The effects of water management on the CO_2 uptake of *Sphagnum* moss in a reclaimed peatland

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SUMMARY

To harvest *Sphagnum* on a cyclic basis and rapidly accumulate biomass, active water management is necessary. The goal of this study is to determine the hydrological conditions that will maximise CO_2 uptake in *Sphagnum* farming basins following the moss-layer transfer technique. Plot CO_2 uptake doubled from the first growing season to the second, but growth was not uniform across the site. Results indicate that the seasonal oscillations in water table (WT) position were more important than actual WT position for estimating *Sphagnum* ground cover and CO_2 uptake when the seasonal WT is shallow (< -25 cm). Plots with higher productivity had a WT range (seasonal maximum – minimum) less than 15 cm, a WT position which did not fluctuate more than ± 7.5 cm, and a low WT standard deviation. Each basin was a CO_2 source during the second growing season, and seasonal modelled NEE ranged from 107.1 to 266.8 g CO_2 m^{-2}. Decomposition from the straw mulch accounted for over half of seasonal respiration, and the site is expected to become a CO_2 sink as the straw mulch decomposes and moss cover increases. This study highlights the importance of maintaining stable moisture conditions to increase *Sphagnum* growth and CO_2 sink functions.

KEY WORDS: carbon dioxide, moss layer transfer technique, Sphagnum farming, straw mulch, water table range

INTRODUCTION

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 (Clymo & Hayward 1982, Taylor & Price 2015) but requires a shallow 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, including reduced specific yield and hydraulic conductivity that limit water transfer to the *Sphagnum* capitula (Price 1996, van Seters & Price 2002, Price *et al*. 2003). To ensure the regeneration of *Sphagnum* moss and to 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 & 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 by spreading *Sphagnum* fragments at a suggested 1:10 ratio, and covering the fragments with a mulch layer to reduce water loss (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 & Price (2013) suggested that after ten years the moisture conditions of regenerated moss layers may still limit carbon sequestration because of a hydrological discontinuity 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 fluctuations (i.e., WT range and standard deviation) 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 have been disturbed for land use activities such as agriculture, forestry and mining (Pouliot *et al*. 2015). The scale of moss production can be increased 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 for water input, Pouliot *et al*. (2015) found that *Sphagnum* establishment was sensitive to the meteorological conditions during the first growing season, i.e. a dry season resulted in reduced establishment. Meanwhile, Taylor & Price (2015) suggested 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*. 2014). However, there is a gap in knowledge on how to optimise the 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 optimising the CO_2 uptake of *Sphagnum* moss; (2) identify an optimal WT position and WT range for CO_2 uptake by *Sphagnum*; and (3) provide recommendations on water management for future *Sphagnum* farming sites.

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) mean 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 in the trenches, adjacent to the baulks. From May to July 2014, six ~ 20 m × 50 m basins, spaced 30 m apart were created within the trenches, separated by the raised baulks (Figure 1).

The surface vegetation was removed from the trenches and the peat surface was levelled 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). This study solely examines the mix of *S. fuscum* and *S. rubellum*, and the other two *Sphagnum* treatments will not be discussed. Prior to moss introduction, perforated drainpipes 10 cm wide were installed 60 cm below the surface in four of the basins. The peat was excavated and set aside, then the pipes were laid down and the peat was placed back on top. 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 1). Two of the basins were installed with a 50 m sub-surface perforated pipe running down the

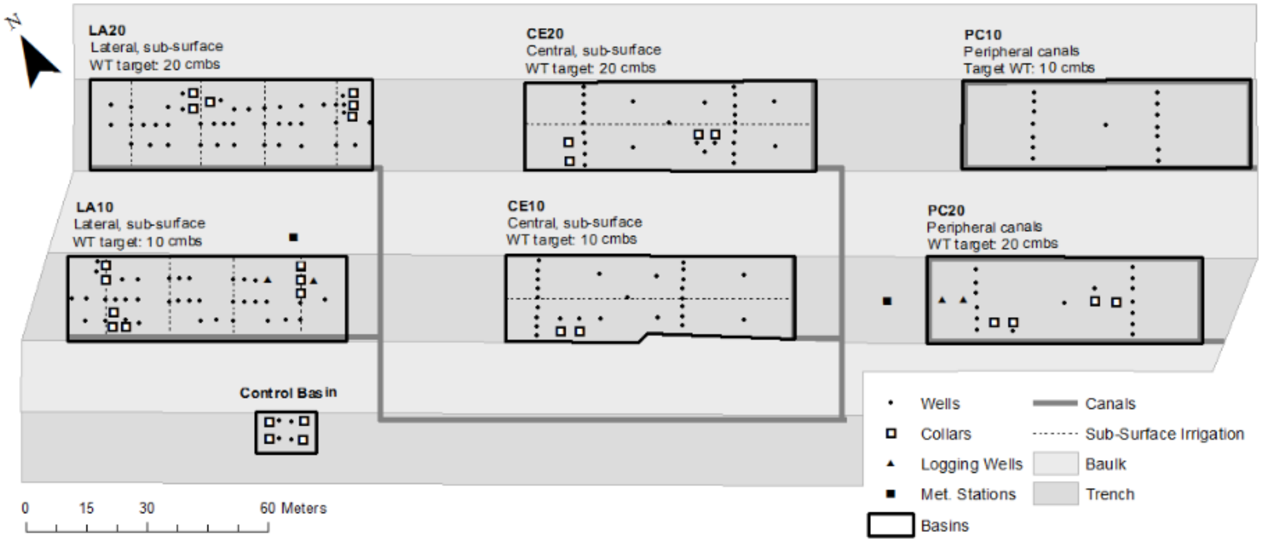

Figure 1. Bog 530 study site, Shippagan, NB, Canada.

centre, 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 × 60 cm × 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 programme. The water levels (excluding the control) were managed through a series of pumps and irrigation tubes connected to a nearby (~ 75 m to the west) pond in the peatland.

METHODS

In the years 2014 and 2015, twenty-eight stationary plots (60 cm × 60 cm × 15 cm deep stainless steel collars inserted into the peat) were established in the mixed moss (*S. fuscum* and *S. rubellum*) treatment, since these are the most commonly found moss species in natural peatlands in the region. Plots (collars) 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 relocated based on observations the previous year in order to capture a broader range of WT positions. The collars were shallow and did not limit water flow. 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 10 July to 14 August in 2014, and from 11 May to 22 August in 2015. The year 2014 will be referred to as "Year 1" and the year 2015 as "Year 2", throughout this article.

Environmental conditions

Two meteorological stations at the site recorded precipitation (Texas automatic tipping-bucket raingauge), 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 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 to the north-west) were used to derive missing precipitation data for May and the end of August in 2014 and 2015, and net radiation data for May 2015. The net radiation 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 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 × 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 cranked 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 was measured at -2.5 and -5 cm with a portable WET-Sensor™ (Delta-T Devices, Cambridge, UK); individual gravimetric calibrations were completed for each hydrological group.

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 analyser (IRGA) (Model-EGM4; PP Systems, Massachusetts, USA) was connected to a transparent acrylic chamber (60 cm × 60 cm × 30 cm) that was placed temporarily 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 that were simulated using fibreglass 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. Values with an R^2 less than 0.70 were discarded as they may indicate disturbance during sampling. Gross ecosystem productivity (GEP) was calculated by subtracting ER from NEE. This article 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 ten 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.

Water levels and variability

Water levels were monitored within a series of wells with a 0.6 m slotted, screened intake, and were either 2.5 or 3.8 cm i.d. 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 1). A linear regression equation was created for the wells at each plot with measurements recorded at a logging pressure transducer to calculate hourly WT levels (minimum R^2 = 0.55, p < 0.001) for calculating Optimal Range Days (ORD; see below).

The variability in WT was calculated with standard deviation (SD), coefficient of variation, interquartile range and WT range to examine how fluctuating water levels impact CO_2 fluxes. Water table range was calculated by subtracting the seasonal maximum and minimum WT. When comparing CO_2 fluxes to WT variability, plots in PC20 were not included because the basin remained frozen for half the study period, which affected the WT variability and *Sphagnum* productivity. It is unclear whether the basin remained frozen because of the design or because of local environmental variables (e.g., snow cover depth). The linear regression analysis between GEP_{max} and WT range had a break in slope that was used to divide the data (see Figure 3) into groups with “stable” WT levels (range less than 15 cm) and “unstable” WT levels (range greater than 15 cm; Table 1). These groups were used to split the field data for statistical analysis, and to separate the plot data for calculating the seasonal CO_2 exchange of each basin.

Growing season basin CO_2 exchange

GEP and ER were modelled to estimate Year 2 seasonal CO_2 exchange; data from Year 1 were too sparse to include in the model. Carbon exchange plots were grouped hydrologically (Table 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):

$$GEP = \frac{Q \times PAR \times GP_{max}}{Q \times PAR + GP_{max}} \qquad [1]$$

where Q is the quantum efficiency and represents the slope of the rectangular hyperbola, and GP_{max} is a theoretical maximum GEP flux (Table 2) 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.

Table 1. Year 2 mean (± SE) field data, sorted by hydrological group, which is based on mean WT position (Wet = shallower than -15 cm, Dry = between -15 and -25 cm) and WT range (Stable = range less than 15 cm, Unstable = range greater than 15 cm). Basin and plot #s column indicates the number of plots in each 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 depth < 15 cm, Range < 15 cm	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 depth < 15 cm, Range > 15 cm	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 depth 15–25 cm, Range < 15 cm	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 depth 15–25 cm, Range > 15 cm	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 1,2,3 & 4	-16.9 (28.9)	2.05 ±0.33	6.84 ±0.23	-4.45 ±0.26	35 ±6.5	n/a

Table 2. 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})**
		GP_{max}	Q	R^2	R_{ref}	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						

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

$$ER=R_{ref}\times e^{E0}\left[\frac{1}{T_{ref}-T_0}\frac{1}{T-T_0}\right] \qquad [2]$$

where R_{ref} is ER (g CO_2 m^{-2} d^{-1}) at the reference temperature (T_{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 fit (R^2 values) (Table 2) was 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 2) and error bars for each basin CO_2 balance (Figure 5) were calculated according to Adkinson & Humphreys (2011). The modelled values were scaled to basin level by grouping the wells into the same hydrological groups (by WT position and WT range) as were used to classify the plots, and applying the corresponding model equation to each well (Table 3). 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).

Statistical Analyses

RStudio, R version 3.2.2, was used for statistical analysis (R Core Team 2015), with a significance level of α = 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 the relationships of ground cover, vertical growth, WT range, GEP_{max} or ER, and WT variability to GEP_{max} and NEE_{max}; and of changes in soil temperature and θ to ER.

Table 3. WT measurements by year and hydrological group (± standard error), n = 13 (2014), n = 16 (2015), except the control n = 13. Basins had different numbers of wells, and each well was coded according to hydrological group, expressed as a percentage of the basin total. This was done to upscale basin CO_2 fluxes into basin seasonal GEP and ER (CO_2 m^{-2}).

	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	-23.2 ±3.7	-16.9 ±7.7
Hydrological Groups	**2015**	**Wells (%)**						
Wet-Stable		25.6	12.0	60.0	5.4	0.0	0.0	-
Wet-Unstable		30.8	40.0	13.3	5.4	11.5	0.0	-
Dry-Stable		20.5	16.0	6.7	27.0	3.8	0.0	-
Dry-Unstable		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 (g CO_2 m^{-2})	2015	-300.7	-246.7	-328.4	-257.5	-233.0	-233.0	-
Modelled Seasonal ER (g CO_2 m^{-2})	2015	521.8	482.4	595.2	486.4	462.2	340.2	-

RESULTS

Meteorological and environmental conditions

Year 1 received 377 mm of rainfall, and Year 2 had 238 mm; the 20-year (1986–2006) normal average precipitation (May to August) was 337 mm (Government of Canada 2015). Average monthly air temperature in both years did not differ by 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, neither of which had sub-surface irrigation, and was most variable in the control, which had no active water management (Table 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 cm^3 cm^{-3}), 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 with 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 start to end of the Year 2 study period. *Sphagnum* growth increased yearly and seasonally, but two plots had 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 2a).

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 1). Plots that had developed a larger *Sphagnum* carpet by the end of Year 2 had greater CO_2 uptake (Figure 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.

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., less variability) was a more significant predictor than WT position for mean GEP_{max}: water table range (seasonal WT max – min) was a significant predictor for mean plot GEP_{max} ($F_{1,18}$ = 10.4, R^2 = 0.36, p = 0.004) and standard deviation and coefficient of variation were significant but weaker predictors for mean plot GEP_{max} ($F_{1,18}$ = 5.2, R^2 = 0.23, p = 0.03, $F_{1,18}$ = 7.2, R^2 = 0.29, p = 0.02). Interquartile ranges of seasonal WT levels were not significant predictors for mean plot GEP_{max} (p = 0.09). The relationship between GEP_{max} and WT range was stronger at the plots within actively managed basins (i.e. not control plots), and water table range ($F_{1,14}$ = 19.42, R^2 = 0.58, p = <0.001) and WT SD ($F_{1,14}$ = 12.3, R^2 = 0.47, p = 0.003) were the metrics for WT variability that explained the highest percent of variability in mean plot GEP_{max} (Figures 3a and 3b). Plots with a WT range <15 cm were more productive than plots with a range >15 cm (Figure 3a). 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) where plots with a WT range <15 cm were more productive (Figure 3a).

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 cm ($F_{1,16}$ = 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 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).

Mean plot ER was significantly higher at collars in basins with a WT target of -10 cm than in basins with a WT target of -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}.

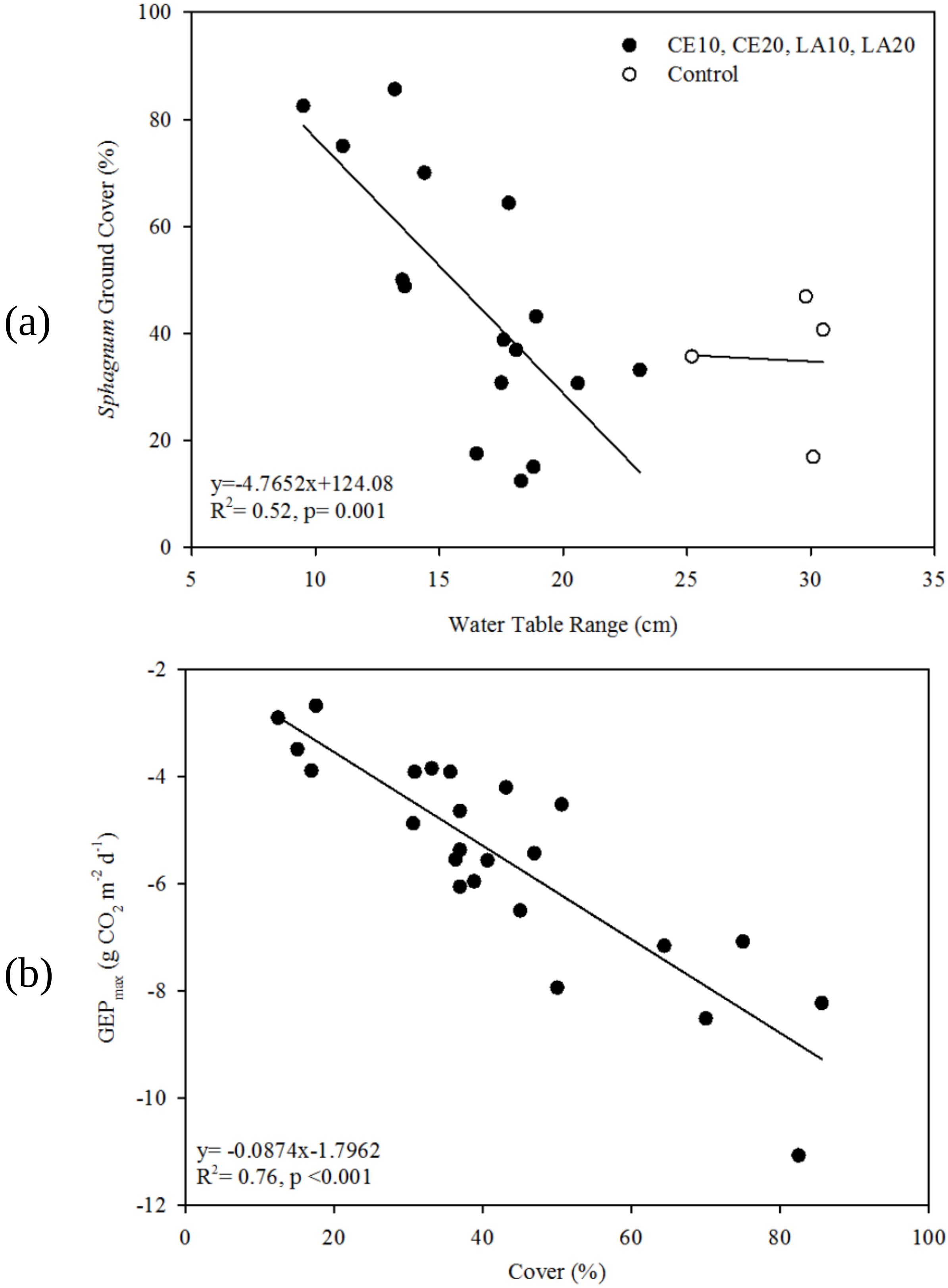

Figure 2. Control of WT range on *Sphagnum* ground cover (a) and the relationship between *Sphagnum* ground cover and gross ecosystem photosynthesis (GEP) when photon flux density of photosynthesis was greater than 1000 µmol m^{-2} s^{-1} (GEP_{max}) (b). Filled symbols show data from the plots within the actively managed basins excluding PC20.

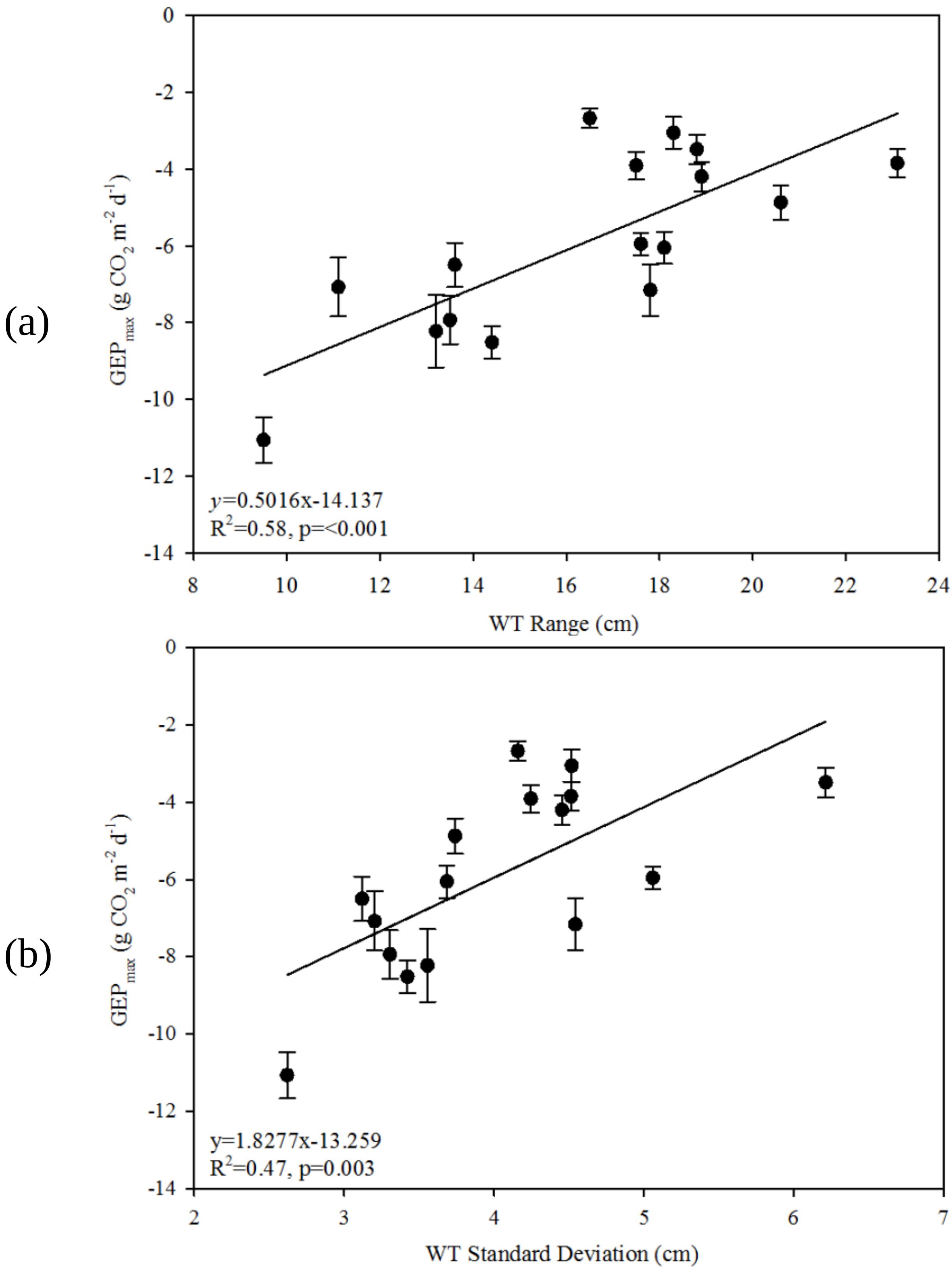

Figure 3. Regression between actively managed mean plot gross ecosystem photosynthesis when photon flux density of photosynthesis was greater than 1000 µmol m^{-2} s^{-1} (GEP_{max}) (a) and 2015 WT range (seasonal maximum – minimum) and one standard deviation from the WT mean. Error bars show SE of GEP_{max} mean (b).

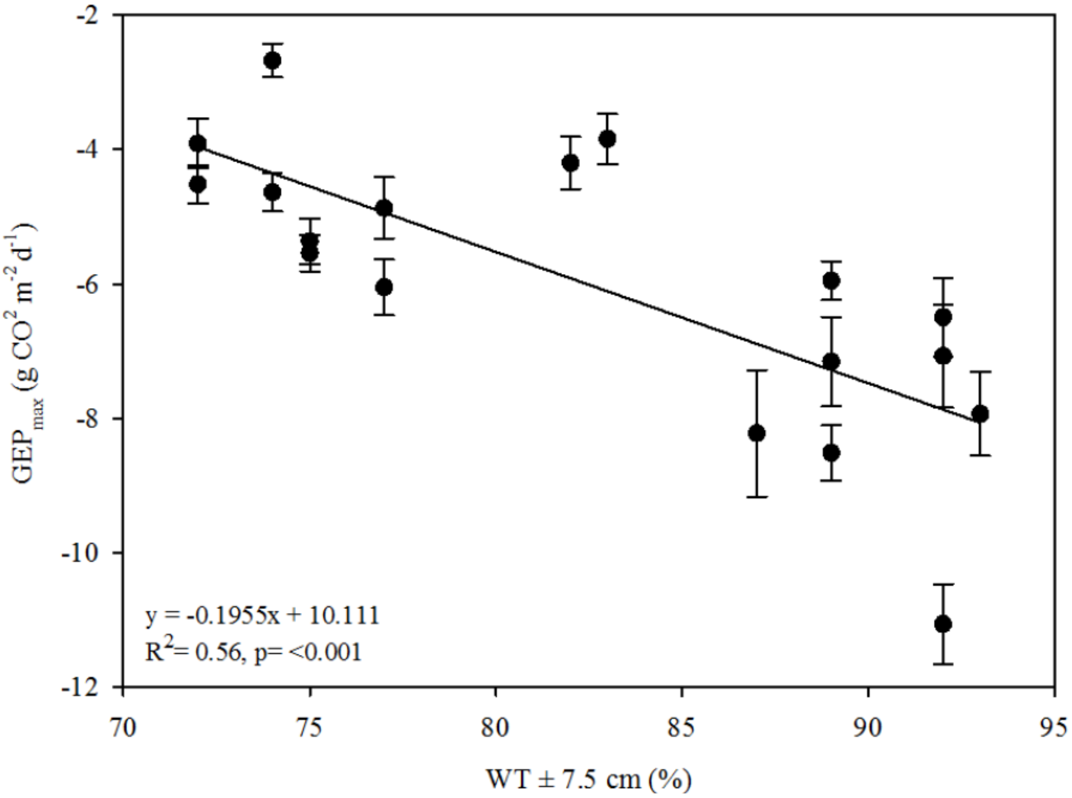

Figure 4. Year 2 mean plot gross ecosystem photosynthesis when photon flux density of photosynthesis was greater than 1000 µmol m-2 s-1 (GEP_{max}) and optimal range days (ORD), which is the number of thawed days in the growing season that the WT remained ± 7.5 cm from the seasonal mean. The control 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.

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 2), 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 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 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 2). Seasonal basin GEP increased from May–June to July–August in the 10 cm target basins CE10, LA10 and PC10 by 14, 29, and 13 %, respectively, and in CE20, LA20 and PC20 by 10, 13 and 11 %, respectively.

Modelled ER was highest where there was the most CO_2 uptake (Table 3); ER was greatest at PC10 and lowest at PC20. Seasonal NEE (GEP + ER) ranged from 107.1 to 266.8 g CO_2 m^{-2} with each basin acting as a CO_2 source. 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 5) and the least amount of *Sphagnum* growth (Table 1), and remained frozen longer.

DISCUSSION

While productivity increased seasonally at all actively managed plots, there were a range of GEP_{max} values (Table 1), suggesting that specific irrigation designs encouraged CO_2 uptake, to varying degrees. 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. 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

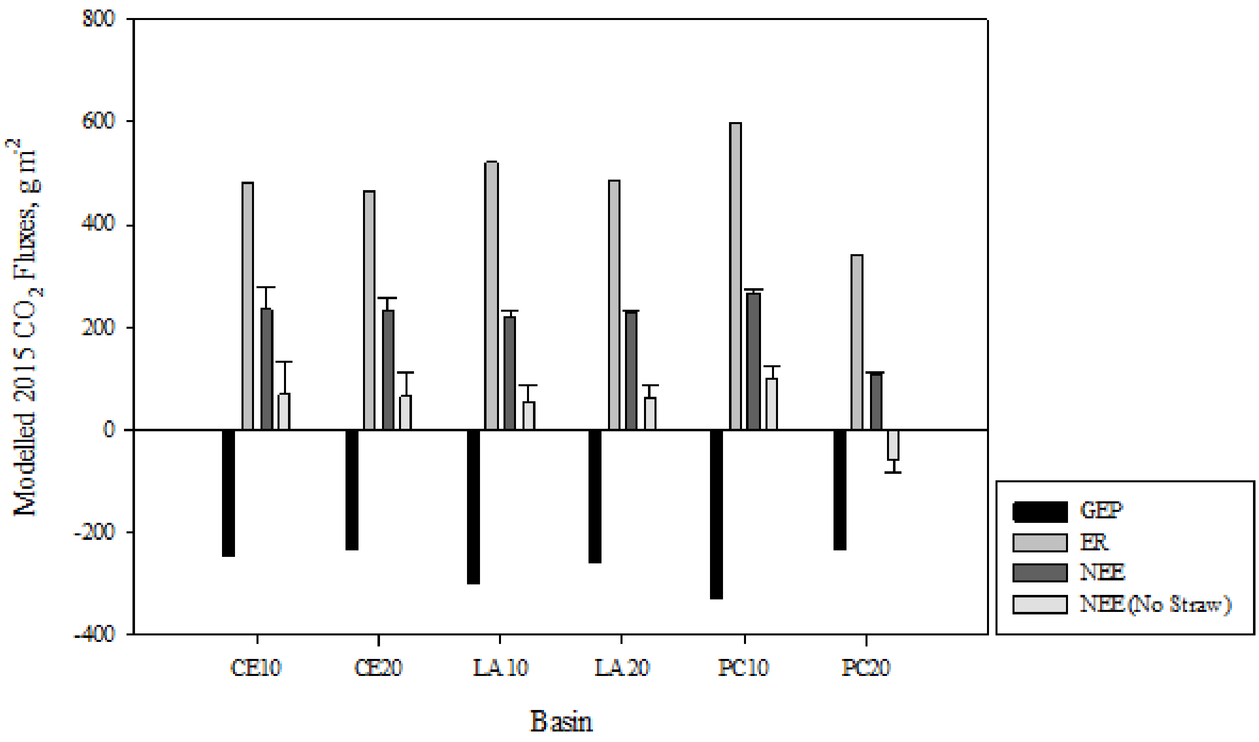

Figure 5. Modelled 2015 CO_2 fluxes of each basin. Error bars were calculated for NEE only.

significant predictor for CO_2 uptake, probably because the deepest mean WT was only -23 cm (Table 1). Studies have found that *Sphagnum* is not limited by WT position when it is shallower than -40 cm (Ketcheson & Price 2011, Taylor *et al*. 2016), suggesting that the WT at the study site in this present study was not low enough to cause a decline in productivity. Furthermore, there was no significant difference in GEP_{max} between basins with a target of -10 cm or -20 cm. The targeted difference in WT position was 10 cm between basins with a -10 or -20 cm target, but in 2015 the observed mean difference between the groups was 5.5 cm (Table 1), indicating that when the WT is shallow (i.e. above -23 cm) 5.5 cm may not result in differences in productivity between groups. 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 the drier 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 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 common. 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 photosynthesising material was available (more moss), and the moss carpet was greater where the WT was more stable (Figure 2a). The 2015 control plots were transported from plots located in an actively managed basin (CE10) in the first growing season (2014). If the control was built in the same year as the actively managed basins (2014), it is likely that there would have been less *Sphagnum* ground cover and lower plot mean GEP_{max} in the control. The results of this study are limited by not having plots with a more variable WT to examine the trend of increasing moisture variability. The regressions for WT range and WT standard deviation were fitted with linear equations (Figure 3), and it is unclear if plots with a higher range or SD than captured in this study would continue to follow this trend, or if a different trend (such as a polynomial fit) would be more appropriate.

In this study, water table range was a useful metric for evaluating WT variability because of a clear split in the data (Figure 3a) used to divide plot GEP_{max} for statistical analysis and into groups for CO_2 flux modelling, and to code the wells by the same groups (Table 3) when upscaling the seasonal CO_2 balance of the basins. However, water table range as a metric for measuring the variability in seasonal WT levels is greatly influenced by extreme values, such as a short but intense precipitation events, since it is the difference between the seasonal WT maximum and minimum. It is also influenced by time of year - it will skew the data by those few measurements at the start of the growing season if the ground has not yet thawed, making otherwise productive plots appear to have an unstable WT. A tool which is not as heavily influenced by extreme events and still captures WT variability is standard deviation, which was also a significant predictor for GEP_{max}. Water table interquartile range did not have a significant statistical relationship with GEP_{max}, indicating that it is important to capture the whole spread of the data. Future projects should be cautious in using WT range, as how the WT oscillates throughout the season is likely to be more important than a handful of days when the WT position is influenced by a major precipitation event, and standard deviation is better suited to capture seasonal oscillations than the absolute maximum – minimum of the WT range calculation.

Considering various irrigation designs, LA10 and PC10 had the highest modelled seasonal GEP (Figure 5), as these basins had the most stable WT levels (Table 1). The configuration of the lateral irrigation design and peripheral canals 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 (Brown 2017). Although peripheral canals also appear to perform well, they reduce the growing surface area, emit more methane per unit area (e.g., Strack & Zuback 2013), and are prone to erosion (Holden *et al*. 2004). However, future research should evaluate the life cycle of sub-surface irrigation, as some issues could occur such as blockage of the perforated pipes. The hummock-forming *Sphagnum* species in this study, *S. rubellum* and *S. fuscum*, are effective at transporting water to the photosynthesising upper layers of the moss (Rydín 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.* 2016). Two plots (LA20 1 and 2) decreased in *Sphagnum* height, and this was 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 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 net CO_2 sink at around 75 % cover (Strack *et al*. 2016), and only three of the plots in Year 2 had cover in this range (Table 1). In a *Sphagnum* farming study, Beyer & 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 2), and when the respiration from the straw was removed from modelled NEE values, the basins were closer to being CO_2 sinks (Figure 5). Hence, the respiration from the straw mulch may have partially 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 1), 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*. 2003a) or during a dry year (McNeil & Waddington 2003, Strack & Zuback 2013), improving the irrigation design can encourage basins to become CO_2 sinks sooner by increasing cover (Figure 2) and maintaining a stable WT, thus resulting in more *Sphagnum* fibre 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 $month^{-1}$. 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 fibre 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).

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 and -20 cm. Straw mulch respiration and irrigation which maintained a shallow WT may have masked the relationship between *Sphagnum* CO_2 uptake and WT position. Regardless, 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 (< 25 cm). *Sphagnum* productivity was greatest when the seasonal WT range was less than 15 cm; and reducing WT fluctuations to less than ± 7.5 cm from the seasonal mean are recommended to optimise the CO_2 uptake of hummock-forming *Sphagnum* species. Water table range as a predictor for CO_2 uptake may be limited at sites with short and intense precipitation events, and standard deviation can be an alternative metric to evaluate the variability in WT position when outliers in WT data are a concern. Plots with a shallower seasonal WT had less variability in WT position, and a target WT between -10 and -15 cm is recommended to reduce fluctuations. 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. Basin LA10 had the second highest modelled seasonal CO_2 uptake as NEE; PC20 had the highest, but also the least respiration as it had the least amount of growth and remained frozen for close to half the study period. 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. 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 mulch 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.

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