The CO_2 dynamics and hydrology of an experimental *Sphagnum* farming site

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.

I understand that my thesis may be made electronically available to the public.

Abstract

Sphagnum farming (or cultivation) is a recent land management strategy in reclaimed peatlands. The goal of *Sphagnum* farming is to cultivate *Sphagnum* fibers on a cyclic basis. *Sphagnum* moss is non-vascular and requires high and stable moisture availability at the growing surface to reduce capillary stresses. However, specific hydrological requirements to maximize *Sphagnum* biomass accumulation (CO_2 uptake) are uncertain, and there is interest in evaluating the water management design (i.e. irrigation) that is best suited for effective water distribution in *Sphagnum* farming operations. The purpose of this thesis was to evaluate the hydrological thresholds to increase *Sphagnum* CO_2 uptake in an experimental *Sphagnum* farming site, and to provide recommendations on how irrigation can be used to increase productivity and upscale the size of operations. The experimental site is in a block-cut peatland south of Shippagan, New Brunswick. From May to July 2014, six 20 x 50 m *Sphagnum* cultivation basins were established within the lowered trenches of the block-cut peatland, each with a different type of active water management design. The CO_2 fluxes were monitored with the closed chamber method, along with hydrological data collected from July 10 to August 14 in 2014, and May 11 to August 22 in 2015. A CO_2 and water balance were calculated for each basin for the 2015 study period.

Research has demonstrated that CO_2 uptake by *Sphagnum* moss in post-extraction peatlands is affected by the position of the water table (WT). At this experimental site, CO_2 uptake by the moss was not limited by dry (WT -15 to -25 cm) or wet (WT < -15 cm) treatments. When the mean WT was shallow (< 25 cm), the fluctuations in WT were found to be more important in limiting/increasing CO_2 uptake. Carbon dioxide uptake was highest where the range in seasonal WT position was < 15 cm. A WT position of -10 to -15 cm is recommended to reduce WT fluctuations and limit excess moisture at the surface. Productivity has the potential to

be further improved by maintaining the daily WT fluctuations < ± 7.5 cm from the seasonal WT mean. When these conditions were met, moss grew by a mean of 1.8 mm/month.

To maintain hydrological conditions necessary for maximum biomass accumulation, topographical features of the reclaimed peatland, such as baulks, drainage canals and adjacent trenches, are important considerations for site scale water flow. Water regulation canals are important hydrological features because they have stabilizing effects on WT levels when they are water input sources, and behave as water sinks when water tables are high in the peat basins. The majority of the water flow occurred towards the deep primary drainage canals. The baulks not adjacent to drainage canals formed water mounds, limiting water flow between the basins. An unmanaged trench that is a relic of the block-cut extraction outside but adjacent to the experimental area, was a large source of ground water input to the site. Leveling the site to a common datum and establishing buffer zones adjacent to drainage canals and adjacent un-restored trenches could reduce water transfer within the sites.

Pumping water into the canals was necessary to reduce the water deficit from high ET and low P during a dry study period. The variability in WT position increased with distance from the water input feature (canals or sub-surface pipes). Increasing the irrigation density (ratio of pipe/canal length to basin area) of the water management design will assist in maintaining stable WT positions. To upscale production sites, irrigation features (canals and pipes) should be installed in ways that complement the topography of the site. Installing these features upslope, and increasing their density (maximum spacing of 12 m) will reduce pumping demands and maintain a stable WT. Post-extraction vacuum harvested sites may be better suited for *Sphagnum* farming than block-cut sites, as they are more accessible to machinery and less landscape

manipulation is required. Future studies should evaluate the feasibility of establishing *Sphagnum* farming sites on post-extraction vacuum harvested peatlands.

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There was something magical about Avondale. I am so proud of all our journeys, and treasure the part of me that glows a little brighter, and fights a little stronger because of your friendship. To my family, everything in this thesis is because of your eternal love and support.

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Dedication

This thesis is dedicated to friendship. May your cups always be full.

To my forever friends and blood, the Brosseau clan. Thank you for everything.

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1.0 Introduction

Peatlands are water-logged ecosystems composed of at least 40 cm of organic material (peat) (National Wetlands Working Group, 1997). Ombrotrophic peatlands receive precipitation as water inputs, and non-vascular *Sphagnum* moss is the primary peat accumulating genus (Clymo & Hayward, 1982). *Sphagnum* moss thrives in cool environments with high moisture availability at the growing surface (Clymo & Hayward, 1982; Price *et al*., 2003). *Sphagnum* peat accumulates because of high rates of productivity and slow decomposition, facilitated by the internal mechanisms of *Sphagnum* in combination with environmental conditions (Clymo & Hayward, 1982; Gorham, 1991). *Sphagnum* is a substrate favoured by the horticultural industry because of its slow decomposition, chemical stability and water retention capabilities (Michel, 2010; De Lucia et al., 2013).

Ombrotrophic peatlands are extracted through techniques such as block-cutting and vacuum harvesting (Lavoie & Rochefort, 1996). These techniques involve draining the upper layers of the peatland through drainage ditches and canals, and removing the upper layers of living, dead and poorly decomposed *Sphagnum* moss (Lavoie & Rochefort, 1996). Draining and removing the upper layers reduces the hydraulic conductivity and specific yield of the remnant peat (Price, 1996; Van Seters & Price, 2002). Active restoration efforts are often necessary for *Sphagnum* re-establishment because the remnant peat properties result in a highly fluctuating WT with poor connectivity to the growing surface, which increases capillary stress and reduces moisture availability at the capitula (Price, 1997; Van Seters & Price, 2002; McCarter & Price, 2015).

To ensure the regeneration of *Sphagnum* moss and return of net CO_2 uptake, these peatlands require active restoration efforts and passive water management, such as blocking of drainage ditches and sometimes creation of bunds (Schouwenaars, 1993; Waddington & Price, 2000; Price *et al*., 2003; Shantz and Price, 2006). A common peatland restoration tool in North American is the Moss Layer Transfer Technique (MLTT) (Quinty & Rochefort, 2003). Along with passive water management, *Sphagnum* fragments are spread and covered with a straw mulch. This method can result in a nearly complete cover of *Sphagnum* within 10 years (McCarter & Price, 2013), and increased CO_2 uptake of the restored site (Strack & Zuback, 2013). However, the success of restored sites is highly dependent on the meteorological conditions present during the first season of establishment (González & Rochefort, 2014).

Success from restoration efforts following the MLTT can be applied to the recently adopted *Sphagnum* farming land-management strategy for post-extraction peatlands. The goal of *Sphagnum* farming is to grow and harvest *Sphagnum* biomass in reclaimed landscapes (Pouliot *et al*., 2015; Beyer & Höper, 2015). Research evaluating the success of MLTT *Sphagnum* farming report that the passive water management techniques used in MLTT restoration practices are not sufficient to optimise *Sphagnum* biomass accumulation (CO_2 uptake) (Pouliot *et al*., 2015; Taylor *et al.,* 2015). Published literature on *Sphagnum* farming is limited; studies in Germany have reported the success of active water management, i.e., pumping water into canals, on biomass accumulation and CO_2 uptake (Muster *et al.,* 2015; Beyer & Höper, 2015; Temmink *et al.,* 2017). However, there is a gap in knowledge on the specific hydrological thresholds necessary to optimise CO_2 uptake of *Sphagnum* moss under different types of irrigation treatments, and how to manage water distribution in large-scale production sites.

1.1 Study Site: Shippagan Bog 530

The study site is an experimental *Sphagnum* fiber farming (or cultivation) area built in a cutover peatland (Bog 530) south of Shippagan, New Brunswick, Canada (47.693°N, 64.763°W). The site is in a wet maritime environment, with 20-year (1986-2006) normal precipitation of 1077 mm (69% of which falls as rain), and mean annual air temperature of 4.8°C (Government of Canada, 2015). Manual peat extraction (block-cutting) occurred at Bog 530 from the 1940s to the 1970s, resulting in ~ 20 m wide linear trenches. The linear trenches alternate between lowered (~ 1 m) trenches (where peat extraction occurred) and raised baulks. There are remnant drainage ditches in the trenches, adjacent to the baulks. The trenches are dominated by spontaneously revegetated *Sphagnum* moss, and the baulks by vascular vegetation, such *Kalmia angustifolia* and *Rhododendron groenlandicum*. Two trenches were chosen for the experimental area, and from May to July 2014, six ~ 20 m x 50 m basins, spaced 30 m apart were created within the trenches. There are 3 basins in the north trench, and 3 basins in the south trench, separated by a raised baulk.

The surface vegetation within the boundaries of the basins was removed, and the peat leveled to ± 5 cm to prepare the surface for *Sphagnum* moss reintroduction. Prior to moss introduction, the landscape of each basin was manipulated with excavators according to the design requirements of the active water management. The designs differed according to the target WT depth, length of canals, and/ or spacing of sub-surface perforated pipes. The six basins have unique names to identify the different types of active water management. The basins are referred to as LA10 & LA20, CE10 & CE20, and PC10 & PC20. The first two letters (CE, LA, PC) denote the type of active water management, and the numbers the targeted WT depth. The site has two different target WT depths for each pair of irrigation designs (i.e. LA10 & LA20) of

-10 or -20 cm. The two different depths were chosen to compare the effectiveness of the water distribution of a specific irrigation design under two different near surface WT depths.

The basin pairs differ according to the canals and sub-surface perforated pipe placement. There were four basins with water regulation canals and sub-surface irrigation, and two basins with water regulation canals only. The first pair of basins (1 in the N trench, 1 in the S trench) have lateral sub-surface irrigation (LA) with perforated (10 cm) pipes, 60 cm below the surface, spaced 12.5 m apart, and connected to a 50 m x 1 m canal along the S edge of the basin. The two basins with central sub-surface irrigation (CE) have one 50 m sub-surface perforated pipe extending through the middle of the basin, connected to a 20 m x 1 m canal at the E edge of the basin. The basins without sub-surface irrigation have 1 m wide peripheral canals (PC).

Water was pumped into the canal of each basin from a nearby pond (~ 75 m west). A shipping container (~ 60 m west) was outfitted with solar panels and controls for pump activation. The pumps are activated manually for the basins when WT position within respective canals dropped below target levels, i.e., when water stopped flowing at the weir and was > 1 cm below the outflow pipe. Each basin had a weir at the east end of the canal, where at the end of the 2015 study period, sensors were installed to monitor canal WT levels for automatic pump activation. The weirs discharged excess water from the basins into secondary drainage canals. The drainage canals for LA10, LA20, CE10 and CE20 join to a single canal in an adjacent trench south of the experimental area, while individual drainage canals for PC10 and PC20 flow to the east, out of the site.

After the installation of irrigation designs, the peat surface was re-leveled to ± 5 cm and *Sphagnum* moss fragments were spread manually over the bare peat. Three different species treatments of *Sphagnum* moss (*S. magellanicum, S. flavicomans* and mix of *S. fuscum* and *S.*

rubellum) were introduced, and covered with straw mulch following the MLTT (Quinty & Rochefort, 2003). A control area was built in 2015 with no active water management. Four 60 cm x 60 cm x 15 cm deep blocks of peat established the previous year were extracted and installed in the control with the intent to create control plots with comparable moss establishment.

Figure 1-1 Photo (2015) of the straw covered experimental basins within the lowered block-cut trenches.

Figure 1-2 Photo (2014) of LA10. Water is pumped into the canal connected to perforated pipes installed below the peat surface, and excess water is discharged at the weirs located at the end of the canal (visible in the foreground between two green boards).

1.2 Research Objectives

Recent studies have reported that *Sphagnum* farming is feasible in reclaimed peatlands, and that maintaining water levels near the surface increases biomass accumulation and CO_2 uptake (Pouliot *et al.,* 2015; Taylor *et al.,* 2015; Muster *et al.,* 2015; Beyer & Höper, 2015; Temmink *et al.,* 2017). In a MLTT *Sphagnum* farming study, Pouliot *et al.* (2015) report that *Sphagnum* establishment was affected by the meteorological conditions of the first growing season when the water inputs into the canals relied solely on precipitation. Another MLTT *Sphagnum* farming study by Taylor and Price (2015) report that excess water limited *Sphagnum* CO_2 uptake, and that active water management, such as sub-surface irrigation, could be used to regulate the WT and increase biomass accumulation. However, the specific hydrological targets necessary to optimise *Sphagnum* fiber growth remain unknown. The objectives of this research are:

1. To determine how active water management impacts the water distribution within experimental *Sphagnum* farming basins, and throughout the experimental area.
2. To evaluate if active water management can be used to increase *Sphagnum* productivity (CO_2 uptake) and identify optimal hydrological thresholds to optimise production.
3. Provide recommendations on designing and upscaling future *Sphagnum* farming sites.

1.3 General Approach

This thesis is composed of two separate manuscript style chapters, which evaluate the hydrological requirements and water management designs necessary for optimal *Sphagnum* fiber CO_2 uptake. Both manuscripts are written with intention for publication. The first manuscript identified the role of different active water management designs on the water distribution within the experimental units, presented a water balance of each experimental unit, and suggested how active water management can be used to meet the hydrological thresholds required for optimal CO_2 uptake. The second manuscript evaluated the CO_2 fluxes, ground cover and vertical growth of *Sphagnum* moss under different hydrological conditions, presented CO_2 balances of each experimental unit (basin), and provided hydrological thresholds for optimal CO_2 uptake. I was primarily responsible for the writing of both manuscripts, as well as the design and execution of the field-work. Together, these manuscripts present the first complimentary CO_2 and water balance of a *Sphagnum* farming site.

2.0 Impacts of irrigation on the hydrology of an experimental *Sphagnum* farming site.

2.1 Context

Sphagnum moss is the primary peat-accumulating genus of ombrotrophic peatlands (Clymo & Hayward, 1982). *Sphagnum* growth is apical, extending vertically from its capitula at the top (Clymo, 1970). The previous seasons' growth forms the matrix from which capillary moisture is drawn since the plant is non-vascular: this is critical for their physiological processes (Clymo, 1970; Ferland & Rochefort, 1997). *Sphagnu*m fiber is favoured in the horticultural industry because of its slow decomposition, chemical stability and high water retention capabilities (Michel, 2010; De Lucia *et al*., 2013). To access *Sphagnu*m fibers, peatlands are drained through a series of ditches and the surface vegetation is removed; peat is extracted using various techniques including block-cutting and vacuum extraction (Lavoie & Rochefort, 1996). Extraction removes the upper layer of living, dead and poorly decomposed mosses, exposing more decomposed deeper layers of peat, and *Sphagnum* recolonization commonly requires active restoration efforts to increase moisture availability at the growing surface (Schouwenaars, 1993; Lavoie & Rochefort, 1996).

Post-extraction management is typically necessary for *Sphagnum* re-establishment because drained and extracted peatlands have lower and more variable seasonal water table (WT) positions and moisture deficits at the surface (Price, 1996; Van Seters & Price, 2002). The seasonally low water table coupled with the strong water retention properties of cutover peat, create a hostile environment for *Sphagnum* reestablishment (Price, 1997). Price and Whitehead (2004) found *Sphagnum* spontaneously regenerated on a cutover peatland only where the seasonal soil water pressure near the surface was above -100 mb, because the strong water retention of the old cutover peat created a capillary barrier that restricts capillary flow into more loosely structured regenerated mosses (McCarter & Price, 2015). Consequently, *Sphag*num mosses are outcompeted by vascular vegetation (Strack *et al.,* 2006), or have limited photosynthesis and growth (McNeil & Waddington, 2003; Strack *et al.,* 2006). The regenerating moss layer has poor water storage capacity and so it retains little moisture delivered by precipitation (Taylor & Price, 2015). Variable moisture content and variable WT levels reduces growth (CO_2 uptake) when the seasonal WT position fluctuates more than 15 cm (Manuscript 2).

The Moss Layer Transfer Technique (MLTT) (Quinty & Rochefort, 2003) is a peatland restoration procedure used widely in North America (cf. González & Rochefort, 2014). *Sphagnum* fragments are spread and covered with straw mulch. Passive water management techniques incorporated with the MLTT include blocking of drainage ditches (Price, 1997), and creating bunds (Shantz & Price, 2006) or peat dams (Ketcheson & Price, 2011). These restoration measures can result in a nearly complete cover of *Sphagnum* within 10 years (McCarter & Price, 2013). However, restoration success is lower at sites where larger areas of unrestored peatlands and active drainage ditches surround the restoration area, or if the restoration measures are followed by a hot summer (González & Rochefort, 2014).

Recent projects have begun to evaluate water management strategies to increase biomass accumulation (CO_2 uptake) by *Sphagnum* moss following the MLTT in *Sphagnum* farming operations (Pouliot *et al.,* 2015; Taylor & Price, 2015). The purpose of *Sphagnum* farming is to grow and harvest *Sphagnum* biomass in reclaimed landscapes (Pouliot *et al*., 2015; Beyer & Höper, 2015). Two *Sphagnum* farming studies in eastern Canada (Pouliot *et al.,* 2015; Taylor & Price, 2015) had blocked ditches as a form of passive water management. They suggest biomass production could be improved with active water management designs that are more effective at regulating the WT, such as sub-surface irrigation and canals (Pouliot *et al.,* 2015; Taylor &

Price, 2015). On this basis, a series of peat fields were prepared within a previously manually block-cut peatland near Shippagan, New Brunswick, each with a different irrigation design. The goal of this study is to provide recommendations regarding the design and operation of irrigation systems that produce hydrological conditions considered optimal for *Sphagnum* biomass production. Optimal hydrological conditions for *Sphagnum* biomass accumulation were evaluated in manuscript 2 based on WT positions and not by individual irrigation arrangement, and include a seasonal water table 10 to 15 cm below the surface and water table variability < 15 cm. In this chapter, the specific objectives are: (1) evaluate the flows and stores of water within and between irrigated sites; and (2) identify irrigation designs that most consistently achieve the target and optimal water tables.

2.2 Study Area

The study area is a trial *Sphagnum* farming site, located south of Shippagan, New Brunswick (Figure 2-1). It was established from May to July 2014 in a block-cut peatland where peat was harvested manually from 1942 to the mid-1970s. These traditional peat extraction methods created a landscape of linear ~ 1 m high and 20 m wide raised baulks, alternating with lower trenches. Two trenches were selected to establish six basins for *Sphagnum* farming, each basin measuring 20 x 50 m, spaced 20 to 30 m apart and separated by raised baulks to the north, or trenches and outflow canals to the east of each basin and south of the site (Figure 2-1). Cardinal directions are used for clarity. The length of the study area from west to east is approximately 210 m, decreasing 1.75 m in elevation. The width of the site is approximately 65 m, with an elevation decrease of 0.54 m from the north baulk to the south baulk.

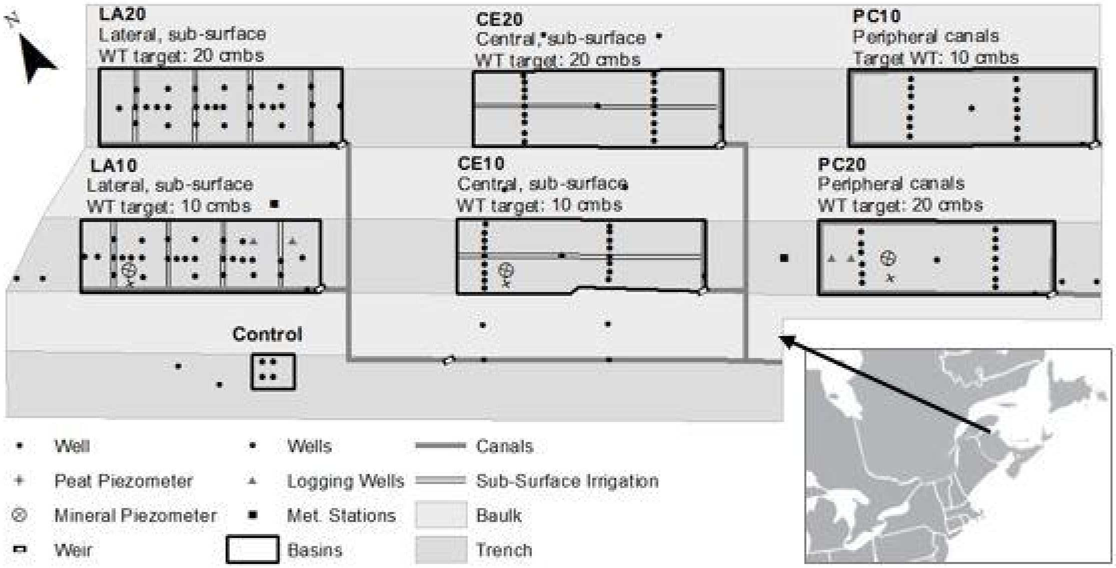


Figure 2-1 Site map of Bog 530 in Shippagan, New Brunswick. Not to scale.

Prior to construction, surface vegetation was removed within the boundaries of the basins, and the peat surface leveled (± 5 cm). There are three basic water distribution designs and two target WT depths that were tested to evaluate their effectiveness. The six basins are referred to as LA10 & LA20, CE10 & CE20, and PC10 & PC20. The first two letters (LA, CE and PC) denote the irrigation design, and the numbers the target WT of either -10 cm or -20 cm (Table 2-1). Lateral sub-surface irrigation (LA) had perforated 10 cm pipes installed 60 cm below surface spaced 12.5 m apart, connected to a 50 m canal along the SW edge. Central sub-surface irrigation (CE) had one 50 m sub-surface perforated pipe running through the center of the basin, connected to a 20 m canal at one end of the basin. Peripheral canals (PC) had no sub-surface irrigation, but 1 m wide canals around the periphery. *Sphagnum* moss requires a high and stable WT to grow on cutover surfaces (Schouwenaars, 1993), so two different WT targets close to the surface (-10 and -20 cm) were chosen.

Table 2-1 Irrigation designs. Elevation and WT are seasonal mean values ± SD. The pumping rate is the pump capacity.

Basin	Irrigation Type	Basin surface area (m^2)	Canal area (m^2)	Pumping rates (L/hr)	Elevation (masl)	WT (masl)
CE10	Central, sub-surface perforated pipe (50 m)	850	20	2454	1.8 ±0.03	1.6 ±0.03
CE20	Central, sub-surface perforated pipe (50 m)	890	20	1983	1.9 ±0.03	1.7 ±0.03
LA10	Four 20 m sub-surface lateral perforated pipes	810	50	2503	1.8 ±0.06	1.7 ±0.06
LA20	Four 20 m sub-surface lateral perforated pipes	815	50	2527	1.9 ±0.06	1.7 ±0.06
PC10	Peripheral canals	690	140	2023	1.7 ±0.02	1.6 ±0.03
PC20	Peripheral canals	570	140	2170	1.7 ±0.01	1.4 ±0.02

Water was pumped from a pond (~ 75 m west) located within the peatland, into the canals of each basin. Each basin had a weir at its SE corner, within its basin water supply canal (Figure 2-1), where excess water discharged into outflow canals. Pumps were activated manually for the basins when WT position within respective canals fell below targeted levels (i.e. if the weirs stopped flowing, and the WT levels dropped > 1 cm below the outflow pipes). The discharge canals for LA10, LA20, CE10 and CE20 joined to a single outflow canal in an adjacent trench south of the site, while individual outflow canals for PC10 and PC20 flow to the east, away from the site (Figure 2-1). After irrigation installation, *Sphagnum* moss was spread manually over the surface and covered with straw mulch following the moss layer transfer technique (MLTT) (Quinty & Rochefort, 2003). A control area was built in 2015 with the intent to create control plots with comparable moss establishment at the start of the 2015 monitoring program by extracting four 60 cm x 60 cm x 15 cm deep blocks of peat established with the MLTT in the previous year.

2.3 Methodology

A network of 180 wells was installed across the site, with water table position monitored twice weekly. In the basins, transects were established by distance from irrigation (i.e. buried perforated pipes at LA and CE, and peripheral canals at PC) at 0, 2, 4, 6 and 8 m where appropriate. CE10 and CE20 were the only basins with wells at 8 m. The wells had a 0.6 m slotted, screened intake, and were either 2.5 or 3.8 cm i.d. Barometrically corrected pressure transducers (Solinst Levelogger), recorded water table elevation hourly at wells installed 0 and 6 m from irrigation in LA10 and PC20. Barometric corrections (Solinst Barologger) were made onsite. Data were collected from May 22 to August 22, 2015 (DOY 142 – 234). There was one month of logged WT data for each CE10 and CE20, alternating at 0 and 6 m from irrigation. Regressions were performed between the logged data and manual measurements to calculate hourly measurements when not otherwise available (minimum $R^2 = 0.55$, $p < 0.001$). Wells with a 1.5 m screened covered perforated intake were installed into the baulks. CE10, LA10 and PC20 had two piezometers with a 0.20 m intake, one of which was installed into the mineral layer that underlays the site, and one that was installed in the peat above the mineral layer. Field hydraulic saturated conductivity (K_{sat}) measurements were conducted at all wells and piezometers via the Hvorslev (1951) time-lag solution (Hvorslev, 1951). A Leica total station was used to reference elevations of all wells, piezometers, weirs, canals, basins and baulks to a common datum. RStudio, R version 3.2.2 was used for statistical analysis (R Core Team, 2015), with a significance of $\alpha = 0.05$. Seasonal means of the data were used for t-test comparisons between -10 and -20 cm WT target groups, and linear regressions were used to evaluate the relationship between volumetric soil moisture content (θ) and WT, and soil water pressure (ψ) and WT, Volumetric soil moisture content (θ) stations were established adjacent to wells 0 and 6 m from irrigation. Semi-weekly measurements sampling the 0 - 6 cm layer were made with a portable WET-Sensor™ (Delta-T Devices, Cambridge, UK) time-domain reflectometry (TDR) device; individual gravimetric calibrations were determined in the laboratory, corresponding to samples that represent different ground covers (Appendix 1). Discharge (Q) from each basin was measured manually by collecting water draining through a pipe inserted through a weir-board at an elevation designed to meet the target water level, and calibrated with pressure transducers that recorded water levels in the canals every 30 minutes. Stage-discharge curves were created for each weir (Appendix 2). During the dry conditions at the end of the season the weirs were blocked periodically with the intention of raising the WT in the basin. The weirs at CE10, LA10, PC10 and PC20 were blocked from day of year (DOY) 196-202, 213-216 and 218-226, and LA20 from 196-202 and 218-226. Four days of data were missing for the weir at LA10 at the end of the season, so a regression was made with a logger in the basin with logged data from the month of August ($p < 0.001$, $R^2 = 0.71$), to fill the gap. Four cores were taken from 0 to 20 cm depths, and transported back to the laboratory to estimate bulk density and specific yield. Bulk density was determined by oven-drying cores at 60°C until they reach a stable weight, and dividing the dry weight by the field volume. Specific yield was calculated by determining the mass loss from saturated to drained condition, following the method described by Price (1996).

Soil water pressure was measured with L-shaped tensiometers, 1 or 1.5 cm i.d, with a porous ceramic cup and an electronic tensiometer (Eijkelkamp, SMS 25003) pressure transducer accurate to ± 1 mb. Blocks of peat were temporarily removed from the basins to expose a profile, into which the tensiometers were carefully installed with a level; peat was removed to create a guide-hole where necessary to reduce compaction at the porous cup. Stakes were placed diagonally away from the ceramic cup into the peat, and the tensiometers were affixed to the stakes to reduce movement and potential detachment of the porous cup from the peat profile. Tensiometers were installed at -2.5 cm in basins with a -10 cm WT target, and at -2.5 cm and -7.5 cm in basins with a -20 cm WT target. Three replicates of the depth profiles were installed at 0 and 6 m from irrigation across the site to represent distance from irrigation (not all basins had the same number of tensiometers). Soil water pressure measurements were taken at least twice a week. The septum stopper was removed when necessary to add water into the column, and given 24 hours to reach hydraulic equilibrium. Soil water pressure was calculated by adding the height of the water column to the manometer reading. During each measurement, WT was also recorded. Soil water pressure (ψ) refers to the positive and negative pressure head in the peat profile, and values are expresses in cm of water (1 cm ≈ 1 mb).

Precipitation (Texas automatic instrument tipping-buckets) and air temperature/relative humidity (Campbell Scientific, CS215-L) were recorded at two different meteorological stations located at opposite ends of the site. One of 3 tipping buckets had a straw layer placed over it at a density approximating that on the ground surface, to estimate rainfall interception. Wind speed/direction (Campbell Scientific, 05103-10-L), net radiation (Campbell Scientific, Q-7.1) and ground heat flux (Hukseflux, HFP01) was recorded at the SE meteorological station. All data were measured every 30 seconds and averaged hourly.

An equation adapted from Priestley & Taylor (1972) was used to calculate equilibrium evapotranspiration (ET_{eq}):

$$ET_{eq} = \alpha\left(\frac{\Delta}{\Delta+\gamma}\right)\left(\frac{Q^{*}-Q_{g}}{L_{v}\rho}\right) \tag{1}$$

where Δ is the slope of the saturation vapour pressure-temperature curve, γ is a psychometric constant (0.066 kPA/°K), Q^* is net radiation (J day^{-1}), Q_g is ground heat flux (J day^{-1}), L_v is the latent heat of vapourization (J kg^{-1}), ρ is the density of water (kg m^{-3}), and in equation 1 $\alpha = 1$. Actual evapotranspiration (*ET*) was determined by calibrating individual α coefficients for each basin based on the slope of the regression between ET_{eq} and ET_{lys}, where ET_{lys} was measured with weighing lysimeters. The lysimeters were 19 L containers filled with a peat monolith, and two were installed per basin. An intact sample was removed and carefully placed into the lysimeter, ensuring the vegetation and mulch at the surface resembled the surrounding environment, and inserted into the basin at the same surface height. The weight of the lysimeters were recorded a minimum of twice weekly, and water was added or removed to ensure that the water levels in the lysimeters were similar to the water table in the basins they represented. The change in weight between the previous measurement (after WT adjustment) and the current measurement (before adjustment) represents the actual water loss (ET_{lys}) from the lysimeter (Appendix 3). Measurements that included days with precipitation were excluded from the regressions. A total of 138 points were used for the site scale regression, and a minimum of 20 for the basin scale calculations.

The seasonal water balance for each basin was calculated as

$$\varepsilon + \Delta S = P + Irr + GW_{in} - ET - Q - GW_{out} \tag{2}$$

where ε is the residual term, ΔS_{basin} is change in soil water storage in the peat profile and change in canal water storage, P is precipitation, Irr is water input from irrigation, GW_{in} is groundwater flowing into the basin, ET is evapotranspiration, Q is discharge at the weirs, and GW_{out} is groundwater flowing out of the basins. Change in storage was calculated as

$$\Delta S = \Delta h(S_y) \quad (3)$$

where Δh is the change in water table and S_y is specific yield. Change in storage for the canals and basins were multiplied by their proportional area to generate comparable change in storage terms. Irrigation inputs were calculated by multiplying pumping times by pumping rates (Table 2-1) over the basin area. Flow of water between basins was calculated with Darcy's law applied to each flow face (basin side) and was estimated between the nearest flow face, baulk, trench, or canal, where applicable. There were 3 different k_{sat} values calculated, as water movement between flow faces occurred either through a baulk, basin or trench (Table 2-2). A geomean K_{sat} value was calculated for the baulks, basins and trenches from the bail test Hvorslev (1951) time-lag solution measurements at the corresponding wells. To improve the representation of the different K_{sat} values throughout the peat profile, each well K_{sat} value (baulk, basin or trench) was averaged with the K_{sat} measurements from the deep peat (Table 2-2).

2.4 Results

Hydraulic conductivity (K_{sat}) was highest near the surface, and decreased with depth to a fine-grained sediment layer (9×10^{-9} m/s). The basins had a higher geomean K_{sat} than the baulks and trenches, and the geomean K_{sat} of the deep piezometers was 1×10^{-8} m/s (Table 2-2). The arithmetic mean K_{sat} of the baulk and deep peat geomean values (3×10^{-6} m/s) was applied through Darcy's law to calculate N/S ground water flows between the basins and baulks. The arithmetic mean K_{sat} of the deep peat and trenches (2×10^{-6} m/s) was used for flow between basins and drainage canals, and the arithmetic mean K_{sat} of the deep peat, trenches and basins (2×10^{-5}

m/s) for flow between basins faces and drainage canals. Residual peat depths were approximately 1.5 m across the site (Table 2-3).

Table 2-2 Mean K_{sat} of the peat piezometers, baulk wells and basin wells. The bold values are the values that were used to calculate ground water flow, the others are for comparison.

	K_{sat} (geomean, m/s)	K_{sat} (arithmetic mean, m/s)
Peat piezometer	**1×10^{-8}**	1×10^{-8}
Baulk wells	**3×10^{-6}**	7×10^{-6}
Basin (range)	**1×10^{-5} to 3×10^{-5}**	2×10^{-5} to 4×10^{-5}
Peat piezo. + baulk	3×10^{-7}	**3×10^{-6}**
Peat piezo. + trench	2×10^{-7}	**2×10^{-6}**
Peat piezo. + basin + trench	8×10^{-6}	**2×10^{-5}**

Table 2-3 Summary of peat properties. Specific yield and bulk density samples are from the top 0 – 20 cm across the site.

	Mean	± SD	Max	Min	n
Peat depth (m)	1.5	0.15	1.3	1.8	15
Specific yield	0.14	0.03	0.18	0.10	11
Bulk density (g/cm^3)	0.11	0.02	0.14	0.09	12

The general direction of water flow was to the south of the experimental area, where there were sharp gradients towards the drainage canals (Figure 2-2). The drainage canals had the lowest local mean WT elevation (~1.21 masl), and the baulks along the N edge had the highest WT (~ 2.0 masl). Water mounds formed in the N baulks and in the baulks separating the basin pairs (Figure 2-2). All basin pairs (LA, CE and PE) were separated by a water table mound associated with the central baulk that minimized groundwater transfer between pairs (i.e. interrupted flow in a southerly direction). The basins with sub-surface irrigation had similar WT elevations (1.61 to 1.70 masl), and the basins with peripheral canals the lowest (1.56 to 1.44 masl), which was a function of site geometry as they were the down gradient in the landscape (Table 2-1). The mean WT elevations were relatively flat in each basin, except for PC10 (Figure 2-2).

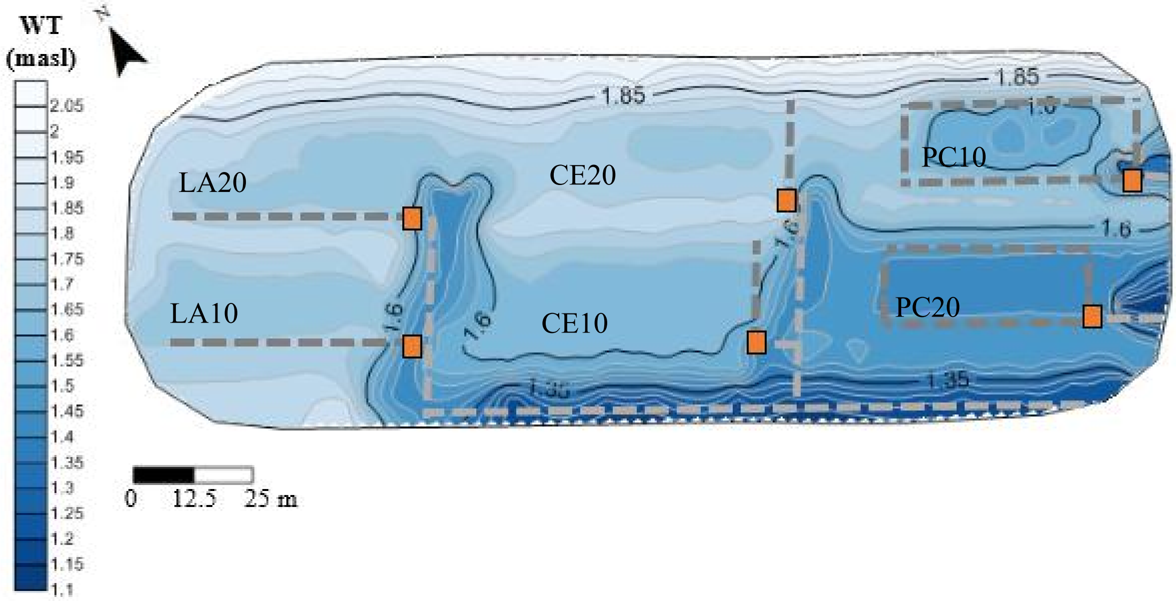


Figure 2-2 Contour map of mean water level (masl) across the site. Dashed dark gray lines represent supply canals, light gray drainage canals and the orange rectangles the weirs.

2.4.1 Precipitation and irrigation inputs

Precipitation (*P*) was the largest water input (238 mm). The 20-year normal (1986-2006) May to August precipitation is 337 mm (Government of Canada, 2015) and comparatively the study period was a dry season. The largest *P* event was 33 mm (DOY 224) (Figure 2-3). Interception from the straw mulch accounted for 17% of the total precipitation, and most interception (9 - 100 %) occurred during events < 5 mm (65 % of rain events were < 5 mm). When rainfall penetrated the mulch layer, there was a WT rise at each basin in response to *P*, regardless of irrigation design (Figure 2-3)

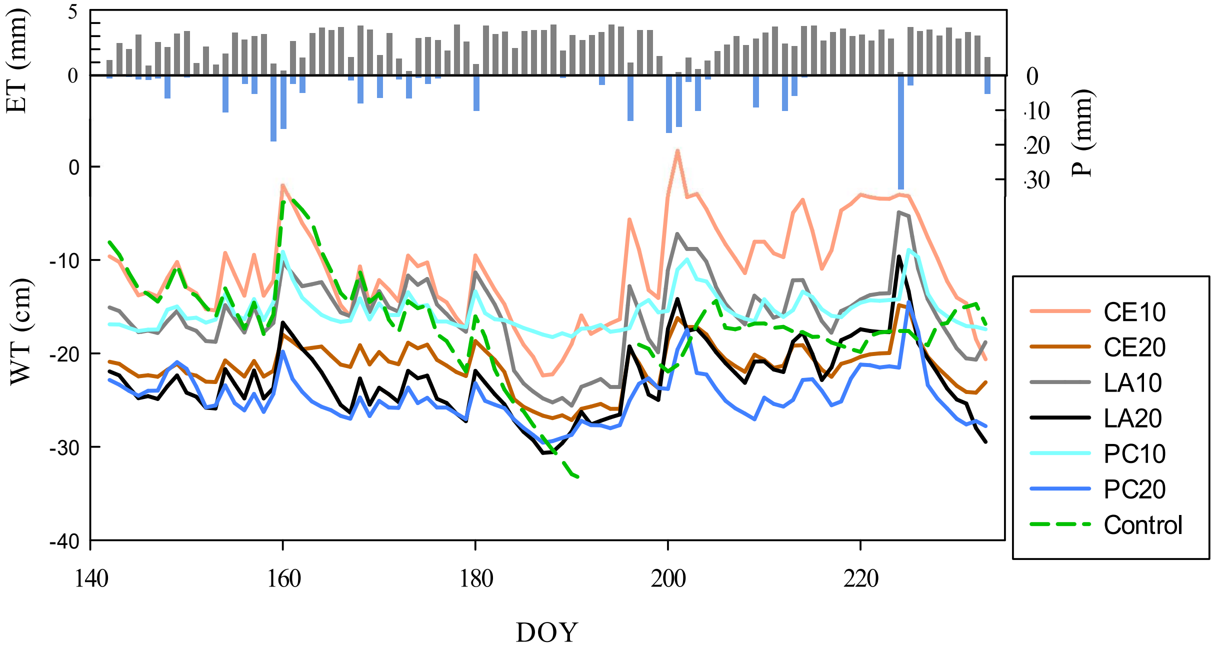


Figure 2-3 Water table (WT), evapotranspiration (*ET*) and precipitation (*P*) from day of year (DOY) 142 - 234. Lines represent daily mean WT levels for each basin and the control.

The mean seasonal WT position of the basins ranged from -13.8 to -22.4 cm (Table 2-4). Basin WT position was higher at the start of the season, and seasonally low levels occurred during the first two weeks of July (DOY 182-199), when there were no rain events greater than 2.6 mm (excluding a 12 mm event on DOY 196) (Figure 2-3). The mean WT at the control experienced a seasonal low of -31.8 (± 0.5) on DOY 199, which was also the lowest of any site. Water levels rose after DOY 199, following four days of rainfall (total 43 mm) (Figure 2-3).

Table 2-4 Field conditions from May 22 to August 22, 2015. Irrigation density is the ratio of irrigation (canals and pipes) length divided by the basin area. Water table is the mean seasonal position of all wells in the basin. Water table range is the mean range (max - min) of wells. *ET* is the seasonal total, water deficit (*WD*) is seasonal *P-ET*.

Basin	Irrigation density (m/m^2)	Mean WT (cm)	WT (cm), DOY 182-199, drying	WT Range (cm)	*ET* (mm)	*WD* (mm)	θ_{-6} (cm^3 cm^{-3})	$\Psi_{-2.5}$ (cm)
CE10	0.1	-15.2 ±5.2	-21.3 ±3.0	17.7 ±3.0	-265.6	-28	0.78 ±0.07	-1.0 ± 7.0
CE20	0.1	-18.1 ±5.7	-24.8 ±3.5	19.3 ±3.5	-215.9	22	0.79 ±0.03	-3.5 ± 6.7
LA10	0.2	-14.6 ±4.7	-19.0 ±3.1	14.7 ±2.7	-229.7	8	0.78 ±0.07	-2.4 ± 7.2
LA20	0.2	-19.4 ±5.8	-24.8 ±4.0	16.5 ±4.0	-199.4	39	0.76 ±0.07	-1.7 ± 5.7
PC10	0.2	-13.8 ±4.0	-17.5 ±2.2	15.2 ±3.3	-270.7	-33	0.76 ±0.07	*n/a*
PC20	0.3	-22.4 ± 3.7	-25.7 ±2.9	13.7 ±1.7	-238.1	-1	0.68 ±0.05	-13.9 ± 5.9
Control	0	-16.7 ± 7.7	-26.4 ±2.0	29.4 ±1.3	n/a	n/a	0.69 ±0.08	n/a

Pumping inputs were greatest during seasonally dry periods (DOY 182-199), inputting from 45 mm (LA20) to 75 mm (CE10) of water, and accounting for over half of the seasonal irrigation inputs during this two-and-a-half-week period. Basins CE10, PC10 and PC20 required the highest irrigation inputs (113, 90 and 87 mm) to attempt to maintain targeted WT. LA10, LA20 and CE20 required the least irrigation input (74 mm). Even so, irrigation inputs were insufficient to maintain targeted WT levels during this dry period, but prevented WT from dropping more than 8 cm below the seasonal mean (Table 2-4). Exceedance probabilities (Figure 2-4a) for the WT falling below the -10 cm target were 79, 83 and 85% for CE10, LA10 and PC10, respectively. The exceedance probabilities for the WT exceeding the -20 cm target were 37 and 48% for CE20 and LA20. PC20, which had the lowest mean WT, exceeded the -20 cm targeted WT 80 % of the time (Figure 2-4b).

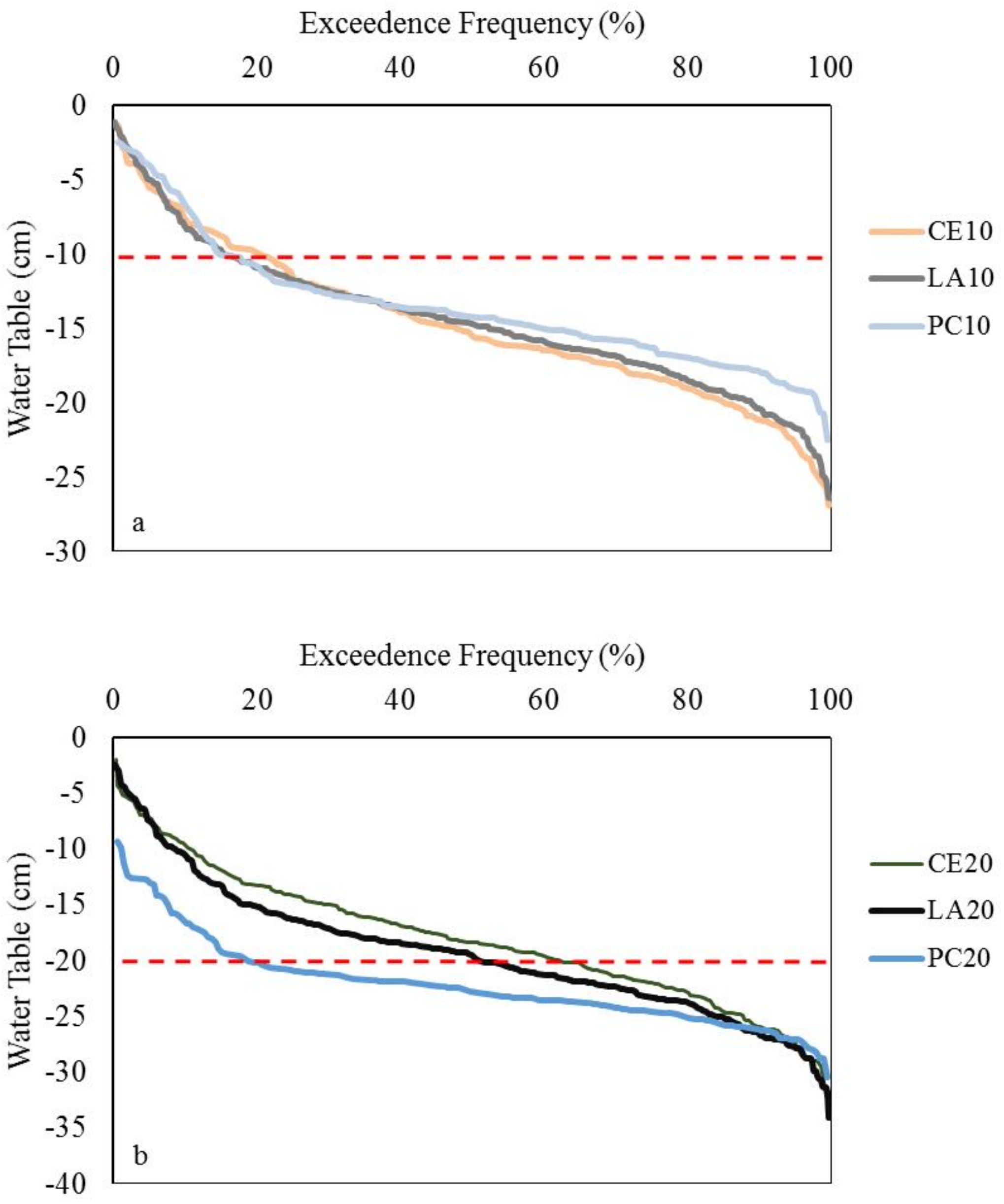


Figure 2-4 Water table position frequency of exceedance for basins with a WT target of -10 cm (a) or -20 cm (b). Dashed red line represents the targeted WT depths of -10 or -20 cm below the surface.

2.4.2 Evapotranspiration

Evapotranspiration was the dominant water loss across the site. Site scale (inclusive of all basins) *ET* (236 mm) was similar to *P* (238 mm). Mean daily *ET* was 2.6 mm ± 1.1 (± SD), and the highest daily *ET* was 3.9 mm (DOY 178). Basin *ET* values ranged 199 - 271 mm, and seasonal *ET* did not significantly differ between basins targeted at a -10 cm WT or -20 cm WT ($t_{3.9}$ = 2.2, p = 0.09), however basins with a higher WT generally lost more water to *ET* than basins with a lower WT (Table 2-6). A water deficit (*P*-*E*) only occurred in Basins CE10 (-28 mm) PC10 (-33 mm) and PC20 (-1 mm) (Table 2-4), which was alleviated through irrigation inputs (Table 2-6).

2.4.3 Discharge, ground water flow and storage changes

Discharge losses (*Q*) from the weirs ranged from 17 to 56 mm. Discharge was the highest at CE20. CE basins had smaller canals; CE20 canal often overflowed from irrigation inputs, although CE10 did not (Table 2-6). The specific yield of canals was assumed to be 1, and that measured for peat was 0.14 (± 0.03) (Table 2-3). Water levels in the basins increased 58 to 109 mm over the season, and in the canals by 8 to 55 mm. Water table in the control decreased by 35 mm. Total storage change ranged from -4.9 (control) to 25 mm (PC20) (Table 2-6).

Ground water inputs were the highest where water mounds formed in the baulks along the N flow face of each basin (Table 2-5) Ground water outputs were along the E flow faces of each basin, towards the secondary drainage canals which connected the basins to the primary drainage canals (Table 2-5). The basins closest to the primary drainage canal (CE10 and PC20) had the highest GW outputs along the S flow face (-10.6 and -11.9 mm) (Table 2-4).

Table 2-5 Ground water inputs (+) and outputs (-) for each side of a basin (flow face). The bold numbers are calculations that were made with the closest possible well, but had no wells associated directly to the flow face.

Basin	N-Side Flow Face (mm)	E-Side Flow Face (mm)	S-Side Flow Face (mm)	W-Side Flow Face (mm)	In-Out (mm)
CE10	+12	-16	-6	-6	-16
CE20	+22	-17	+6	-38	-27
LA10	**+8**	-45	**+8**	+3	-27
LA20	**+22**	-61	**+14**	**-6**	-31
PC10	**+26**	-8	**+17**	-6	+29
PC20	**+25**	-4	**-20**	-4	-3

2.4.4 Water balance

The water balance for each basin was calculated between May 22 and August 22, 2015, with basin-specific inputs and outputs (except *P*). Basin water inputs were precipitation (*P*), irrigation (*Irr*) and groundwater (GW_{in}); the outputs were evapotranspiration (*ET*), ground water (GW_{out}) and discharge (*Q*) The water budget residual terms represented < 10 % at all sites, except for PC10 (12 %) (Table 2-6).

Table 2-6 Water balance for each basin. For the control *GW*in is assumed = *GW*out. ε is the residual.

Basin	*P* (mm)	*Irr* (mm)	GW_{in} (mm)	*ET* (mm)	GW_{out} (mm)	*Q* (mm)	ΔS (mm)	ε (mm)	Error (%)
CE10	238	113	12	266	40	17	15	25	7
CE20	238	74	28	216	55	56	11	1	< 1
LA10	238	74	17	230	45	40	17	-2	1
LA20	238	74	36	199	67	32	21	29	8
PC10	238	90	43	271	14	27	13	46	12
PC20	238	87	25	239	28	48	25	11	3
Control	238	0	0	236	0	0	-4.9	7	3

2.4.5 Irrigation design impacts on water distribution

The range in WT position varied according to irrigation design. Basins that had higher irrigation densities (ratio of water supply canal and pipe lengths to basin area) had the lowest WT ranges over the study period (Figure 2-5). The basin with the highest irrigation density (PC20) had the lowest range in WT position over the study period (Figure 2-5), even though it had the lowest mean WT position (Table 2-4). PC20 and PC10 had different irrigation densities because PC20 had less surface area, a product of the size of the trenches from peat excavation. Basins with the lowest irrigation density (CE10 and CE20) had WT ranges over the study period that exceeded 15 cm (Table 2-7). The water table range at the control (29.4 cm) was larger than at all irrigated sites and the WT position during drying events were lower than at the irrigated sites (Table 2-3).

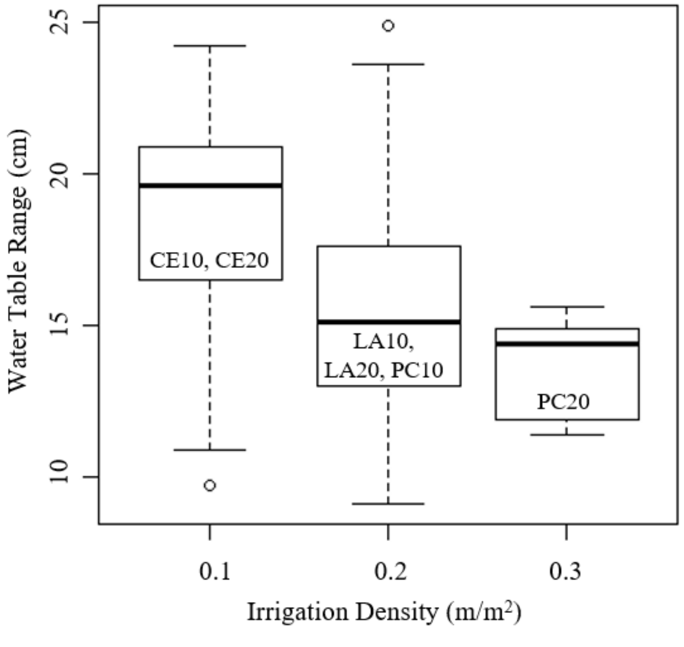


Figure 2-5 Boxplot of water table range and irrigation density (ratio of total pipe and canal length / basin area).

The largest range was always at the most distal location with respect to the irrigation water source, regardless of irrigation density. The smallest mean WT range in the sub-surface irrigation systems was at 0-m from irrigation (Table 2-7), directly over the buried perforated pipe (e.g. 13.0 cm at LA10). At sites with peripheral canals the smallest range was in the wells closest to the canals (11.8 cm at PC20 2 m), but not in the canal itself (Table 2-7). The variability in WT position was more pronounced at basins with a lower mean WT, except for PC20 (Table 2-4). The probability of a well exceeding the 15 cm WT range threshold increased with distance from irrigation (water source) (Table 2-7), and was more pronounced at sites with lower irrigation density (CE10 and CE20) and a low WT with moderate irrigation density (LA20). Basins with a low irrigation density, CE10 and CE20, exceeded the desired WT range 100% of the time, 4 and 6 m from the perforated pipes (Table 2-7).

Table 2-7 Water table range (± SD) at 0, 2, 4 and 6 m from water supply. The second column is the probability that the range of the wells exceeded the 15 cm threshold. Note: Exceedance was not calculated for PC10 and PC20 at 0 m (canals) because they were blocked for part of the study period.

	0 m		**2 m**		**4m**		**6 m**	
Basin	Range (cm)	Exceedance (%)	Range (cm)	Exceedance (%)	Range (cm)	Exceedance (%)	Range (cm)	Exceedance (%)
CE10	15.6 ±1.2	67	16.6 ±1.2	75	20.3 ±1.2	100	20.2 ±1.2	100
CE20	14.6 ±4.2	33	19.4 ±4.5	75	19.3 ±2.9	100	21.1 ±0.8	100
LA10	13.0 ±1.9	25	14.0 ±3.5	33	15.8 ±1.4	67	16.3 ±2.9	73
LA20	13.8 ±3.7	33	15.6 ±3.2	67	20.7 ±3.9	100	18.5 ±2.4	100
PC10	18.0 ±2.3	n/a	13.8 ±4.1	25	13.6 ±0.8	0	16.5 ±4.7	25
PC20	44.0 ±9.3	n/a	11.8 ±0.5	0	14.5 ±0.5	0	15.2 ±0.4	67

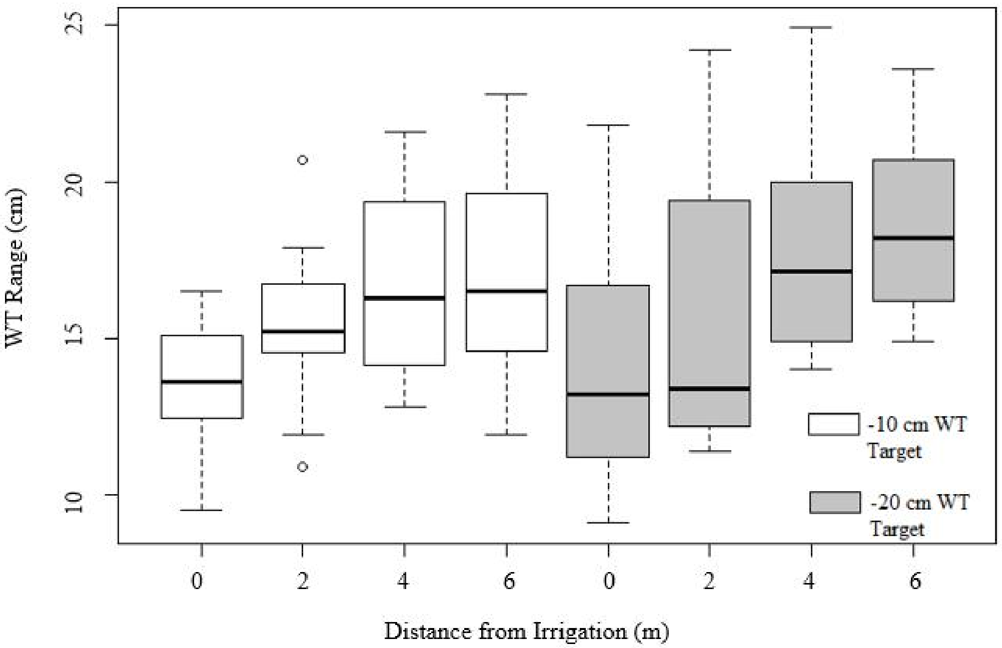


Figure 2-6 WT Variability by distance from irrigation (m) between -10 cm WT target basins (CE10, LA10, PC10) and -20 cm target WT basins (CE20, LA20, PC20). The center line is the median value, top and bottom of the boxes the 25th and 75th percentiles, and the bars the 5th and 95th percentiles. For basins with sub-surface irrigation, distance from irrigation is the distance from sub-surface perforated pipes.

Mean θ in the top 6 cm of irrigated sites ranged from 0.79 to 0.68 $cm^3\ cm^{-3}$ (Table 2-4). Mean daily basin-averaged θ decreased with deeper WT ($F_{1,79}$= 53, $r^2 = 0.40$, p = < 0.001). The lowest recorded basin daily mean θ values were 0.61 $cm^3\ cm^{-3}$ at PC20 (WT -25 cm), and 0.59 $cm^3\ cm^{-3}$ at the control (WT -31 cm). Volumetric water content also declined over the study period at the control, ranging from 0.82 $cm^3\ cm^{-3}$ to 0.59 $cm^3\ cm^{-3}$. The basins with sub-surface irrigation had no significant difference between VWC at 0 m and 6 m from irrigation ($p > 0.05$ for all basins), while the basins with peripheral canals had significantly different θ at 0 m and 6 m from canals (PC10: p = 0.009, PC20: p = 0.04); mean θ was higher and less variable 6 m from canals.

Soil water pressures (ψ) 2.5 cm below the surface ($\psi_{-2.5}$) had a seasonal mean of -5.2 (± 7.3) cm throughout the site, and pressure was lower where mean WT levels were deeper ($F_{1,63}$ =

126.2, $R^2 = 0.69$, $p < 0.001$). Seasonal $\psi_{-2.5}$ exhibited similar trends to WT and θ: lower at the start of the season than the end, and lowest (-8.2 cm ± 5.6) between DOY 182-199 when seasonally low WT levels occurred. The mean ψ (± range) of -2.2 ±35 cm and -8.6 ±34 cm for the -10 and -20 cm WT targets were significantly different ($t_{215} = 6.3$, p = < 0.001).

2.5 Discussion

The 2015 field conditions were dry, an ideal opportunity to evaluate the benefits and limitations of each irrigation design. Each basin maintained hydrological conditions necessary for *Sphagnum* growth (high moisture, low pressure) in a cutover peatland (Price & Whitehead, 2004), as pumping water into the basins helped to reduce the water shortage from low *P* and high *ET*. The canals and sub-surface perforated pipes acted as both sinks and sources of water, depending on the position on the landscape and the WT levels in the canals, which varied according to weather conditions and pump activity. Water table elevation decreased from areas of higher elevation at the north edge of the experimental area (baulks) towards the deep drainage ditches to the south (Figure 2-2).

Active water management reduced the impacts of low *P* and high *ET* demands by maintaining a WT that did not decrease during dry periods to the extent it did at the control site, which had a seasonal low of -29.4 cm (12.7 cm lower than the seasonal mean) (Table 2-4). The WT response did not occur or was minimal when rain events were < 5 mm, because of the 9 to 100 % interception from the straw mulch. During *P* events greater than 5 mm, WT levels responded quickly (Figure 2-3) because of a small intercepting layer (two years of growth) and the small compact pores of the remnant peat (Schouwenaars, 1993), that resulted in a measured specific yield of 0.14 (± 0.03). During rain events the water table in the peat fields, where S_y =

0.14, rose more rapidly than in the adjacent canals, that have $S_y = 1$, so the basin canals acted as water sinks, facilitated by the sub-surface perforated pipes. During dry periods the water table in the peat fields declined below the water level in the canal, because of their differences in S_y, as well as the addition of pumped water.

Evapotranspiration was the largest water loss from each basin, but water deficits were readily replenished in all basins by their respective irrigation systems. Mean daily *ET* was 2.6 (± 1.1) mm, similar to a daily *ET* rate of 2.9 mm reported at a restored block-cut peatland with similar ground cover and number of growing seasons post restoration, but with a higher mean WT (8.6 mm) (Malloy & Price, 2014). The basins with the highest *ET* loss had a mean WT closest to the surface (CE10 and PC10) (Table 2-4) but required the highest irrigation inputs (Table 2-6). There was not a statistical significant difference in *ET* loss between basins with a shallow or deep WT, but basins with a shallow WT consistently lost more water to *ET* (Table 2-6). PC20 had the lowest mean WT, and it seems unlikely that it should have more water loss to *ET* than LA10, LA20 and CE20, which all had higher mean WT positions (Table 2-4). This may reflect variation inherent in using lysimeters, in which the level of wetness or density of straw mulch cover may not have fairly mimicked the conditions in the basins they are supposed to represent. Notwithstanding the results for PC20, it is likely that *Sphagnum* farming operations with a shallow WT will lose more water to *ET* and will thus require more pumping inputs.

Variability in water level position was greater with distance from the irrigation feature (Figure 2-6). Thus, the perforated pipes or canals modulated WT variability, but became less effective with increasing distance and decreasing irrigation density. Because LA10 had four preferential pathways (sub-surface irrigation) and a long canal (50 m) the WT across the basin should be more stable than CE10 (Table 2-4), which only had one sub-surface perforated pipe down the center of the basin and a short canal (20 m) at one end**.** While the range of water table was 3 cm less in LA10 than in CE10 (Table 2-4), their variability and ability to meet the targeted water table was not notably different, based on their duration series (Figure 2-4a). The basins with a -20 cm target were better able to maintain WT targets than those with -10 cm WT targets during a dry year (Figure 2-4), and based on the same arguments for LA10 and CE10, the stability of the LA20 was slightly better than at CE20 (Figure 2-4b). PC20 had a lower mean WT (-22.4), an artifact of the height of the weir, but the presence of canals surrounding PC10 and PC20 resulted in the lowest variability in WT position, as open water can reduce WT variability in adjacent peatland (Larose *et al.,* 1997). WT stability is important for maximizing CO_2 uptake (Manuscript 2). Maintaining a higher WT will maintain high near surface θ and ψ, but near surface θ and ψ at all basins were much higher than thresholds for *Sphagnum* establishment (-100 cm) noted by Price and Whitehead (2004). PC20 had the lowest mean WT, and consequently the lowest θ and ψ values (Table 2-4).

Ground water inputs were the highest at basins along the NE transect (LA20, CE20 and PC10) (Table 2-5), because of inputs from the raised baulks and parallel trenches outside of the experimental area, where water may have accumulated during the wetter 2014 summer, and from the 2015 snowmelt. LA10 and LA20 had GW inputs into the basin canals from water mounds in the adjacent baulks (Figure 2-2), which reduced pumping times and volumes (Table 2-6). LA10 was the only basin on the S transect that received water from the adjacent S baulk, as the outflow canal on the S trench started east of the basin (Figure 2-2). A water mound did not form in the baulks at the south end of the experimental area because of the sharp gradient towards the drainage canal, unlike at the N and central baulk (Figure 2-2). Ground water outputs were the highest at LA10 (67 mm), which had an outflow canal E of the basin (Figure 2-2). The majority of ground water flow out of the basins was towards >1 m deep outflow canals (Figure 2-2). Future sites should consider placing basin canals in areas were water inputs from adjacent landforms can contribute water during dry seasons, but should ensure adequate weirs in the canals to discharge excess water during wet seasons. A buffer zone between the primary deep drainage canals and the *Sphagnum* farming site can reduce groundwater loss from basins.

The ground water flow of some of the basins may be overestimated because of a lack of wells in the adjacent baulks (N-S gradients were determined with baulk wells adjacent to CE10 and CE20). The north flow faces of LA20 and PC10 had high GW inputs (22 and 26 mm) (Table 2-5), which were estimated from wells north of CE20, and values may be overestimated. The ground water flow calculations were more sensitive to the estimation of K_{sat}. Hydraulic conductivity values of the basins were an order of magnitude higher than reported by Taylor & Price (2015) in an experimental *Sphagnum* farming site in the same region (average 1 x 10^{-4} m/s compared to 2 x 10^{-5} m/s in this study). If K_{sat} was lower by an order of magnitude, with values closer to those reported by Taylor & Price (2015), or if a harmonic mean was applied instead of arithmetic, specific discharge would be reduced. An arithmetic mean was selected because flow is assumed to be parallel to the layers of the peat profile. Groundwater flows likely converged towards the outflow canals, thus assumptions of water flow parallel to the water table required for Dupuit-Forchheimer flow assumptions (Freeze & Cherry, 1979) may not have been met. However, error that may have been caused by this are likely much smaller than uncertainty associated with estimating hydraulic conductivity. Change in storage caused by changes in soil moisture was considered negligible, and not included in the storage change calculation because active water management prevented changes greater than 0.04 cm^3 cm^{-3}. Changes in soil moisture for the control were not included, because data were only available for the top 6 cm, and did not extend to the end of the study period.

Discharge may be underestimated at CE10 because manual measurements of high flow are lacking, and the weir overflowed frequently (personal observations). The canal capacity (ability to accept pumping inputs), and thus its ability to stabilize water levels, was less in CE10 and CE20 because of their small (short) canals (20 m^2). These canals could easily be filled to reach the target WT, yet overflowed easily, decreasing the available water supply to the adjacent basin and requiring more time for the basin to reach the target WT. If future sites use small canals, the pumping capacity should be reduced to limit Q water losses.

2.6 Conclusions

This study is the first that evaluated the effectiveness of different types of irrigation designs on the water distribution in an experimental *Sphagnum* farming site established in a post-extraction peatland. Local water flows are strongly affected by the topography of the reclaimed landscape and position of drainage canals. The formation of water mounds in baulks minimized water transfer between basins, and ground water flow primarily occurred towards deep drainage canals. González & Rochefort (2014) report that restored sites surrounded by unrestored sections had lower success because nearby active drainage ditches resulted in less favourable hydrological conditions. In this study, the surrounding unrestored trenches likely contributed water to the site, as the experimental basins were graded to a lower elevation. Future projects should consider leveling basins to a common elevation, and canals should be build upslope and perpendicular to the existing canals to reduce the impacts of the regional slope on ground water flow.

Pumping water into the basins was necessary during a dry year to reduce the water deficit from low *P* and high *ET*. Pumping inputs prevented WT levels from falling more than 8 cm below the seasonal mean during dry periods, but were insufficient for maintaining a position of -10 cm. A WT of -10 cm was maintained less than 20 % of the time, and managers may consider lowering the target WT to -15 cm during a dry season. Basins with a deeper WT (LA20 and CE20) best maintained targets WT levels, but the CE design is not recommended because of low irrigation density that increased the range in WT position. Variability in WT position increased with distance from the pipes and canals. If there is a distance greater than 12 m between canals, productivity may decrease with increasing distance from the stabilizing effects of the canals. Sub-surface irrigation can be used to increase irrigation density in larger sites to maintain stable moisture conditions and optimise productivity. Water retention features, such as small ponds along the edge of the basins, baulks or areas of higher elevation could also assist in reducing peak flow, while reducing irrigation pumping demands.

3.0 The effects of water management on the CO_2 uptake of *Sphagnum* moss in an experimental *Sphagnum* farming site.

3.1 Context

Sphagnum peat is a substrate favoured by the horticultural industry because of its water retention capabilities, chemical stability and slow decomposition (Michel, 2010; De Lucia *et al.*, 2013). *Sphagnum* moss is the primary peat-accumulating genus of ombrotrophic peatlands, and thrives in environments with high moisture content at the growing surface (Clymo & Hayward, 1982; Ferland & Rochefort, 1997). *Sphagnum* has a morphological structure that facilitates capillary rise and water retention to maintain moistness in the capitulum (Hayward and Clymo, 1982; Taylor & Price, 2015) but requires a high water table (WT) to reduce capillary stresses (Price *et al*., 2003). It generates acidity that helps it to outcompete vascular plants (van Breemen, 1995), and *Sphagnum* peat accumulates in cool environments where the aforementioned conditions result in high moss productivity and slow decomposition (Clymo & Hayward, 1982; Gorham, 1991).

To extract *Sphagnum* peat, the upper layers of the ombrotrophic peatlands are drained through a series of ditches, and the less decomposed upper layers are removed using techniques such as block-cutting and vacuum harvesting (Lavoie & Rochefort, 1996). This results in a deeper and more variable WT (Schouwenaars, 1993; Price, 1996). Sites that are not restored generally remain CO_2 sources (Waddington *et al*., 2002; Strack *et al*., 2014) with little to no *Sphagnum* re-establishment because of the altered hydrology and hydrophysical properties of the remaining peat profile (Price *et al.* 2003). To ensure the regeneration of *Sphagnum* moss and resume CO_2 uptake, these peatlands require restoration by blocking of drainage ditches and sometimes by creating bunds to reduce water loss from the site (Schouwenaars, 1993;

Waddington & Price, 2000; Price *et al*., 2003; Shantz and Price, 2006). Vegetation can be reintroduced with the moss layer transfer technique (MLTT), a restoration procedure used to promote re-establishment of *Sphagnum* on bare peat surfaces (Quinty & Rochefort, 2003; González & Rochefort, 2014). While this method was shown to produce a substantial moss layer eight years after restoration at the restored Bois des Bel peatland in Quebec (Isselin-Nondedeu *et al.* 2007), McCarter and Price (2013) showed that after 10 years the moisture conditions of regenerated moss layers may still limit carbon sequestration because of a hydrological disconnect between the cutover peat and *Sphagnum* surface. Nevertheless, the MLTT was successful in increasing the CO_2 uptake of the Bois-des-Bel site (Strack & Zuback, 2013).

The seasonal WT regime is driven by meteorological conditions, subject to the hydraulic properties of the peat such as specific yield (Price & Whitehead, 2001; Price *et al*., 2003), which is a function of the pore size distribution, and hence botanical origin and state of decomposition (McCarter & Price, 2014). These processes and properties ultimately control the soil moisture conditions within the peat profile and *Sphagnum* moss, and thus CO_2 uptake (Silvola *et al*., 1996). Tuittila *et al*. (2004) and Riutta *et al*. (2007) suggest that the optimal WT position to promote CO_2 uptake and growth of *Sphagnum* is -8.5 to -12 cm, depending on the species. However, the effect of WT range (i.e., extent of WT fluctuation) on *Sphagnum* CO_2 uptake is not well documented. If the hydrology can be managed effectively, it may be possible to optimise CO_2 uptake (biomass accumulation) of the site.

Sphagnum farming, a type of peatland paludiculture, is a recently adopted land-management strategy for post-extraction peatlands. The goal of *Sphagnum* farming is to grow and harvest *Sphagnum* biomass on a renewable basis (Pouliot *et al*., 2015; Beyer & Höper, 2015). *Sphagnum* farming can be established on previously extracted peatlands using the MLTT

(Taylor & Price, 2015), and on peatlands that were disturbed for land use activities such as agriculture, forestry and mining (Pouliot *et al*., 2015). Increasing the scale of moss production can be achieved through the implementation of irrigation, which limits the hydrological variability caused by climatic stresses (Pouliot *et al*., 2015; Taylor & Price, 2015). In a *Sphagnum* farming site where the water management design involved a series of manual weirs and blocked ditches, and relied solely on precipitation as a water input, Pouliot *et al*. (2015) found that *Sphagnum* establishment was subject to the meteorological conditions during the first growing season. Meanwhile, Taylor and Price (2015) suggest that biomass production could be improved with sub-surface irrigation to regulate the WT. Similarly, *Sphagnum* fragments grow successfully in areas where the water inputs are regulated with water management designs such as floating mats, sub-surface drainage, and canals (Gaudig *et al*., 2013). However, there is a gap in knowledge on how to optimise CO_2 uptake of *Sphagnum* moss under different types of irrigation treatments and in large-scale production sites.

Water management strategies have the potential to improve *Sphagnum* farming. The objective of this study is to evaluate whether productivity can be increased with irrigation in an experimental *Sphagnum* farming site following the MLTT, under seven different water management designs. The specific objectives are to (1) evaluate the effectiveness of different sub-surface irrigation designs for optimizing the CO_2 uptake of *Sphagnum* moss; (2) identify an optimal WT position and WT range for *Sphagnum* CO_2 uptake; and (3) provide recommendations on water management for future *Sphagnum* farming sites.

3.2 Study Site

The study site is located in a cutover peatland (Bog 530) south of Shippagan, New Brunswick, Canada (47.693°N, 64.763°W). The site has a mean annual air temperature of 4.8°C, and is located in a wet maritime environment with a 20-year (1986-2006) normal precipitation of 1077 mm, 69% of which falls as rain (Government of Canada, 2015). Peat extraction previously occurred from the 1940s to the 1970s at Bog 530 using the manual block-cutting method, resulting in a landscape with ~ 20 m wide alternating linear trenches. The trenches are separated by ~ 1 m high, 20 m wide raised baulks and drainage ditches run parallel to the trenches, adjacent to the baulks. From May to July 2014, six ~ 20 m x 50 m basins, spaced 30 m apart were created within the trenches, separated by the raised baulks (Figure 3-1).

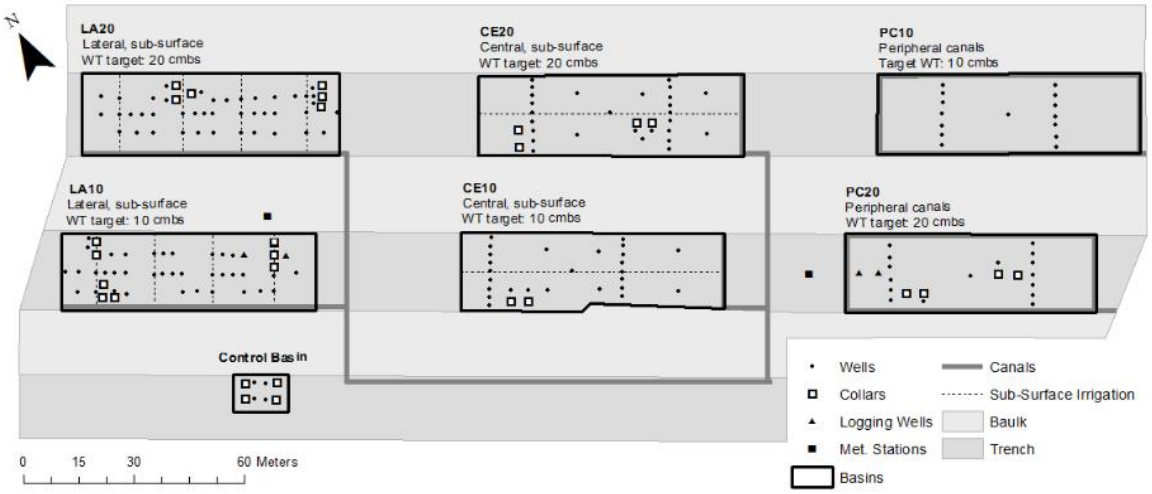


Figure 3-1 Study site of Bog 530 in Shippagan, New Brunswick.

The surface vegetation was removed from the trenches and the peat surface was leveled to ± 5 cm. Three different species treatments of *Sphagnum* moss (*S. magellanicum, S. flavicomans* and mix of *S. fuscum* and *S. rubellum*) were introduced manually over the bare peat and covered with straw mulch following the MLTT (Quinty & Rochefort, 2003). Prior to moss introduction, perforated drainpipes were installed 60 cm below the surface in four of the basins. Two of the basins had perforated pipes installed laterally every 12.5 m, and are denoted in this study as either LA10 or LA20, LA signifying "lateral" and the subsequent numbers the targeted WT depth (Figure 3-1). Two of the basins were installed with a 50 m sub-surface perforated pipe running down the center, denoted as CE10 and CE20, CE for "central". Two of the basins had no sub-surface irrigation installed, and instead had canals measuring ~ 1 m wide and ~ 60 cm deep around the periphery, denoted as PC10 and PC20, PC for "peripheral canals". In 2015, a control area was built by extracting four 60 cm x 60 cm x 15 cm deep blocks of peat established with the MLTT in the previous year, with the intent to create control plots with comparable moss establishment at the start of the 2015 monitoring program. The water levels (excluding the control) were managed through a series of pumps and irrigation tubes connected to a nearby pond in the peatland (~ 75 m west).

3.3 Methodology

In the years 2014 and 2015, twenty-eight stationary plots (60 cm x 60 cm x 15 cm deep stainless steel collars inserted into the peat) were established in the mixed moss (*S. fuscum* and *S. rubellum*) treatment, since this is most commonly found in natural peatlands in the region. Plots were located to capture the broadest range in WT depths: in 2014, they were placed according to distance from the irrigation feature, and in 2015 modified based on observations the previous year in order to capture a broader range of WT positions. Wells were installed adjacent to each group of two plots in 2014, and each plot in 2015, to measure the WT. Boardwalks were installed near each plot to reduce the disturbance during sampling. Data were collected from July 10 to

August 14 in 2014, and May 11 to August 22 in 2015. The year 2014 will be referred to as “year 1” and 2015 as “year 2” throughout this study.

3.3.1 Environmental conditions

Two meteorological stations at the site recorded precipitation (Texas automatic tipping-bucket rain gauge), photosynthetically active radiation (PAR) (Campbell Scientific, PQS1L), soil temperature at 5 cm depth with a thermocouple wire, air temperature/relative humidity (Campbell Scientific, CS215-L), and wind speed (Campbell Scientific, 05103-10-L) measured every 30 seconds and averaged hourly (Figure 3-1). Two pressure transducers (Solinst Levelogger) placed near each meteorological station, compensated for barometric pressure with a Solinst Barologger, recorded the WT position every hour. Data from a meteorological station in Bas-Caraquet, ~ 12 km NW, were used to complete missing precipitation data for May and the end of August in 2014 and 2015, and net radiometer data for May 2015. The net radiometer data were used to create a regression with PAR at the study site to complete missing PAR data for May 2015. Long-term data (1986-2006) were available from Haut-Shippagan, ~ 5 km from the study site, and were used to calculate the 20-year average precipitation for the region (Government of Canada, 2015).

The percent cover of *Sphagnum* capitula in each plot was recorded at the start and end of the growing season. A 3 cm x 3 cm square was randomly placed on the surface of each plot, and the visually estimated capitula cover within the grid was recorded. The measurement was repeated eight times and averaged to estimate total percent cover. *Sphagnum* height increase was measured with crank wires (Clymo, 1970) in the plots at the start and end of the field season. Soil temperature profiles were recorded at -2 and -5 cm and at subsequent 5 cm intervals until -

30 cm with a portable thermocouple probe and thermometer (HH200A Omega Handheld Thermometer), and volumetric soil water content measured at -3 and -6 cm with a portable WET-Sensor™ (Delta-T Devices, Cambridge, UK); individual gravimetric calibrations were completed for each hydrological group.

Water levels were monitored with a series of wells. Each plot had a well associated with it, and each basin had additional wells at 0, 2, 4, 6 and 8 m, if appropriate, away from the respective irrigation supply point (Figure 3-1). The range in WT was calculated by subtracting the seasonal maximum and minimum WT. When comparing CO_2 fluxes to WT range, plots in PC20 were not included because the basin remained frozen for half the study period, which affected the WT range and *Sphagnum* productivity. It is unclear whether the basin remained frozen because of the design, or because of local environmental variables. A linear regression equation was created for the wells at each plot from a logging pressure transducer to calculate hourly WT levels (minimum $R^2 = 0.55$, $p < 0.001$). RStudio, R version 3.2.2, was used for statistical analysis (R Core Team, 2015), with a significance level of $\alpha = 0.05$. Welch's two sample t-tests were conducted to compare seasonal means of θ or GEP between the different WT treatments (-10 or -20 cm). Linear regressions between data were used to evaluate relationships between ground cover, vertical growth, WT range, GEP_{max} or ER, WT range on GEP_{max} and NEE_{max}, and changes in soil temperature and θ on ER.

3.3.2 Carbon dioxide exchange

Net ecosystem exchange (NEE) of CO_2 was measured using the closed chamber technique (Alm *et al.*, 1997) approximately twice per week at each plot. Any vascular vegetation (sparse) within the plot was clipped at the start of each measurement to meet the scope of this study, which is an evaluation of *Sphagnum* productivity. A portable infrared gas analyzer (IRGA) (Model-EGM4; PP Systems, Massachusetts, USA) was connected to a transparent acrylic chamber (60 cm x 60 cm x 30 cm) that was placed over the plots. Two battery-powered fans mixed the air within the chamber, and the lip on the collar was filled with water to prevent air leakage. Measurements of CO_2, photosynthetically active radiation (PAR), temperature, and relative humidity (RH) were made within the chamber for 120 s and recorded every 15 s (starting at 0 s). The chamber was vented after each measurement. Measurements were made under full light and reduced light conditions, which were simulated using fiberglass mesh shrouds. Ecosystem respiration (ER) was determined with an opaque shroud. The linear change in CO_2 concentration was used to calculate NEE and ER, and corrected for chamber volume and temperature. Gross ecosystem productivity (GEP) was calculated by subtracting ER from NEE. This paper uses the convention that negative CO_2 flux represents a sink of CO_2 from the atmosphere into the ecosystem. GEP_{max} was determined when light was non-limiting (PAR > 1000 μmol m^{-2} d^{-1}; Bubier *et al*, 2003). In 2014, data from 10 plots were removed from the analysis because there were fewer than two GEP_{max} measurements. Mulch was removed from the moss in four of the plots to measure respiration from the moss, which was subtracted from the ER of adjacent plots with straw to calculate daily average straw respiration. Straw respiration was multiplied by the number of days in the season to calculate the seasonal value.

3.3.3 Growing season basin CO_2 exchange

GEP and ER were modelled to estimate year 2 seasonal CO_2 exchange; data from year 1 was too sparse to include in the model. Carbon exchange plots were grouped hydrologically (Table 3-1) according to average seasonal WT position and WT range. GEP was modelled for each group using measured GEP and PAR, and rectangular hyperbola according to Strack *et al*. (2014):

$$\mathrm{GEP}=\frac{\mathrm{Q} \times \mathrm{PAR} \times \mathrm{GP}_{\mathrm{max}}}{\mathrm{Q} \times \mathrm{PAR} + \mathrm{GP}_{\mathrm{max}}}$$

where Q is the quantum efficiency and represents the slope of the rectangular hyperbola, and $\mathrm{GP}_{\mathrm{max}}$ is a theoretical maximum GEP flux reached (Table 3-3) and is the asymptote of the rectangular hyperbola. Separate empirical models were created for the early (May-June) and mid-late parts (July-August) of the growing season.

Ecosystem respiration was modelled in relation to measured soil temperature at -5 cm using the equation from Günther *et al*. (2014):

$$\mathrm{ER}=\mathrm{R}_{\mathrm{ref}}\times \mathrm{e}^{\mathrm{E0}}\left[\frac{1}{\mathrm{T}_{\mathrm{ref}}-\mathrm{T}_0}\,\frac{1}{\mathrm{T}-\mathrm{T}_0}\right]$$

where $\mathrm{R}_{\mathrm{ref}}$ is ER (g CO^2 m^{-2} d^{-1}) at the reference temperature ($\mathrm{T}_{\mathrm{ref}}$) of 283.5 K, E0 is the activation energy (K), T_0 is a constant, describing temperature at which biological processes start (237.48 K); and T is the soil temperature at - 5 cm during measurement.

Net ecosystem exchange was calculated by adding modelled GEP and ER for each WT group. Model errors (R^2 values) (Table 3-3) were determined by creating a regression between measured field NEE and model NEE (Aurela *et al.* 2002; Günther *et al*. 2014). Standard error for each hydrological group (Table 3-3) and error bars for each basin CO_2 balance (Figure 3-5) was calculated according to Adkinson *et al.* (2011). The model values were scaled to the basin level by grouping the wells by the same hydrological groups (by WT position and WT range) used to classify the plots, and applying the corresponding model equation to each well (Table 3-1). Dividing the field values this way allowed WT range to be included in the estimated growing CO_2 exchange, and allowed for the scaling of NEE across the basins. Carbon dioxide flux of the control was not modelled because data collection did not begin until the start of June, and did not represent the start of the growing season (May - June).

Table 3-1 WT measurements by year and hydrological group (± standard error), n = 13 (2014), n = 16 (2015), except the control n = 13.

	Year	LA10	CE10	PC10	LA20	CE20	PC20	Control
Mean WT (cm)	2014	-10.9 ±4.2	-7.8 ±4.4	-7.9 ±4.4	-15.7 ±6.9	-11.3 ±6.9	-18.8 ±4.6	-
	2015	-14.6 ±4.7	-15.8 ±5.2	-13.8 ±4.0	-19.3 ±5.8	-18.2 ±5.6	-22.4 ±3.7	-16.7 ±7.7
Hydrological Groups (cm)	**2015**	**Wells (%)**						
Wet-Stable WT < 15, Range < 15		25.6	12.0	60.0	5.4	0.0	0.0	-
Wet-Unstable WT < 15, Range > 15		30.8	40.0	13.3	5.4	11.5	0.0	-
Dry-Stable WT 15-25, Range < 15		20.5	16.0	6.7	27.0	3.8	0.0	-
Dry-Stable WT 15-25, Range > 15		23.1	32.0	20.0	62.2	84.6	0.0	-
PC20		0.0	0.0	0.0	0.0	0.0	100.0	-
Total wells (n)		*39*	*25*	*15*	*37*	*26*	*16*	-
Modelled Seasonal GEP (CO_2 m^{-2})	2015	-300.7	-246.7	-328.4	-257.5	-233.0	-233.0	-
Modelled Seasonal ER (CO_2 m^{-2})	2015	521.8	482.4	595.2	486.4	462.2	340.2	-

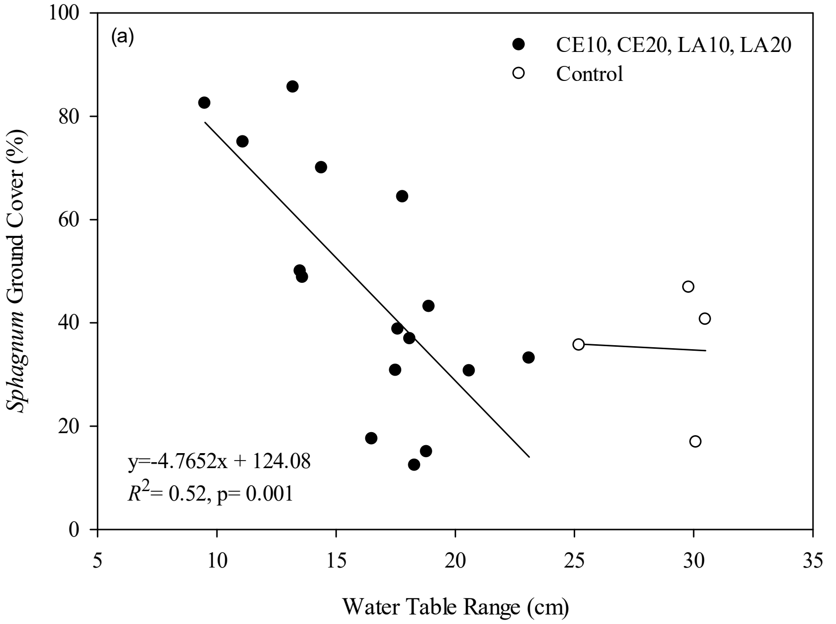
3.4 Results

3.4.1 Meteorological and environmental conditions

Year 1 was characterized as wet with May to August rainfall of 377 mm, and year 2 as dry with 238 mm. The 20-year (1986-2006) normal average (May to August) was 337 mm (Government of Canada, 2015). Average monthly air temperature in both years did not vary more than 0.3 °C from the 20-year normal. The amount of precipitation received was reflected in a higher (year 1) or lower (year 2) WT; basin mean WT in year 1 was -11.8 ± 0.20 cm (mean ±

standard error) and -17.1 ± 0.12 cm in year 2. In general, the WT was lowest in PC20 and highest in PC10, both of which had no sub-surface irrigation, and was the most variable in the control, which had no active water management (Table 3-1). In year 2, mean θ at 0 to -6 cm, which was controlled by WT position ($F_{1,22} = 15.5$, $R^2 = 0.41$, $p < 0.001$), was 0.64 to 0.82 cm^3 cm^{-3} (0.72 ± 0.01), and did not vary significantly between plots with a WT target of -10 or -20 cm ($t_{13.6} = -0.53$, $p = 0.6$). The control had the only plots that declined in θ throughout the study period, and where average θ fell below 0.60 cm^3 cm^{-3}.

At the end of year 2, plot *Sphagnum* cover varied from 12.4 to 82.5 % (mean ± standard error = 44.1 ± 4.1 %), an average increase of 16 % from year 1, which ranged from 12 to 65% (38 ± 3.1 %). Plots with a greater range in WT had less *Sphagnum* cover (Year 1: $F_{1,10} = 7.5$, $R^2 = 0.43$, $p = 0.021$, Year 2: $F_{1,18} = 6.3$, $R^2 = 0.27$ $p = 0.018$). Plots that had a higher percent cover also had the highest height increase ($F_{1,18} = 32.7$, $R^2 = 0.63$, $p < 0.001$). Average *Sphagnum* height increase was -0.26 to 1.64 cm (0.40 ± 0.33) from the start to the end of the year 2 study period. *Sphagnum* growth increased yearly and seasonally, but two plots did have a decrease in height: LA20 1 and 2 (these sites experienced a period of inundation or excess mulch accumulation in year 1). Plots with a stable WT range generally had higher *Sphagnum* ground cover, except for the control (Figure 3-2a).



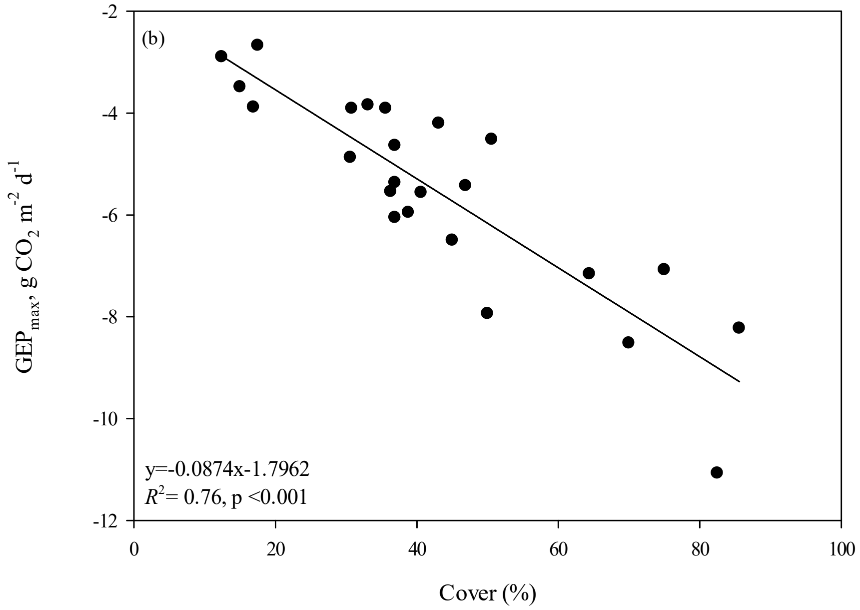


Figure 3-2 Control of WT range on *Sphagnum* ground cover (a) and the relationship between *Sphagnum* ground cover and gross ecosystem photosynthesis (GEP) when photon flux density of photosynthesis was greater than 1000 µmol m^{-2} s^{-1} (GEP_{max}).

3.4.2 Controls on plot scale CO_2 fluxes

Mean CO_2 uptake (GEP_{max}) doubled from year 1 ($n = 14$, -2.85 ± 0.26) to year 2 ($n = 24$, -5.60 ± 0.42), but varied across the site (Table 3-2). Plots that had developed a larger *Sphagnum* carpet by the end of year 2 had greater CO_2 uptake (Figure 3-2b). *Sphagnum* ground cover was a significant predictor for GEP_{max} in both years (year 1: $F_{1,10} = 7.4$, $R^2 = 0.42$, $p = 0.02$ year 2: $F_{1,22} = 69.7$, $R^2 = 0.76$, $p < 0.001$) and vertical growth in year 2 ($F_{1,18} = 21.64$, $R^2 = 0.56$, $p < 0.001$). Because of limited GEP_{max} data from year 1, hereafter the primary focus of analysis will be for year 2 unless otherwise stated.

Table 3-2 Year 2 mean (±SE) field data, sorted by hydrological group.

Hydrological Groups	Basin and plot #s	WT (WT range) (cm)	NEE_{max} (g CO_2 m^{-2} d^{-1})	ER (g CO_2 m^{-2} d^{-1})	GEP_{max} (g CO_2 m^{-2} d^{-1})	Ground Cover (%)	Crank Wire (cm)
Wet-Stable WT < 15, Range < 15	LA10 3 & 4	-12.4 (12.2)	-0.58 ±0.43	6.85 ±0.57	-7.54 ±0.64	80.3 ±5.3	0.55 ±0.05
Wet-Unstable WT < 15, Range > 15	CE10 1 & 2 CE20 1 & 2	-12.6 (19)	1.78 ±0.23	4.67 ±0.26	-3.56 ±0.23	31.1 ±5.3	0.28 ±0.08
Dry-Stable WT 15-25, Range < 15	LA10 1, 2, 5 & 6	-17.3 (13)	-1.07 ±0.22	7.14 ±0.26	-8.34 ±0.41	62.8 ±8.2	0.62 ±0.19
Dry-Unstable WT 15-25, Range > 15	LA20 1,2,3 & 4 CE20 3 & 4	-21.5 (19)	0.66 ±0.18	5.39 ±0.18	-4.98 ±0.29	33 ±7.7	0.16 ±0.14
PC20	PC20 1, 2, 3 & 4	-23.2 (11)	0.14 ±0.16	4.31 ±0.24	-4.83 ±0.26	40 ±3.5	0.32 ±0.04
Control	CB 1-4	-16.9 (28.9)	2.05 ±0.33	6.84 ±0.23	-4.45 ±0.26	35 ±6.5	n/a

Plot mean GEP_{max} was not significantly different between basins with a target WT of -10 or -20 cm ($t_{9.6}$ -2.0, $p = 0.08$), and mean WT was not a significant predictor for GEP_{max} ($p = 0.76$). Maintaining a stable WT (i.e., lower WT range) was a more significant predictor than WT position for mean GEP_{max} ($F_{1,18} = 10.4$, $R^2 = 0.36$, p = 0.004) and NEE_{max} ($F_{1,22}=14.2$, $R^2 = 0.40$, p = 0.001). The relationship between GEP_{max} and WT range was stronger at the plots within actively managed basins ($F_{1,14}= 19.42$, $R^2 = 0.58$, p = <0.001) (i.e. not control plots); plots with a WT range <15 cm were more productive than plots with a range >15 cm (Figure 3-3). Plots with a stable (<15 cm) and unstable (>15 cm) WT range had significantly different GEP_{max} ($t_{8.6}$ -4.8, p = 0.001). The relationship between GEP_{max} and WT range was further supported by investigating daily variability in WT. GEP_{max} was significantly controlled by the number of days during which the peat was thawed and WT remained within ± 5 ($F_{1,16} = 8.1$ $R^2 = 0.34$, p = 0.01) or 7.5 cm ($F_{1,16} = 21.61$ $R^2 = 0.58$, p <0.001) from the seasonal mean WT (Figure 3-4). Instantaneous θ in the top 6 cm was a weak predictor for GEP_{max} at all plots ($F_{1,22} = 4.7$, $R^2 = 0.18$, p = 0.04), while more of the variation in the GEP_{max} of dry plots (WT -15 to -25 cm) was explained by θ at 0 to -3 cm ($F_{1,12}=14.5$, $R^2 = 0.55$, p = 0.002).

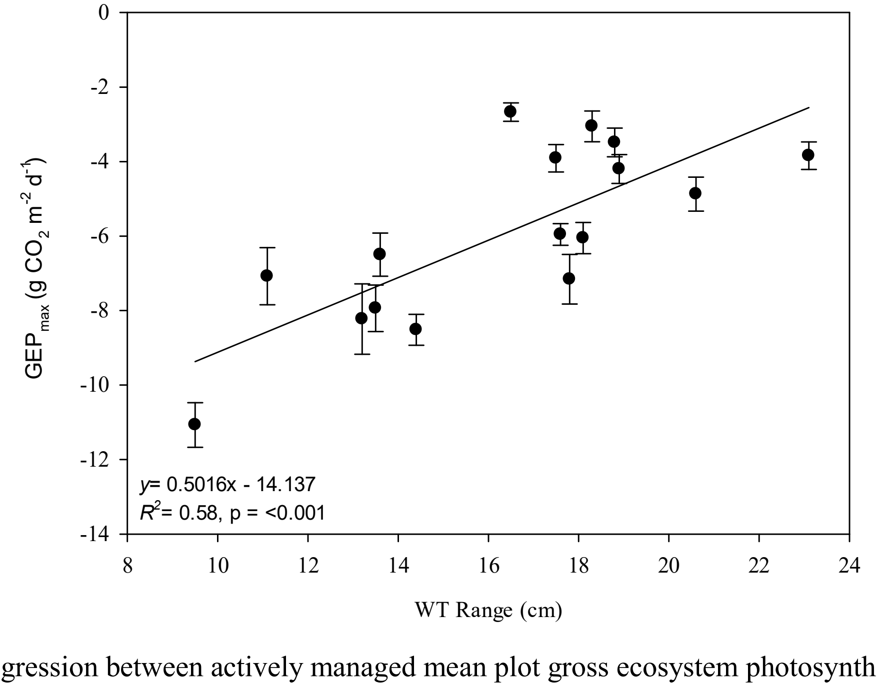


Figure 3-3 Regression between actively managed mean plot gross ecosystem photosynthesis when photon flux density of photosynthesis was greater than 1000 µmol m^{-2} s^{-1} (GEP_{max}) and WT range (Year 2). Error bars show SE of the mean.

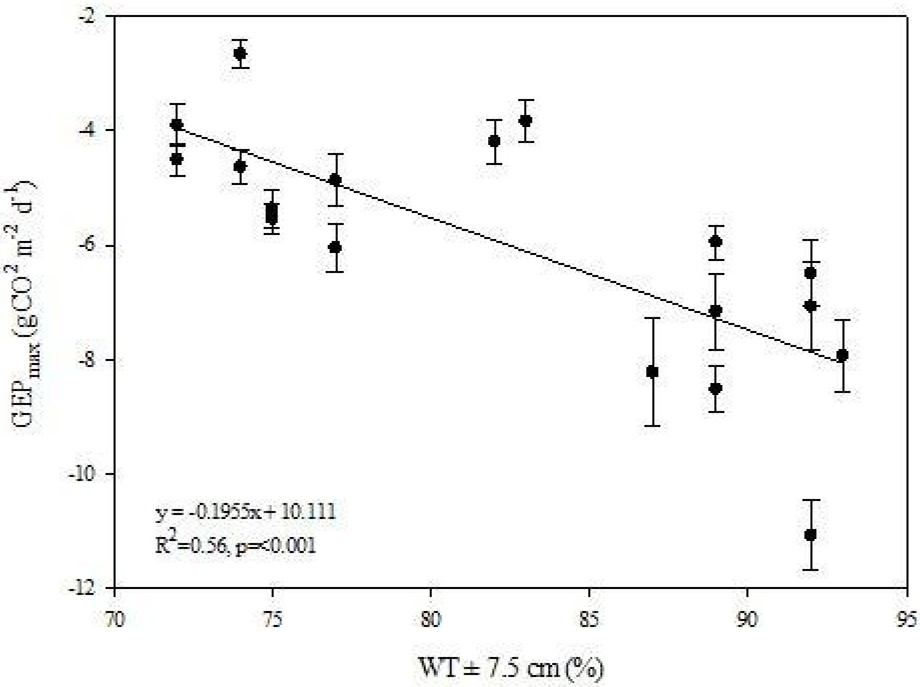


Figure 3-4 Year 2 mean plot gross ecosystem photosynthesis when photon flux density of photosynthesis was greater than 1000 µmol m^{-2} s^{-1} (GEP$_{max}$) and optimal range days (ORD), which is the number of thawed days in the growing season that the WT remained ± 7.5 cm from the seasonal mean. The control was not included because data collection does not represent the start of the growing season. LA20-1 and LA20-2 were not included because they were the only two plots that decreased in cover, and this is attributed to inundation in year 1, or measurement error.

Mean plot ER was significantly different between basins with a WT target of -10 or -20 cm ($t_{10.7} = 3.7$, $p = 0.003$). Variability in ER was partially accounted for by soil temperature at -5 cm depth and *Sphagnum* ground cover ($F_{1,19} = 16.1$, $R^2 = 0.42$ $p < 0.001$, $F_{1,22} = 15.7$, $R^2 = 0.47$, $p < 0.001$, respectively). There was no strong relationship between mean plot ER and θ when grouping all of the measurements together. There was a significant negative relationship between mean plot ER and θ at -0 to -6 cm when comparing plots with a WT range > 15 cm ($F_{1,8} = 16$, $R^2 = 0.67$, $p = 0.003$), regardless of being wet or dry. The respiration from the straw mulch contributed an average of 1.67 (± 0.19) g CO_2 m^{-2} d^{-1}.

3.4.3 Modelled CO_2 exchange

The empirical models for net CO_2 exchange within the hydrological groups explained 67 – 78 % of the variation in data (Table 3-3), except for the wet-unstable group, where only 47 % of the variation was explained, possibly leading to underestimation (smaller sink). The plots with the greatest modelled seasonal GEP had a stable WT, regardless of being wet or dry (Table 3-2). When upscaled to the basin level, PC10 and LA10 had the greatest CO_2 uptake as GEP, and CE20 and PC20 the lowest (Figure 3-5). The effect of water management design on GEP was greater at the end of the growing season, when clearer differences were observed in GEP between basins (Table 3-2). Seasonal basin GEP increased from May-June and July-August in the -10 cm target basins CE10, LA10, and PC10 by 14, 29, and 13 %, respectively, and CE20, LA20, and PC20 by 10, 13 and 11 %, respectively.

Table 3-3 Model parameters and estimated total seasonal NEE and straw respiration.

WT Group		Parameters (GEP)			Parameters (ER)			Model Error (NEE)	Model NEE (g CO_2 m^{-2})	Model NEE (no straw) (g CO_2 m^{-2})
		Gpmax	Q	R^2	Rref	E0	R^2	R^2		
Wet-Stable	Start	5.60	0.065	0.71	3.31	266.8	0.80	0.72	295.9 ±3.5	128.9 ±23.4
	End	13.0	0.031	0.81						
Wet-Unstable	Start	4.57	0.006	0.71	2.72	206.7	0.57	0.47	229.8 ±1.7	62.8 ±21.0
	End	4.21	0.022	0.72						
Dry-Stable	Start	8.37	0.021	0.77	4.28	154.2	0.51	0.78	193.9 ±18.4	26.9 ±38.0
	End	12.22	0.030	0.79						
Dry-Unstable	Start	5.26	0.011	0.64	3.60	142.8	0.51	0.7	236.4 ±4.0	69.4 ±23.9
	End	7.25	0.018	0.70						
PC20	Start	6.28	0.009	0.79	2.82	177.3	0.68	0.67	104.1 ±3.9	-62.9 ±23.8
	End	6.22	0.020	0.74						

Modelled ER was highest where there was the most CO_2 uptake (Table 3-1); ER was greatest at PC10, and lowest at PC20. Seasonal NEE (GEP + ER) ranged from 104.1 to 295.9 g CO_2 m^{-2} with each basin acting as a CO_2 source (Table 3-3). Respiration from the straw contributed 167 (± 19) g CO_2 m^{-2}, which accounted for over half of seasonal ER. When straw ER was subtracted from modelled ER, PC20 was a CO_2 sink, although it also had the lowest GEP and ER (Figure 3-5) and the least amount of *Sphagnum* growth (Table 3-2), and remained frozen longer.

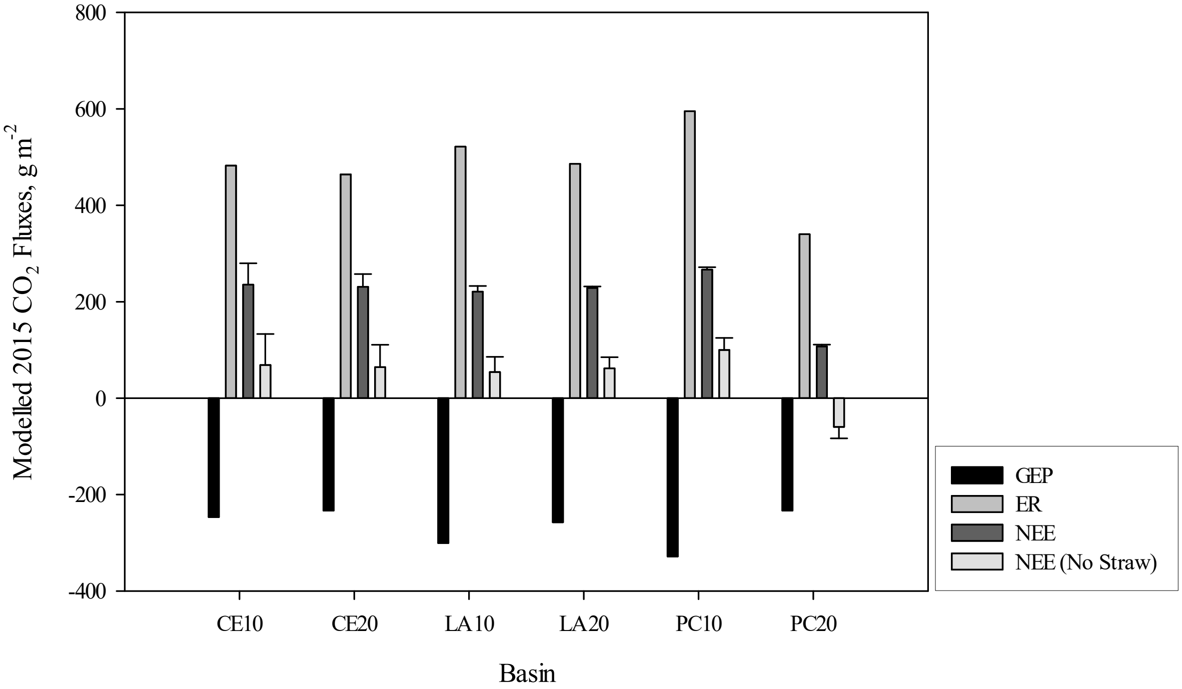


Figure 3-5 Modelled 2015 CO_2 fluxes of each basin. Error bars were only calculated for NEE.

3.5 Discussion

While productivity increased seasonally at all actively managed plots, there were a range of GEP_{max} values (Table 3-2), suggesting that specific irrigation designs encouraged CO_2 uptake, to varying degrees. Sub-surface irrigation was effective in increasing productivity, especially where it restricted the WT range, which was more important than actual WT position for encouraging *Sphagnum* CO_2 uptake and ground cover establishment. Maintaining a stable WT is necessary for increasing CO_2 uptake because of the importance of uniform wetness conditions on *Sphagnum* establishment (Price & Whitehead, 2001), and for increasing CO_2 uptake during periods of seasonally low WT levels. While a wet first season is crucial for *Sphagnum* establishment (González & Rochefort, 2014), a stable WT may be the important condition present during the wet season, since drying cycles, which limit productivity (McNeil & Waddington, 2003), are less pronounced. In year 2, as the moss carpet grew, more of the variability in CO_2 was explained by *Sphagnum* ground cover than in year 1, indicating a degree of covariance. The increase in GEP_{max} was a function of how much photosynthesizing material was available (more moss), and the moss carpet was greater where the WT was more stable (Figure 2-2a). However, WT range is also important for influencing GEP_{max} directly, as moisture condition affects rates of photosynthesis (McNeil & Waddington, 2003). Plots that had seasonal WT ranges of less than 15 cm had higher rates of CO_2 uptake than plots with a range greater than 15 cm (Figure 2-3), and in year 2 this was considered the threshold for limiting or increasing productivity as there was a natural split in the data around this WT range (Figure 2-3). However, if the daily WT can be controlled to fluctuate less than ± 7.5 cm or ± 5 cm from the seasonal mean, further CO_2 uptake can likely be achieved (Figure 2-4).

Water table levels have previously been found to influence CO_2 fluxes in *Sphagnum* moss (e.g., Silvola *et al*., 1996; Robroek *et al*., 2009); however, in this study WT was not a significant predictor for CO_2 uptake. Studies have suggested that *Sphagnum* is not limited by WT position when it is shallower than -40 cm (Ketcheson & Price, 2011; Taylor *et al*., 2015), and McNeil and Waddington (2003) reported that modelled GEP of wet sites (WT -18 to -21 cm) were higher than dry sites (WT -31 cm), suggesting that the WT at the study site in this present study was not low enough to observe a decline in productivity when comparing different water treatments. While a high WT position may not significantly improve CO_2 uptake, it can be important for *Sphagnum* growth as WT controls the near-surface θ (Taylor & Price, 2015). At this site θ at the surface was a weak predictor for mean GEP_{max}. However, it was significant at dry plots (WT -15 to -25 cm), because a lower WT combined with altered water storage properties of the cutover peat resulted in more pronounced wetting/drying cycles, which are known to reduce CO_2 uptake (Gerdol *et al*., 1996; McNeil & Waddington, 2003). Maintaining a higher WT will improve CO_2 uptake by limiting fluctuations in moisture conditions. Moore *et al.* (2015) found that sites with WT shallower than -14 cm had less pronounced wetting/drying cycles than sites with a WT of approximately -15 to -18 cm, regardless of WT position. Although in this present study CO_2 uptake in the wet-stable and dry-stable groups was the highest, a WT target of less than -15 cm can maximise CO_2 uptake by reducing moisture stress on photosynthesizing capacities of the moss by limiting fluctuations in moisture conditions.

Considering various irrigation designs, LA10 and PC10 had the highest modelled seasonal GEP (Figure 2-5), as these basins had the most stable WT levels (Table 3-1). The configuration of the lateral irrigation design minimised the distance to the source and sink of water, thus modulating WT fluctuations and creating more favourable growing conditions across the entire basin surface. Although peripheral canals also appear to perform well, they are not recommended as they reduce the growing surface area and emit more methane per unit area (e.g., Strack & Zuback, 2013). Peripheral canals may be less effective at maintaining a stable WT if production area is increased, because of the relatively poor water retention of the cutover peat (Price & Whitehead, 2001). Canals are also prone to erosion (Holden *et al*., 2004), highlighting the importance of sub-surface irrigation for optimizing production. However, future research should evaluate the lifecycle of sub-surface irrigation, as some issues could occur such as blockage of the perforated pipes. The *Sphagnum* hummock-forming species in this study, *S. rubellum* and *S. fuscum*, are effective at transporting water to the photosynthesizing upper layers of the moss (Rydin, 1985; McCarter & Price, 2014), and this competitive advantage may limit the productivity of hummock species when there is excess moisture, particularly when the thickness of the newly established moss layer is < 5cm (Taylor *et al.* 2015)**.** Two plots decreased in *Sphagnum* height (LA20 1 & 2), and this was likely attributed to a prolonged period of inundation in year 1. Therefore, while maintaining a stable WT is important, irrigation designs also need to be responsive to excess moisture availability, draining basins quickly to prevent extended periods of inundation.

Despite fairly quick *Sphagnum* establishment following MLTT, all basins were CO_2 sources in year 2 (Figure 2-5). Vascular plants, which are known for having higher rates of short-term CO_2 uptake (Strack *et al*., 2016), were present at the site, but not included in this study (clipped). Moss is a NEE sink at around 75% cover (Strack *et al*., 2016), and only three of the plots in year 2 had cover in this range (Table 3-2). In a *Sphagnum* farming study, Beyer and Höper (2015) reported that their site was a CO_2 sink after five years. In the present study respiration from the straw mulch contributed over half of the seasonal ER (Table 3-3), and when the respiration from the straw was removed from modelled NEE values, the basins were closer to being CO_2 sinks (Figure 3-5). Hence, the respiration from the straw mulch may have masked the relationship between WT and *Sphagnum* peat CO_2 fluxes. Straw mulch has been reported to be a substantial component of a CO_2 source in the first few years post-restoration, with increasing CO_2 emissions under wet conditions (Waddington *et al*., 2003b), and research has shown that the straw takes approximately three years to decompose (Waddington *et al.*, 2003a). Because of the decomposition of the straw mulch, clipped vascular vegetation, and plot ground cover at less than 75 % (Table 3-2), the *Sphagnum* farming basins in this study were not CO_2 sinks in the second growing season. While it is not unusual for a restored site to be a CO_2 source in the first few years post-restoration (Waddington *et al*., 2010) or during a dry year (McNeil & Waddington, 2003b; Strack & Zuback, 2013), improving the irrigation design can encourage basins to become CO_2 sinks sooner by increasing cover (Figure 2-2a and b) and maintaining wet conditions, thus resulting in more *Sphagnum* fiber accumulation during dry years.

To be able to calculate cultivation dates, predict growth trajectories, or design effective water management systems, a heuristic tool is necessary in the *Sphagnum* farming context. The results of this research can be used to create a tool to calculate Optimal Growing Days (OGD), a modified version of Growing Degree Days used in agriculture (Wang, 1960). An OGD occurs when the ground is thawed, the WT target is -10 to -15 cm, and the daily WT fluctuates less than ± 7.5 cm from the mean WT position. During the second growing season of this study, when these conditions were met, the *Sphagnum* grew 1.8 mm/month. Combining lateral sub-surface irrigation with an automatic weir design could maintain the daily WT within ± 7.5 cm throughout the growing season and at a target of -10 to -15 cm, which would increase *Sphagnum* CO_2 uptake and fiber production. Further research is necessary to identify optimal temperature targets by species and geographical region for biomass accumulation, and to determine the water management requirements for different species throughout the production cycle, as hydrophysical properties and WT regimes will change as the *Sphagnum* profile thickens (Taylor & Price, 2015).

3.6 Conclusions

Research has demonstrated that the WT position in post-extraction peatlands will affect the CO_2 uptake of *Sphagnum* moss. At the experimental irrigated *Sphagnum* farming site investigated in this study, there was no significant difference in the CO_2 uptake of the moss between production basins with WT targets of -10 or -20 cm. The seasonal and daily fluctuations of the WT were found to be more important than the actual WT position for increasing/limiting CO_2 uptake when the WT was shallow (< 22 cm). Based on these results, land managers will be able to set different WT targets each year according to meteorological conditions. If it is a dry year, a WT target of -10 cm does not necessarily need to be maintained. However, if the WT drops below -15 cm, there will be more pronounced fluctuations in moisture conditions, which will limit CO_2 uptake, thus reducing biomass accumulation. In the first two production years, a WT target of -10 to -15 cm and daily fluctuations of less than ± 7.5 cm from the seasonal mean are recommended to optimise the CO_2 uptake of hummock-forming *Sphagnum* species. Results from this study can also be applied to restoration monitoring. After measures have been taken to reduce water loss from the site (i.e. bunds or ditch filling), monitoring WT fluctuations will determine where the moss carpet growth and CO_2 uptake will be the highest, and where additional water management may be necessary.

Land managers will need to consider irrigation designs that limit WT fluctuations to increase *Sphagnum* biomass accumulation. In this study, lateral sub-surface irrigation was effective at maintaining stable moisture conditions, since the spacing of the perforated pipes (12.5 m spacing) effectively distributed water throughout the basin. Furthermore, sub-surface irrigation can be used to increase the scale of the production site, reducing the impacts of residual peat on WT variability in block-cut peatlands. Land managers should also consider the type of mulch and density of mulch application because it will affect CO_2 fluxes, as the straw mulch in this study contributed to over half the seasonal ER. The basins at the site were CO_2 sources in the second growing season following establishment, but will likely become sinks as the moss cover increases and the straw decomposes. The hydrological requirements presented to optimise CO_2 uptake are for *S. rubellum* and *S. fuscum*; further research is necessary for hollow *Sphagnum* species in the context of *Sphagnum* farming.

4.0 Conclusions and recommendations for upscaling

The WT data indicate that the perforated pipes, canals, baulks, and drainage ditches are important considerations for site scale hydrological processes. Upscaling *Sphagnum* farming operations and maintaining stable WT conditions will require building these features according to the regional slope to manage ground water flow, along with irrigation density (pipes and canals) of 0.2 to 0.3 to reduce WT fluctuations (Figure 2-5). Sub-surface irrigation can be used to increase the irrigation density of a larger production site. However, canals were also able to maintain a stable WT with increasing distance from the water source (Table 2-7). Mean WT variability remained < 16 cm as far as 6 m from the PC canals, similar to the irrigation in LA10. If the canal is upslope of the basin, and the basin is 12 m wide, sub-surface irrigation is probably not necessary to reduce fluctuations. Basins wider than 12 m have areas further away from the stabilizing effects of the canals, thus will likely have lower productivity (Chapter 2). In this study, the deep outflow canals to the S and E enhanced GW loss, so a wider buffer area between the *Sphagnum* farming operations and outflow canals should be considered. Automated weirs in the irrigation canals would be better able to retain water when necessary, and discharge it during wet periods, to modulate WT fluctuations.

The design of canals along the peripheral canal (PC) maintained stable WT conditions, but this design reduces the growing surface (Table 2-1) and accessibility to the basin. Mechanized harvesting from *Sphagnum* farming sites with peripheral canals will not be possible unless access roads are built over the canals. It should also be noted that canals will increase CH_4 emissions (Strack & Zuback, 2013), are prone to erosion (Holden *et al*., 2004), and may require more maintenance (i.e. unblocking). A design which combines good WT stability and accessibility is one long canal along the length of the basin (i.e. LA). A WT target of -10 cm will maintain high near surface θ and ψ, and reduce fluctuations in WT because of a small unsaturated zone and less variability in moisture conditions during precipitation events.

The extracted peatland chosen for *Sphagnum* farming operations should ideally have less-decomposed peat with a high specific yield to reduce WT fluctuations, a relatively flat post-harvest landscape, previously established canals and be accessible to machinery. Some of these conditions already exist on post-vacuum harvested sites, which may provide advantages compared to block-cut peatlands. The block-cut landscape has baulks with barriers (water mounds), reducing GW flow between basins. However, since block-cutting is no longer a common technique, the landscape will require more preparation. The older operations on block-cut sites will likely have peat that is more oxidized, thus lower specific yield (Van Seters and Price, 2002), and have spontaneously revegetated areas that will need to be removed and the peat surface leveled. Block-cut sites will need to be made accessible to machinery by building roadways between the baulks in the trenches, and removing the trees and other vascular vegetation on the baulks. Currently there is no published research on the suitability of post-vacuum harvested sites for *Sphagnum* farming. Vacuum harvested sites with recently finished extraction operations may be better suited than older block-cut sites. They already have drainage canals that can become water regulation (irrigation) canals, good accessibility and require less landscape manipulation than block-cut sites. Canals already run along the length of the field, and the peat surface is relatively flat and un-vegetated. The typical 30 m spacing between canals will service ~15 m of adjacent peatland, which is larger than the ideal value reported in this study for this peat. Consequently, the 30 m canal spacing may not provide a stabilizing effects on the WT in the center of the peat field, and productivity may be reduced there. Check-dams or water control weirs will be needed at distances dictated by the longitudinal surface slope of the peat fields, so that target water tables can be maintained. A WT of -10 cm may be more difficult to maintain during a dry season, and the targeted depth can be reduced to -15 cm without limiting CO_2 uptake, if moisture conditions remain stable. Future studies should investigate the suitability of vacuum harvested peatlands for *Sphagnum* farming.

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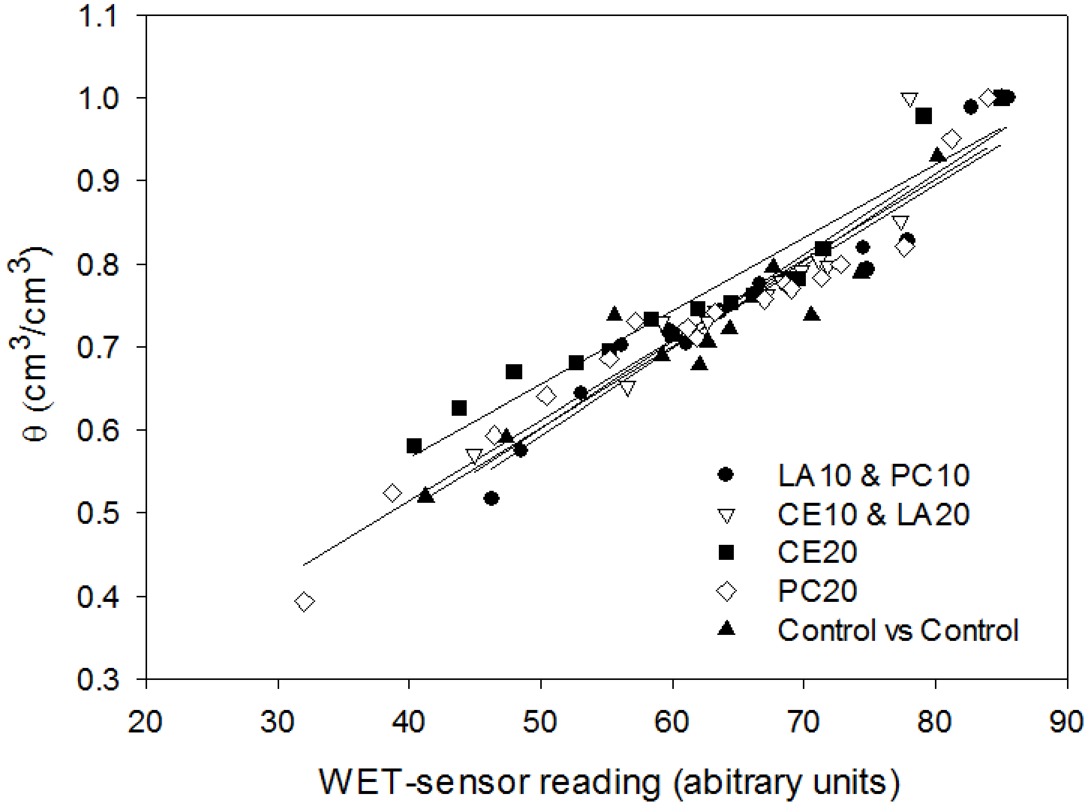
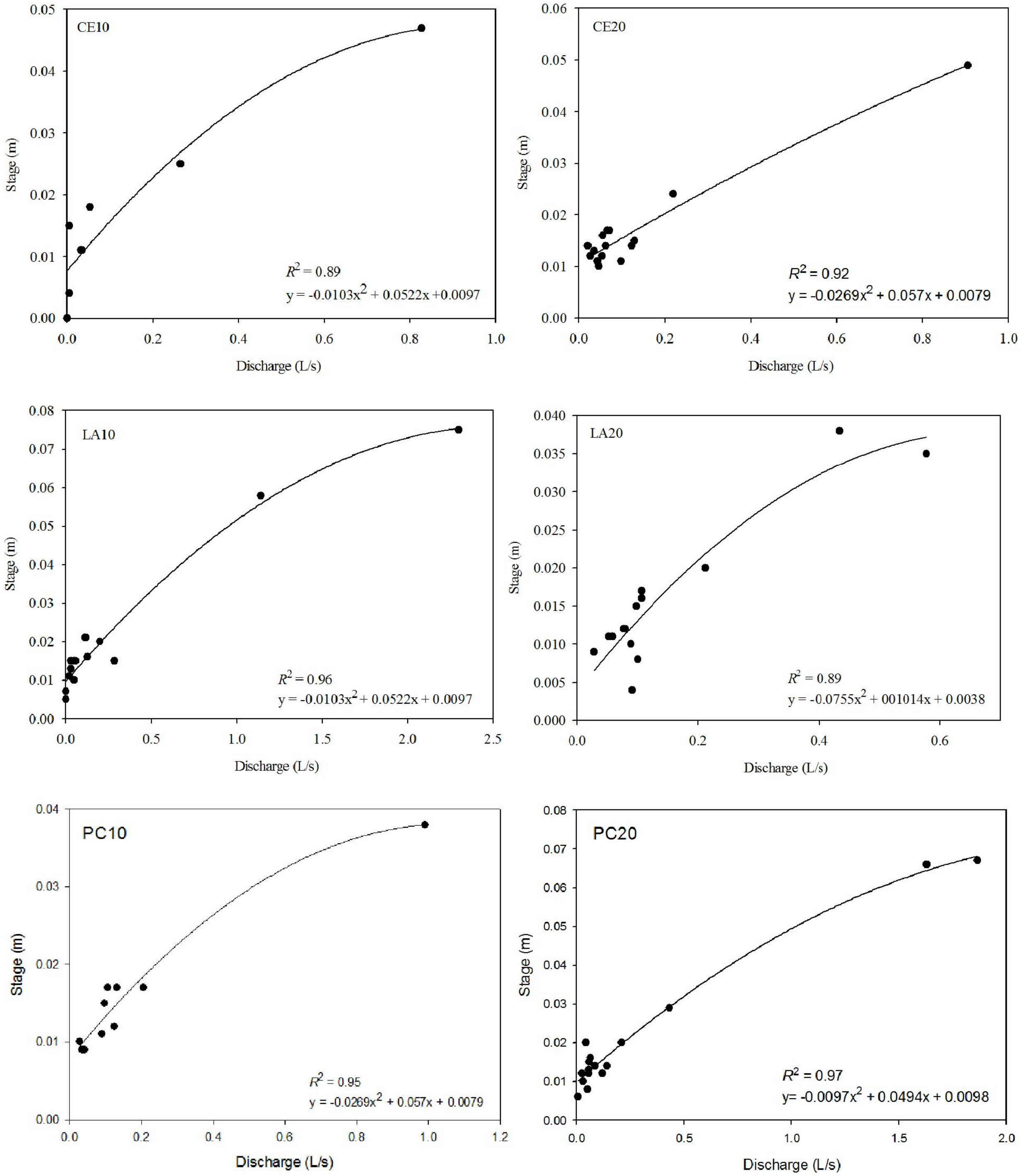
Appendix 1. WET-Sensor Calibration



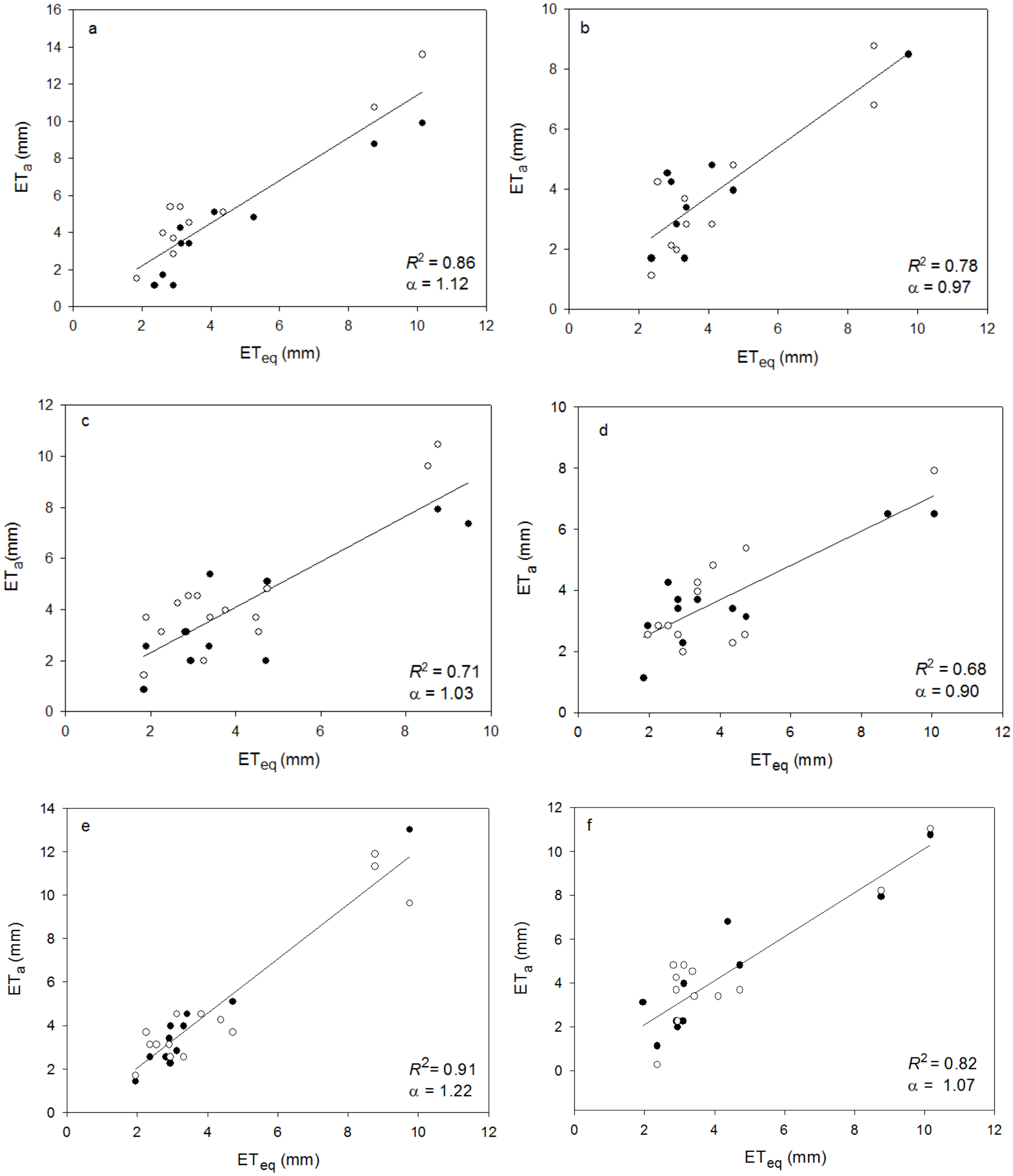
Appendix 1 WET-sensor calibration curves for 0-6 cm at each basin. Gravimetrically-measured soil moisture contents plotted against WET-sensor measurements. The highest measured field value was used as saturation (θ = 1.0 cm^3/cm^{-3}). Calibrations were made according to similar vegetation covers (i.e. LA10 & PC10 and CE10 & LA20).

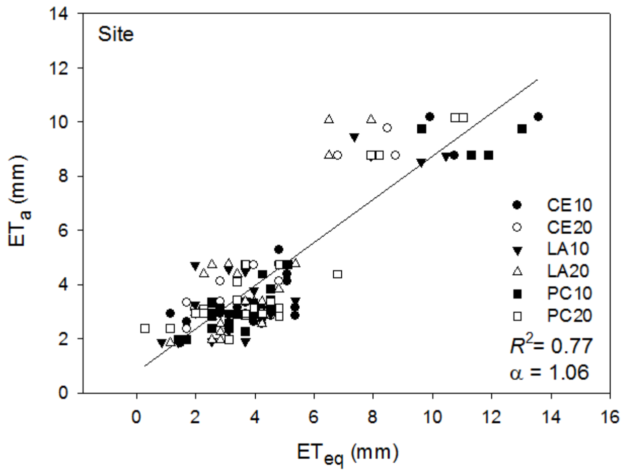
Appendix 2. Stage discharge rating curves for outflow weirs



Appendix 2 Stage discharge ratings curves for outflow weirs of each basin. High flow measurements were taken when the weirs were unblocked.

Appendix 3. Lysimeter calibrations





Appendix 3 α-plots for ET_{eq} and ET_a for each basin. Black and white circles represent the two different lysimeters per basin (Black = lysimeter 1, white = lysimeter 2). Each graph is a different basin: a. CE10, b. CE20, c. LA10, d. LA20, e. PC10, and f. PC20. All points combined showed in Site. All slopes are significant at $p < 0.0001$.