five vegetation plots, with mulched and weeding treatments (Borkenhagen, unpublished data). Plot types included control (bare peat), moss, seedlings, seedling-moss and seeds. Moss, seedlings and seedling-moss plots were 17 m x 18 m, whereas control and seed plots were 8 m x 18 m. Each plot was divided into four sub-plots (~9 x 9 m), with two covered by wood-strand mulch and two weeded for non-peatland species. Moss was harvested from a donor fen, 8 km west of the constructed site, chosen due to presence of rich-fen moss species (i.e. *Tomenthypnum nitens, Aulacomnium palustre, Sphagnum warnstorfii).* The upper 10 cm of moss was mechanically harvested from previously disturbed cut lines, to be used in the moss-layer transfer technique (Quinty & Rochefort, 2003). The moss was hand spread on the constructed site to a thickness of ~1 cm. Seedlings were germinated in a greenhouse (Coast 2 Coast Restoration) and hand planted at the constructed site. Seedlings included salt-tolerant (*Juncus balticus, Triglochin maritima, Calamagrostis inexpansa*) and freshwater (*Carex aquatilis, Betula pumila*) species.

Figure 2-1 Map of the Nikanotee Fen. Ponds outlined in this map had permanent standing water during the study period. Note the outflow at the spill box to the northeast of the fen.

2.3 Methods

Environmental and microclimatic variables

Data were collected from May to August 2014, the second growing season post-construction. Thirty-one study plots were selected within the experimental plot design (Figure 2.1), including control (n=6), moss (n=6), moss-mulch (n=7), salt-tolerant seedlings (n=6) and salt-tolerant seedling-mulch (n=6). All plots were in weeded treatments to remain constant between plot types and reduce the influence of non-peatland species. Plots were chosen randomly across a hydrological gradient but flooded sections were avoided. Freshwater seedling, seeds and seedling-moss plots were not monitored due to time and equipment constraints. In 2014, new peat was placed on the west side of the fen to fill large ponds (Figure 2.1). This area was not part of the original fen design and therefore was not included in this study.

Plot measurements were collected 3-4 times weekly from June 1 to August 15. Water table and 0-5 cm soil moisture (θ; Delta-T Devices WET-Sensor) were measured to characterize differences in plot-scale hydrology. Field θ measurements were corrected with a gravimetrically-determined calibration curve developed for the constructed fen peat using WET-Sensor readings taken from a sample with a known volume as it dried (calibration curve shown in Appendix 1). Relative humidly (*RH*) and temperature (*T*; Vaisala HUMICAP® HMP42, temperature corrected at 20°C) were measured at the plot surface (under mulch in mulched plots) to monitor the near-surface microclimate. Logging surface *RH* and *T* (Vaisala HMT337) measurements were averaged at 30-minute intervals over control, moss and moss-mulch (under mulch) treatments. Seedling and seedling-mulch plots did not have logging systems due to instrument limitations. Plot-scale thermal regimes were monitored using soil temperature profiles (Omega copper-constantan thermocouple) with manual measurements at 2.5, 5, 10, 20 and 30 cm.

Stomatal resistance (Decagon SC-1 porometer) and leaf area index (*LAI*; AccuPAR LP-80, 1 m sensor length) were measured monthly at 23 locations in seedlings, seedling-mulch, seedling/moss and seedling/moss-mulch plots, including dominant salt-tolerant (*Juncus balticus*, n = 11) and freshwater (*Carex aquatilis*, n = 12) species. Measurements were made within a permanent 60 x 60 cm quadrat in each plot. *LAI* was measured indirectly in the field at half vegetation height under full sun conditions at mid-day. Triplicate porometry measurements were taken at the base, mid-height and top of one plant within each quadrat. Measurements were taken on a single leaf; open space was accounted for if the leaf did not cover the porometer's full aperture. Reported vegetation height was the average of all plants within the quadrat.

Energy fluxes and evapotranspiration

A roaming meteorological station was used to account for spatial variability and compare energy fluxes between plot types. The station was moved over five cover types (Figure 2.1) for 7-10 day periods from May 28 to August 15. The cover types included bare peat, moss, moss-mulch, seedlings and ponds. Seedling-mulch was not included due to time limitations, trends were assumed similar to seedling plots. Each cover had two measurement periods over the season except for bare peat. Air temperature (T_a) and *RH* were recorded with a HOBO Onset logger installed 1.0 m above the peat surface, housed in a perforated reflective cup to minimize heating by direct solar radiation. Net radiation (Q^*) was also recorded at 1.0 m with a Kipp & Zonen

NRLite net radiometer. A height of 1.0 m was chosen for the net radiometer to capture only one cover type, as the measurement radius is approximately 10 x sensor height. To measure ground heat flux, 2 heat flux plates (Q_G; HFT3 REBS) were installed 5 cm below the peat surface (one plate after July 13), and were paired with a soil temperature profile (copper-constantan thermocouple) with measurements at 2.5, 7.5 and 17.5 cm depths. Studies have suggested that heat flux plates underestimate fluxes in organic soils, specifically in peatlands, due to poor contact between the plate and peat (Halliwell & Rouse, 1987; Rouse *et al*., 1987). However, due to the dense, decomposed nature of the constructed fen peat, errors in the plate values can be assumed negligible. For pond measurements, a boardwalk was built into the Central Pond where the station was mounted. The temperature profile was set at 0, 5 and 10 cm below the pond surface (Q_G plates were not used in the pond). The net radiometer was installed in the middle of the pond at 1.0 m. The roaming station recorded all measurements at one-minute intervals which were averaged every 30-minutes.

To calculate continuous seasonal energy fluxes for each cover type the roaming station measurement periods were regressed against a “permanent” fen meteorological station for the same time periods. The permanent station measured Q^* (CNR4 Kipp and Zonen) at 2 m, T_a and RH (HOBO Onset) at 1.75 m and precipitation (Texas Electronics tipping bucket; located ~100 m south of the fen). Q_G (HFT3 REBS and HFP01SC Hukseflux) was measured at a separate station with plates (5 cm below peat surface) under 4 plot types: moss-mulch, seedling-mulch, seedling/moss-mulch, seed-mulch. The roaming station Q_G was regressed against the most representative Q_G site at the permanent station (i.e. roaming station moss Q_G was regressed against moss-mulch Q_G at the permanent station). Two regression equations, early and late season, were used to calculate the aforementioned variables for each cover type. All regression relationships had an $R^2 \geq 0.70$.

The surface energy balance was calculated for each cover type as follows,

$$Q^* = Q_G + Q_E + Q_H \tag{2.1}$$

where Q^* is the net radiative flux, Q_G is the ground heat flux, Q_E is the latent heat flux and Q_H is the sensible heat flux (W/m^2). Heat storage in the mulch layer (S) was included in the Q_G term for mulched plots and calculated as,

$$S = C_M \frac{\Delta T}{\Delta t} \Delta z \tag{2.2}$$

where C_M is the heat capacity of the mulch (J/m^3°C), T is temperature (°C), t is time (s) and z is depth (0.02 m). Price *et al.* (1998) calculate C_M as 0.9 C_{air} + 0.1 C_{veg}, where the heat capacity of vegetation was assumed to be ~ 0.7 that of water (Miller, 1981). In ponds, the energy stored in the water column, Q_W, replaces Q_G in Eq (2.1). Q_W was calculated calorimetrically, as described in Halliwell & Rouse (1987), using the pond temperature profile and the known heat capacity of water (Oke, 1987),

$$Q_W = C_W \frac{\Delta T}{\Delta t} \Delta z + \kappa_T \frac{\Delta T}{\Delta z} \tag{2.3}$$

where C_W is the heat capacity of water (4.18 x 10^6 J/m^3°C) and κ_T is thermal diffusivity (m^2/s).

Plot-scale equilibrium evapotranspiration (ET_{eq}) was calculated using the Priestley-Taylor available energy-based approach (Priestley & Taylor, 1972). The Priestley-Taylor equation calculates ET_{eq} as,

$$\lambda ET_{eq} = \frac{\Delta}{\Delta + \gamma} (Q^* - Q_G) \tag{2.4}$$

where Δ is the slope of the saturation vapour-pressure curve (kPa/°C) and γ is the psychrometric constant (0.00662 kPa/°C at 20°C) and λ is the latent heat of vaporization (MJ/kg)

Actual evapotranspiration (ET_a) was measured 3-4 times weekly using weighing lysimeters located in each of the 31 study plots and 3 floating evaporation pans located in the SW and Central ponds (Figure 2.1). Lysimeters (10 L) were filled with peat and covered with the representative plot vegetation and mulch. Seedlings were transplanted into lysimeters at the time of planting in 2013 and remained healthy and visually representative of surrounding seedlings during the years of this study. Evaporation pans (53 x 35 cm) were clear plastic to minimize heating and attached to flexible polyethylene foam tubes to ensure they followed pond stage fluctuations. Water loss from the evaporation pans was measured using incremented tape along the sides of the pans. Water was added to the lysimeters and evaporation pans when needed to maintain a similar water level as the surrounding environment. ET_{eq} can be related to ET_a using,

$$\alpha = ET_a/ET_{eq} \qquad (2.6)$$

where α is the Priestley-Taylor coefficient of evaporability, which is the slope of the regression. All ET_a/ET_{eq} relationships had an $R^2 \geq 0.47$ and were significant at $p < 0.01$ (α-plots shown in Appendix 2). Under equilibrium conditions $\alpha = 1$; however, these conditions are uncommon. Therefore, α-adjusted ET_{eq} is herein referred to as *ET*.

Statistical Analysis

Data sets were tested for normality using the Shapiro-Wilk test. For normally distributed datasets, an ANOVA was used to determine differences among group means, whereas the non-parametric Kruskal-Wallis one-way analysis of variance was used when a normal distribution could not be assumed. If significant effects were found, a post-hoc pairwise t-test (parametric) or Wilcoxon rank sum test (non-parametric) with a Bonferroni adjustment was used to isolate differences between groups. Regression analyses were used to test for significant relationships between *ET* and environmental variables. Normality and homoscedasticity of significant relationships were checked visually using residual plots. A 95% confidence level ($\alpha = 0.05$) was the significance threshold for all tests. R statistical software (R Core Team, 2013) was used for all statistical data analyses.

2.4 Results

Climate

The study site received 132 mm of precipitation (*P*) from June 1 to August 15 (Figure 2.2), less than the 30-year regional average (211 mm; Environment Canada, 2015). The average rainfall event was approximately 3.9 mm, with the largest event delivering 14.2 mm on July 29 (DOY 210). Average daily air temperature during the study period was 19°C, ranging from 7.9°C on June 5 (DOY 156) to 26.8°C on July 14 (DOY 195; Figure 2.2). No significant difference was found between air temperatures (T_a; 1 m) of the different plot types and over the pond (Kruskal-Wallis, $p > 0.05$; Table 2.1).

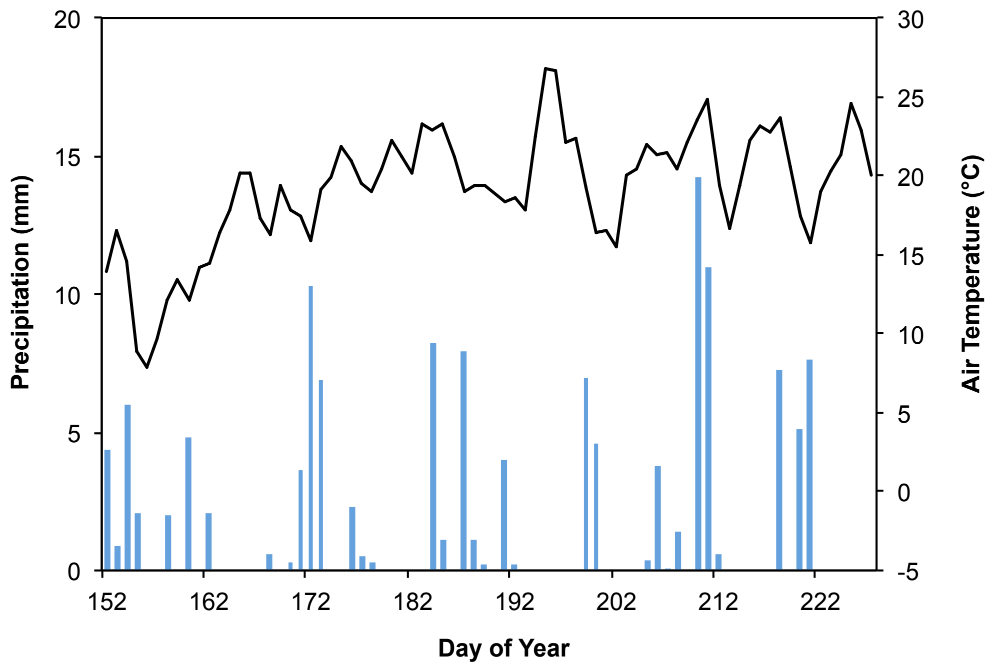

Figure 2-2 Total daily precipitation (bars) and mean daily air temperature (line) from June 2 to August 15, 2014.

Table 2-1 Summary of evapotranspiration and environmental variables for each plot type and ponds in 2014. Evapotranspiration is shown as α-adjusted (*ET*) and average daily rates. Air temperature (T_a) was measured at 1 m above the surface. Ground temperature (T_g) and soil moisture (θ) were averaged over a 0-5 cm depth. Water table (*WT*) is presented as cm below ground surface (bgs). Plot ET rates with different letters indicates a significant difference ($p < 0.05$).

* No T_a data over seedling-mulch plots; it is assumed similar to T_a over unmulched seedling plots.

Cover Type	*ET* (mm)	*ET* rate (mm/day)	Alpha (α)	T_a (°C)	T_g (°C)	θ (cm^3/cm^3)	*WT* (cm bgs)
Pond	331	4.4 [a]	1.35	18.9	20.3	---	---
Control	246	3.2 [bc]	1.14	20.2	20.2	0.87	6
Moss	212	2.8 [bd]	0.98	19.2	19.2	0.86	5
Moss-Mulch	179	2.4 [d]	0.91	19.5	19.5	0.83	7
Seedlings	294	3.9 [ae]	1.40	19.1	22.1	0.87	5
Seedlings-Mulch	273	3.6 [ce]	1.33	19.1*	20.0	0.86	5

Plot-scale energy balance and evapotranspiration

Seasonal energy flux trends were similar between all cover types (not shown), however magnitudes differed between plots and open water (Table 2.2). Q^* was the highest over open water compared to all plot types, whereas moss-mulch and seedling plots had the lowest average Q^* over the season. Daytime pond Q_W was slightly higher on average compared to plot Q_G values, although nighttime Q_W were significantly lower (Kruskal-Wallis, $p < 0.05$). Daytime Q_G did not differ significantly between plot types (Kruskal-Wallis, $p > 0.05$); however, nighttime mulched plot Q_G was consistently higher (i.e. less negative) than respective unmulched plots. Mulch heat storage was similar between both moss-mulch and seedling-mulch plots, yet had a negligible influence on plot Q_G. Although net seasonal mulch heat storage was minimal, it represented 16% and 19% of noon Q_G in moss-mulch and seedling-mulch plots, respectively. Available energy ($Q^* - Q_G - S$) followed a trend where ponds > moss > control > seedlings > seedling-mulch > moss-mulch (Table 2.2). Figure 2.3 compares available energy between bare peat and vegetated plots. Available energy over both seedling and seedling-mulch plots is similar to that over bare peat (falls on 1:1 line; Figure 2.3b). Moss-mulch plots consistently have lower available energy than bare peat; however, available energy over unmulched moss plots is more variable and generally equal to or greater than that over bare peat (Figure 2.3a).

Table 2-2 Summary of daily mean energy fluxes (W/m^2) from each plot type and the pond. Q_G divided into daytime and nighttime fluxes. Available energy (Q^* - Q_G - S) was calculated with daily average Q_G values (not shown). Mulch heat storage (S) only calculated for mulched plots.

[*] No Q^* data over seedling-mulch plots; it is assumed similar to Q^* over unmulched seedling plots.

Cover Type	Q^*	Q_G		S	Q_E	Q_H	Q^* - Q_G - S
		7:00-20:30 h	21:00-6:30 h				
Pond	141	38	-26	---	92	37	129
Control	130	31	4	---	81	29	110
Moss	130	31	1	---	81	31	112
Moss-Mulch	123	32	10	0.8	73	26	100
Seedlings	125	32	-6	---	79	30	109
Seedlings-Mulch	125[*]	34	-1	0.6	76	29	106

Plot ET_{eq} was related to ET_a via the α coefficients presented in Table 2.1. All values where α > 1 means ET_a exceeds ET_{eq} for these cover types. Moss and moss-mulch were the only plots where α < 1. After α-adjustments, plot-scale *ET* trends followed ponds > seedlings > seedling-mulch > control > moss > moss-mulch. Cumulative *ET* increased steadily over the study season (Figure 2.4a and b) and exceeded *P* for all cover types after June 12 (DOY 163). *P*-*ET* ranged from -46 mm over mulch-moss plots to -199 mm over open water.

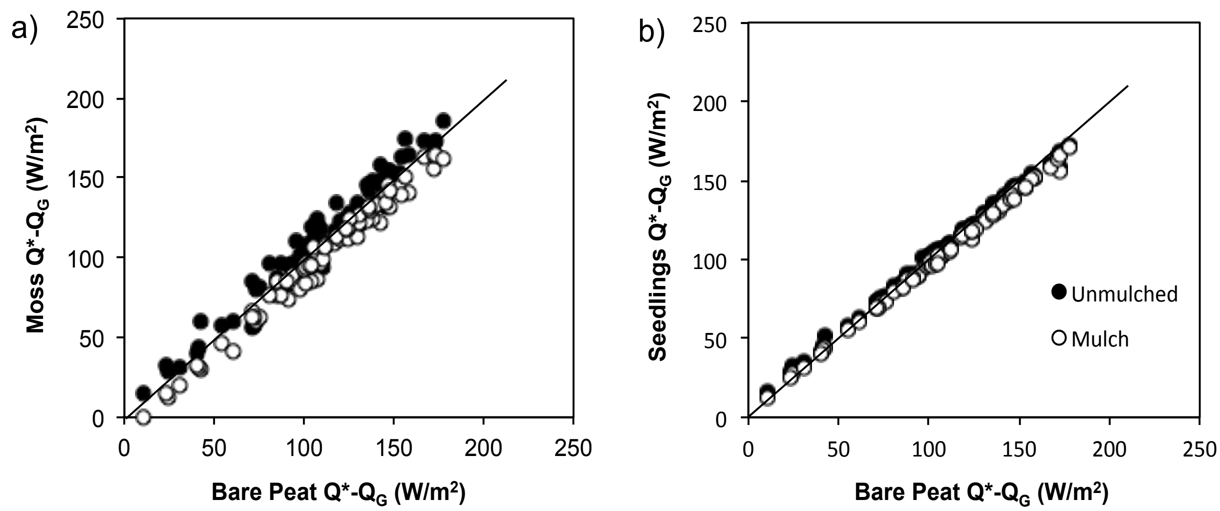

Figure 2-3 Available energy relationships between bare peat and a) moss plots and b) seedling plots. Mulched plot available energy includes mulch heat storage (*S*). The solid line represents a 1:1 ratio.

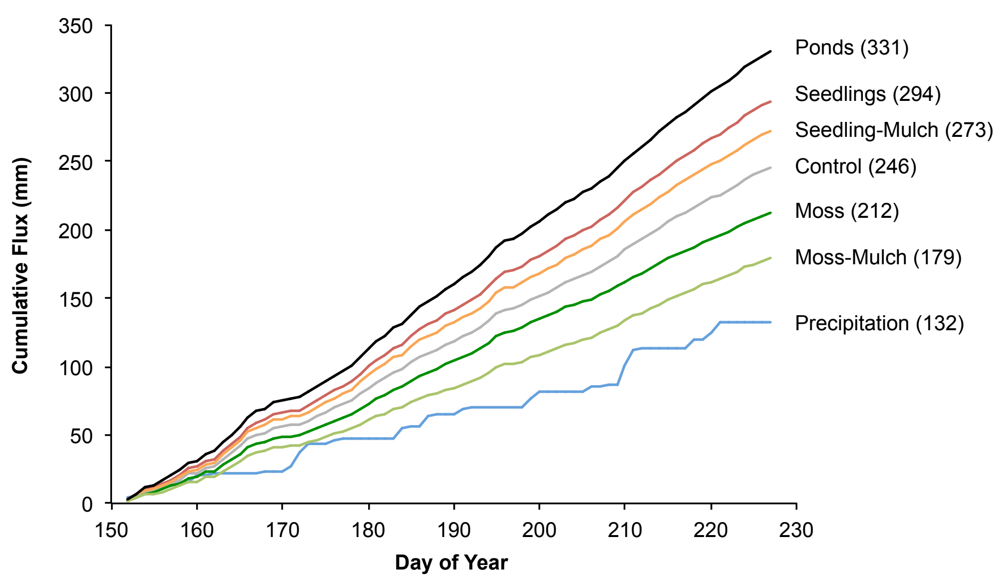

Figure 2-4 Cumulative evapotranspiration for plots and ponds relative to cumulative precipitation from June 2 to August 15, 2014.

The greatest increase in plant height and leaf area index (*LAI*) occurred between June and July (Figure 2.5a & b), whereas stomatal resistance decreased in seedling plots from June to August (Figure 2.5c). Decreasing stomatal resistance is consistent with an increase in mean *ET* rates from June to August (3.4 and 4.0 mm/day, respectively). However, there was no significant difference between measurement periods (Kruskal-Wallis, $p > 0.05$). Mean seedling height and *LAI* increased over the study season (Figures 2.5a and b). *LAI* was significantly different between June and August in both unmulched and mulched seedling plots, whereas only mulched plots had significant increases in seedling heights from June to August (Kruskal-Wallis, $p < 0.05$).

Average water tables for each plot type only ranged from 1 to 12 cm below the ground surface and θ remained > 0.69 within all plots. Therefore, there was no significant relationship between θ and *ET* ($p > 0.05$; Figure 2.6a), while a weak (R^2=0.15) yet significant relationship exists between water table and *ET* ($p < 0.05$; Figure 2.6b). However, when specific plot *ET* versus water table relationships are considered, only the seedling and seedling-mulch relationships were significant (R^2 = 0.22 and 0.23 respectively).

Seasonal mean peat temperatures (T_g) of each plot type are shown in Table 2.1, averaged over 0-5 cm. There was no significant relationship between T_g and *ET* or with T_g profiles between control, moss and seedling plots (Kruskal-Wallis, $p > 0.05$). T_g did differ significantly with depth from 2.5 to 30 cm in all plot types over the study season (Kruskal-Wallis, $p < 0.05$). Although there was little variability in T_g between vegetation types, seedling plots showed a notable increase in T_g at depths > 10 cm (Figure 2.7). Later in the season, after July 4 (DOY 185), 30 cm T_g in seedling plots were ~3°C higher on average compared to other plot types (not shown).

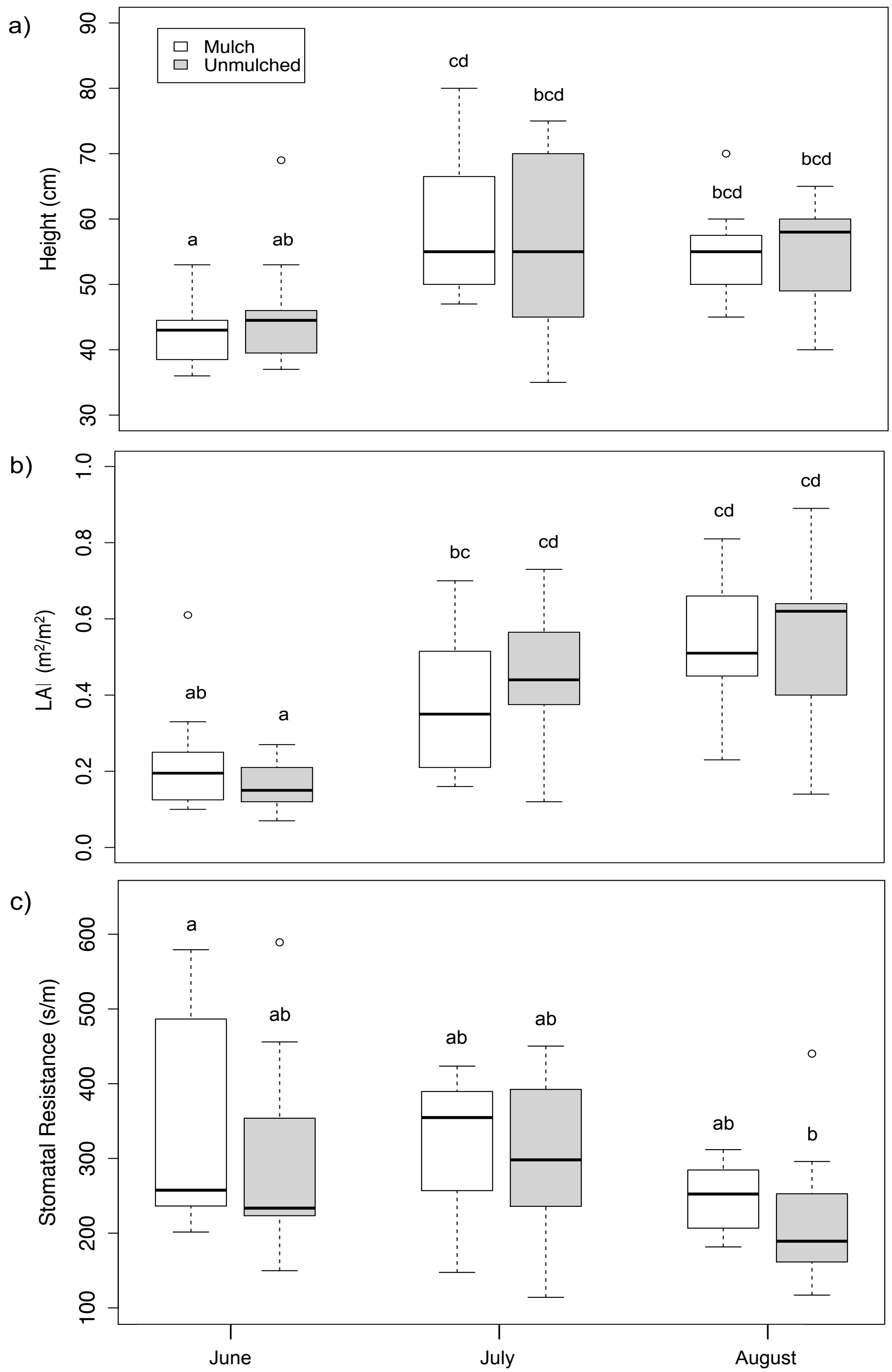

Figure 2-5 Seedling a) height, b) leaf area index (*LAI*) and c) stomatal resistance over the study season. Box plots represent the median, 25th and 75th percentile and whiskers indicate the maximum and minimum values. Points that extend beyond the whiskers are outliers. Means with different letters indicates a significant difference ($p < 0.05$).

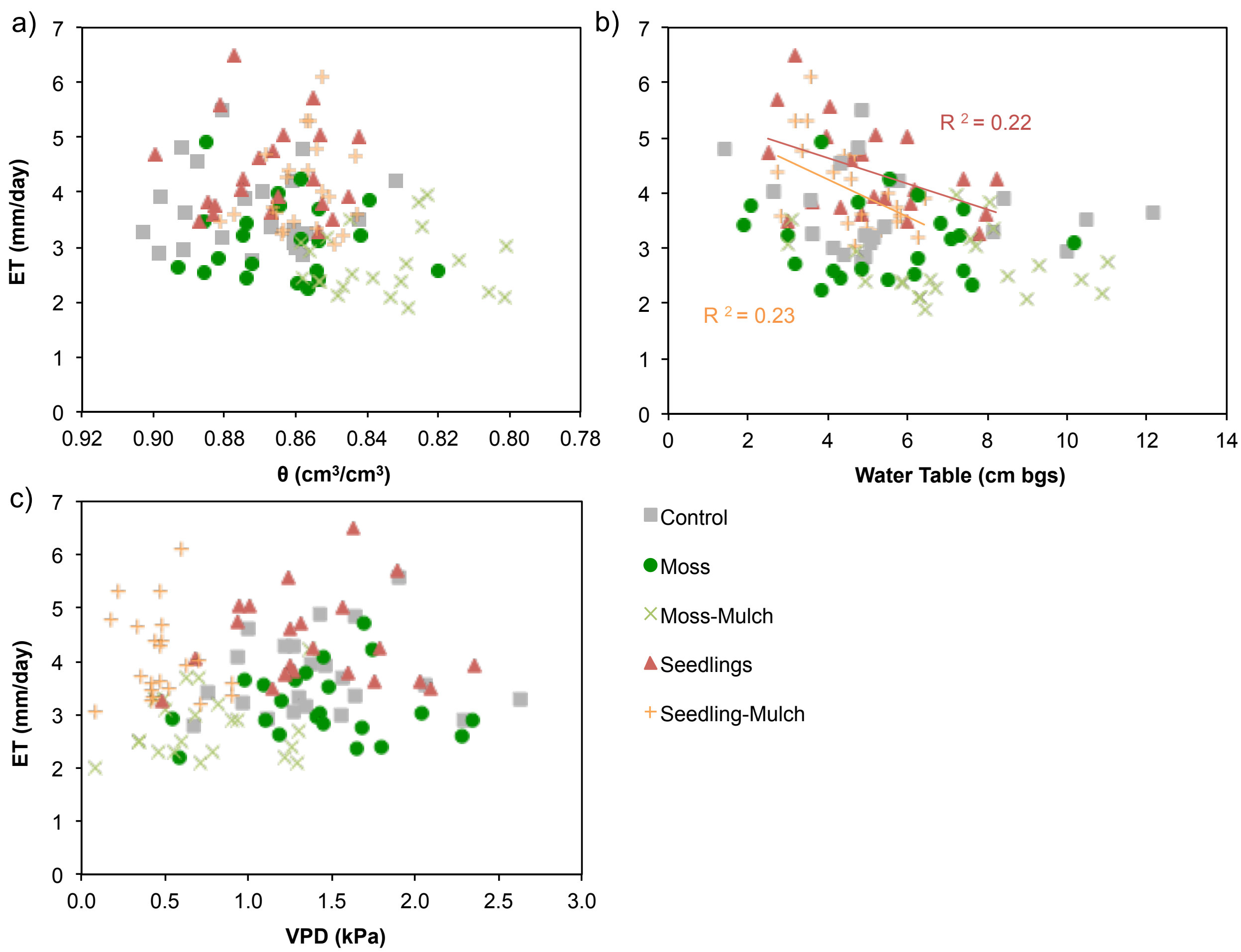

Figure 2-6 Relationships between daily mean evapotranspiration (*ET*) and a) soil moisture (*θ*) b) water table c) vapour pressure deficit (*VPD*) for each plot type. Significant relationships ($p < 0.05$) are indicated by trendlines and R^2 values.

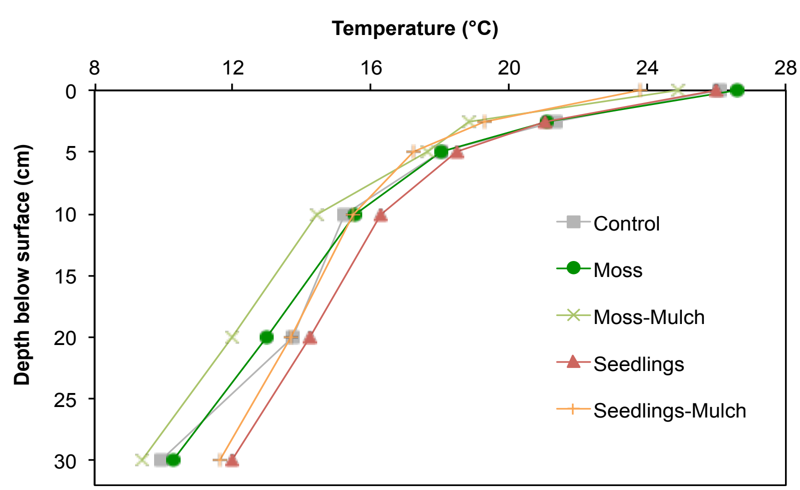

Figure 2-7 Seasonal mean plot type soil temperatures. One standard deviation ranged from 2.3 - 4.7 for all plot types. Standard deviation generally increased with T_g depth. Zero depth measured at peat surface.

Influence of mulch cover

Although, moss-mulch rates were the lowest and significantly different from all cover types (Table 2.1), they did not differ significantly from unmulched moss plots. Similarly, seedling-mulch plots showed lower rates than unmulched seedling plots, however, they did not differ significantly from seedling or control plots (ANOVA, $p > 0.05$). There were no significant differences between seedling height, *LAI* or stomatal resistance between mulched and unmulched plots (Figure 2.5a, b and c; Kruskal-Wallis, $p > 0.05$). Peak *ET* rates in mulched plots were 0.9 and 0.2 mm/day less than unmulched plots for moss and seedlings, respectively.

Mulch increased *RH* at the peat surface, reducing near-surface temperatures and vapour pressure deficit (*VPD*). Near-surface *RH* in a mulched-moss plot was at 100% for 23 and 51% longer than over unmulched moss and bare peat, respectively (Figure 2.8). Air temperature (T_a) at the surface was ~2°C lower on average under mulch (Figure 2.7). Consequently, *VPD* beneath mulch (0.6 kPa) was significantly lower than over unmulched plots (1.4 kPa; paired t-test, $p < 0.001$). However; *VPD* measured at 1 m was not significantly different between plot types (ANOVA, $p > 0.05$). Although *ET* did not have a significant relationship with *VPD* ($p > 0.05$; Figure 2.6c), *ET* rates from moss-mulch plots are relatively low and appear to be clustered within a small range, suggesting some mulch control on *ET* in moss-mulch sites. In contrast, seedling-mulch plots show high *ET* rates within a range of low *VPD*, suggesting near-surface *VPD* does not influence *ET* in seedling plots.

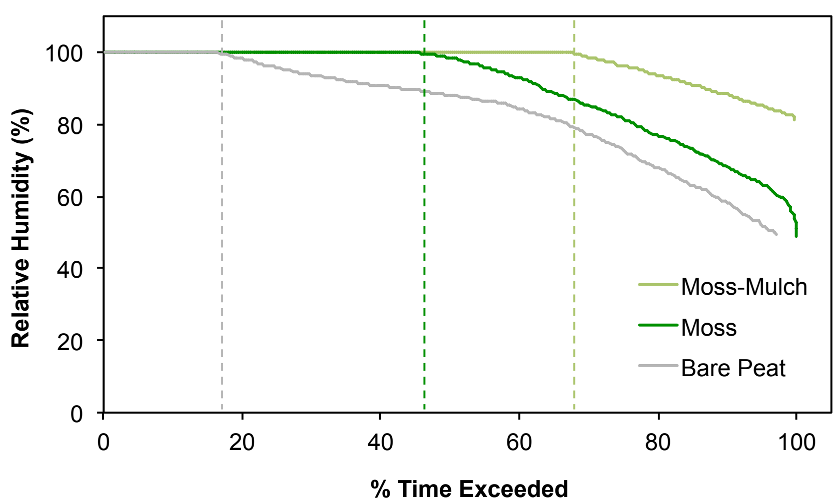

Figure 2-8 Exceedance probability curve for surface relative humidity. Dashed lines indicate percent time at 100% relative humidity for each plot type.

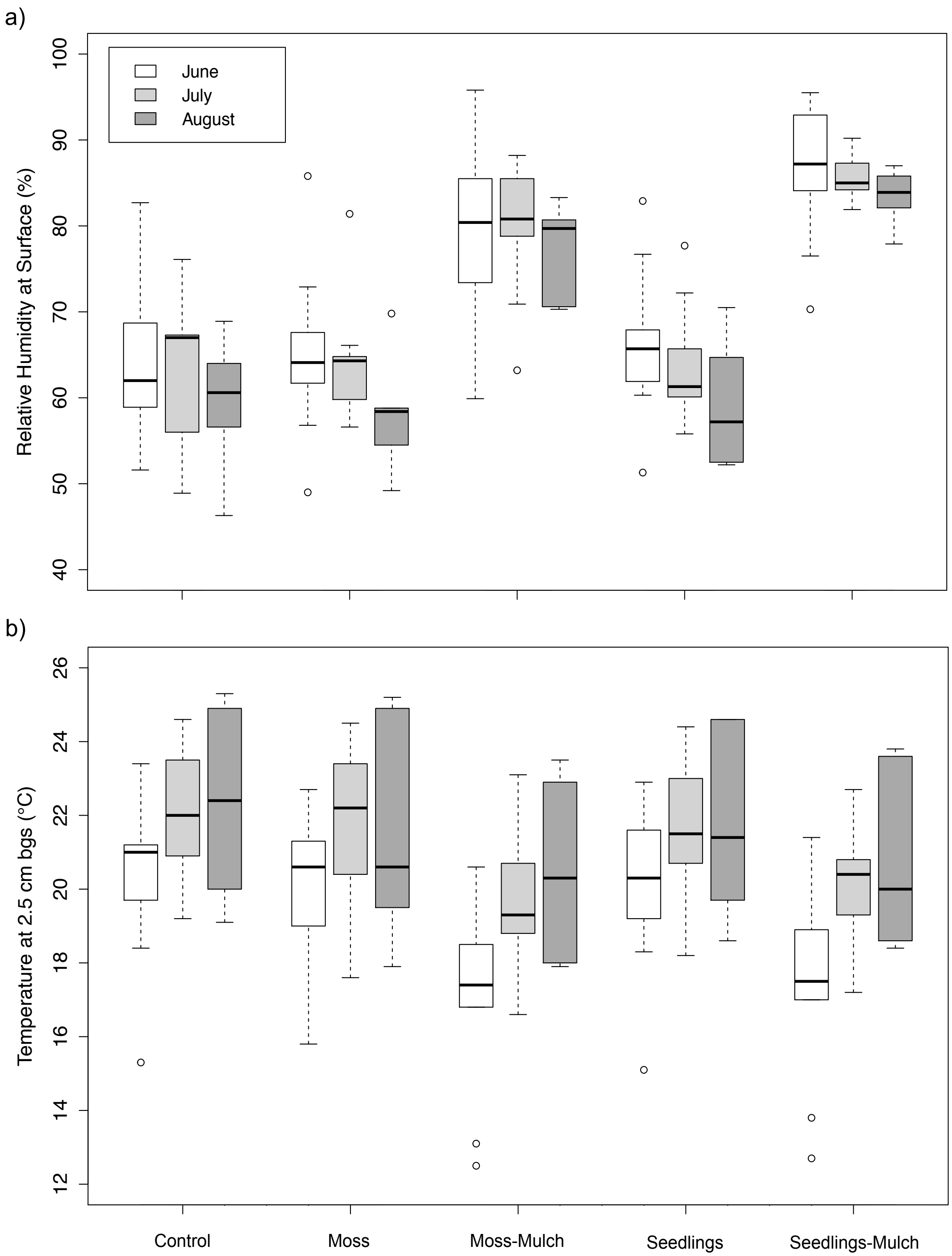

Figure 2-9 Changes in a) surface relative humidity and b) soil temperature for each plot type over the study season. Box plots represent the median, 25th and 75th percentile and whiskers indicate the maximum and minimum values. Points that extend beyond the whiskers are outliers.

Mulch reduced T_g significantly at 2.5 cm, but did not appear to have an impact on T_g past 5 cm (Figure 2.7). Moss-mulch T_g was significantly different from all plots except seedling-mulch, whereas seedling-mulch only showed a weak significant difference ($p = 0.048$) from control plots (Kruskal-Wallis, $p < 0.05$). Similar to near-surface T_a, 2.5 cm T_g was ~2°C lower in mulched plots (Figure 2.7). The importance of mulch cover lessened over the study season. While *RH* remained significantly higher under mulch for the entire season (Figure 2.9a; Kruskal-Walis, $p < 0.05$), T_g at 2.5 cm increased significantly from June to August in mulched plots (Figure 2.9b; Wilcoxon test, $p < 0.05$). Consequently, there was no significant difference in 2.5 cm T_g between all plots in August.

2.5 Discussion

Vegetation controls on surface energy and evapotranspiration

Available energy was greatest over open water but varied minimally between vegetation types. While control and moss plots had higher Q^*, these plots also had greater Q_G fluxes compared to seedling plots. Differences in energy fluxes between the pond and fen were likely caused by differences in thermal regimes. Open water albedo is similar to that of wet peat (~0.05; Oke, 1987) and therefore unlikely to result in a significant difference in Q^*. However, higher Q^* over the pond could be a result of reduced longwave emittance since the surface temperature of the pond, as reflected by T_a over the ponds, was lower than that over the plots (Table 2.1). Larger fluxes and greater differences between day and nighttime values in pond Q_W compared to plot Q_G (Table 2.2) are likely due to a more rapid energy transfer within the shallow water column (~10 cm; Petrone *et al*., 2007) caused by higher thermal conductivity of water compared to peat and convective mixing (Oke, 1987; Petrone *et al*., 2008). Q_E constantly exceeded Q_H and accounted for the largest portion of surface energy fluxes over all cover types, likely due to prevalently wet conditions in the fen for the entire study period.

ET_{eq} is largely controlled by available energy and therefore followed the same trends across all plot types. The α-values relating ET_a to ET_{eq} indicate that all cover types, except moss and moss-mulch, exceeded ET_{eq} (Table 2.1). Petrone *et al.* (2007) observed similar trends in a WBP peatland complex, where α-values < 1 over moss-dominated surfaces and > 1 over open water. Low α-values in moss plots can be attributed to the mosses' limited ability to vertically transmit water under dry conditions (Price, 1997; Goetz & Price, 2015) and possibly poor connectivity to the underlying placed peat, as observed post-restoration in some harvested sites (McCarter & Price, 2014). Taylor and Price (2015) observed that the water table-θ relationship weakened with regenerated moss profile height, the moss layer on these plots was still thin (~1 cm), and probably does not yet greatly influence moisture connectivity. The poor relationship between *ET* and θ or water table position is likely due to consistently wet conditions with a very small range in θ and water table that do not result in a limitation in water availability. High α-values in seedling plots are likely due to large observed root growth and the their ability to access the water table, increasing transpiration from these plots (Romanov, 1968; Takagi *et al*., 1999; Farrick & Price, 2009). Connectivity of vascular plants to the water table through rooting likely explains the stronger relationship between *ET* and water table position for these plots (Figure 2.6b; Rezanezhad *et al.,* 2012). Despite increased *ET* in seedling plots through transpiration, open water *ET* surpassed that of the adjacent vegetated fen, likely due to increased fetch and thus turbulent mixing over the pond (Petrone *et al*., 2007). Lower *ET* rates of seedling plots can be explained by the physiological controls of vascular plants on water vapour loss. Phillips *et al.,* (2015) found that stomatal resistance can increase under waterlogged and saline conditions. Therefore, consistently high water tables observed on the constructed fen could limit transpiration. Transpiration rates could also be affected if saline conditions develop in the future due to the presence of salts in oil sands process-affected waters.

A decrease in stomatal resistance in seedling plots over the season supports an increase in *ET* since leaf stomata control water loss through transpiration (Oke, 1987). The *LAI* and stomatal resistance relationship are similar to other studies (Schulze *et al*., 1995; Leuning *et al*., 1995), where increasing *LAI* indicates larger leaf surfaces contribute to canopy conductance. Furthermore, surface roughness is a function of vegetation height and *LAI*, which positively affects *ET* due to turbulent mixing as they increase over the season (Oke, 1987). Higher soil temperatures at depth in seedling plots (Figure 2.7) may be a result of poor atmospheric mixing at the surface of these plots. Sheltering from the seedlings is likely creating a laminar boundary layer where diurnal temperature changes are dampened (Oke, 1987), similar to mulch layers (Hares & Novak, 1992).

Effects of mulch on evapotranspiration

Q^* was consistently lower over moss-mulch plots than unmulched moss plots. Sharratt and Campbell (1994) found that straw mulch on agricultural fields had an albedo from 0.2-0.3, which increased reflected radiation and thus lowered Q^* (Novak *et al.,* 2000). A similar comparison between mulched and unmulched seedling plots cannot be made as there are no Q^* data over seedling-mulch plots. Similar daytime Q_G under all plot types shows that mulch did not have a significant effect on daytime Q_G fluxes, which contrasts with findings from other studies (Price *et al*., 1998; Petrone *et al*., 2004). However, lower nighttime Q_G losses under mulch compared to respective unmulched plots shows that mulch preferentially limited heat loss at night. This is likely due to the insulating effects of the mulch (Price *et al.,* 1998), as nighttime near-surface soil temperatures were on average greater in mulched versus unmulched plots (17.1 vs. 15.9°C, respectively). Furthermore, this is the first study using wood-stand mulch in peatland reclamation, whereas pervious studies used straw. The mass of the wood mulch is likely greater than that of straw and therefore has the ability to store more energy. Therefore, although the calculated heat storage of mulch appeared negligible, it may be slightly underestimated in this study.

Mulched plots had lower *ET* rates than the respective unmulched vegetation. However, mulched and unmulched seedling plots did not differ as greatly as mulched versus unmulched moss. Similarities between seedling plots are likely because mulch cover only limited soil evaporation, whereas transpiration rates were comparable between both plot types (Figure 2.5c). *VPD* at 1 m did not differ between mulched and unmulched seedling plots and therefore, likely did not cause the slight differences in stomatal resistance. Lower near-surface *VPD* and thus lower *ET* from mulch plots is a result of poor mixing within the mulch (Hares and Novak, 1992), evident by higher *RH* in mulch compared to the unmulched surfaces (Figure 2.8). The importance of mulch on T_g lessened over the season with no significant relationship between *ET* and plot T_g, therefore lower T_g under mulch likely does not affect *ET* rates from these plots.

Reclamation implications

In the sub-humid WBP, this study shows that mulching is an important reclamation practice for the conservation of water in peatland reclamation, especially when used with moss re-vegetation strategies. Borkenhagen (unpublished data) showed that mulch improved moss establishment during the first 2 years post-reclamation, with greatest percent cover when moss was combined with mulch and seedling treatments. Similarly, Price *et al.* (1998) and Rochefort *et al*. (2003) found mulch was important for protecting moss during the establishment phase of a restored peatland. Mulch reduced water loss through *ET* and created a microclimate more favorable for peatland vegetation establishment. Malloy and Price (2014) provide evidence that a moss-sedge cover in a restored fen evaporated well below the potential rate. However, mulch did not appear to affect seedling *ET* or seedling establishment (Borkenhagen, unpublished data) and therefore may not be needed in vascular vegetation treatments. Furthermore, considering high levels of vascular emergence in moss plots (Borkenhagen, unpublished data) and the similar effects of seedlings to those of mulch in regulating energy fluxes, planting seedling may not be necessary in future reclamation projects depending on re-vegetation goals.

Additionally, during drying events mulch appeared to accumulate salts (salt-crusting observed on mulch), reducing soil and pore-water electrical conductivity under mulch (Scarlett, unpublished data). This may help regulate the accumulation of dissolved minerals that locally are present through aeolian deposition and the presence of oil sands process-affected waters in groundwater discharge to the fen (Rezanezhad *et al.,* 2012). Fen mosses are sensitive to elevated salinity (Pouliot *et al*., 2012; Rezanezhad *et al.,* 2012; Pouliot *et al*., 2013). The importance of straw mulch decreases substantially after 3 years because it decomposes rapidly, and is associated with elevated CO_2 emissions (Petrone *et al*., 2001, Waddington *et al*., 2003). However, due to the greater mass and chemistry of the wood-strand mulch used in this study, decomposition may be slowed and its water and energy regulation effect could persist for longer.

2.6 Conclusions

Vegetation type plays a significant role in controlling *ET* from the constructed fen, where all plot types showed lower *ET* rates than open water. Seedling plots showed the greatest *ET* rates compared to moss and control plots likely due to the connectivity of vascular plants to the water table and their ability to transpire. However, available energy alone did not provide an accurate estimate of *ET*. Alpha-values show that $ET_a > ET_{eq}$ in all plot types, except in moss plots, where $\alpha < 1$.

Mulch reduced *ET* in moss plots, but had less of an impact on seedling plots, as it had no noticeable effect on vascular stomatal resistance. Q^* was lower over mulch probably due to a higher albedo, whereas insulation from the mulch and mulch heat storage (although small) increased Q_G. Thus, available energy was lower in mulched plots under all energy conditions, reducing *ET*. Mulch dampened temperature fluctuation, keeping the surface and upper peat profile cooler during the day and warmer at night. Mulch also created a near-surface microclimate that increased *RH* and lowered *VPD* in the mulch layer, further mitigating *ET* losses.

Further research is required to determine the role of mulch after the initial years post-reclamation and in the mitigation of salt accumulation at the surface. Consideration of the cumulative effect of vegetation and treatment types is required to develop recommendations for future peatland reclamation projects. Knowledge of the combined implications for the hydrology, ecology and biogeochemistry are necessary to develop future planting strategies and create a successful, self-sustaining fen ecosystem.

3.0 Manuscript 2: Plot-scale hydrodynamic variability of a constructed fen, Fort McMurray, Alberta

3.1 Introduction

In the Athabasca Oil Sands region of Alberta, where wetlands cover > 50% of the Western Boreal Plain (WBP) (Vitt *et al*, 1996), overburden materials including vegetation and soils are stripped off the land to access the underlying oil sand bearing formations. As a result, the extraction processes of open-pit mining leaves an unnatural, undulating landscape, which promotes the establishment of ecosystems non-native to the region (Price *et al.,* 2010). Due to their complexity, the re-establishment of peatland ecosystems had not been tested prior to the Suncor Energy Inc. and Syncrude Canada Ltd. pilot fen creation projects. The Nikanotee Fen on the Suncor Energy Inc. lease, which is the focus of this investigation, was designed based on the conceptual and numerical model proposed by Price *et al.* (2010), where peat stripped for accessing oil-bearing deposits was placed in a constructed watershed designed to provide the requisite groundwater supply. The design aimed to create a self-sustaining, carbon-accumulating ecosystem, capable of supporting representative fen species and resilient to normal stresses (Daly *et al*., 2012).

As reclaiming landscapes to peatland is a newly tested concept, the hydrology of a constructed fen is currently unknown, specifically the effects of disturbed, placed peat and vegetation treatments on the soil water dynamics. Peatland hydrology is highly dependent on the peat properties (Boelter & Verry, 1978; Price, 2003), vegetation water requirements (Kim & Verma, 1996) and meteorological controls (Petrone *et al.,* 2004). The peat used in the construction of the Nikanotee fen was highly disturbed during extraction and placement and therefore cannot be expected to have a natural structure or stratigraphy. There are limited studies on the hydrophysical properties of placed peat used in reclamation. Nwaishi *et al*. (2015) present the physical properties and saturated hydraulic conductivity of the constructed fen peat in comparison to those of the dewatered donor site and a local natural fen and found that current placement methods greatly alter hydrophysical peat properties. Nwaishi *et al.* (2015) discuss the potential ecohydrological impacts of the placed peat properties, however, direct measurement of spatial variability of these properties and the influence of different plot types on the fen's hydrology were not considered. Furthermore, the unsaturated zone hydrology of placed peat has not yet been studied.

There have been more comprehensive hydrological studies focusing on peatland restoration following peat harvesting for energy or horticultural use (e.g. Price, 1997; Schlotzhauer & Price, 1999; Petrone *et al.,* 2004; Ketcheson & Price, 2011; McCarter & Price, 2013), which creates a landscape similar in some respects to that of a constructed peatland. Cutover harvested peatlands have had their vegetation and upper peat profiles removed, exposing deeper, more decomposed layers (Price *et al.,* 2003), similar to the peat used in the constructed fen. However, although compacted, the natural structure of the unused deeper peat profiles remain intact in harvested sites, unlike the placed peat of the constructed fen which has been highly disturbed through the salvage process. Yet, despite differences in peat structure, restoration of harvested peatlands provides a partial analogue for landscape reclamation to peatland. Both practices are left with dewatered, highly decomposed peat, resulting in smaller pore sizes, decreased hydraulic conductivity and higher soil water retention capacity (McCarter & Price, 2014). These properties are uncharacteristic of natural surface peat profiles and create complications in the reestablishment of the desired vegetation, particularly mosses (Price *et al.,* 2003).

Rochefort *et al.* (2003) outline restoration practices for North American peatlands, however, these practices are focused on *Sphagnum* dominated bogs in Quebec and eastern Canada. Although these methods (i.e. moss-transfer, mulching) have been previously tested at restored harvested sites (e.g. Bugnon *et al.,* 1997; Price *et al*., 1998; McCarter & Price, 2013; Malloy & Price, 2014), they have not been applied in a post-mined oil sands landscape. In the WBP fens cover > 50% of the oil sands region (Vitt *et al*, 1996), and although *Sphagnum* mosses are present, these fens are primarily dominated by brown mosses with dense vascular cover (Chee & Vitt, 1989). Transpiration from vascular plants affects the soil water dynamics of peatlands, drying the near surface and lowering the water table (Takagi *et al.*, 1999; Farrick & Price, 2009; Rezanezhad *et al*., 2012). Mulch covers have been shown to keep moisture at the peat surface (Price *et al*., 1998; Petrone *et al*., 2004). However, they have not been tested in the dry sub-humid climate of the WBP, where potential evapotranspiration typically exceeds precipitation (Devito *et al*., 2005).

To date, there are limited studies evaluating the hydrophysical properties and soil water dynamics of a constructed fen, specifically the influences of disturbed, placed peat and different vegetation treatments. It is hypothesized that vegetation and mulch treatments will significantly influence soil water dynamics due to differences in water conducting mechanisms (i.e. vascular vs. non-vascular tissue) and the sheltering effects of mulch. It is expected that plots with vascular plants will have greater evapotranspiration rates, thus reducing soil moisture, whereas evaporative losses will be mitigated in mulched plots. However, variability in peat properties, surface elevation and thus water table position will further affect plot-scale soil water dynamics, which could mute the effects of individual plot types. Therefore, this study aims to evaluate the effects of peat placement and specific vegetation treatments (Borkenhagen, unpublished data) on the hydrology of the Nikanotee constructed fen. The specific objectives of this study are to 1) characterize plot-scale soil water dynamics with respect to vegetation type, mulch and surface elevation, 2) quantify the hydrophysical properties of the placed peat and their spatial variability, and 3) determine the impact of the placed peat on unsaturated zone hydrological processes.

3.2 Study Site

The Nikanotee Fen (56.932° N, 111.417° W; Figure 3.1) is a 2.9 ha constructed peatland which sits in a larger 32 ha constructed watershed on the Suncor Energy Inc. lease, 20 km north of Fort McMurray, Alberta. In this region of the WBP average temperatures (1981-2010) range from -17.4°C (January) to 17.1°C (July) and average annual precipitation is 419 mm, of which ~76% is rainfall (measured at the Fort McMurray Airport ~ 33 km south of the study; Environment Canada, 2010). Construction of the fen was completed in January 2013 and planted in June 2013. The peat used in the construction of this site was harvested from a drained natural fen on the lease, where the top ~ 30 cm of peat was discarded to exclude invasive post-drainage weeds. Consequently, the donor peat used in the fen's construction was well-decomposed with no living moss or other plant material and had an average bulk density of 0.15 g/cm^3. The peat was immediately transported to the constructed site upon harvesting (not stockpiled) and placed to a depth of approximately 2 m. The peat was placed over a three-week period in layers starting in the east and moving west across the fen. The placed peat was highly disturbed during the harvesting processes, losing its natural structure and in places incorporating a small fraction of the mineral sediments underlying the donor fen. As a result Nwaishi *et al*. (2015) found that the horizontal/vertical hydraulic conductivity anisotropy ratio decreased from 1.5 to 1 between the donor and constructed site, respectively. Furthermore, average bulk density measured from 0-60 cm of the placed peat (0.19 g/cm^3) was greater than that of the donor peat (0.16 g/cm^3; Nwaishi *et al*., 2015).

The experimental planting was based on a factorial design that was divided into 12 blocks, each with replicates of five vegetation plots (Borkenhagen, unpublished data). Plot types included control (bare peat), moss, seedlings, seedling-moss and seeds. Moss, seedlings and seedling-moss plots were 17 m x18 m, whereas control and seed plots were 8 m x 18 m. Each plot was divided in to four sub-plots (~9 x 9 m), where two were covered in wood-strand mulch and two were weeded for non-fen species. Moss was harvested from a cut-line on a donor fen, 8 km west of the constructed site that was dominated by rich-fen moss species (i.e. *Tomenthypnum nitens, Aulacomnium palustre, Sphagnum warnstorfii).* The upper 10 cm of moss was mechanically harvested for use in the moss-layer transfer technique (Quinty & Rochefort, 2003). The moss was hand spread on the appropriate plots on constructed site to ~1 cm thickness. Seedlings were germinated in a greenhouse (Coast 2 Coast Restoration) and hand planted at the constructed site. Seedlings included salt-tolerant (*Juncus balticus, Triglochin maritima, Calamagrostis inexpansa*) and freshwater (*Carex aquatilis, Betula pumila*) species. Note – here we do not report on the success of the vegetation treatments, only the effect of the treatment on the hydrology of the site.

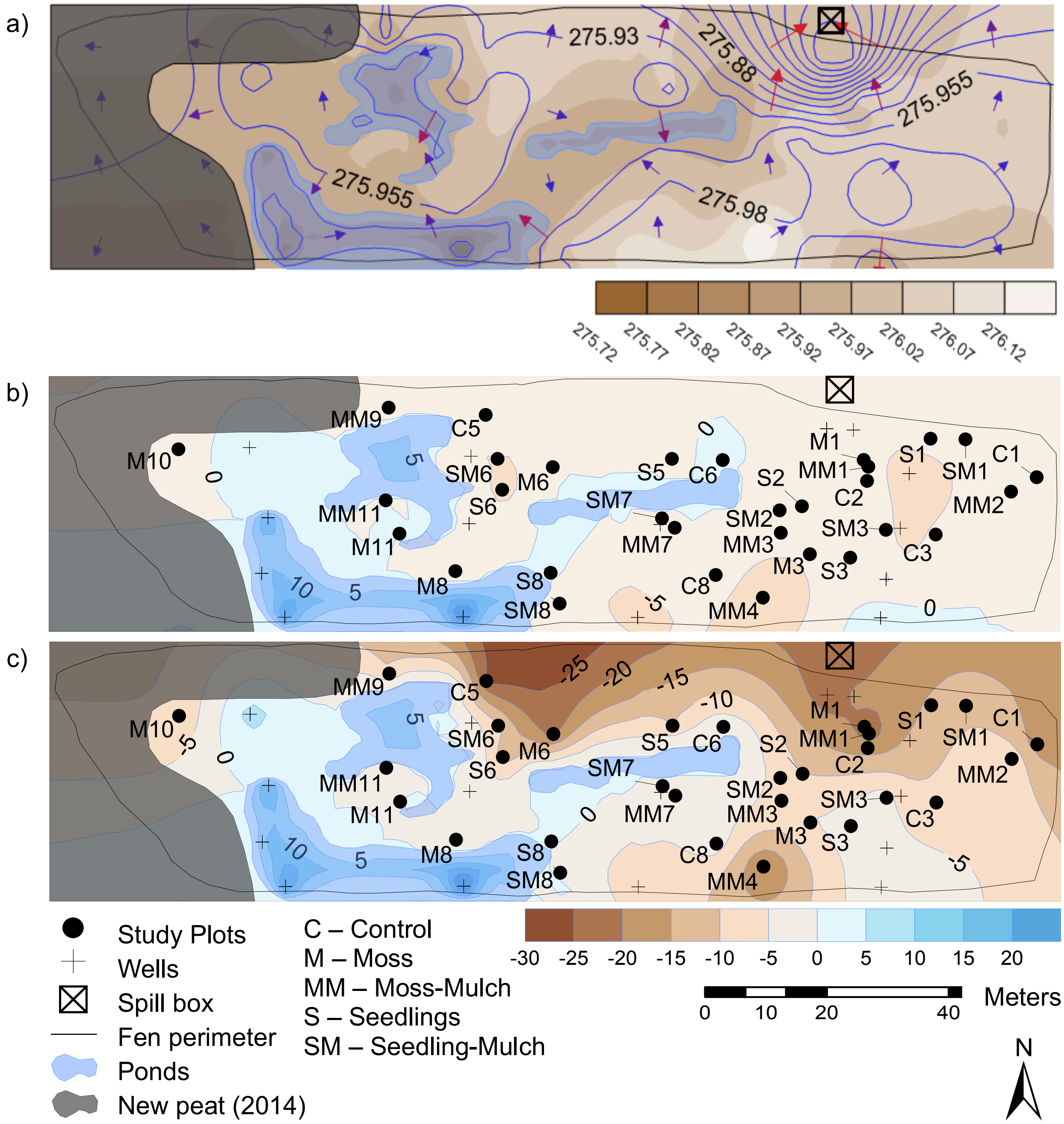

Figure 3-1 a) Surface elevation and average water table elevation of the Nikanotee Fen presented in meters above sea level. Groundwater flow illustrated by vector direction and magnitude. Water table contours in cm relative to ground surface also shown for a b) wet (August) and c) dry (June) period. Numbers following plot abbreviations indicate the experimental block number. Note the outflow at the spill box to the northeast of the fen.

3.3 Methods

Field data collection

Thirty-one study plots were selected within the experimental plot design (Figure 3.1). For the experiment reported herein, the plot types examined included control (n=6), moss (n=6), moss-mulch (n=7), salt-tolerant seedlings (n=6) and salt-tolerant seedling-mulch (n=6). All plots were in weeded treatments to remain constant between plot types and reduce the influence of non-peatland species. Plots were chosen randomly across a hydrological gradient but flooded sections were avoided. In 2014, new peat was placed on flooded sections of the west side of the fen; this area was not part of the original fen design and therefore was not included in this study. Freshwater seedling, seeds and seedling-moss plots were not monitored due to time and equipment constraints.

Plot-scale hydrology was monitored 3-4 times weekly from June 1 to August 15 in 2014, during the second season of plant establishment. Manual water table measurements were taken at wells or small pits where the water table was shallow enough (< 15 cm). An average of three volumetric soil moisture (θ; Delta-T Devices WET-Sensor) measurements representing the 0-5 cm depth were taken at each plot. Field θ measurements were corrected with a gravimetrically-determined calibration curve developed for the constructed fen peat using WET-Sensor readings taken from a sample with a known volume that was progressively dried and weighed (calibration curve shown in Appendix 1). Manual tensiometers were used to measure pore water pressure (ψ) at 5 cm below the surface in each plot. θ and ψ were also measured in 2013, the first year post construction, from July 10 to August 15. In 2013 data were collected at the same frequency from 24 of the aforementioned 31 study plots.

Weighing lysimeters (10 L) were installed in each plot, filled with peat and covered with the representative plot vegetation and mulch. Seedlings were transplanted into lysimeters at the time of planting in 2013 and remained healthy and visually representative of surrounding seedlings during the years of this study. Lysimeters used in conjunction with data from the fen meteorological station to estimate evapotranspiration using the equilibrium evapotranspiration (ET_{eq}) approach (Priestley & Taylor, 1972), where evapotranspiration (ET) is calculated as,

$$ET = \alpha \left(\frac{\Delta}{\Delta + \gamma}\right)\left(\frac{Q^* - Q_G}{\lambda\rho}\right) \tag{3.1}$$

where Δ is the slope of the saturation vapour-pressure curve (kPa/°C), γ is the psychrometric constant (0.00662 kPa/°C at 20°C), λ is the latent heat of vaporization (MJ/kg) and ρ is the density of water (kg/m^3). The coefficient of evaporability, α, has a value of 1 for ET_{eq} (Priestley and Taylor, 1972), and otherwise is the slope of the regression relating actual evapotranspiration (ET_a) obtained from the lysimeters to the calculated ET_{eq}. Individual α-values were derived for each plot type (α-plots shown in Appendix 2) to calculate representative plot-scale α-adjusted ET_{eq}, herein referred to as *ET*. Aerially weighted site average *ET* was calculated based on the known areas of plots, ponds and unplanted fen. Unplanted areas were considered to have comparable *ET* rates to control plots (see also Chapter 2).

Precipitation was measured manually and logged with a tipping bucket rain gauge (Texas Electronics tipping bucket; located ~100 m south of the fen). The effects of mulch and seedlings on precipitation interception were quantified using throughfall troughs (100 cm x 9 cm) installed near the ground surface in salt-tolerant and freshwater seedling plots (n=2) and under mulch "baskets" with representative mulch percent cover (n=2). Troughs drained into buckets, which were weighed to quantify throughfall.

Nine 0-5 cm peat samples were taken using 5 cm dia. PVC rings at 6 locations across the fen (n = 54) to quantify spatial variability in hydrophysical peat properties. All sampling locations were bare peat, since the objective was to characterize the variability caused by placement, not treatment. Additional peat profiles from 0 – 20 cm were sampled using the method as described above at 3 locations across the fen (east, middle, west). All samples were sealed airtight with plastic wrap and frozen to retain moisture and structure.

Laboratory analysis

Vertical saturated hydraulic conductivity (K_{sat}), bulk density, porosity, specific yield and mineral content were determined in the laboratory for the surface peat samples from the six sampling locations (n = 54). K_{sat} was measured using a Darcy permeameter following the constant-head method outlined in Hoag and Price (1987). K_{sat} was calculated using Darcy's Law,

$$K_{sat} = \frac{Q}{A(\Delta h/\Delta l)} \quad (3.2)$$

where Q is the discharge rate (mL/s), A is the flow face area (cm^2) and $\Delta h/\Delta l$ is the hydraulic gradient. Specific yield was calculated from the weight change after 24 hours of gravity drainage of a saturated sample. Samples were oven-dried at 80°C until they reach a stable weight (~48 hr) to determine bulk density (ρ_b). Eighteen sub-samples (n = 3 at each location) were analyzed for their percent mineral content using loss-on-ignition (LOI), where samples were finely ground and heated to 500°C for 4h following the methods described by Pansu and Gautheyrou (2006). A weighted particle density (ρ_p) was then determined for each sample using a known particle density of the fen peat (1.7; McCarter, unpublished data) and a standard mineral particle density of 2.65 (Freeze & Cherry, 1979). Porosity (ϕ) was calculated as,

$$\phi = 1 - (\rho_b/\rho_p) \tag{3.3}$$

Unsaturated hydraulic conductivity (K_{unsat}) and θ retention were measured at ψ-steps of -5, -10, -15, -20, -25 cm of water on 5 cm long segments of the peat profile cores (0-20 cm; n =12), therefore each depth (0-5, 5-10, 10-15 and 15-20) had triplicate measurements. It should be noted that the 15-20 cm segment of the west profile was discarded due to an unrepresentatively large mineral content. The $\psi - \theta$ and $K_{unsat} - \psi$ curves were determined using the method outlined in McCarter and Price (2015). Briefly, each sample was placed on a tension plate covered in 25 µm mesh that was connected to an outflow flask. The flask had a constant head and was adjusted relative to the midpoint of the sample to control the ψ (-5, -10, -15, -20, -30 cm). Samples and flasks were covered to minimize evaporative losses and allowed to equilibrate for ~ 7 days (< 1 g/day change), after which they were weighed to determine the θ at each tested ψ. At this time K_{unsat} was measured by placing a second 25 µm mesh tension plate on top of the sample, attached to a reservoir with a constant head equal to the equilibrated ψ from the top of the sample. The outflow flask was then lowered by half the sample height to achieve a uniform ψ across the sample, creating a hydraulic gradient of 1. The flask drained into a graduated cylinder to measure Q. Samples were run for ~ 1 hour to equilibrate before K_{unsat} was calculated from Q using Darcy's Law (Eq. 3.2).

Statistical Analysis

Data sets were tested for normality using the Shapiro-Wilk test. For normally distributed datasets, an ANOVA was used to determine differences among group means, whereas the non-parametric Kruskal-Wallis one-way analysis of variance was used when a normal distribution could not be assumed. If significant effects were found, a post-hoc pairwise t-test (parametric) or Wilcoxon rank sum test (non-parametric) with a Bonferroni adjustment was used to isolate significant differences between groups.

A repeated measures general linear mixed-effects model (GLM) was used to quantify the relationships between measured peat properties and their influence on K_{sat}, where the model used $\log K_{sat}$ to normalize the distribution. Simple regression analyses were used to test for significant relationships between water table and ψ and θ. Normality and homoscedasticity of the residuals of the GLM and significant regression relationships were checked visually using residual plots (Appendix 3). A 95% confidence level ($\alpha = 0.05$) was the significance threshold for all tests. R statistical software (R Core Team, 2013) was used for all statistical data analyses.

2.4 Results

Climate and hydrology

The study site received 132 mm of precipitation (*P*) from June 1 to August 15, less than the 30-year regional average (211 mm; Environment Canada, 2015). The average rainfall event was approximately 3.9 mm, with the largest event delivering 14.2 mm on July 29 (DOY 210; Figure 3.2). Average daily air temperature was 19°C, ranging from 7.9°C on June 5 (DOY 156) to 26.8°C on July 14 (DOY 195; not shown). Site average evapotranspiration (*ET*) totaled 260 mm, averaging 3.5 mm/day with maximum rates in early July (DOY 185; Figure 3.2). Cumulative *ET* exceeded cumulative *P* over the course of the study period (Chapter 2).

Mulch and seedling *P* interception each averaged ~1 mm per event over the study season. Figure 3.3 illustrates that storm magnitude did not have an effect on mulch interception, with no noticeable differences in interception between small and large events. However, the relative importance of seedling interception appears to increase during larger events. While mulch and seedling interception was small for individual rain events, it accounted for 32 and 29% of total seasonal *P*, respectively. Table 3.1 shows that the largest seasonal water deficit (*P* – *ET*) was in seedling plots, while mulched plots showed a greater deficit than respective unmulched plots.

The elevation of the peat surface varied 40 cm across the fen (Figure 3.1a), with the lowest elevations in ponds and highest points to the southeast. Figure 3.1 also illustrates average water table elevation and thus groundwater flow directions across the fen. The east side drains toward the outflow, while the west side appears to be poorly connected to the outflow, at least near the surface, and instead flows towards the large ponded depressions. As a result, plot water tables on the west side of the fen were significantly higher than the east (Wilcoxon test, $p < 0.01$). On average plot water tables varied 7 cm between the wet and dry periods presented in Figures 3.1b and c. However, changes in water table position > 20 cm were observed at the higher elevation points and near the outflow (Figure 3.1), whereas lower elevation areas experienced small (< 5 cm) or no water table fluctuations between the two periods. Considering, plot elevations only varied 24 cm between the highest (MM4) and lowest (C6) plots (Figure 3.1), observed water table differences were substantial. Plot water table position was significantly related to plot elevation ($p < 0.01$, Figure 3.4) under all hydrological conditions, however, the strongest relationships were observed under wet conditions ($R^2 = 0.73$).

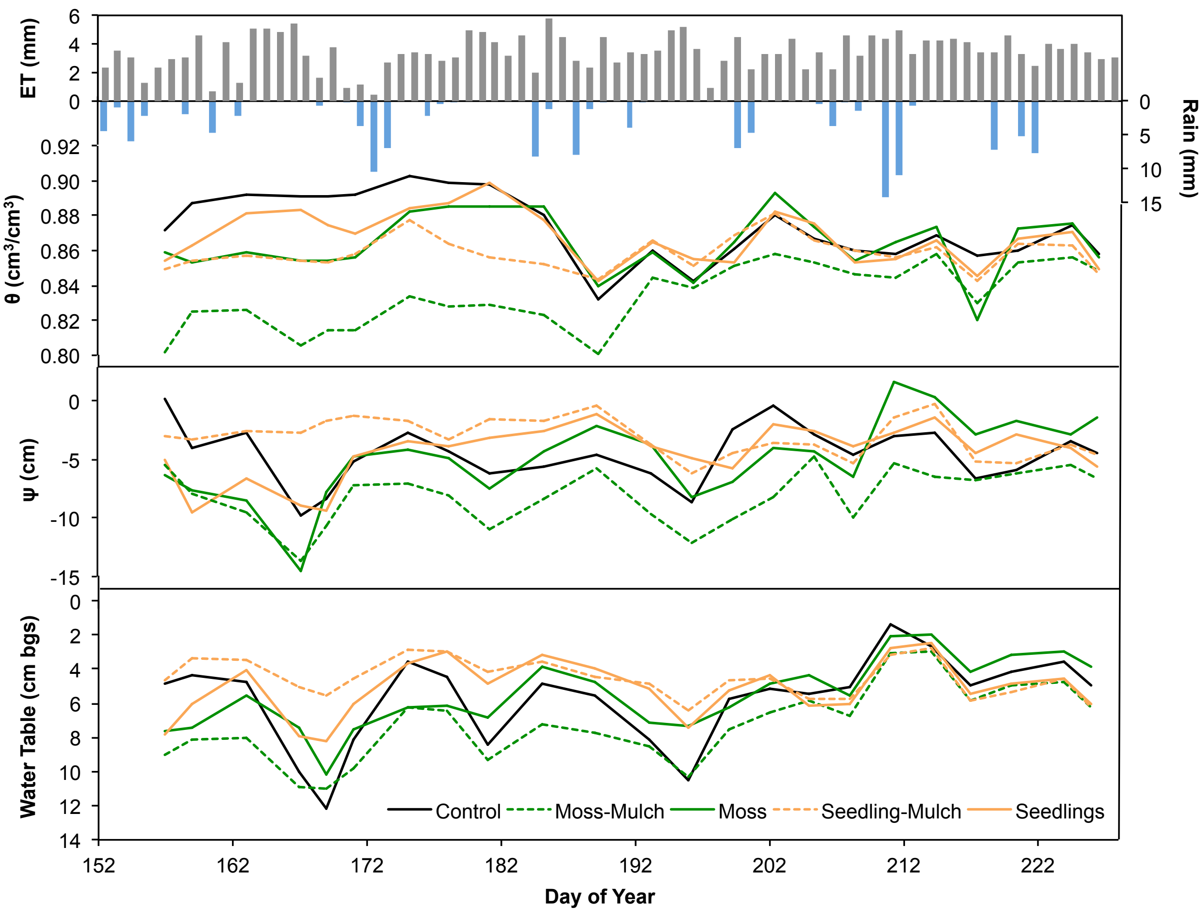

Figure 3-2 Time series of average soil water dynamics for each plot type. Evapotranspiration (*ET*) is an aerially weighted average site value. Water table presented as cm below ground surface (bgs). Note pressure (ψ) measured in mbar, where 1 mbar ≈ 1 cm.

Table 3-1 Summary of plot hydrology and *ET* for each plot type. Average pore water pressure (ψ) and soil moisture (θ) shown for 2013 and 2014 study seasons. Water table (*WT*). *ET* and *P-ET* are only from 2014. *P-ET* represents average plot total *ET* subtracted from total precipitation (accounting for interception in mulched and seedling plots). Plot averages with different letters indicates a significant difference ($p < 0.05$). 1 standard deviation is shown in parenthesis.

Plot Type	*ET* (mm/day)	*P – ET* (mm)	*WT* (cm bgs)	2013		2014	
				ψ (mbar)	θ (cm^3/cm^3)	ψ (mbar)	θ (cm^3/cm^3)
Control	3.2 ^{ab} (±1.2)	-114	6 ^{ab} (±5)	-6.8 (±11.4)	0.85 ^{a} (±0.04)	0.5 ^{ab} (±7.1)	0.87 ^{a} (±0.02)
Moss	2.8 ^{ac} (±1.0)	-80	5 ^{ab} (±5)	-5.9 (±11.6)	0.83 ^{b} (±0.04)	0.2 ^{ac} (±6.2)	0.86 ^{ab} (±0.04)
Moss-Mulch	2.4 ^{c} (±0.9)	-89	7 ^{a} (±6)	-8.5 (±12.6)	0.80 ^{bc} (±0.07)	-3.1 ^{b} (±6.2)	0.83 ^{c} (±0.04)
Seedlings	3.9 ^{bd} (±1.3)	-200	5 ^{ab} (±4)	-4.4 (±6.3)	0.87 ^{a} (±0.03)	0.6 ^{c} (±4.7)	0.87 ^{a} (±0.02)
Seedlings-Mulch	3.6 ^{bd} (±1.3)	-209	5 ^{b} (±3)	-4.7 (±5.6)	0.81 ^{c} (±0.04)	1.9 ^{c} (±3.9)	0.86 ^{b} (±0.02)

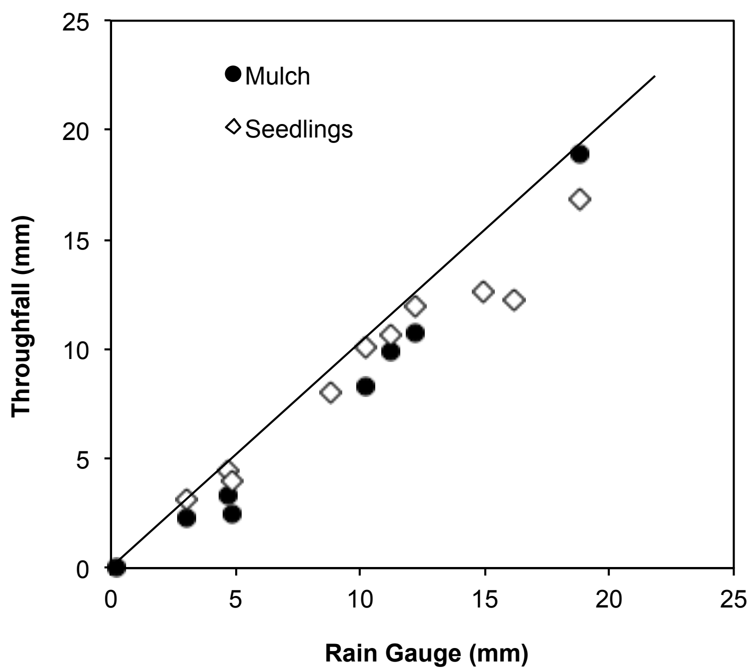

Figure 3-3 Effective throughfall through mulch and seedlings compared to total *P* per event. Y-axis shows the effective rain throughfall per storm event. The solid line represents a 1:1 ratio.

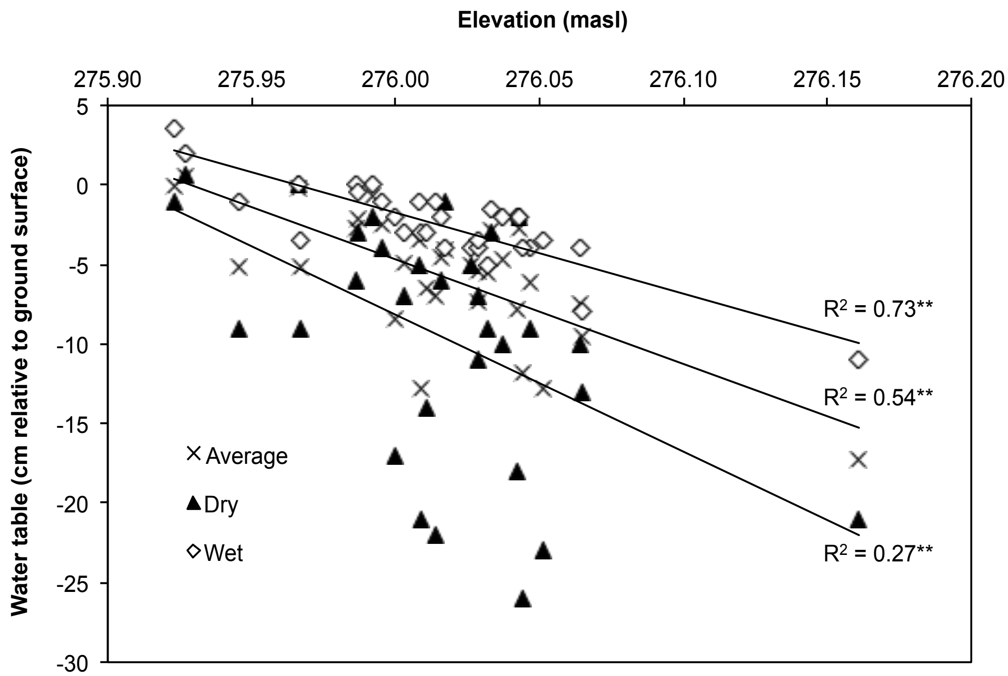

Figure 3-4 Plot water table positions related to plot elevations under wet, dry and average conditions. ** = significant slope at $p < 0.01$.

Plot-scale soil water dynamics

The average fen water table increased by 15 cm from 2013 to 2014, yet received 110 mm less *P* in 2014 (June 1 – August 5). Higher water levels resulted in higher plot pore water pressures (ψ) and soil moisture (θ) in 2014, while drier conditions in 2013 caused greater variability between plot types (Table 3.1). However, moisture trends between plot types remained similar during the different hydrologic regimes of the two years. Over the 2014 study season, plot water tables generally increased and became less variable (Figure 3.2). Plot ψ trends closely followed water table, while θ was not consistently related to water table in some plot types, notably control and unmulched moss and seedling plots (Figure 3.2). These plots experienced high θ despite lower relative water tables positions prior to DOY 185. However, following peak *ET* rates on DOY 185, θ decreased in all plots and more closely mirrored water table position. Moss-mulch and seedling-mulch θ more closely followed respective water table positions over the study season. Water table position and ψ were generally more responsive of *P* events than θ, and less affected by consistent and higher *ET* rates later in the season (i.e. post DOY 185; Figure 3.2).

Relationships between ψ and water table in 2014 were significant in all plot types ($p < 0.01$; Figure 3.5) and exhibited similar responses to changes in water table. ψ – water table relationships for control, moss and moss-mulch plots showed greater ranges in ψ reflecting their greater range of water table positions. Consistently shallower water tables in seedling and seedling-mulch plots (< 14 cm bgs) gave weaker ψ – water table relationships (R^2=0.61 and 0.28, respectively). In contrast, θ – water table responses varied more between plot types (Figure 3.6). However, all relationships were significant ($p < 0.05$), except in control plots ($p > 0.05$), where changes in water table were only very weakly translated into changes in θ. Thus control plots were found to have a small range in near-surface θ despite displaying large variability in ψ under the same water table conditions. Moreover, mulched plots appear to have a slightly stronger θ response to water table than respective unmulched plots.

Although average plot water tables only ranged from 5-7 cm below ground surface (bgs) in 2014, there was a significant difference between water table depths between the moss-mulch and seedling-mulch plots (Kruskal-Wallis, $p < 0.05$; shown in Table 3.1). θ and ψ also differed significantly between plot types despite a limited range in plot averages (Kruskal-Wallis, $p < 0.05$; shown in Table 3.1). *ET* rates were found to significantly differ between plot types (ANOVA, $p < 0.001$; Table 3.1). The greatest *ET* rates were measured in seedling plots, followed by control and moss plots. Average *ET* rates of mulched plot were lower than respective unmulched vegetation, although not significantly (ANOVA, $p > 0.05$, shown in Table 3.1). θ responses to peak seasonal *ET* rates on DOY 185 (5.8 mm/day) were less dramatic in mulched plots compared to unmulched plots (Figure 3.2). Although, no significant relationships between θ and *ET* ($p > 0.05$) were found for any plot types, seedling and seedling-mulch plots showed weak yet significant relationship between water table and *ET* ($p < 0.05$). To minimize the effects of variable water table positions and *ET* rates, individual plots where water table did not differ significantly (~5 cm bgs; Kruskal-Wallis, $p > 0.05$) were compared and showed few significant differences in θ and ψ (Figure 3.7). No significant differences were found between plot θ (Kruskal-Wallis, $p > 0.05$), and ψ differences were only significant between the control and moss-mulch plots (Kruskal-Wallis, $p < 0.05$; Figure 3.7), where moss-mulch ψ was notably higher than that of the control plot.

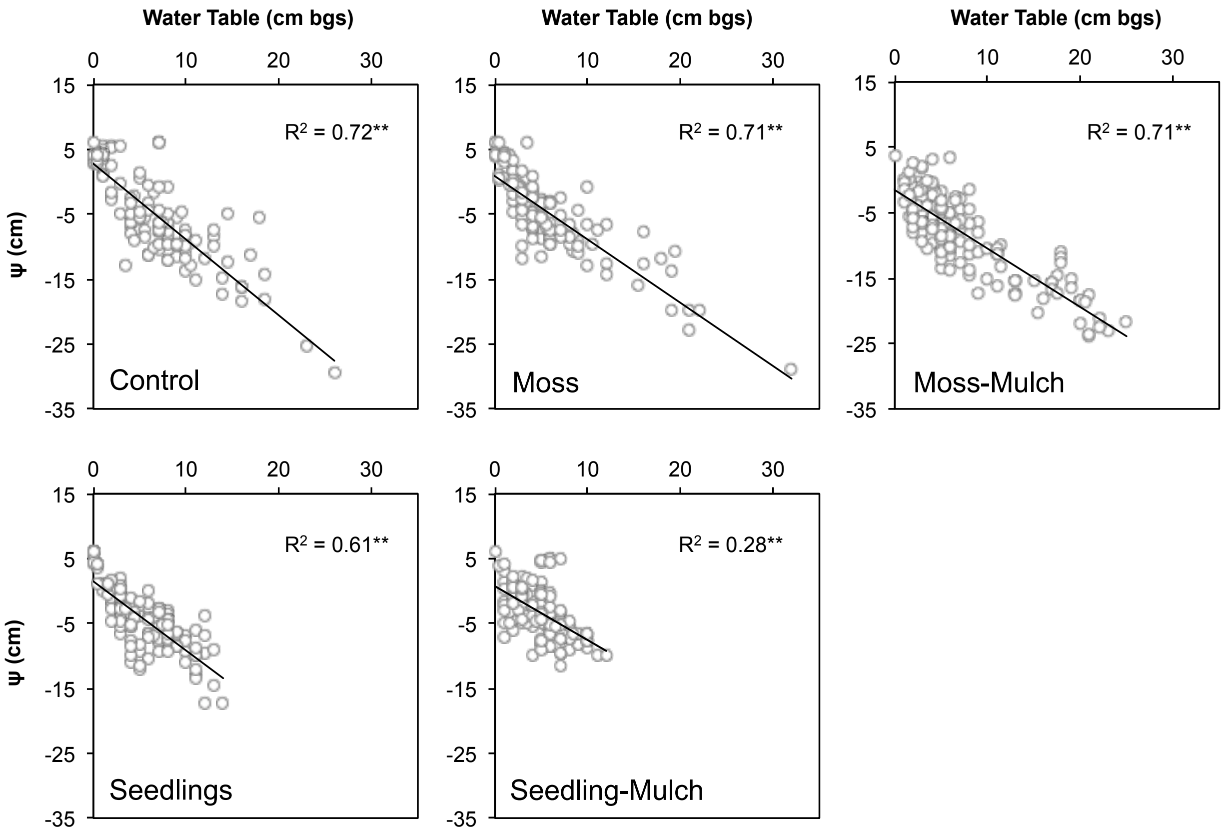

Figure 3-5 Pressure (ψ) and water table relationships for each plot type.
** = significant slope at $p < 0.01$.

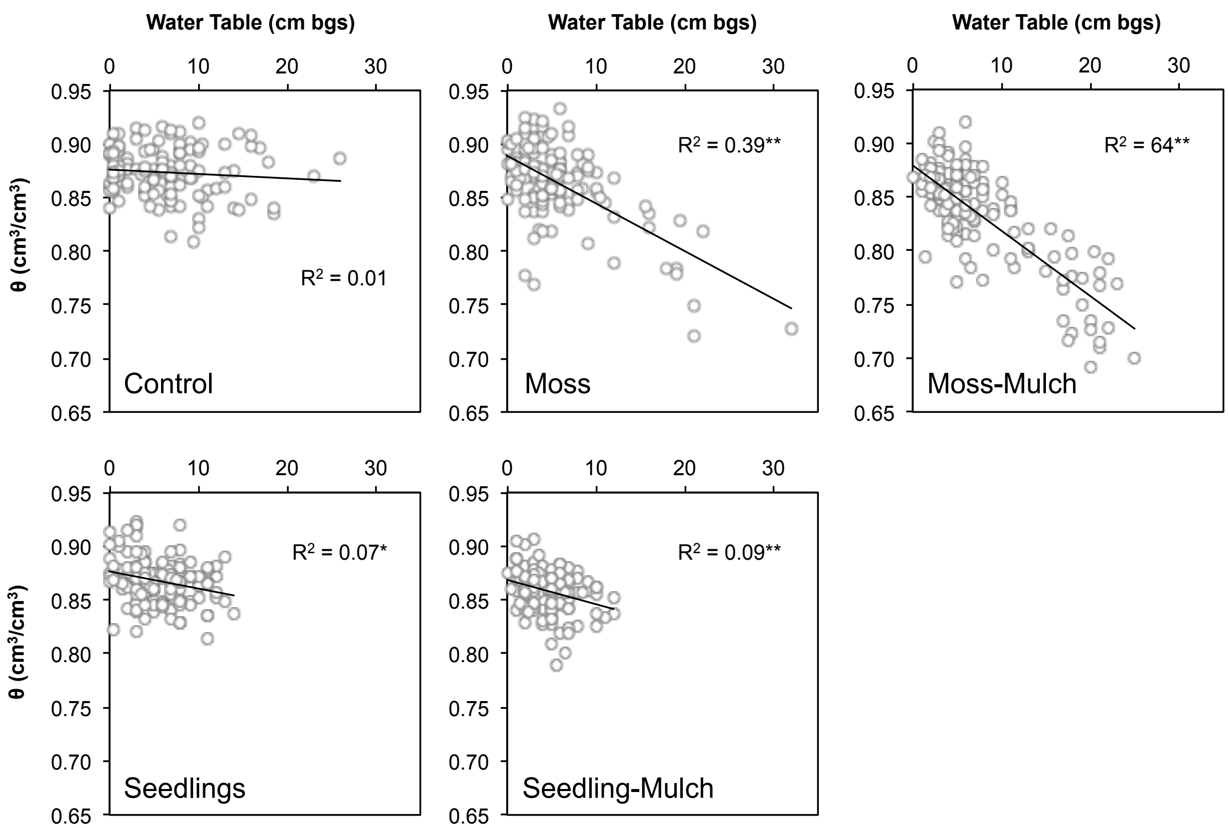

Figure 3-6 Soil moisture (*θ*) and water table relationships for each plot type.
** = significant slope at p < 0.01; * = significant slope at p < 0.05.

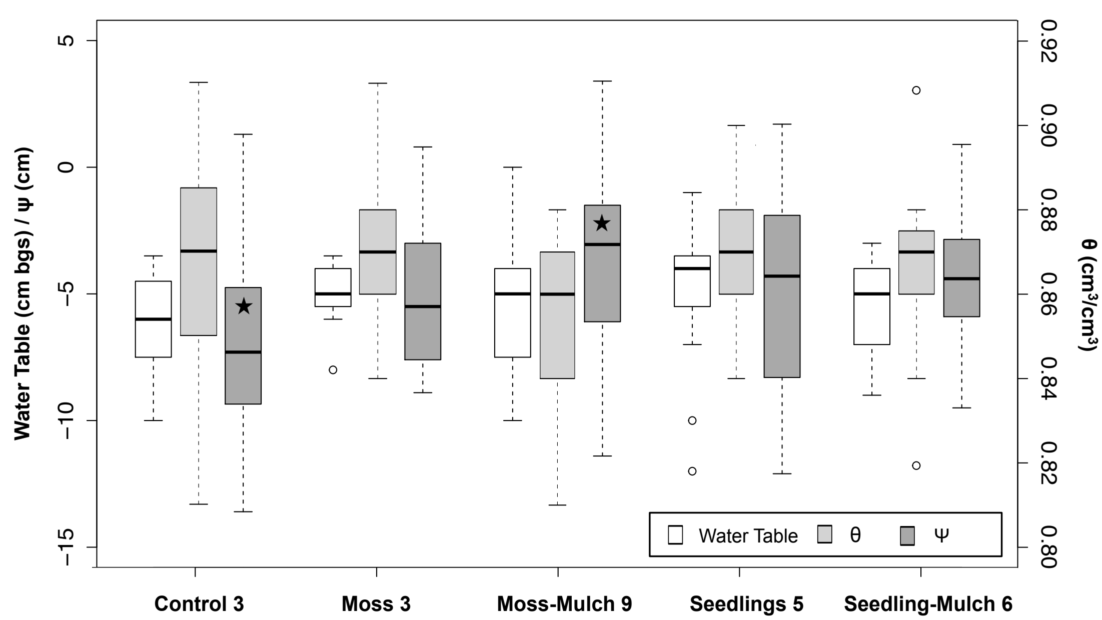

Figure 3-7 Soil water dynamics of individual plots where water table did not differ significantly. Box plots represent the median, 25th and 75th percentile and whiskers indicate the maximum and minimum values. Points that extend beyond the whiskers are outliers. Numbers next to the plot type on the x-axis indicate individual block numbers. Stars indicate a significant difference ($p < 0.05$).

Hydrophysical properties

The placed peat was highly variable across the site, where most measured properties (except specific yield) varied significantly with sampling location (p-values shown in Table 3.2). Saturated hydraulic conductivity (K_{sat}) ranged three orders of magnitude ($10^{-2} – 10^{-4}$), yet the GLM showed no significant relationship to any of the measured physical properties ($p > 0.05$; Appendix 3). Furthermore, the GLM also showed that none of the physical properties (bulk density, porosity, specific yield) were significantly related to each other, except porosity and bulk density, which is likely an artifact of the use of bulk and particle density in porosity calculations. The relationships between mineral content and the other properties could not be tested due to limited mineral content sample size. Samples contained a large proportion of mineral, especially at the surface where a thin layer of mineral sediment was visible at some plots (0-5 cm; Table 3.2), which is evident in their higher bulk density values. Figure 3.8 illustrates the bulk density profile of the peat, where average bulk densities in the upper profile (0-55 cm) generally decreased with depth. Unusually high bulk densities at the surface are likely a result of elevated mineral contents (Table 3.2). In the lower peat profile (> 55 cm) bulk density increases, averaging 0.22 g/cm^3 (Figure 3.8).

Figure 3.9a shows the $\psi – \theta$ relationships for the upper 20 cm of the placed peat profile. Water retention was substantially lower in the surface (0-5 cm) layer at all ψ-steps, despite all layers having comparable saturated θ contents ($\psi = 0$). Water retention is similar between 5-10, 10-15 and 15-20 cm layers at all ψ-steps. Hysteresis was present in all layers, where lower θ were observed at each ψ-step when the sample was re-wet; this was most evident in the 0-5 cm layer. Figure 3.9b illustrates $K_{unsat} – \psi$ relationships were similar for all aforementioned layers. K_{unsat} dropped 2 orders of magnitude ($10^{-4} – 10^{-6}$) in all layers from $\psi = -5$ and $\psi = -25$. While K_{unsat} of the 15-20 cm layer was lower at all ψ-steps, values only varied within ~ 1 order of magnitude between layers at any given ψ.

Table 3-2 Summary of hydrophysical peat properties from 6 sampling locations across the fen. All samples are from the peat surface (0-5 cm), unless otherwise indicated. P-values indicate if the measured parameter varied significantly between sampling locations (NS = not significant at the 0.05 level). Test statistics represent the F-statistic for parametric ANOVA tests (i.e. specific yield, K_{sat}) and the chi-squared value for non-parametric Kruskal-Wallis tests (i.e. bulk density, porosity). Mineral content could not be tested for significance due to limited sample numbers at each location.

		Mean	+/-SD	Max	Min	n	p-value	Test statistic
Bulk Density (g/cm^3)		0.27	0.05	0.43	0.20	54	< 0.05	18.75
Porosity		0.88	0.02	0.91	0.81	53	< 0.05	19.40
Specific Yield		0.05	0.02	0.10	0.03	54	NS	1.10
% Mineral	0-5 cm	47.8	6.9	64.7	40.4	18	---	---
	5-20 cm	32.3	9.3	48.2	19.4	8	---	---
K_{sat} (cm/s)		3.3×10^{-3}	3.9×10^{-3}	2.6×10^{-2}	3.9×10^{-4}	53	< 0.05	7.84

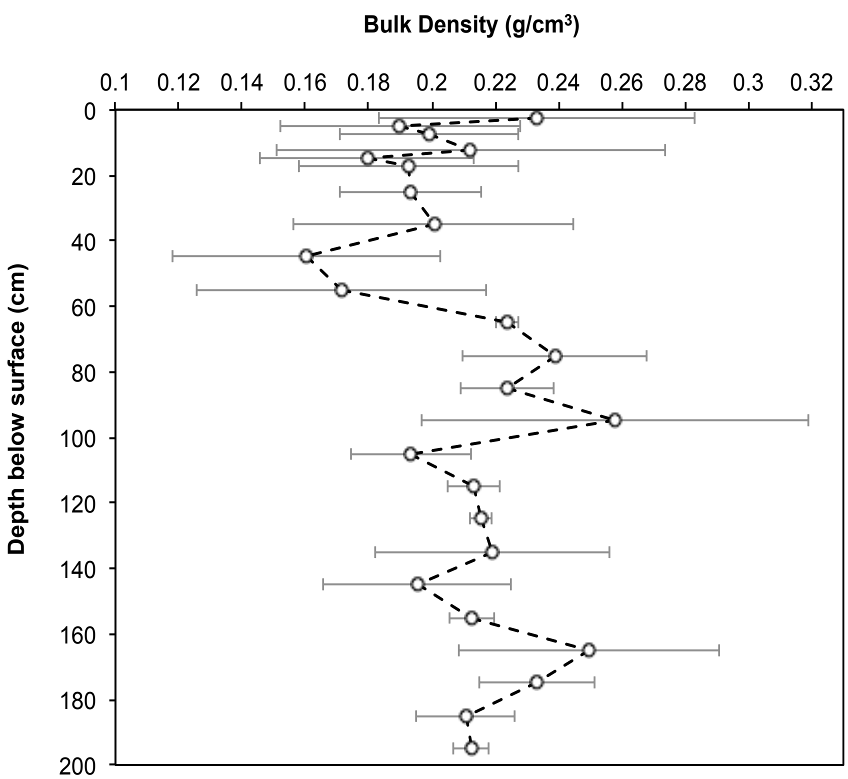

Figure 3-8 Bulk density for the placed peat profile (n = 57 at 2.5 depth, n = 2-4 for all other depths). Error bars indicate 1 standard deviation.

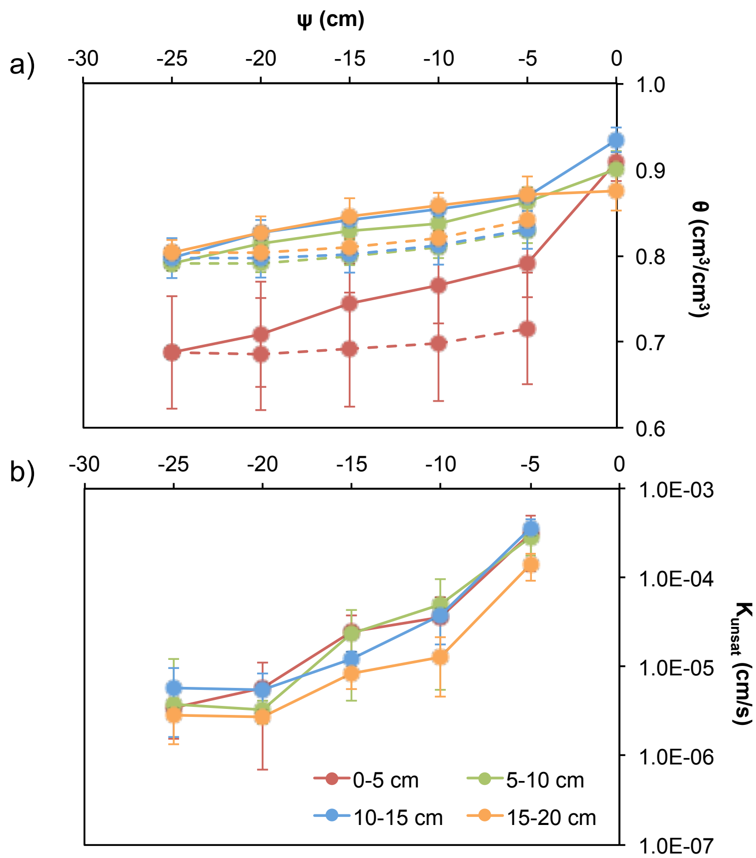

Figure 3-9 a) $\psi - \theta$ retention and b) $K_{unsat} - \psi$ curves for the upper 20 cm of the peat profile (n=3 for all layers). θ at ψ=0 determined from sample porosity. Solid and dashed lines in a) show drying and wetting curves, respectively. Error bars indicate 1 standard deviation.

3.5 Discussion

While studies such as Price *et al.* (1998) and Petrone *et al.* (2004) illustrate the importance of vegetation reestablishment and mulching during the initial years post-restoration on a system's hydrology, treatment type in this study did not show a significant control on soil water dynamics. Higher water tables in 2014 compared to 2013, despite less *P* in 2014, can likely be explained by higher water levels in the constructed upland (Ketcheson, unpublished data) and thus greater groundwater supply to the fen. Differences in plot elevations influenced water table position and thus soil water dynamics, as plots located at higher elevations had consistently lower water tables (Figure 3.4). Although not significantly different from other plot types, moss-mulch plots had the highest average elevation (Figure 3.1a), which likely contributed to lower water tables and thus lower θ and ψ in these plots in both 2013 and 2014 (Table 3.1). Plot pore water ψ typically mirrored water table, whereas θ was less clearly related to water table fluctuations in most plots

(Figures 3.2 and 3.6). Generally weak θ – water table relationships (Figure 3.6) are likely due to the hysteresis effects during wetting and drying events. Higher average θ contents (Table 3.1) and weaker responses to water table fluctuations in unmulched plots (i.e. control, moss and seedling; Figure 3.2) suggests that θ in the upper 0-5 cm of these plots was more strongly influenced by P inputs. The stronger θ – water table relationships (Figure 3.6) and muted responses to P in mulched plots (Figure 3.2) suggests that mulch interception (Figure 3.3) reduced the amount of θ available at the plot surface (Price *et al.,* 1998). Furthermore, $P - ET$ in mulched plots shows a greater water deficit despite lower ET rates than respective unmulched plots (Table 3.1), caused by mulch interception. However, high θ contents in unmulched seedling plots suggests that seedling interception did not noticeably reduce θ at the surface of these plots. The specific effects of mulch interception on near-surface θ contents are difficult to elucidate due to significant differences in plot water table levels. However, despite slightly higher water deficits ($P - ET$) in mulched plots, θ contents appear to be less affected by high ET rates than unmulched plots (Figure 3.2). In addition to lower ET rates, ET from mulched plots includes water that had been intercepted, in part mitigating the potential negative effects of interception on θ contents in these plots (Price *et al.,* 1998).

The highly heterogeneous hydrophysical properties of the fen peat (Table 3.2) caused by the peat salvage and placement methods contrasts strongly with the layered heterogeneity of undisturbed peatlands (Beckwith *et al.,* 2003). Moreover, the porosity and specific yield were lower and bulk density was substantially higher than measured values from a local reference fen (Goetz & Price, 2015a; Nwaishi *et al*., 2015), but comparable to the range of values for the same constructed fen reported by Nwaishi *et al*. (2015). Bulk density was also comparable to that documented at an unrestored harvested peatland (McCarter & Price, 2014), despite differences in botanical composition. The salvaged peat for the constructed fen and that from drained and harvested peatlands were both dewatered prior to peat extraction. The increased aeration resulted in increased decomposition and altered physical properties stemming from the collapse of the pore-structure. Furthermore, a general increase in bulk density with depth (Figure 3.8) is likely due to repeated compaction from the placement of upper peat layers during construction. The exception to this trend is the high bulk densities occurring at the surface (0-5 cm), a result of greater mineral content (Table 3.2). This is caused by a thin layer of mineral sediment found over much of the fen, derived from erosion of the constructed upland during high rainfall events and snowmelt (Ketcheson & Price, submitted). Mineral contents within the upper 20 cm of the placed peat are comparable to values reported by Nwaishi *et al*. (2015) for this site. High bulk densities at the surface, thus high capillarity strength, have been found to limit the hydrological connectivity with the overlaying moss layer that has a looser structure (McCarter & Price, 2014), which could potentially result in lower θ and ψ in the moss itself as it develops at the constructed site.

Water retention of the placed peat (Figure 3.9a) is substantially greater than measured values from a reference fen (Goetz & Price, 2015a). Increased water retention capacity of the constructed fen peat is a result of the relatively small pore-size distribution associated with peat of greater bulk density (Goetz & Price, 2015a, McCarter and Price, 2014). Despite high retention capacity, the lack of natural structure in the disturbed peat resulted in low K_{unsat} for given ψ-steps over all depths, and values that were approximately an order of magnitude lower than deeper (catotelm) peat from the reference fen (Goetz & Price, 2015a) and from cutover bog peat from harvested sites (McCarter & Price, 2014; Taylor & Price, 2015). However, the role of botanical composition of the peat was not determined. K_{sat} of the surface peat was comparable to vertical K_{sat} measured by Nwaishi *et al*. (2015), but averaged an order of magnitude lower than surface K_{sat} at harvested sites (cutover peat; McCarter & Price, 2014; Taylor & Price, 2015). Other studies have found relationships between K_{sat} and physical properties such as bulk density or porosity (Boelter, 1968; Branham & Strack, 2014; Taylor & Price, 2015), yet based on the GLM these relationships were not found to be significant in this study ($p > 0.05$). The independence of K_{sat} from other measured properties and significant dependence on location illustrates the heterogeneity of the constructed fen peat.

The high variability in the hydrophysical properties of the placed peat likely had a substantial effect on the lack of evident trends found between plot type hydrology. During the first few years post-planting, influences of the different plot types could be masked by the high variability of the peat itself (Table 3.2). Therefore, due to the influence of peat properties on water retention and thus θ content, plot soil water dynamics likely largely depend on plot location within the fen as opposed to vegetation type and presence of mulch. Locations with greater θ retention capacity and K may be able to hold onto and transmit water for effectively. Differences in soil water dynamics between plot types can also be attributed to differences surface elevation and thus high spatial viability in water table position across the fen (Figure 3.1

and 3.4). This is supported when plots with statistically similar water tables showed comparable soil water dynamics (Figure 3.7). Significant difference between control and moss-mulch ψ in these plots could be attributed to higher *ET* rates over bare peat control plots (Table 3.2; Price, 1996; Petrone *et al.,* 2004), however; it could also be an artifact of only having one sampling location to compare. Although plot surface elevation only differed 24 cm across the fen, this resulted in large seasonal water table fluctuations (> 20 cm), predominantly in higher elevation areas (Figure 3.1). This is likely due to the low specific yield of the placed peat (0.03-0.1), compared to that of a natural fen (0.1-0.8; Goetz & Price, 2015b). Therefore, fluctuating water tables yet consistently wet conditions (average $\theta > 0.80$) throughout this study likely muted any effects of vegetation or mulch on soil water dynamics, as most plots showed no significant differences in θ or ψ under comparable water table positions.

3.6 Conclusions and recommendations

During the initial years post-construction of the Nikanotee Fen, surface elevation and spatially variable water table levels appear to govern soil water dynamics, as opposed to plot type. Despite successful moss and seedling establishment during the first growing seasons post-construction (Borkenhagen, unpublished data), differences in soil water dynamics between vegetation treatments seem to be masked by variable and relatively high water tables in both the 2013 and 2014 study seasons. Despite slightly stronger θ – water table relations in mulched plots, when plots with similar water tables were compared, mulch treatments did not appear to strongly affect soil water dynamics. Mulched plots generally had slightly lower near-surface θ contents than respective unmulched plots, likely due to *P* interception caused by the mulch layer. Although the effects of mulch on the fen's hydrology are not statistically significant in this study, Borkenhagen (unpublished data) observed a > 60% increase in moss percent cover under mulch. Therefore, the presence of mulch likely creates a favorable microclimate for moss establishments, evident by lower *ET* rates in these plots (see Chapter 2.0).

Significant spatial variability of the placed peat hydrophysical properties further contributed to the lack of evident trends in plot-scale hydrology. As a result plot soil water dynamics were largely influenced by plot location within the fen as opposed to treatment type. As noted by Nwaishi *et al.* (2015), findings from this study highlight the importance of maintaining the quality of the peat used in reclamation projects. The high water retention capacity of the decomposed placed peat may affect the ecohydrological function by limiting hydrological connectivity to the moss layer as it establishes and becomes thicker. Therefore, it is recommended that measures be taken from the time of dewatering (i.e. reduced aeration time) to post-construction (i.e. silt fencing between uplands and peatland) to limit decomposition, predominantly for peat placed at the surface. Differences in elevation caused large water table variability across the fen, which masked the effects of vegetation and mulch treatments. Price *et al.* (1998) found that the creation of microtopography did not significantly alter moisture conditions or improve moss establishment in a restored post-harvested bog peatland and was thus unnecessary. However, variability in surface topography and water table position could result in greater species diversity and ultimately the successful establishment of a peatland ecosystem. As the fen develops, litter deposition and moss accumulation will likely further drive the development of microtopography through new peat formation. It is therefore important that ongoing studies be conducted in the coming years to track the effects of greater vegetation establishment and peat formation, as well as capture drier conditions that may elucidate the effects of different plot types on soil water dynamics.

4.0 Conclusions and implications

This study is the first to assess the influence of plot types on energy fluxes and the hydrology of a constructed fen in a post-mined oil sands landscape. While the re-establishment of vegetation and addition of mulch significantly influenced available energy and *ET* rates, it did not show a significant control on plot soil water dynamics in this study. Although cumulative *ET* exceeded *P* in all plots, vegetation successfully mitigated *ET* losses, as open water had the highest rates. *ET* was further reduced in mulched plots, due to higher near-surface *RH* and lower *VPD* in these plots. Mulch appeared to have a stronger effect on moss plots compared to seedlings plots, as it had no noticeable effect on transpiration. However plot hydrology did not appear to control *ET,* which was only weakly significantly related to water table position in seedlings plots. During the initial years post-construction, spatially variable hydrophysical peat properties and surface elevation and thus water table levels, appear to govern soil water dynamics and mask the influences of vegetation and mulch treatments. Mulched plots generally had slightly lower near-surface θ contents than respective unmulched plots, likely due to *P* interception created by the mulch layer. Although, slightly greater water deficits (*P-ET*) were observed in mulched plots, *ET* from mulched plots includes water that had been intercepted, in part mitigating the potential negative effects of interception on θ contents in these plots. The specific effects of mulch on plot-scale hydrology is difficult to elucidate due to significant differences in plot water table levels.

Analysis of individual plot elevations showed that elevations ranged 24 cm between plots, which resulted in water table fluctuation > 20 cm. High water table variability, predominantly in higher elevation plots, appears to mask the influences of vegetation and mulch treatments on soil water dynamics. Although plot-scale hydrology (i.e. θ, ψ and water table) differed significantly between plot types, when plots with similar water tables were compared, vegetation type did not show a significant control on plot hydrology. While variable water tables appear to mute the effects of specific plot types, variability in surface topography and water table position could result in greater species diversity and ultimately the successful establishment of a peatland ecosystem.

Furthermore, the salvage and placement methods of the peat created an unnatural structure and heterogeneous hydrophysical properties across the fen, which likely further masked trends between plot hydrology. Despite high retention capacity, the lack of structure and increased decomposition in the disturbed peat resulted in comparatively low K_{sat} and K_{unsat}, limiting water redistribution. Thus, plot soil water dynamics were largely influenced by elevation and location dependent peat properties, as opposed to treatment type. Therefore, it is recommended that measures be taken from the time of dewatering to post-construction to limit unnecessary disturbance and decomposition, predominantly for peat placed at the surface. The high water retention capacity of the decomposed placed peat may affect the fen's ecohydrological function by limiting hydrological connectivity to the moss layer as it establishes and becomes thicker. Conversely, the fen could become sedge-dominated where the newly formed peat could have comparable physical properties to those of the placed peat (i.e. high bulk density, low specific yield). In this situation, hydrological connectivity between layers would not be impeded by a capillary barrier.

While mulch did not significantly affect soil water dynamics in this study, it had an important effect on ET given the dry sub-humid climate of the WBP. Despite comparatively lower θ contents, near-surface θ and ψ in mulched plots remained within a range ($\theta > 69\%$) that was still well suited for moss establishment and survival. These findings are supported by greater moss percent cover in mulched plots (Borkenhagen, unpublished data), which suggested a positive trade off between the effects of mulch interception and reduced ET losses in moss-mulch plots. However, the same effects on ET were not observed in seedling-mulch plots, therefore mulching seedlings appears unnecessary if hydrologic conditions are favorable (i.e. high water tables) during the first years post-planting. Furthermore it is recommended that ponds be limited in oil sands reclamation, as this study shows they act as windows for high evaporative losses where $ET >> P$.

As reclaiming landscapes to peatland is a newly tested concept, this study provides insight in the hydrology of specific planting designs with a focus on the effects of mulch in the sub-humid climate of the WBP. This research is relevant to a broad range of reclamation practices, not only in the oil sands region, but in the larger WBP where wetlands dominate the landscape despite high evaporative demands. Further research is required to track the effects of greater vegetation establishment and determine the role of mulch after the initial years post-reclamation. Capturing the fen's hydrological processes under drier conditions may elucidate the effects of different plot types on soil water dynamics. Furthermore, consideration of the cumulative effects and combined implications of vegetation and treatment types on the hydrology, ecology and biogeochemistry are necessary to develop future planting strategies. A comprehensive study of these processes would provide greater insight into the necessary conditions required to create a successful, self-sustaining fen ecosystem.

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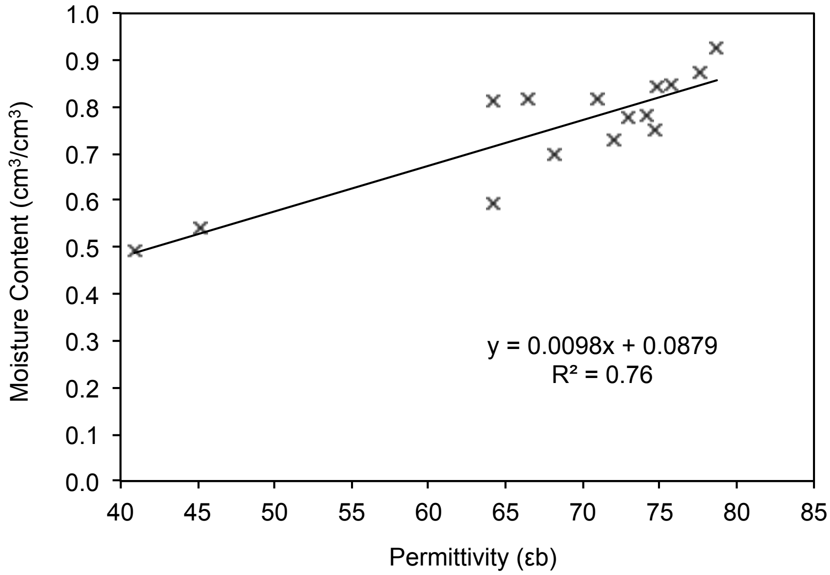
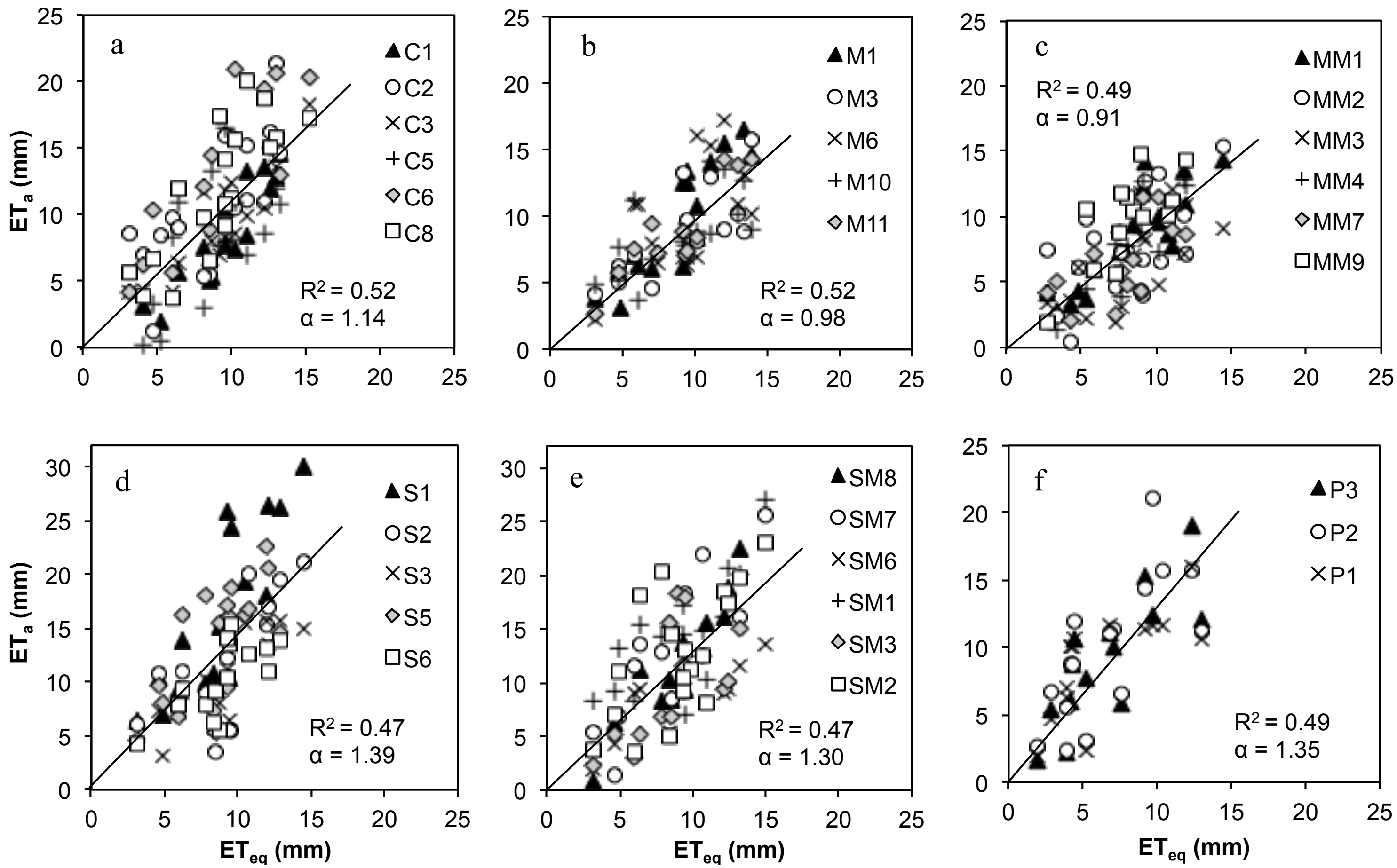
Appendix 1



Appendix 1 Wet-Sensor calibration curve. Gravimetrically-measured soil moisture contents plotted against recorded permittivity values from the Wet Sensor device. Calibration samples were saturated in water with an electrical conductivity representative of field values (~230 mS/m).

Appendix 2

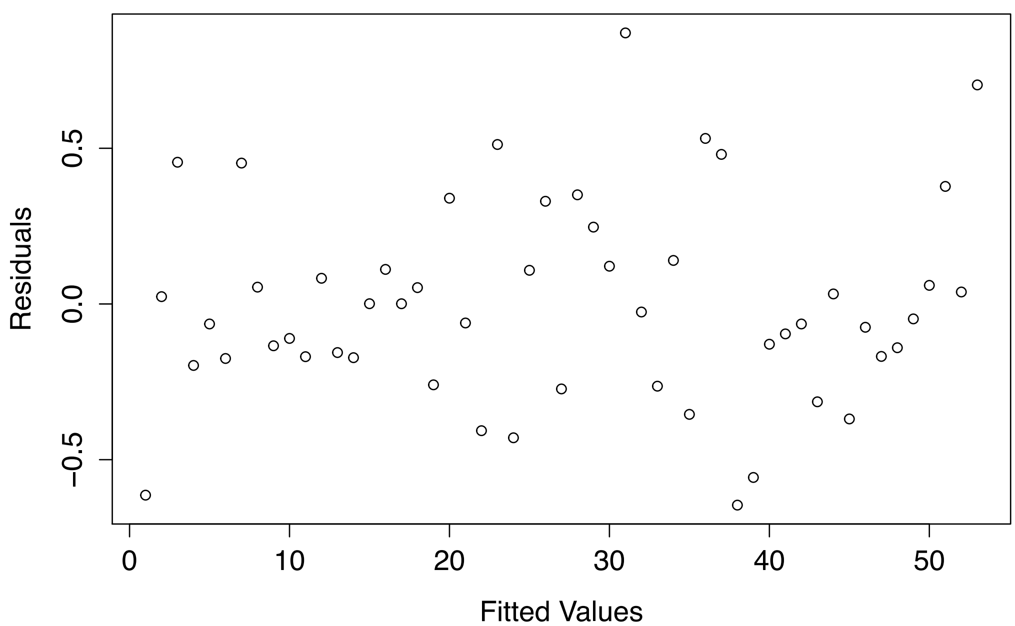


Appendix 2 α-plots relating ET_{eq} to ET_a for all individual plot lysimeters in a) control, b) moss, c) moss-mulch, d) seedling, and e) seedling-mulch plots. Evaporation pan α-plots shown for f) ponds. All slopes significant at $p < 0.01$. M8, MM11 and S8 plots not included due to lack of measurement points and poor relationships ($R^2 < 0.2$).

Appendix 3

Appendix 3 – Table Output from the general linear mixed-effects model (GLM) showing dependence of K_{sat} (response variable) on peat properties (predictor variables). A random effect of "Location" was added to account for repeated measures at each sampling location (n = 6). DF indicates degrees of freedom. Residual SD indicates 1 standard deviation in the model residuals.

	Slope	Std. Error	DF	n	p-value	t-statistic	F-statistic
Bulk Density (g/cm^3)	0.33	1.74	44	54	0.85	0.19	0.52
Porosity	2.23	2.92	44	53	0.45	0.77	0.59
Specific Yield	0.81	3.26	44	54	0.81	0.25	0.06
Random effect	Location						
Residual SD	0.34						



Appendix 3 – Figure Residual plot of K_{sat} model plotted against the fitted values from the model. Note no systematic patterns.