

1 Carbon dioxide flux and net primary production of a boreal treed bog: responses to warming and water  
2 table lowering simulations of climate change

3

4 **Tariq M. Munir<sup>1,3</sup>, Mendel Perkins<sup>1</sup>, Emily Kaing<sup>1</sup> and Maria Strack<sup>1,2</sup>**

5 [1] Department of Geography, University of Calgary, Calgary, Alberta, Canada

6 [2] Department of Geography and Environmental Management, University of Waterloo, Waterloo, ON,  
7 Canada

8 [3] Geology, St. Mary's University, Calgary, Alberta, Canada

9 Correspondence to: T. M. Munir ([tmmunir@ucalgary.ca](mailto:tmmunir@ucalgary.ca))

10

## 11 **Abstract**

12 Mid-latitude treed bogs represent significant carbon (C) stocks and are highly sensitive to global climate  
13 change. In a dry continental treed bog, we compared three sites; control, recent (1-3 years;  
14 experimental) and older drained (10-13 years; drained) with water levels at 38, 74 and 120 cm below  
15 the surface, respectively. At each site we measured carbon dioxide (CO<sub>2</sub>) fluxes and estimated tree root  
16 respiration ( $R_r$ ; across hummock-hollow microtopography of the forest floor) and net primary  
17 production (NPP) of trees during the growing seasons (May to October) of 2011-2013. The CO<sub>2</sub>-C  
18 balance was calculated by adding net CO<sub>2</sub> exchange of the forest floor ( $NE_{ff} - R_r$ ) to the NPP of the  
19 trees.

20 From cooler and wetter 2011 to the driest and the warmest 2013, the control site was a CO<sub>2</sub>-C sink of  
21 92, 70 and 76 g m<sup>-2</sup>, the experimental site was a CO<sub>2</sub>-C source of 14, 57 and 135 g m<sup>-2</sup>, and the drained  
22 site was a progressively smaller source of 26, 23 and 13 g CO<sub>2</sub>-C m<sup>-2</sup>, respectively. The short-term  
23 drainage at the experimental site resulted in small changes in vegetation coverage and large net CO<sub>2</sub>  
24 emissions at the microforms. In contrast, the longer-term drainage and deeper water level at the drained  
25 site resulted in the replacement of mosses with vascular plants (shrubs) at the hummocks and lichen at  
26 the hollows leading to the highest CO<sub>2</sub> uptake at the drained hummocks and significant losses at the  
27 hollows. The tree NPP (including above- and below-ground growth and litter fall) in 2011 and 2012  
28 were significantly higher at the drained site (92 and 83 g C m<sup>-2</sup>) than at the experimental (58 and 55 g C  
29 m<sup>-2</sup>) and control (52 and 46 g C m<sup>-2</sup>) sites.

30 We also quantified the impact of climatic warming at all water table treatments by equipping additional  
31 plots with open-top chambers (OTCs) that caused a passive warming on average of  $\sim 1$  °C and  
32 differential air warming of  $\sim 6$  °C at mid-day full sun across the study years. Warming significantly  
33 enhanced shrub growth and CO<sub>2</sub> sink function of the drained hummocks (exceeding the cumulative  
34 respiration losses at hollows induced by the lowered water level  $\times$  warming). There was an interaction  
35 of water level with warming across hummocks that resulted in the largest net CO<sub>2</sub> uptake at the warmed  
36 drained hummocks. Thus in 2013, the warming treatment enhanced the sink function of the control site  
37 by 13 g m<sup>-2</sup>, reduced the source function of the experimental by 10 g m<sup>-2</sup>, and significantly enhanced the  
38 sink function of the drained site by 73 g m<sup>-2</sup>. Therefore, drying and warming in continental bogs is  
39 expected to initially accelerate CO<sub>2</sub>-C losses via ecosystem respiration but persistent drought and  
40 warming is expected to restore the peatland's original CO<sub>2</sub>-C sink function as a result of the shifts in  
41 vegetation composition and productivity between the microforms and increased NPP of trees over time.

## 42 **1 Introduction**

43 Northern peatland ecosystems have accumulated  $\sim 547$  Pg carbon (C; 1Pg =  $10^{15}$  g) as a result of  
44 functioning as a steady but persistent sink throughout the Holocene (Yu, 2012; Tarnocai et al., 2009).  
45 The accumulated peatland C stocks equal approximately one third of the global terrestrial soil C pool  
46 (Grosse et al., 2011; Ciais et al., 2013). Mid-latitude peatlands in north-west North America are often  
47 covered by trees, in contrast to open bogs in north-east North America (Turetsky et al., 2002). Forested  
48 bogs have greater net primary production (NPP) to decomposition ratios and hence return higher  
49 accumulation rates than those of open bogs (Clymo et al., 1998). The C stocks of the western boreal  
50 treed bogs may respond differently to warming and drought than those of eastern boreal open fens  
51 (Kettles and Tarnocai, 1999), and may lead to an accelerated positive feedback to climate change  
52 (Gruber et al., 2004; Limpens et al., 2008; Bhatti et al., 2012; Stocker et al., 2013). Future climatic  
53 changes are expected to be severe at mid-latitudes (Vitt et al., 2009; Kettles and Tarnocai, 1999; IPCC,  
54 2007) that has a dense coverage (50%) of peatlands (Tarnocai, 2006).

55 Carbon exchange in peatlands occurs in the forms of the uptake of C from the atmosphere via gross  
56 primary photosynthesis (GPP) and the release of C to the atmosphere by respiration ( $R$ ) of plants  
57 (autotrophic) and microorganisms (heterotrophic). The sum of GPP (-) and  $R$  (+) is defined as the net  
58 ecosystem exchange (NEE) of CO<sub>2</sub>. Net uptake of CO<sub>2</sub> causes assimilation of C in the form of plant  
59 biomass and accumulation of C in the form of soil organic matter. The GPP,  $R$  and NEE of the forest  
60 floor are represented by  $GPP_{ff}$ ,  $R_{ff}$  and  $NEE_{ff}$ , respectively. Tree root respiration is represented by  $R_r$ .

61 The changes in peatland air/soil temperature and water level can change GPP and  $R$  independently (Ow  
62 et al., 2008). Warm and dry conditions in peatlands can either promote  $\text{CO}_2$  uptake by enhancing GPP  
63 or diminish uptake by limiting moisture (Roulet et al., 2007; Charman et al., 2013) or accelerate  $\text{CO}_2$   
64 release by enhancing  $R$  (Hanson et al., 2000; Davidson and Janssens, 2006; Lund et al., 2010; Ise et al.,  
65 2008; Cai et al., 2010). In a dwarf-shrub pine bog, Pihlatie et al. (2010) found that the  $\text{CO}_2$  flux peak  
66 followed tightly the increase in air and soil temperature, being higher (uptake) on warm, and lower (up  
67 to emission) on cold days. They found increase in the net uptake and emission by  $4.3 \text{ g C m}^{-2} \text{ d}^{-1}$  and  $2.5$   
68  $\text{g C m}^{-2} \text{ d}^{-1}$ , respectively, coincident with an average increase in air and soil temperature from  $0 \text{ }^\circ\text{C}$  (late  
69 April) to  $27 \text{ }^\circ\text{C}$  (early June). Long-term drawdown of water table in forested bogs significantly increased  
70 tree productivity of a Canadian (Lieffers and Rothwell, 1987) and a Finnish peatland (Heikurainen and  
71 Pakarinen, 1982; Lohila et al., 2011). For example, in a 35 year old forestry drained (40 cm below-  
72 ground at the end of study) pine bog, a very high NEE of  $-871 \pm 100 \text{ g C m}^{-2} \text{ yr}^{-1}$ , and a tree  
73 productivity of  $240 \pm 30 \text{ g C m}^{-2} \text{ yr}^{-1}$  were reported by Lohila et al. (2011). A sedge fen with water table  
74 25 cm below-ground was reported to emit  $8.21 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$  (Aurela et al., 2007). In a treeless fen,  
75 Riutta et al. (2007) reported average seasonal ecosystem respiration to be  $810 \text{ g CO}_2 \text{ m}^{-2}$ . The ecosystem  
76 respiration increased by 18% and 20% due to lowering of water level by 14 cm and 22 cm, respectively.  
77 However, the variation in respiration may not always be linked to fluctuation in water table; it may be  
78 related more directly to variation in moisture availability. Therefore, water table is a major control on  
79 respiration in peatlands, and peat soil moisture is sensitive to lowering of water table (Moore et al.,  
80 2006; Parmentier et al., 2009; Moore, 2002).

81 Tree root respiration ( $R_r$ ) may account for a significant proportion of forest floor respiration ( $R_{ff}$ ) in  
82 forested bogs (Lohila et al., 2011). Therefore, isolating  $R_r$  from  $R_{ff}$  is critical to attribute forest floor C to  
83 various sources of soil respiration and to fill knowledge gaps related to source/sink dynamics (Hanson  
84 et al., 2000; Janssens et al., 2001) of boreal treed bogs under a climate change scenario. The isolated  $R_r$   
85 can be used to compare net exchange of the forest floor ( $\text{NE}_{ff}$ ) and NPP of a treed peatland with those of  
86 an open peatland, provided the major controls (e.g., temperature and water table) remain unchanged.  
87 The contribution of  $R_r$  to  $R_{ff}$  has been quantified using the closed chamber technique in various forest  
88 ecosystems. The  $R_r$  was separated from  $R_{ff}$  by subtracting trenched plots' respiration from control plots  
89 at a black spruce forest in Quebec by Hermle et al. (2010) and  $R_r$  was found to be 24% of  $R_{ff}$ . However,  
90 the percentage was found to be higher, at 37% in a subtropical forest of mixed alder Cyprus plantations  
91 (Wang et al., 2008) in a similar trenching experiment. Hanson et al. (2000) have reported even higher  
92 mean root/rhizomicrobial respiration values of 46% and 60% for forest and nonforest vegetation,  
93 respectively. Munir et al. (2014) reported that the growing season  $R_r$  increased from  $43 \text{ g C m}^{-2}$  to  $94 \text{ g}$

94 C m<sup>-2</sup> following ten years of lowered water table (~120 cm) in a boreal bog, but the time scale for the  
95 change remains unclear.

96 Continental peatlands are predicted to be drier under warming climatic conditions. The drier conditions  
97 may favour some species in peatland communities to yield more NPP than others and, as a result, plant  
98 composition will shift, leading to changes in species dominance (Sternberg et al., 1999). In northern  
99 bogs, the balance could shift towards a shrub/tree dominated system (Weltzin et al., 2001; Lohila et al.,  
100 2011), which in combination with deeper water tables could lead to an increase in both soil (Ise et al.,  
101 2008) and plant respiration (Tarnocai et al., 2009). A shift in species dominance after drainage in a  
102 Swedish peatland accelerated soil respiration rates ranging from 513 to 6516 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup> (Von-Arnold  
103 et al., 2005). The shifts in species dominance (coverage) and composition varied between microforms  
104 (e.g. hummocks (H) and hollows (W)) in peatlands (e.g. Strack et al., 2006). Likewise, the responses of  
105 CO<sub>2</sub> flux and NPP to manipulations in local climate (warming) (Lafleur and Humphreys, 2008; Johnson  
106 et al., 2013) and local environment (water table) (Strack et al., 2006; Munir et al., 2014) also varied  
107 between the microforms.

108 Warming response studies have used open-top chambers (OTCs) to manipulate ambient temperature to  
109 quantify the response of CO<sub>2</sub> exchange in peatlands at northern latitudes. For example, Sullivan et al.  
110 (2008) used OTCs in a Greenland rich fen for warming hollow and hummock microforms to evaluate  
111 responses of CO<sub>2</sub> fluxes and vegetation changes to warming manipulation. A significant increase in  
112 GPP<sub>ff</sub> was found at both of the microforms in response to the OTC warming of ~1 °C. However,  
113 Johnson et al. (2013) neither found any consistent increase in warming provided by the OTCs nor any  
114 effect on GPP<sub>ff</sub> or R<sub>ff</sub> of a treeless poor fen. Weltzin et al. (2003) used overhead infrared lamps to  
115 induce warming on bog mesocosms and found that the soil temperature at 15 cm below surface  
116 increased up to 4.5 °C and water table dropped to 20 cm. The increase in soil temperature and decrease  
117 in water table elevation increased cover of shrubs by 50% and decreased cover of graminoids by 50%.

118 Although several studies have been conducted on NPP and CO<sub>2</sub> exchange in western Canadian  
119 peatlands, many unknowns remain. The CO<sub>2</sub> balance and tree biomass of 10 ombrotrophic treed bog  
120 sites in Alberta, were quantified by Wieder et al. (2009), but responses to the major controls of  
121 temperature and water table were not evaluated. The response of a bog to decade long water table  
122 manipulation was quantified by Munir et al. (2014), but the impact of the warming manipulations  
123 remained unexplored. The impact of warming manipulation and microtopography on CO<sub>2</sub> balance  
124 responses was also not investigated by Adkinson et al. (2011) in their climatic temperature and short-  
125 term drought study on Alberta fens. They also did not estimate the tree productivity of the forested fen

126 nor the contribution of  $R_r$ . The  $\text{CO}_2$  fluxes at hummock and hollow (or lawn) microforms affected by  
127 OTC warming were quantified by Sullivan et al. (2008) in a Greenland fen and Johnson et al. (2013) in  
128 an Alaskan fen, but responses to water table fluctuations in the studied open fens remained  
129 indeterminate. Therefore, evaluation of peatland tree productivity and net forest floor  $\text{CO}_2$  exchange  
130 responses to potential warming and water table lowering expected under a climate change scenario is  
131 required to fill the knowledge gaps on how a treed continental bog will feedback to the expected  
132 changes in climate. Thus, our unique investigation answers this question by quantifying  $\text{CO}_2$ -C balance  
133 of a mid-latitude treed continental bog (having hummock and hollow microforms) subjected to warming  
134 and water table manipulations, by adding net forest floor  $\text{CO}_2$ -C exchange to tree productivity-C uptake.  
135 Moreover, we isolate  $R_r$  from  $R_{ff}$  to better understand proportional response of  $R_r$  to potential short and  
136 longer-term water table draw down under climate change.

137 Thus, the goal of our research was to quantify the responses of  $\text{CO}_2$  flux and NPP to potential climatic  
138 warming and subsequent lowering of water table. We used three sites within a continental boreal bog  
139 chosen at Wandering River, Alberta, Canada and monitored the  $\text{CO}_2$  flux and the plant biomass over a  
140 three year study period (2011-2013). Our specific objectives were: 1) to compare  $\text{CO}_2$  flux responses at  
141 microforms to warming and water level manipulations using the control, experimental and drained sites  
142 in an ombrotrophic continental bog, 2) to quantify changes in tree NPP and  $R_r$  at the sites in response to  
143 the water level manipulations, and 3) to determine changes in ground layer biomass at the microforms  
144 and sites in response to the warming and water level manipulations.

## 145 **2 Methods**

### 146 **2.1 Study Sites**

147 Research was conducted in a dry ombrotrophic bog located near the township of Wandering River,  
148 Alberta, Canada, during the growing seasons (1<sup>st</sup> May to 31<sup>st</sup> October) of 2011-2013. Three sites were  
149 chosen or created having various water levels: an undisturbed water level site (~38 cm below surface)  
150 called CONTROL (55° 21' N, 112° 31' W), an experimentally lowered water level site (~35 cm lower  
151 than the control) called EXPERIMENTAL (55° 21' N, 112° 31' W), and a 10 year old drained site (~74  
152 cm lower than the control) called DRAINED (55° 16' N, 112° 28' W). The creation of the experimental  
153 and drained sites has been described in detail by Munir and Strack (2014). Mean precipitation and  
154 temperature for the period May to October for this sub-humid continental region are 382 mm and 11.7  
155 °C, respectively, based on 30-year (1971-2000) averages (Environment Canada, 2013). Mean  
156 precipitation and air temperature for the growing seasons of 2011, 2012 and 2013, measured using an  
157 on-site weather station, were 13.1 °C, 13.2 °C, 14.1 °C and 403 mm, 282 mm, 267 mm, respectively.

158 Mean water table position ( $\pm$  standard deviation) at the control site ( $-55.8 \pm 21.6$ ) was not different from  
159 that at the experimental site ( $-56.7 \pm 20.4$ ) prior to the water table manipulation in 2011 (negative  
160 values represented below-ground water table; ANOVA,  $F_{1,5} = 0.55$ ,  $p = 0.492$ ). Mean electrical  
161 conductivity (EC,  $\mu\text{S cm}^{-1}$ ) and pH of pore water in the control ( $16.6 \pm 0.7$  and  $4.1 \pm 0.1$ , respectively)  
162 and experimental ( $15.2 \pm 2.5$  and  $4.4 \pm 0.3$ , respectively) sites were also found to be similar (ANOVA,  
163 EC:  $F_{1,5} = 0.84$ ,  $p = 0.401$ ; pH:  $F_{1,5} = 2.63$ ,  $p = 0.166$ ). All sites were underlain by sandy clay substrate  
164 and had peat depth exceeding 4 m.

165 The Wandering River bog has been classified as a treed low shrub bog with typical mosaic of hummock  
166 and hollow microforms (Riley, 2003). In 2011, the control and experimental site microforms were  
167 found equally dominated by *Sphagnum* mosses (e.g. *Sphagnum fuscum*) with sparse shrubs (e.g.  
168 *Rhododendron groenlandicum*) whereas the drained site hummocks had the greatest coverage of shrubs  
169 and the drained hollows had the greatest coverage of lichens. The most abundant type of tree in the bog  
170 was black spruce (*Picea mariana*) that constituted  $> 99\%$  of the tree stand with  $25,766$  stems  $\text{ha}^{-1}$   
171 consisting of  $37\%$  taller trees ( $> 137$  cm height) up to  $769$  cm high. The black spruce stand had an  
172 average canopy height of  $168$  cm, projection coverage of  $42\%$  and basal area of  $73.5$   $\text{m}^2 \text{ha}^{-1}$ . This  
173 description applies to the whole bog having the control, experimental and drained sites (Munir et al.,  
174 2014).

175 We chose six hummocks and six hollows from the available microtopography at each of the control,  
176 experimental and drained sites. Each of the chosen microforms (plot) was fitted with a  $60$  cm  $\times$   $60$  cm  
177 permanent steel collar having groove at the top and inserted approximately  $5$ - $6$  cm in to the peat surface  
178 (to keep disturbance minimal). Adjacent to each plot, a perforated PVC water well (diameter =  $3.5$  cm)  
179 covered with nylon cloth at the lower  $150$  cm was inserted into the peat to measure water level  
180 manually every time  $\text{CO}_2$  flux is measured. Two automatic water level loggers (Levellogger Junior  
181 3001, Solinst, Georgetown, Ontario, Canada) were installed at each of the three sites in two randomly  
182 selected wells: one at a hummock and the other at a hollow plot. These levelloggers recorded  
183 temperature compensated water levels continuously at  $20$  minute intervals throughout the three growing  
184 seasons (except at the drained hollow between May to early July 2011 due to malfunction of the  
185 levellogger). A Barologger (Barologger Gold, Solinst; height =  $100$  cm) was also installed to  
186 compensate water levels for barometric pressure changes. These records caught short-term water level  
187 fluctuations caused by precipitation events that were not captured by weekly manual measurements. In  
188 May 2011, at each site, randomly selected three hummocks and three hollows were equipped with  $60$   
189 degree,  $50$  cm tall open-top hexagonal chambers (OTCs) of top and basal, side to side dimensions of  
190  $104$  and  $162$  cm, respectively.

191 The OTCs (Molau and Mølgaard, 1996) were constructed using 3.5 mm thick, translucent plexiglas  
192 (SUN-LITE HP, Solar Components Corporation, Manchester, New Hampshire, USA) to passively  
193 warm internal air and soil (at 5 cm depth) by about 1°C (Hollister and Webber, 2000). Inside each OTC,  
194 two automatic data loggers (HOBO Pro V2, Onset computer corporation, Bourne, MA, USA) were  
195 installed at a height of 25 cm above-ground and facing north to avoid direct solar radiation loading. One  
196 of the HOBOs logged OTC air temperature only, and the other logged OTC air as well as soil (5 cm)  
197 temperatures. To log ambient temperatures, duplicate sets of the two HOBOs were also installed outside  
198 the OTCs at all sites. The HOBOs continuously logged temperatures at 20-minute intervals during the  
199 growing seasons. Snowpack disturbance was minimized by dismantling the OTCs each October and  
200 reinstalling back on plots early May.

## 201 **2.2 CO<sub>2</sub> flux**

202 We measured CO<sub>2</sub> flux in biweekly campaigns during the growing seasons (May to October) of 2011-  
203 2013 using a closed chamber having dimensions 60 cm × 60 cm × 30 cm (length × width × height),  
204 made of clear acrylic and corrected for transmittance (88%). The inside of the chamber was equipped  
205 with two low speed battery-operated fans to circulate air inside the chamber during and between the  
206 measurements. However, the chamber had no pressure equilibrium port installed. The instantaneous  
207 CO<sub>2</sub> concentration inside the chamber headspace was measured with a portable infrared gas analyser  
208 (PP systems, USA, EGM-4) having a built-in sampling pump operating at a flow rate of 350 ml minute<sup>-1</sup>  
209 and compensating automatically for pressure and temperature fluctuations during the measurements.  
210 The photosynthetically active radiation (PAR) was measured with a quantum sensor (PP systems, USA)  
211 placed at the top of the chamber. All PAR data collected using the portable PAR sensor was multiplied  
212 with a factor of 0.88 to obtain corrected values of the PAR inside the chamber accounting for its  
213 transmittance. The temperature inside the chamber was measured using a thermocouple thermometer  
214 (VWR Int., USA). All of the concomitant measurements were made during a short chamber deployment  
215 period (Lai et al., 2012) of 1.75 minutes at 15 seconds intervals. Synchronous to the flux measurements,  
216 soil temperatures at the depths of 2, 5, 10, 15, 20 cm were measured with a thermocouple thermometer  
217 at all plots. Water table relative to moss surface was measured at each CO<sub>2</sub> flux measurement occasion  
218 from a permanently installed well associated with each plot.

219 At each plot, a total of 276 CO<sub>2</sub> flux measurements in 29 campaigns, were made during the daytime of  
220 growing seasons (May to October; 2011-2013). Each campaign lasted for about 7 days during which  
221 fluxes were measured at 2 to 3 occasions at each plot. At each flux measurement occasion we made a  
222 total of five or six measurements: 2-3 full sun, a single layer shroud, a double layer shroud and finally

223 an opaque tarp (for  $R_{ff}$ ). The chamber was air-flushed for enough time between the measurements to  
224 equilibrate the headspace concentration with that of the ambient air.

225 The  $CO_2$  flux measurements when the chamber was covered with an opaque tarp represented  $R_{ff}$ . The  
226  $R_{ff}$  represents only forest floor respiration (ground-layer above-ground biomass respiration + soil  
227 respiration + root respiration (shrubs + herbs + trees)).  $GPP_{ff}$  was determined as the difference between  
228  $NE_{ff}$  and  $R_{ff}$ . Negative values indicate an uptake of  $CO_2$  by the ecosystem. The  $NE_{ff}$  was calculated  
229 using the exponential change in chamber headspace  $CO_2$  concentration (Kutzbach et al., 2007)  
230 regressed with time, as a function of volume, pressure and air temperature inside the chamber,  
231 according to the ideal gas law. The exponential regression was applied following Munir et al. (2014)  
232 because covering the soil and vegetation can manipulate the spontaneous  $CO_2$  fluxes across soil-  
233 vegetation-air continuum (Hanson et al., 1993; Davidson et al., 2002; Denmead and Reicosky, 2003;  
234 Kutzbach et al., 2007) likely due to suppression of natural pressure fluctuations (Hutchinson and  
235 Livingston, 2001) and possible alteration in turbulence between measured intervals (Hutchinson et al.,  
236 1993). Therefore, the  $CO_2$  fluxes determined using linear regression likely result in underestimation of  
237 fluxes under closed chamber environment (Kutzbach et al., 2007). The linear fluxes compared with the  
238 exponential fluxes have been found to be up to 40% lower over chamber closure time of only two  
239 minutes (Kutzbach et al., 2007).

240 The  $GPP_{ff}$  and  $NE_{ff}$  were represented by  $GPP_{max}$  and  $NE_{max}$ , respectively, when the photon flux density  
241 of PAR was greater than  $1000 \mu mol m^{-2} s^{-1}$ . As modeled values of maximum GPP were most likely  
242 never achieved in reality, these values represented a more realistic estimate of  $CO_2$  exchange when light  
243 was not limiting, as reported by Bubier et al. (2003). We used these to statistically compare  $CO_2$   
244 exchange at the microforms and to better understand its controls (e.g., changes in water level, air and  
245 soil temperature, and vegetation coverage). The instantaneous  $CO_2$  flux component data presented (e.g.,  
246 Fig. 4) are three growing seasons' averages for all occasions when  $PAR > 1000 \mu mol m^{-2} s^{-1}$ .

### 247 2.2.1 Seasonal $CO_2$ flux modeling and validation

248 The growing season (May to October)  $GPP_{ff}$  was estimated using an exponential empirical model  
249 (Munir et al., 2014) parameterized separately for each water level treatment  $\times$  warming  $\times$  microform  
250 type  $\times$  year combination. The seasonal  $GPP_{ff}$  was estimated according to (modified from Riutta et al.,  
251 2007):

$$252 \quad GPP_{ff} = \frac{PAR \times P_{max}}{PAR + k} \times e^{\left[-0.5 \times \left(\frac{WL - WL_{opt}}{WL_{tol}}\right)^2\right]} \times e^{\left[-0.5 \times \left(\frac{T - T_{opt}}{T_{tol}}\right)^2\right]} \quad (1)$$



253 where  $P_{\max}$  denotes the potential maximum rate of  $GPP_{ff}$  ( $g\ CO_2\ m^{-2}\ d^{-1}$ ) not constrained by water level  
254 and/or temperature, and  $k$  represents the PAR level at which half of the  $P_{\max}$  occurs. The WL represents  
255 water level (cm),  $WL_{opt}$  and  $WL_{tol}$  are parameters in a  $GPP_{ff}$  Gaussian response to WL when  $GPP_{ff}$  is  
256 optimum, and the width of the curve, respectively. The  $T$  denotes soil temperature at 5 cm deep ( $T_{soil\ 5cm}$ ,  
257 °C),  $T_{opt}$  and  $T_{tol}$  are parameters in a  $GPP_{ff}$  Gaussian response to  $T$  when  $GPP_{ff}$  is optimum, and the width  
258 of the curve, respectively. The  $GPP_{ff}$  model parameters (standard errors),  $r^2$  values, and standard errors  
259 of the estimates at the control, experimental and drained microforms are presented in Appendix A.

260 The relationship between  $R_{ff}$  with  $T_{soil\ 5cm}$  was found to be linear. Therefore, the seasonal  $R_{ff}$  was  
261 estimated using a multiple linear regression with  $T_{soil\ 5cm}$  and water table position by:

$$262\ R_{ff} = a \times T + b \times WT + c \quad (2)$$

263 where  $a$ ,  $b$  and  $c$  are regression coefficients, and their values for each water level treatment  $\times$  warming  $\times$   
264 microform type  $\times$  year combination are presented in Appendix B.

265 Applying equations (1) and (2), seasonal  $GPP_{ff}$  and  $R_{ff}$  were estimated for each 20 minute period  
266 between 1<sup>st</sup> May and 31<sup>st</sup> October of 2011-2013, averaged daily and summed separately for the growing  
267 seasons using continuous PAR (LI-190, LI-COR, Nevada, USA, connected to a CR1000 data logger,  
268 Campbell Scientific Canada, Edmonton, AB), WL (Levellogger Junior, Solinst, USA) and  $T_{soil\ 5cm}$  (Onset  
269 HOBOware Pro, MA, USA) measurements made on site. The seasonal  $NE_{ff}$  was calculated by adding  
270 seasonal estimates of  $GPP_{ff}$  and  $R_{ff}$ . Because some environmental variables were missing for first 5 days  
271 of May 2011 and first 21 days of May 2012, they were filled by assuming that the first measured value  
272 was representative of the whole missing period. The field measured values of  $GPP_{ff}$  and  $R_{ff}$  were  
273 compared with the model predicted values obtained using SPSS 21.0. Validation of the models showed  
274 excellent agreement between the measured and the modeled values (Fig. 1).

### 275 **2.2.2 Tree root respiration**

276 To isolate  $R_r$  from  $R_{ff}$ , a trenching method was used following Wang et al. (2008). From the available  
277 microtopography adjacent to the regularly monitored flux plots, we chose an additional eight hummocks  
278 and eight hollows at each of the control and drained sites, and a fewer four hummocks and four hollows  
279 at experimental site (due to its smaller area). Each microform plot had an area of 60 cm  $\times$  60 cm. At all  
280 sites, half of the chosen microform types were incised around up to a depth of 30 cm and wrapped with  
281 a thick polythene sheet to prevent root ingrowth, while disturbance was kept minimal. The other half of  
282 the microform plots were left intact (having all tree roots) to quantify the respiration rate difference  
283 from those of trenched (having minimal tree roots) plots. All of the plots were kept free of surface  
284 vegetation during the trenching experiment in the growing season of 2012 so that  $R_r$  could be estimated

285 by difference without the additional complicating factors of differences in autotrophic respiration  
286 between plots due to slight difference in vegetation (Wang et al., 2008). The CO<sub>2</sub> emissions from all  
287 plots were measured on average weekly using the same instruments and chamber (with opaque shroud)  
288 used for the measurement of NE<sub>ff</sub>.  
289 The plots were trenched in early May 2012 while respiration measurements were carried out in July-  
290 September 2012. While the trenching is used to separate  $R_r$  from  $R_{ff}$ , it also adds fresh litter to the peat  
291 that can add to the initial heterotrophic soil respiration. However, it has been assumed in trenching  
292 experiments that the trenched roots die off within a short time and that afterwards the measured  $R_{ff}$  can  
293 solely be attributed to heterotrophic soil respiration (Hanson et al., 2000; Hermle et al., 2010; Wang et  
294 al., 2008). Trenching immediately disrupts the supply of recent photosynthates to the roots, and  
295 mycorrhiza and associated bacteria that suffer from the lack of labile C. In trenching experiments  
296 Bowden et al. (1993), Boone et al. (1998) and Rey et al. (2002) have shown that C content of  
297 decomposing fine roots in trenched plots contributed little to  $R_r$  and becomes stable a few months after  
298 trenching. Also, the root exclusion experiment may not be useful if extended through a complete annual  
299 cycle, as over such a long period there is the possibility of reinvasion of roots into the previously root-  
300 free trenched plot (Edwards and Norby, 1999). While it is clear that findings from such trenching  
301 measurements should be interpreted carefully, the primary focus of this paper is to quantify  $R_{ff}$  while  
302 investigating  $R_r$  to better understand and separate the contribution of various processes to shifts in  $R_{ff}$   
303 following drainage.

## 304 **2.3 Biomass and tree productivity**

### 305 **2.3.1 Ground-layer biomass**

306 At the end of our field work in October 2013, we collected the ground-layer biomass samples from  
307 triplicate of each microform type at each of the three sites. The above-ground biomass samples were  
308 collected by clipping duplicate representative quadrats (each measuring 10 cm × 10 cm) adjacent to  
309 each of the ambient plots, and from between the OTC wall and the plot collar from warmed plots. The  
310 biomass was clipped (using sharp scissors) at the base of capitulum at 1 cm below moss surface  
311 following Loisel et al. (2012). The below-ground biomass samples were collect by soil coring (using a  
312 serrated saw) to 20 cm depth only, due to difficulty in collecting and processing a large number of  
313 samples to deeper depth. The cores were sectioned into 0-10 cm and 10-20 cm depths at the time of  
314 sample collection and taken to the Ecohydrology laboratory, University of Calgary, and sorted into fine  
315 (< 2 mm) and coarse (> 2 mm) diameter fractions.

### 316 **2.3.2 Tree biomass and productivity**

317 Three 10 m × 10 m quadrats in the areas directly surrounding the NE<sub>ff</sub> flux plots at each of the control  
318 and drained sites, and one quadrat at experimental site (due to its smaller area) were laid out in May  
319 2011. The study areas were not large and these quadrats covered most of the trees in the study areas.  
320 The trees were categorized into tall (> 137 cm height) and short (< 137 cm height) for biomass and  
321 productivity estimation. The taller trees were measured for their height, diameter at breast height (DBH)  
322 and basal diameter (DB), and their biomass was calculated by using an allometric equation (dry biomass  
323 = 0.153(tree DBH)<sup>2.248</sup>) from Grigal and Kernik (1984). All short trees were also measured for their  
324 heights only. Twenty short trees were harvested parallel to the forest floor and transported to the  
325 laboratory, oven dried at 80 °C for 48 hours (until constant weight), and their biomass used to create an  
326 an allometric equation (dry biomass = 0.0085(tree height)<sup>2.2088</sup>; R<sup>2</sup> = 0.93; p < 0.001) we generated by  
327 regressing height with oven-dried weight. This was used to estimate the biomass of all other short trees.

328 NPP of the tree stand for above-ground parts was estimated for 2011 and 2012, following Szumigalski  
329 and Bayley (1996) and Thormann and Bayley (1997). They estimated NPP of an Alberta ombrotrophic  
330 bog of hummock-hollow microtopography by adding incremental biomass of the trees to their litter  
331 production (17% of above-ground incremental biomass m<sup>-2</sup> yr<sup>-1</sup> for *Picea mariana*). We estimated tall  
332 trees incremental biomass based on tree ring widths measured using DendroScan (Varem-Sanders and  
333 Campbell, 1996). The incremental biomass of the short trees was estimated by regressing leader length  
334 with height following Macdonald and Lieffers (1990) and Mullin et al. (1992). Summation of tall and  
335 short tree biomass increments for a year represented incremental biomass of the tree stand for above-  
336 ground parts of trees for that year. To account for litter, an additional 17% was added to this  
337 summation. The new summation represented NPP for above-ground parts of the tree stand (Szumigalski  
338 and Bayley, 1996). We did not measure incremental biomass of the below-ground parts of trees due to  
339 the desire to limit disturbance to our research sites and allow for future monitoring. Therefore, we used  
340 an allometric equation (tree root biomass = 0.222\*tree above-ground biomass) generated by Li et al.  
341 (2003) for estimating the incremental biomass of the tree roots. We did not measure tree productivity  
342 for 2013, instead used 2012 productivity values to calculate NEE for this last year of the study.

#### 343 **2.4 CO<sub>2</sub>-C balance (NE<sub>ff</sub> + NPP - R<sub>r</sub>)**

344 To calculate CO<sub>2</sub>-C balance, the NE<sub>ff</sub> (-GPP<sub>ff</sub> + R<sub>ff</sub>) and NPP (incremental tree biomass of above-ground  
345 and below-ground parts of tree stand + stand litter) in term of mass of C were added together separately  
346 for the sites and the growing seasons (May 1 to October 31) of 2011-2013. The R<sub>r</sub> was excluded to  
347 avoid double counting as incremental biomass of below-ground parts of the tree stand already  
348 accounted for R<sub>r</sub>. Assuming that the dry biomass has a C content of 50%, the CO<sub>2</sub>-C balance equation  
349 for the treed bog sites is as:

350 
$$NEE = NE_{ff} + IC_{tree\_ag} + IC_{tree\_bg} + L_{tree} - R_r \quad (3)$$

351 where NEE denotes Net Ecosystem Exchange,  $NE_{ff}$  represents net exchange of the forest floor,  $IC_{tree\_ag}$   
352 and  $IC_{tree\_bg}$  represent incremental C from biomass growth of the above-ground and below-ground parts  
353 of the tree stand, respectively,  $L_{tree}$  is tree litter production and  $R_r$  is tree root respiration. We estimated a  
354 seasonal value of  $R_r$  by determining it as a proportion of  $R_{ff}$  based on instantaneous measurements and  
355 then estimating it as this proportion of the modelled seasonal  $R_{ff}$ . Seasonal  $CO_2$  fluxes at hummocks and  
356 hollows were upscaled by multiplying mean estimated growing season  $CO_2$  exchange by their  
357 respective coverage of 56 and 44%, 55 and 45%, and 52 and 48% at the control, experimental and  
358 drained sites, respectively (Table 4).

## 359 **2.5 Data analysis**

360 To estimate treatment effects on instantaneous  $CO_2$  flux components ( $GPP_{ff}$ ,  $R_{ff}$ ,  $NE_{ff}$ ,  $R_r$ ,  $NE_{ff}$  without  
361  $R_r$ ) we used separate linear mixed-effects models (SPSS 21.0) with  $CO_2$  flux component as the response  
362 variable, and water level treatment, warming (OTC), microtopography and year as fixed effects. Since  
363 the same plots were measured in each study season, year was also taken as repeated measures within the  
364 same model (Table 3). We used the same fixed effects and repeated measures in all mixed-effects  
365 ANOVA models (described below). All two-way, three-way and four-way interactions between fixed  
366 effects were also included in the models. We used compound symmetry covariance structure for  
367 repeated measures analysis (Jennrich and Schluchter, 1986). A mean value of flux determined at each  
368 plot in each growing season was used for all analyses. Mean  $CO_2$  flux components data were normally  
369 distributed in all years (Kolmogorov-Smirnov Z: 2011,  $p = 0.910$ ; 2012,  $p = 0.767$ ; 2013,  $p = 0.624$ ).

370 To quantify treatment effects on ground-layer biomass, we also used multiple response linear mixed-  
371 effects model (SPSS 21.0) with moss biomass, vascular biomass, lichen biomass and total biomass as  
372 the response variables, and water level treatment, warming (OTC) and microtopography as fixed  
373 effects. All two-way and three-way interactions between fixed effects were also included in the models.  
374 A mean value of biomass quantified at each plot was used for all analyses. Mean biomass data were  
375 normally distributed (Kolmogorov-Smirnov Z: 1.189,  $p = 0.118$ ).

## 376 **3 Results**

### 377 **3.1 Microclimate and environment**

378 At the Wandering River bog air and soil temperatures and precipitation were monitored during the  
379 growing seasons (May to October) of 2011-2013. The weather during the study period was warmer by  
380 1.36 °C, 1.38 °C and 2.44 °C, and wetter by 42 mm in 2011 and drier by 79 mm and 94 mm in 2012 and  
381 2013, respectively, than 30 year means at Athabasca, Alberta (meteorological data have been described

382 under “Methods”). The average undisturbed water level at the control, and manipulated water levels at  
383 the experimental and drained sites were clearly different at the start of the study period in 2011 at 38  
384 cm, 73 cm and 112 cm (below moss surface), respectively. The declining precipitation and rising air  
385 temperature from 2011 to 2013 further lowered the water level at all sites and microforms. From 2011  
386 to 2013 the water level declined at hummocks by 9 cm, 8 cm and 8 cm and at hollows by 6 cm, 6 cm  
387 and 4 cm at the control, experimental and drained sites, respectively. Three and thirteen years after  
388 initial drainage, the water levels at the experimental and drained sites were lower than at the control site  
389 by on average 36 cm and 82 cm, respectively (Fig. 2).

390 The OTCs resulted in significantly warmer growing season air temperature ( $T_{\text{air}}$ ; ANOVA,  $F_{2, 24} =$   
391  $215.87, p < 0.001$ ) by an average ( $\pm$  SD) of  $1.0 \pm 0.0$  °C at the control,  $0.9 \pm 0.0$ °C at the experimental  
392 and  $0.8 \pm 0.5$  °C at the drained site (Table 1) consistently over the three study years. The OTC warming  
393 at hollows was also significantly greater than at hummocks (ANOVA,  $F_{1, 24} = 4.85, p = 0.037$ ). The  
394 increasing  $T_{\text{air}}$  significantly warmed the growing season soil temperature at 5 cm depth ( $T_{\text{soil } 5\text{cm}}$ ;  
395 ANOVA,  $F_{1, 24} = 37.59, p < 0.001$ ) by an average of  $1.0 \pm 0.3$  °C at the control,  $0.7 \pm 0.1$  °C at  
396 experimental and  $0.7 \pm 0.3$  °C at the drained site (Table 1) consistently over the three study years. The  
397 rising  $T_{\text{air}}$  warmed the  $T_{\text{soil } 5\text{cm}}$  the least ( $0.4 \pm 0.3$  °C) at drained hummocks and the most ( $1.3 \pm 0.2$  °C)  
398 at the control hollows. Average soil temperature at 30 cm depth ( $T_{\text{soil } 30\text{cm}}$ ) below the OTC equipped  
399 plots was not significantly different than that at the same depth at non-OTC plots across all sites  
400 (ANOVA,  $F_{2, 24} = 0.71, p = 0.053$ ) and microforms (ANOVA,  $F_{1, 24} = 0.95, p = 0.339$ ). Diurnal  $T_{\text{air}}$  and  
401  $T_{\text{soil } 5\text{cm}}$  patterns in the OTCs were significantly related to PAR ( $R^2 = 0.81, 0.87$ , respectively) across the  
402 microtopography at all sites. During mid-day bright sunny conditions the air warming at OTC equipped  
403 plots was greater than that at non-OTC plots by averages of 4 °C, 5 °C and 9 °C at hummocks, and by 5  
404 °C, 7 °C and 6 °C at hollows in the control, experimental and drained sites, respectively. Similarly, the  
405 direct solar loading increased the  $T_{\text{soil } 5\text{cm}}$  at the OTC plots greater than at non-OTC plots by averages of  
406 5 °C, 3 °C and 8 °C at hummocks, and by 2 °C, 4 °C and 8 °C at hollows in the control, experimental and  
407 drained sites, respectively (Fig. 2).

## 408 **3.2 Biomass and incremental tree growth**

### 409 **3.2.1 Ground-layer biomass**

410 The moss biomass at the drained site was significantly lower compared to the control site ( $F_{2, 24} = 3.78$ ,  
411  $p = 0.013$ ), but not different compared to the experimental site ( $p = 0.076$ ), while the control and  
412 experimental sites were not significantly different compared to each other ( $p = 0.412$ ; Table 2). This  
413 indicates a strong decline of moss biomass with long-term and deeper drainage. The moss biomass were

414 not significantly different across microtopography ( $F_{1,24} = 0.10, p = 0.749$ ) or warming treatments ( $F_{1,24} = 0.51, p = 0.481$ ). Also no interaction between the treatments was found.

416 The vascular plant biomass (mostly woody shrubs) at the control and experimental sites was not  
417 significantly different compared to each other ( $F_{2,24} = 36.79, p < 0.970$ ), but was significantly lower  
418 compared to the drained site ( $p < 0.001$ ; Table 2). Of all the three plant functional groups (moss,  
419 vascular, lichen), only vascular plants were significantly affected by warming ( $F_{1,24} = 6.83, p = 0.015$ )  
420 and microform type ( $F_{1,24} = 41.99, p < 0.001$ ). There were interactions of water level with microform  
421 leading to significantly greater vascular plant growth at drained hummocks ( $F_{2,24} = 33.70, p < 0.001$ ),  
422 and with warming resulting in significantly greater growth at the drained warmed plots ( $F_{2,24} = 3.78, p$   
423  $= 0.013$ ), compared to the control and experimental ambient and warmed microforms. There was a  
424 significant interaction between water level, microform and warming resulting in significantly greater  
425 biomass of vascular plants at the warmed drained hummocks ( $p < 0.001$ ) compared to the control and  
426 the experimental ambient and warmed microforms. In fact, the long-term deep water level at hummocks  
427 had a significant interaction with warming ( $F_{1,24} = 8.72, p = 0.007$ ) to increase vascular plant growth.  
428 The vascular plant biomass at the ambient drained hollows was the lowest of all plots (Table 2).

429 The lichen biomass also grew significantly more over the course of longer-term deeper drainage at the  
430 drained site ( $F_{2,24} = 13.52, p = 0.002$ ) compared to short-term shallower drainage at the experimental  
431 and control sites, which were not significantly different compared to each other ( $p = 0.958$ ; Table 2).  
432 There was a significant interaction between water level and microform ( $F_{2,24} = 3.86, p = 0.035$ )  
433 resulting in significantly greater lichen biomass at the warmed drained hollows ( $p = 0.011$ ), although  
434 warming did not increase lichen biomass significantly ( $p = 0.441$ ). There was limited growth of lichen  
435 in the control site (Table 2).

436 As a whole, there was a significant interaction between water level, warming and microform that  
437 resulted in a significant increase in the overall ground-layer, above-ground biomass at the warmed  
438 drained hummocks ( $F_{2,36} = 32.95, p = 0.030$ ). The lowest above-ground biomass was found at the  
439 ambient experimental hummocks (Table 2). The total below-ground root biomass (including tree roots)  
440 was not statistically different between the sites or the microforms. However, total root biomass was  
441 highest at the warmed, drained microforms (Table 2).

### 442 **3.2.2 Above-ground tree biomass**

443 Above-ground tree biomass was higher in the control site than that in the experimental and drained sites  
444 by an average of  $156 \text{ g m}^{-2}$  and  $178 \text{ g m}^{-2}$ , respectively (Table 2, 4). However, the above-ground tree  
445 growth during 2011-2012 was significantly higher in the drained site ( $66$  and  $60 \text{ g C m}^{-2}$ ) than that at the

446 experimental (42 and 39 g C m<sup>-2</sup>) and the control (38 and 33 g C m<sup>-2</sup>) sites ( $F_{2, 11} = 6.95, p = 0.011$ ).  
447 There was no significant difference between the control and experimental sites ( $F_{2, 11} = 0.87, p = 0.712$ ).  
448 Below-ground incremental tree biomass was estimated using equations given by Li et al. (2003). The  
449 tree root productivity was calculated to be 8 and 7 g C m<sup>-2</sup> at the control, 9 and 9 at the experimental,  
450 and 15 and 13 g C m<sup>-2</sup> at the drained sites in 2011 and 2012, respectively.

451 Tree stand data prior to the study period was not available. We measured the data at the start of our  
452 study in 2011 and have described this in detail under “study sites” section. Heterogeneity between the  
453 tree quadrats laid out at each site was large; however, the small size of the study sites limited our ability  
454 to construct more replicates in the study area. We cannot be certain that the tree biomass at each study  
455 site was identical before the study. However, based on the tree ring growth, we did see that the increase  
456 in tree productivity coincided with the inadvertent drainage at the drained site 10 years prior to the start  
457 of this study. The productivity at the drained site trees was clearly different from that of the control and  
458 experimental site trees. Thus, we are confident that the changes in the productivity estimated represent a  
459 clear response to the interaction of water level elevation and the duration of drainage.

### 460 3.3 CO<sub>2</sub> fluxes

#### 461 3.3.1 Measured CO<sub>2</sub> fluxes

462 GPP<sub>max</sub> was significantly affected by water level, microtopography and year, but there was no direct  
463 significant effect of OTC warming on GPP<sub>max</sub> (Table 3). The GPP<sub>max</sub> at the control (-15.4 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>)  
464 and drained (-12.8 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>) sites were not significantly different from each other but were  
465 different from that at the experimental site (-7.8 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>). There was a higher GPP<sub>max</sub> at  
466 hummocks (-14.4 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>) than at hollows (-9.8 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>). Microform and warming had a  
467 significant interaction with each other as well as interactions each individually with water level. The  
468 GPP<sub>max</sub> in 2011 and 2012 were not significantly different from each other but from the highest value  
469 that occurred in the warmest 2013. Year had significant interactions individually with water level  
470 leading to higher GPP<sub>max</sub> at the control site by 2013; with microform increasing GPP<sub>max</sub> to -21.2 g CO<sub>2</sub>  
471 m<sup>-2</sup> d<sup>-1</sup> at hummocks by 2013; and with warming, increasing GPP at warmed but not unwarmed plots by  
472 2013. Although OTC warming did not have a significant effect directly on productivity, there was a  
473 significant interaction with water level, microform and year resulting in significantly higher  
474 productivity (-25.8 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>) at the warmed drained hummocks in 2013.

475  $R_{ff}$  was significantly affected individually by all four study factors; water level, microtopography, OTC  
476 warming and year (Table 3). The  $R_{ff}$  at the control (13.1 g CO<sub>2</sub> m<sup>-2</sup> d<sup>-1</sup>) and experimental (14.5 g CO<sub>2</sub> m<sup>-2</sup>  
477 d<sup>-1</sup>) sites were not significantly different from each other but were lower compared to that at the

478 drained site ( $16.9 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ). The  $R_{ff}$  was significantly different between hollow ( $16.9 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ )  
479 and hummock ( $14.2 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) microforms, and between ambient ( $13.5 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) and warmed  
480 ( $16.7 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) plots. The  $R_{ff}$  in 2011 ( $14.3 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) and 2013 ( $14.7 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) were not  
481 significantly different from each other but from the highest ( $16.3 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) that occurred in the first  
482 drier than average year 2012. There was an interaction between microform and year leading to  
483 significantly higher emissions at hollows ( $16.8 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) in 2012. Warming had a significant  
484 interaction with microform and year resulting in significantly higher  $R_{ff}$  at warmed hollows in 2012  
485 ( $19.1 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ). The significantly greater emissions were likely due to the significantly higher  
486 contributions of  $R_r$  ( $5.03$  and  $6.80 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) to  $R_{ff}$  at the experimental and drained hollows,  
487 respectively, compared to  $1.51 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$  at the control hollows. The  $R_r$  at the drained hummocks  
488 ( $3.3 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) was not significantly different compared to that at the experimental hummocks ( $3.4$   
489  $\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ), but significantly different compared to that at the control hummocks ( $4.3 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ).  
490  $NE_{max}$  (including  $R_r$ ) was significantly affected individually by water level, microtopography, OTC  
491 warming and year, and all four interactively (Table 3). All sites were significantly different from each  
492 other: the control site forest floor was a sink of  $1.4 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$  while the experimental and drained  
493 sites were sources of  $6.5$  and  $4.1 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ , respectively. There was a significant interaction of water  
494 level with microform resulting in net emissions at experimental hollows ( $10 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) and drained  
495 hollows ( $9.8 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) compared to net uptake at the control microforms (hollows =  $-1.1 \text{ g CO}_2 \text{ m}^{-2}$   
496  $\text{d}^{-1}$ ; hummocks =  $-1.8 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) and the drained hummocks ( $-1.5 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ). The water level  
497 also had a significant interaction with warming leading to net emissions from warmed plots at the  
498 experimental site ( $10.2 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) and the drained site ( $4.2 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) compared to net uptake at  
499 the ambient control plots ( $-2.1 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ), while warmed plots had significantly higher emissions  
500 ( $NE_{ff} = 4.5 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ) than ambient plots ( $1.7 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ ). The water level also had a significant  
501 interaction with study year with highest net uptake of  $-6.3 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$  at the control site in 2013, the  
502 year not significantly different compared with 2011 and 2012. Subtracting  $R_r$  from  $NE_{max}$  (to consider  
503 the net exchange of the ground layer only), converts the control microforms and drained hummocks to  
504 larger sinks of  $\text{CO}_2$ , while considerably reduces emissions at the drained hollows and experimental  
505 microforms (Table 4).

### 506 3.3.2 Modeled $\text{CO}_2$ fluxes (excluding $R_r$ ) for growing season (1<sup>st</sup> May to 31<sup>st</sup> October)

507 Based on empirical models (Eqs. 1 and 2), in 2011, the ground layer at the control site was a sink of  $42$   
508  $\text{g CO}_2\text{-C m}^{-2}$ , while the drained and experimental sites were large sources of  $118$  and  $72 \text{ g CO}_2\text{-C m}^{-2}$ ,  
509 respectively (Table 4). In 2012 and 2013, the ground layer at the control site was a reduced  $\text{CO}_2\text{-C}$  sink  
510 of  $24$  and  $30 \text{ g m}^{-2}$ , respectively; the drained site was a reduced  $\text{CO}_2\text{-C}$  source of  $106$  and  $96 \text{ g m}^{-2}$ ,



511 respectively; while the experimental site was an enhanced CO<sub>2</sub>-C source of 112 and 189 g m<sup>-2</sup>,  
512 respectively.

513 In 2011, OTC warming of the forest floor microforms converted the control site to a greater CO<sub>2</sub>-C sink  
514 of 52 g m<sup>-2</sup>, drained site to a smaller CO<sub>2</sub>-C source of 84 g m<sup>-2</sup> and experimental site to a greater CO<sub>2</sub>-C  
515 source of 177 g m<sup>-2</sup>. Across the study years, warming of the microforms at the control and drained sites  
516 on average increased the uptake of carbon (Table 4). In contrast, warming at the experimental site on  
517 average enhanced CO<sub>2</sub> emissions much higher than uptake and resulted in net larger release of CO<sub>2</sub> to  
518 the atmosphere. The highest emissions at the experimental and drained hollows were largely due to a  
519 substantial contribution by  $R_r$ . Averaged across years, exclusion of  $R_r$  from  $NE_{ff}$  makes the control site a  
520 greater sink and experimental and drained sites a smaller source of forest floor CO<sub>2</sub> (Table 4, Fig. 4).

### 521 **3.4 CO<sub>2</sub>-C- balance ( $NE_{ff} + NPP - R_r$ )**

522 To calculate the final balance of CO<sub>2</sub> fluxes and tree biomass productivity, we added seasonal estimated  
523  $NE_{ff}(-R_r)$  to estimated tree incremental growth (above and below-ground) and tree litter production. We  
524 estimated the CO<sub>2</sub>-C balance separately for the three growing seasons of 2011-2013. The control site  
525 was a larger sink ( $\pm$  SD) of 92 ( $\pm$  12) g C m<sup>-2</sup> in 2011 than that of 70 ( $\pm$  10) and 76 ( $\pm$  38) g C m<sup>-2</sup> in  
526 2012 and 2013, respectively. The experimental site was a progressively increasing source of 14 ( $\pm$  5),  
527 57 ( $\pm$  44) and 135 ( $\pm$  45) g C m<sup>-2</sup> in 2011, 2012 and 2013, respectively. On the other hand, the drained  
528 site was a progressively declining source of 26 ( $\pm$  14), 23 ( $\pm$  15) and 13 ( $\pm$  2) g C m<sup>-2</sup> through 2011-  
529 2013, respectively. OTC warming of microforms consistently increased uptake at the control site by -  
530 13, -19 and -6 g C m<sup>-2</sup> from 2011 to 2013, respectively. The warming also converted the drained site to  
531 a sink of C by 34, 52 and 71 g C m<sup>-2</sup> in 2011, 2012 and 2013, respectively. In contrast, the warming  
532 enhanced emissions at the experimental site resulting in losses of 105, 100 and 10 g C m<sup>-2</sup> through the  
533 study years, respectively. In all cases, as warming was not applied directly to the trees any impact on  
534 their growth could not be included in the study. The warming treatment overall increased the CO<sub>2</sub>-C  
535 uptake at hummocks and enhanced the emissions at hollows. Averaged across the study years, the  
536 warming interacted with deeper and longer drainage to restore the peatland's original CO<sub>2</sub>-C sink  
537 function (Fig. 5).

## 538 **4 Discussion**

539 This study estimated the CO<sub>2</sub>-C balance of a sub-humid, continental treed bog by combining the C  
540 exchange values derived from modeled CO<sub>2</sub> flux and tree productivity, separately for the growing  
541 seasons (May to October) of 2011, 2012 and 2013. The control site in this bog was a growing season  
542 sink of 92, 70 and 76 g C m<sup>-2</sup> along years from slightly wetter and warmer to drier and warmer than

543 average, respectively (Table 4). Depending on the length of time since fire, Wieder et al. (2009)  
544 reported that the ombrotrophic bogs in the same region represented an annual CO<sub>2</sub> sink of 120 to 220 g  
545 C m<sup>-2</sup> and thus our values are slightly below this range. Within the same boreal region of northern  
546 Alberta as the present study, Adkinson et al. (2011) also reported net growing season CO<sub>2</sub> uptake across  
547 three study years of -110 and -35 to -154 g C m<sup>-2</sup> at poor fen and rich fen sites, respectively, and thus  
548 our control site sink values are close to the value at the poor fen. However, a higher yearly CO<sub>2</sub>  
549 accumulation rate of -144 g C m<sup>-2</sup> in a treed fen in the same boreal region is reported by Syed et al.  
550 (2006).

551 Methane (CH<sub>4</sub>) is also an important component of the C balance in peatland ecosystems. However,  
552 over-all seasonal CH<sub>4</sub>-C losses were reported to be 0.34, 0.61 and 0.07 g C m<sup>-2</sup> at our control,  
553 experimental and drained sites, respectively (Munir and Strack, 2014). Therefore, the CH<sub>4</sub> fluxes are a  
554 minor component of the seasonal C balance at our dry continental bog sites. Carbon can also be lost  
555 from the system with hydrologic flows. This would include dissolved organic C, particulate organic C  
556 and dissolved inorganic C. Given the deep water level and dry conditions in these continental bogs,  
557 discharge from the study areas during the growing season was also likely small. This suggests the CO<sub>2</sub>-  
558 C exchange likely represents the majority of the C balance at these sites.

#### 559 **4.1 Weather effects**

560 Previous findings have revealed that dry and warm summer conditions can reduce net CO<sub>2</sub> uptake in  
561 peatlands by enhancing respiration greater than production (Aurela et al., 2007; Cai et al., 2010; Bhatti  
562 et al., 2012; Alm et al., 1999). Likewise, the net CO<sub>2</sub> uptake (NE<sub>ff</sub>) at our control and experimental sites  
563 were lower in the drier and warmer growing seasons (2012 and 2013) of the study. This reduction was  
564 due to the substantial increase in R<sub>ff</sub> at the hollows exceeding the combined increase in GPP<sub>ff</sub> at the  
565 microforms especially in 2012 (Table 4). The steady and consistent increase in R<sub>ff</sub> at the control hollows  
566 might be due to the weather-driven moderate decline in water level (Fig. 2) and stressed vegetation  
567 (data not presented here) observed at the hollows. However, the abrupt increase in R<sub>ff</sub> noticed at the  
568 experimental hollows might be due to the influence of experimental lowering of water table negatively  
569 affecting hollow vegetation more than adjacent hummocks. In contrast, there was only a minor  
570 fluctuation in GPP<sub>ff</sub> or R<sub>ff</sub> at the drained site in 2012 and 2013 compared to 2011, and thus stability in  
571 net CO<sub>2</sub> exchange at this long-term drained site could be due to the dominance of vascular ground-layer  
572 vegetation, as opposed to the control and short-term drained sites having greater coverage of mosses  
573 (Fig. 3, Table 2, 3).

#### 574 **4.2 Water table manipulation effects**

575 The one to three years of water table drawdown, converted our bog site forest floor (excluding  $R_f$ ) from  
576 a sink of 42, 24 and 30 g C m<sup>-2</sup> in 2011, 2012 and 2013, respectively, to a progressively larger source of  
577 72, 112 and 189 g C m<sup>-2</sup> in 2011, 2012 and 2013, respectively. A net loss of CO<sub>2</sub>-C in response to a  
578 short-term disturbance has been reported by Laiho (2006) in a bog and Chivers et al. (2009) in a fen  
579 ecosystem. The 11-13 years of deeper water level also showed a net loss that was higher in 2011 (118 g  
580 C m<sup>-2</sup>) and declined slightly through the later years (106 and 96 g C m<sup>-2</sup> in 2012 and 2013, respectively).  
581 The drained and experimental sites had consistently increasing emissions at the hollows and decreasing  
582 emissions at the hummocks from 2011 to 2013, although the emissions at the experimental site were  
583 highest. These net loss values of CO<sub>2</sub>-C at the short and longer-term drained sites compare well with  
584 those of other experimentally drained peatlands as reported by Von-Arnold et al. (2005), Cai et al.  
585 (2010) and Simola et al. (2012). The rapid decline in water table in the experimental site possibly  
586 initiated vegetation desiccation that progressed through the study years. In contrast, the longer-term  
587 drainage drove hummock habitat to be more favourable for woody shrubs of higher water use efficiency  
588 and longer root system. That was likely why the drained site hummocks had declining net emissions  
589 with warming and drying of the growing seasons.

#### 590 **4.3 OTC warming effects**

591 The control site sink strength was enhanced by OTC warming leading to greater CO<sub>2</sub>-C uptake as NEE  
592 (including NE<sub>ff</sub> and trees) by 13, 19 and 6 g C m<sup>-2</sup> (represented by  $C_w$  in Table 4) in the growing seasons  
593 from 2011 to 2013, respectively. The lowest sink differential (warmed – ambient) of 6 g C m<sup>-2</sup> was  
594 noticed in the warmest and driest year 2013 similar to the findings of Aurela et al. (2007) and Lafleur  
595 and Humphreys (2008). They also reported that increased growing season temperature enhanced GPP<sub>ff</sub>  
596 but extreme seasonal temperature reduced the GPP<sub>ff</sub> and accelerated  $R_{ff}$  in a sub-arctic fen. The increase  
597 in GPP<sub>ff</sub> and/or  $R_{ff}$  has also been reported by Sullivan et al. (2008) in a Greenland rich fen and Weltzin  
598 et al. (2001) in bog mesocosms, both in disagreement with Johnson et al. (2013) who reported that there  
599 was no consistent effect of OTC warming on the CO<sub>2</sub> flux components because of subtle warming. At  
600 our short-term drained (experimental) site, the OTC warming greatly accelerated emissions, causing  
601 differential increases of 105, 100 and 10 g CO<sub>2</sub>-C m<sup>-2</sup> from 2011 to 2013, respectively (Table 4). An  
602 abrupt differential increase in the first year of water table drawdown could be due to an accelerated  
603 microbial decomposition of easily decomposable substrate (Keller and Bridgham, 2007; Cai et al.,  
604 2010) due to the limiting capillary rise to the drying moss (Waddington and Price, 2000) and extremely  
605 stressed vegetation observed in the first two years of warming treatment. However, our long-term  
606 drained site had 13 years of transitioning to a habitat favourable for the drought resistant vascular  
607 vegetation. A peatland forest floor subjected to long-term deeper drainage developed drought resistant

608 vascular vegetation and trees with deeper root system compared to that under shallower water level  
609 conditions. The stable increase in the growth of shrubs and trees in the thicker oxic zone can accelerate  
610 accumulation rate equal to or exceeding its original productivity before forestry drainage (Hermle et al.,  
611 2010; Lohila et al., 2011). Thus our drained site microforms equipped with OTCs, responded with  
612 consistently increasing differential NEE of -34, -52 and -73 g C m<sup>-2</sup> in 2011, 2012 and 2013,  
613 respectively. Thus, warming led to greater CO<sub>2</sub> uptake. Our findings together with those of others (e.g.  
614 Bubier et al., 2003; Aurela et al., 2007; Sullivan et al., 2008; Weider et al., 2009; Lohila et al., 2011)  
615 demonstrate the critical interaction of temperature with wetness for GPP<sub>ff</sub> and R<sub>ff</sub> response as either of  
616 the factors alone could not illustrate the overall growth response of bog vegetation under changing  
617 microclimatic and environmental conditions.

#### 618 4.4 Microform effects

619 Peatland microforms have been reported to respond with different magnitudes and in different  
620 directions to changes in water table, warming, and other climatic and environmental conditions. For  
621 example, Waddington and Roulet (2000) reported significantly greater CO<sub>2</sub> uptake at the wetter lawn  
622 than that at the drier ridge in an eccentric raised bog in Sweden, over two growing seasons. Similarly, in  
623 a cool temperate fen in Canada, Strack et al. (2006) demonstrated higher GPP<sub>max</sub> at drained hollows  
624 than that at drained hummocks in contrast to the control microforms and speculated that the persistently  
625 lowered water tables would result in flattening of the peatland microtopography. Contrastingly, in this  
626 study in a dry continental treed bog in Alberta, we found that after thirteen years of deepest drainage  
627 treatment the GPP<sub>max</sub> and GPP<sub>ff</sub> were in fact the highest at drained hummocks, increasing from cooler  
628 2011 to warmer 2013. Conversely, R<sub>ff</sub> and R<sub>t</sub> were the highest at the experimental and drained hollows,  
629 also increasing towards warmer 2013. Interestingly, the CO<sub>2</sub> uptake was even higher at the warmed  
630 drained hummocks, while CO<sub>2</sub> release was also even higher at the warmed drained hollows and  
631 experimental microforms compared to the ambient microforms at these sites (Fig. 4, Table 4). The  
632 significantly increased GPP<sub>max</sub> at ambient and even higher at warmed drained hummocks were probably  
633 due to enhanced growth and greater biomass of vascular vegetation (shrubs; Table 2, Fig 3).  
634 Conversely, replacement of most of the moss (dominantly *Sphagnum*) biomass by lichens at ambient  
635 and warmed drained hollows led to the measured reduction in GPP<sub>max</sub> and GPP<sub>ff</sub> (Fig. 3, Table 2, 4).  
636 Moreover, drained and experimental hollows were the largest sources of CO<sub>2</sub> in all years. Thus, we  
637 expect hummocks to have increasing equilibrium peat depth and hollows to have decreasing  
638 equilibrium peat depth as an effect of drainage over the long run. These predictions contradict with  
639 those of Strack et al. (2006) due to contrasting microclimatic and environmental conditions of the two  
640 studies but corroborate with those of Munir et al. (2014) due to same climatic and environmental

641 conditions. However, these studies together support a general humpbacked relationship of peat  
642 accumulation with water level (Belyea, 2009). Therefore, combining the CO<sub>2</sub> dynamics at the ambient  
643 and warmed experimental and drained microforms demonstrates that climate forced declining water  
644 levels in ombrotrophic continental bogs would result in hummocks growing higher and hollows  
645 deepening.

#### 646 **4.5 Water table manipulation and warming effects on vegetation**

647 Interactions between soil and plant communities have been predicted to play a major role in  
648 determining the response of net exchange of CO<sub>2</sub> in peatlands to a climate change scenario (Weltzin et  
649 al., 2001; Kardol et al., 2010; Moore et al., 2002) of water level lowering and global warming (Ciais et  
650 al., 2013). Ground-layer biomass was significantly affected in response to thirteen years of drainage  
651 (water level ~120 cm;  $F_{2,36} = 49.42, p < 0.001$ ) and OTC average warming of ~1 °C or mid-day full sun  
652 diurnal air warming of ~6 °C or 5 cm deep soil warming of ~5 °C ( $F_{2,36} = 6.46, p = 0.015$ ; Fig. 2, 3).  
653 The shift in biomass coverage and composition was also different between the microforms ( $F_{2,36} =$   
654 24.14,  $p < 0.001$ ); increased biomass at hummocks compared to that at hollows. However, no  
655 significant difference in vegetation biomass or composition was found after a three years of drainage of  
656 water level ~76 cm ( $p = 0.162$ ). Interestingly, along a gradient of decreasing water level, shrub biomass  
657 increased at hummocks, lichens biomass increased at hollows, while moss biomass decreased at all  
658 microforms at the continental bog sites. Along the same gradient of decreasing water level, the warming  
659 treatment enhanced shrub biomass at the hummocks from 2011-2013, indicated by an interaction of  
660 water table × warming × microform × year ( $F_{2,36} = 8.24, p = 0.001$ ). The accumulated NPP ratio of  
661 below-ground: above-ground shifted from 1.86 before warming to 2.00 after warming, suggesting a  
662 shift in C allocation in response to warming treatment. The three bog functional plant groups (moss,  
663 shrub, lichen) differed in their response to water level and warming due to their differential response of  
664 life-forms and species characteristics of each community (Weltzin et al., 2000). The drainage-driven  
665 and warming-induced increases in vascular biomass we found were also reported by Moore et al. (2002)  
666 and Laine et al. (2011), and Weltzin et al. (2000), respectively.

#### 667 **4.6 Water table manipulation and warming effects on biomass and NPP**

668 We report above-ground biomass (including ground-layer and canopy-layer) to be within the range of  
669 values previously published for bog studies. The published data for ground-layer biomass across 16  
670 bogs and above-ground tree biomass across 20 bogs varied quite broadly with means of 1900 g m<sup>-2</sup> (±  
671 224) and 2177 g m<sup>-2</sup> (± 2259), respectively (Moore et al., 2002). Our data for above-ground tree  
672 biomass (2031 ± 379) fall within the range of published values. However our ground-layer biomass  
673 average (1236 ± 130 g m<sup>-2</sup>) is less than 1900 g m<sup>-2</sup> (± 224) reported by Moore et al. (2002) because they

674 drew 110 cm deep peat cores for quantifying below-ground biomass versus our core depth of only 20  
675 cm. Therefore, it is likely that we might have underestimated the below-ground biomass particularly at  
676 the drained site with up to 120 cm thick oxic zone. However, this still more likely included almost all of  
677 the below-ground biomass as Lieffers and Rothwell (1987) could find only 6% of the root biomass  
678 below 20 cm depth in a drained bog (water level below 80 cm) in north central Alberta.

679 Although above-ground tree biomass decreased along our gradient of deeper water level, productivity of  
680 the trees (measured by determining above-ground incremental tree growth) increased along the same  
681 gradient (Table 2, 4). The highest above-ground tree biomass estimated at the control site was due to  
682 thinner oxic zone supporting mainly denser stand but smaller diameter trees and higher number of  
683 shorter trees. The higher productivity in the drier sites was due to thicker aerated peat and supporting  
684 higher availability of nutrients (Paavilainen and Päivänen, 1995). Therefore, trees react almost instantly  
685 to changes in the local water table (Linderholm and Leine, 2004), as occurred in the experimental site  
686 that showed higher productivity than the control but lesser than the drained site. The response time to  
687 reach maximum tree productivity after drainage has been reported to be ~10 years (Seppala, 1969;  
688 Linderholm and Leine, 2004) which strongly supports significantly highest productivity at our 10-13  
689 years old drained site of deepest water table of ~120 cm. The measured  $R_t$  consistently increased at all  
690 sites along a gradient of warming year (growing season), but was highest at the experimental site in all  
691 years due to readily available substrate and desiccating vegetation at this short-term lowered water level  
692 site. Drainage induces significantly higher coverage and biomass of vascular plants that offset some of  
693 the loss of CO<sub>2</sub> occurring due to deepening of oxic zone and increasing of decay rates (Ise et al., 2008).  
694 Therefore, although our drained site forest floor was always a source of CO<sub>2</sub>, warming induced  
695 significantly increased ground-layer biomass that shifted this site to be a sink of C. This sink function  
696 coupled with higher tree productivity significantly enhanced the sink function of the drained site (Fig.  
697 5). Conversely, the dramatic lowering of water table at the experimental site severely destabilized the  
698 ecosystem functioning that was further deteriorating with warming treatment along the study seasons  
699 (2011-2013). However, the differential emissions (warmed – ambient) were noticed to be declining  
700 through the study years, indicating that the bog ecosystem may have been reaching a new equilibrium  
701 after an initial stress.

## 702 **5 Conclusions**

703 In a mid-latitude dry continental treed bog, there was a transitional shift in biomass coverage and  
704 composition between the microforms in response to a longer-term water level lowering and OTC  
705 warming. In fact, the moss biomass was replaced by vascular plant biomass (mostly woody shrubs) at

706 hummocks and lichen biomass at hollows. The shrub biomass growth was significantly increased in  
707 response to a three year OTC warming of  $\sim 1^{\circ}\text{C}$  in the longer-term and deeper water level treatment.

708 The deeper water level combined with OTC warming induced enhanced growth of woody shrubs and  
709 drove the drained hummocks to become the largest net sink of  $\text{CO}_2$  across all sites and microforms.  
710 Conversely, the short-term, as well as the longer-term, water level lowering converted the hollows to be  
711 the largest net sources of  $\text{CO}_2$ . However, the 11-13 years of deeper water level lowering coupled with  
712 OTC warming increased the forest floor net uptake of  $\text{CO}_2$  exceeding well above the losses via  
713 respiration at the drained microforms. The significantly increased tree productivity in response to the  
714 longer-term deeper drainage (NPP-C) added to the  $\text{NE}_{\text{ff}}\text{-C}$  ( $-R_r$ ) converted the drained site from a  
715 moderate C source, to become a sink of C close to the bog's original sink strength (Fig. 5).

716 Averaged across study years, an OTC warming of  $\sim 1^{\circ}\text{C}$  (and differential mid-day full sun air warming  
717 of  $\sim 6^{\circ}\text{C}$ ) interacted with water level treatment to enhance the sink function of the undisturbed site,  
718 enlarge source strength of the experimental site and restore the sink strength of the drained site. This  
719 pattern is a strong indicator that climatic warming that drives persistent lowering of water level for  
720 longer-term is expected to restore the original sink function of continental treed bogs after an initial  
721 short duration of net C losses. We also infer that mid-latitude continental treed bogs are sensitive but  
722 adaptive ecosystems that are expected to respond to climatic warming and drying almost instantly by  
723 supporting development of woody roots that penetrate deeper for optimum supply of moisture and  
724 nutrients to the newly adapted surface vegetation. Although the deepening of water table initially leads  
725 to larger net emissions to the atmosphere, persistent drying and warming transforms the moss habitat  
726 (characterized by near surface water level) to vascular plant habitat (characterized by deeper water  
727 level) leading to a shift to woody shrubs and trees with deeper root systems. The bog trees adapt better  
728 to lower water levels and increase productivity by widening ring width, lengthening leader length and  
729 increasing belowground biomass allocation.

### 730 **Acknowledgements**

731 This research was funded by Alberta Innovates Technology Futures and University of Calgary. SunGro  
732 Horticulture provided access to the sites. We thank Dr. Tak Fung for statistical support, Dr. Bin Xu,  
733 Courtney Campbell, Sasha van Stavel, Magnus Keith, Heather Yeung and Jordanna Branham for field  
734 and Melanie Bird for laboratory help. Comments from Larry Flanagan, Jagtar Bhatti and two  
735 anonymous reviewers helped improve the manuscript.

736

737

738 **References**

- 739 Adkinson, A. C., Syed, K. H., and Flanagan, L. B.: Contrasting responses of growing season ecosystem  
740 CO<sub>2</sub> exchange to variation in temperature and water table depth in two peatlands in northern Alberta,  
741 Canada, *Journal of Geophysical Research: Biogeosciences*, 116, 1-17, 2011.
- 742 Alm, J., Schulman, L., Walden, J., Nykänen, H., Martikainen, P. J., and Silvola, J.: Carbon balance of a  
743 boreal bog during a year with an exceptionally dry summer, *Ecology*, 80, 161-174, 1999.
- 744 Aurela, M., Riutta, T., Laurila, T., Tuovinen, J. P., Vesala, T., Tuittila, E.-S., Rinne, J., Haapanala, S.,  
745 and Laine, J.: CO<sub>2</sub> exchange of a sedge fen in southern Finland: the impact of a drought period, *Tellus*  
746 *B*, 59, 826-837, 2007.
- 747 Belyea, L. R.: Nonlinear dynamics of peatlands and potential feedbacks on the climate system, in:  
748 *Carbon Cycling in Northern Peatlands*, Geophys. Monogr. Ser., AGU, Washington, DC, 5-18, 2009.
- 749 Bhatti, J., Jassal, R., and Black, T. A.: Decarbonization of the atmosphere: role of the boreal forest  
750 under changing climate, in: *Recarbonization of the Biosphere*, Springer, 203-228, 2012.
- 751 Boone, R. D., Nadelhoffer, K. J., Canary, J. D., and Kaye, J. P.: Roots exert a strong influence on the  
752 temperature sensitivity of soil respiration, *Nature*, 396, 570-572, 1998.
- 753 Bowden, R. D., Nadelhoffer, K. J., Boone, R. D., Melillo, J. M., and Garrison, J. B.: Contributions of  
754 above-ground litter, below-ground litter, and root respiration to total soil respiration in a temperate  
755 mixed hardwood forest, *Can. J. Forest Res*, 23, 1402-1407, 1993.
- 756 Bubier, J., Crill, P., Mosedale, A., Frohling, S., and Linder, E.: Peatland responses to varying  
757 interannual moisture conditions as measured by automatic CO<sub>2</sub> chambers, *Global Biogeochemical*  
758 *Cycles*, 17, 35-13, 2003.
- 759 Cai, T., Flanagan, L. B., and Syed, K. H.: Warmer and drier conditions stimulate respiration more than  
760 photosynthesis in a boreal peatland ecosystem: Analysis of automatic chambers and eddy covariance  
761 measurements, *Plant, Cell & Environment*, 33, 394-407, 2010.
- 762 Charman, D., Beilman, D., Blaauw, M., Booth, R., Brewer, S., Chambers, F., Christen, J., Gallego-Sala,  
763 A., Harrison, S., and Hughes, P.: Climate-related changes in peatland carbon accumulation during the  
764 last millennium, *Biogeosciences*, 10, 929-944, 2013.
- 765 Chivers, M., Turetsky, M., Waddington, J., Harden, J., and McGuire, A.: Effects of experimental water  
766 table and temperature manipulations on ecosystem CO<sub>2</sub> fluxes in an Alaskan rich fen, *Ecosystems*, 12,  
767 1329-1342, 2009.
- 768 Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway,  
769 J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R., Piao, S., and Thornton, P.: Carbon and Other  
770 Biogeochemical Cycles. In: *Climate Change 2013: The Physical Science Basis. Contribution of*  
771 *Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*  
772 *[Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex*  
773 *and P.M. Midgley (eds.)]*, Cambridge University Press, Cambridge, United Kingdom and New York,  
774 NY, USA., 2013.
- 775 Clymo, R., Turunen, J., and Tolonen, K.: Carbon accumulation in peatland, *Oikos*, 368-388, 1998.



- 776 Davidson, E., Savage, K., Verchot, L., and Navarro, R.: Minimizing artifacts and biases in chamber-  
777 based measurements of soil respiration, *Agricultural and Forest Meteorology*, 113, 21-37, 2002.
- 778 Davidson, E. A., and Janssens, I. A.: Temperature sensitivity of soil carbon decomposition and  
779 feedbacks to climate change, *Nature*, 440, 165-173, 2006.
- 780 Denmead, O. T., and Reicosky, D. C.: Tillage-induced gas fluxes: comparison of meteorological and  
781 large chamber techniques, in: *Proceedings of the 16th Triennial Conference of International Soil Tillage*  
782 *Research Organizations*, 13-18, 2003.
- 783 Edwards, N. T., and Norby, R. J.: Below-ground respiratory responses of sugar maple and red maple  
784 saplings to atmospheric CO<sub>2</sub> enrichment and elevated air temperature, *Plant and Soil*, 206, 85-97, 1999.
- 785 Grigal, D., and Kernik, L.: Generality of black spruce biomass estimation equations, *Canadian Journal*  
786 *of Forest Research*, 14, 468-470, 1984.
- 787 Grosse, G., Harden, J., Turetsky, M., McGuire, A. D., Camill, P., Tarnocai, C., Frohling, S., Schuur, E.  
788 A., Jorgenson, T., and Marchenko, S.: Vulnerability of high-latitude soil organic carbon in North  
789 America to disturbance, *Journal of Geophysical Research: Biogeosciences (2005–2012)*, 116, 2011.
- 790 Gruber, N., Friedlingstein, P., Field, C., Valentini, R., Heimann, M., Richey, J., Lankao, P., Schulze, E.,  
791 ChenTung, C., and Raupach, M.: The vulnerability of the carbon cycle in the 21st century: an  
792 assessment of carbon-climate-human interactions, *The global carbon cycle: integrating humans, climate*  
793 *and the natural world*, 45-76, 2004.
- 794 Hanson, P., Wullschleger, S., Bohlman, S., and Todd, D.: Seasonal and topographic patterns of forest  
795 floor CO<sub>2</sub> efflux from an upland oak forest, *Tree physiology*, 13, 1-15, 1993.
- 796 Hanson, P., Edwards, N., Garten, C., and Andrews, J.: Separating root and soil microbial contributions  
797 to soil respiration: a review of methods and observations, *Biogeochemistry*, 48, 115-146, 2000.
- 798 Heikurainen, L., and Pakarinen, P.: Peatland classification. In *Peatlands and their utilization in Finland*,  
799 *Finnish National Committee of the International Peat Society*, Helsinki, 1982.
- 800 Hermle, S., Lavigne, M. B., Bernier, P. Y., Bergeron, O., and Paré, D.: Component respiration,  
801 ecosystem respiration and net primary production of a mature black spruce forest in northern Quebec,  
802 *Tree physiology*, 30, 527-540, 2010.
- 803 Hutchinson, G., Guenzi, W., and Livingston, G.: Soil water controls on aerobic soil emission of gaseous  
804 nitrogen oxides, *Soil Biology and Biochemistry*, 25, 1-9, 1993.
- 805 Hutchinson, G., and Livingston, G.: Vents and seals in non-steady-state chambers used for measuring  
806 gas exchange between soil and the atmosphere, *European Journal of Soil Science*, 52, 675-682, 2001.
- 807 IPCC: Impacts, Adaptation and Vulnerability: Contribution of working group II to the fourth  
808 assessment report of the intergovernmental panel on climate change. M.L. Parry, O.F. Canziani, J.P.  
809 Palutikof, P.J. van der Linden and C.E. Hanson, P. J (eds.), Cambridge University Press, Cambridge,  
810 United Kingdom, 976, 2007.
- 811 Ise, T., Dunn, A. L., Wofsy, S. C., and Moorcroft, P. R.: High sensitivity of peat decomposition to  
812 climate change through water-table feedback, *Nature Geoscience*, 1, 763-766, 2008.

813 Janssens, I., Lankreijer, H., Matteucci, G., Kowalski, A., Buchmann, N., Epron, D., Pilegaard, K.,  
814 Kutsch, W., Longdoz, B., and Grünwald, T.: Productivity overshadows temperature in determining soil  
815 and ecosystem respiration across European forests, *Global Change Biology*, 7, 269-278, 2001.

816 Jennrich, R. I., and Schluchter, M. D.: Unbalanced repeated-measures models with structured  
817 covariance matrices, *Biometrics*, 805-820, 1986.

818 Johnson, C., Pypker, T., Hribljan, J., and Chimner, R.: Open top chambers and infrared lamps: A  
819 comparison of heating efficacy and CO<sub>2</sub>/CH<sub>4</sub> dynamics in a northern Michigan peatland, *Ecosystems*, 1-  
820 13, 2013.

821 Kardol, P., Cregger, M. A., Company, C. E., and Classen, A. T.: Soil ecosystem functioning under  
822 climate change: plant species and community effects, *Ecology*, 91, 767-781, 2010.

823 Keller, J. K., and Bridgham, S. D.: Pathways of anaerobic carbon cycling across an ombrotrophic-  
824 minerotrophic peatland gradient, *Limnology and Oceanography*, 52, 96-107, 2007.

825 Kettles, I. M., and Tarnocai, C.: Development of a model for estimating the sensitivity of Canadian  
826 peatlands to climate warming, *Geographie physique et Quaternaire*, 53, 323-338, 1999.

827 Kutzbach, L., Schneider, J., Sachs, T., Giebels, M., Nykänen, H., Shurpali, N., Martikainen, P., Alm, J.,  
828 and Wilmking, M.: CO<sub>2</sub> flux determination by closed-chamber methods can be seriously biased by  
829 inappropriate application of linear regression, *Biogeosciences*, 4, 1005-1025, 2007.

830 Lafleur, P. M., and Humphreys, E. R.: Spring warming and carbon dioxide exchange over low Arctic  
831 tundra in central Canada, *Global Change Biology*, 14, 740-756, 2008.

832 Lai, D., Roulet, N., Humphreys, E., Moore, T., and Dalva, M.: The effect of atmospheric turbulence and  
833 chamber deployment period on autochamber CO<sub>2</sub> and CH<sub>4</sub> flux measurements in an ombrotrophic  
834 peatland, *Biogeosciences*, 9, 3305-3322, 2012.

835 Laiho, R.: Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of  
836 lowered water levels, *Soil Biology and Biochemistry*, 38, 2011-2024, 2006.

837 Laine, A. M., Bubier, J., Riutta, T., Nilsson, M. B., Moore, T. R., Vasander, H., and Tuittila, E.-S.:  
838 Abundance and composition of plant biomass as potential controls for mire net ecosystem CO<sub>2</sub>  
839 exchange, *Botany*, 90, 63-74, 2011.

840 Li, Z., Kurz, W. A., Apps, M. J., and Beukema, S. J.: Belowground biomass dynamics in the carbon  
841 budget model of the Canadian forest sector: Recent improvements and implications for the estimation of  
842 NPP and NEP, *Canadian Journal of Forest Research*, 33, 126-136, 2003.

843 Lieffers, V., and Rothwell, R.: Rooting of peatland black spruce and tamarack in relation to depth of  
844 water table, *Canadian Journal of Botany*, 65, 817-821, 1987.

845 Limpens, J., Berendse, F., Blodau, C., Canadell, J. G., Freeman, C., Holden, J., Roulet, N., Rydin, H.,  
846 and Schaepman-S, G.: Peatlands and the carbon cycle: from local processes to global implications – a  
847 synthesis, *Biogeosciences*, 5, 1475-1491, 2008.

- 848 Linderholm, H. W., and Leine, M.: An assessment of twentieth century tree-cover changes on a  
849 southern Swedish peatland combining dendrochronology and aerial photograph analysis, *Wetlands*, 24,  
850 357-363, 2004.
- 851 Lohila, A., Minkkinen, K., Aurela, M., Tuovinen, J.-P., Penttilä, T., Ojanen, P., Laurila, T., and Neftel,  
852 A.: Greenhouse gas flux measurements in a forestry-drained peatland indicate a large carbon sink,  
853 *Biogeosciences*, 8, 2011.
- 854 Loisel, J., Gallego-Sala, A., and Yu, Z.: Global-scale pattern of peatland Sphagnum growth driven by  
855 photosynthetically active radiation and growing season length, *Biogeosciences*, 9, 2737-2746, 2012.
- 856 Lund, M., Lafleur, P. M., Roulet, N. T., Lindroth, A., Christensen, T. R., Aurela, M., Chojnicki, B. H.,  
857 Flanagan, L. B., Humphreys, E. R., and Laurila, T.: Variability in exchange of CO<sub>2</sub> across 12 northern  
858 peatland and tundra sites, *Global Change Biology*, 16, 2436-2448, 2010.
- 859 Macdonald, S. E., and Lieffers, V. J.: Photosynthesis, water relations, and foliar nitrogen of *Picea*  
860 *mariana* and *Larix laricina* from drained and undrained peatlands, *Canadian Journal of Forest Research*,  
861 20, 995-1000, 1990.
- 862 Moore, P. D.: The future of cool temperate bogs, *Environmental Conservation*, 29, 3-20, 2002.
- 863 Moore, T. R., Bubier, J. L., Frohling, S. E., Lafleur, P. M., and Roulet, N. T.: Plant biomass and  
864 production and CO<sub>2</sub> exchange in an ombrotrophic bog, *Journal of Ecology*, 90, 25-36, 2002.
- 865 Moore, T. R., Lafleur, P. M., Poon, D. M. I., Heumann, B. W., Seaquist, J. W., and Roulet, N. T.:  
866 Spring photosynthesis in a cool temperate bog, *Global Change Biology*, 12, 2323-2335, 2006.
- 867 Mullin, T., Morgenstern, E., Park, Y., and Fowler, D.: Genetic parameters from a clonally replicated  
868 test of black spruce (*Picea mariana*), *Canadian Journal of Forest Research*, 22, 24-36, 1992.
- 869 Munir, T., and Strack, M.: Methane flux influenced by experimental water table drawdown and soil  
870 warming in a dry boreal continental bog, *Ecosystems*, 17, 1271-1285, 2014.
- 871 Munir, T., Xu, B., Perkins, M., and Strack, M.: Responses of carbon dioxide flux and plant biomass to  
872 water table drawdown in a treed peatland in northern Alberta: a climate change perspective,  
873 *Biogeosciences*, 11, 807-820, 2014.
- 874 Ow, L. F., Griffin, K. L., Whitehead, D., Walcroft, A. S., and Turnbull, M. H.: Thermal acclimation of  
875 leaf respiration but not photosynthesis in *Populus deltoides* × *nigra*, *New Phytologist*, 178, 123-134,  
876 2008.
- 877 Paavilainen, E., and Päivänen, J.: *Peatland forestry: ecology and principles*, Springer, 1995.
- 878 Parmentier, F., Van der Molen, M., de Jeu, R., Hendriks, D., and Dolman, A.: CO<sub>2</sub> fluxes and  
879 evaporation on a peatland in the Netherlands appear not affected by water table fluctuations,  
880 *Agricultural and Forest Meteorology*, 149, 1201-1208, 2009.
- 881 Pihlatie, M., Kiese, R., Brüggemann, N., Butterbach-Bahl, K., Kieloaho, A.-J., Laurila, T., Lohila, A.,  
882 Mammarella, I., Minkkinen, K., and Penttilä, T.: Greenhouse gas fluxes in a drained peatland forest  
883 during spring frost-thaw event, *Biogeosciences*, 7, 1715-1727, 2010.

- 884 Rey, A., Pegoraro, E., Tedeschi, V., De-Parri, I., Jarvis, P. G., and Valentini, R.: Annual variation in  
885 soil respiration and its components in a coppice oak forest in Central Italy, *Glob. Change Biol*, 8, 851-  
886 866, 2002.
- 887 Riley, J. L.: *The Vascular Flora of the Hudson Bay Lowland and Its Postglacial Origins*, NRC Research  
888 Press, 2003.
- 889 Riutta, T., Laine, J., and Tuittila, E.-S.: Sensitivity of CO<sub>2</sub> exchange of fen ecosystem components to  
890 water level variation, *Ecosystems*, 10, 718-733, 2007.
- 891 Roulet, N. T., Lafleur, P. M., Richard, P. J., Moore, T. R., Humphreys, E. R., and Bubier, J.:  
892 Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland, *Global*  
893 *Change Biology*, 13, 397-411, 2007.
- 894 Seppala, K.: Post-drainage growth rate of Norway spruce and scots pine on peat (in Finnish with  
895 English summary), *Acta Forestalia Fennica*, 93, 1-17, 1969.
- 896 Simola, H., Pitkänen, A., and Turunen, J.: Carbon loss in drained forestry peatlands in Finland,  
897 estimated by re-sampling peatlands surveyed in the 1980s, *European Journal of Soil Science*, 63, 798-  
898 807, 2012.
- 899 Sternberg, M., Brown, V. K., Masters, G. J., and Clarke, I. P.: Plant community dynamics in a  
900 calcareous grassland under climate change manipulations, *Plant Ecology*, 143, 29-37, 1999.
- 901 Stocker, B. D., Roth, R., Joos, F., Spahni, R., Steinacher, M., Zaehle, S., Bouwman, L., and Prentice, I.  
902 C.: Multiple greenhouse-gas feedbacks from the land biosphere under future climate change scenarios,  
903 *Nature Climate Change*, 3, 666-672, 2013.
- 904 Strack, M., Waddington, J., Rochefort, L., and Tuittila, E. S.: Response of vegetation and net ecosystem  
905 carbon dioxide exchange at different peatland microforms following water table drawdown, *Journal of*  
906 *Geophysical Research: Biogeosciences (2005–2012)*, 111, 2006.
- 907 Sullivan, P. F., Arens, S. J., Chimner, R. A., and Welker, J. M.: Temperature and microtopography  
908 interact to control carbon cycling in a high arctic fen, *Ecosystems*, 11, 61-76, 2008.
- 909 Syed, K. H., Flanagan, L. B., Carlson, P. J., Glenn, A. J., and Van Gaalen, K. E.: Environmental control  
910 of net ecosystem CO<sub>2</sub> exchange in a treed, moderately rich fen in northern Alberta, *Agricultural and*  
911 *Forest Meteorology*, 140, 97-114, 2006.
- 912 Szumigalski, A. R., and Bayley, S. E.: Net above-ground primary production along a bog-rich fen  
913 gradient in central Alberta, Canada, *Wetlands*, 16, 467-476, 1996.
- 914 Tarnocai, C.: The effect of climate change on carbon in Canadian peatlands, *Global and Planetary*  
915 *Change*, 53, 222-232, 2006.
- 916 Tarnocai, C., Canadell, J., Schuur, E., Kuhry, P., Mazhitova, G., and Zimov, S.: Soil organic carbon  
917 pools in the northern circumpolar permafrost region, *Global Biogeochemical Cycles*, 23, 1-11, 2009.
- 918 Thormann, M. N., and Bayley, S. E.: Above-ground net primary production along a bog-fen-marsh  
919 gradient in southern boreal Alberta, Canada, *Ecoscience*, 4, 374-384, 1997.

- 920 Tokida, T., Mizoguchi, M., Miyazaki, T., Kagemoto, A., Nagata, O., and Hatano, R.: Episodic release  
921 of methane bubbles from peatland during spring thaw, *Chemosphere*, 70, 165-171, 2007.
- 922 Turetsky, M., Wieder, K., Halsey, L., and Vitt, D.: Current disturbance and the diminishing peatland  
923 carbon sink, *Geophysical Research Letters*, 10.1029/2001GL014000, 2002.
- 924 Varem-Sanders, T. M. L., and Campbell, I. D.: DendroScan: a tree-ring width and density measurement  
925 system. Canadian Forest Service, Northern Forestry Centre, Edmonton, Alta. Spec. Rep. 10, 1996.
- 926 Vitt, D. H., Wieder, R. K., Scott, K. D., and Faller, S.: Decomposition and peat accumulation in rich  
927 fens of boreal Alberta, Canada, *Ecosystems*, 12, 360-373, 2009.
- 928 Von-Arnold, K., Hanell, B., Stendahl, J., and Klemetsson, L.: Greenhouse gas fluxes from drained  
929 organic forestland in Sweden, *Scandinavian Journal of Forest Research*, 20, 400-411, 2005.
- 930 Waddington, J. M., and Price, J. S.: Effect of peatland drainage, harvesting, and restoration on  
931 atmospheric water and carbon exchange *Physical Geography [Phys. Geogr.]*, 21, 433-451, 2000.
- 932 Waddington, M. J., and Roulet, N. T.: Carbon balance of a boreal patterned peatland., *Global Change  
933 Biology*, 6, 87-97, 2000.
- 934 Wang, X., Zhu, B., Wang, Y., and Zheng, X.: Field measures of the contribution of root respiration to  
935 soil respiration in an alder and cypress mixed plantation by two methods: trenching method and root  
936 biomass regression method, *European Journal of Forest Research*, 127, 285-291, 2008.
- 937 Weltzin, J. F., Pastor, J., Harth, C., Bridgham, S. D., Updegraff, K., and Chapin, C. T.: Response of bog  
938 and fen plant communities to warming and water-table manipulations, *Ecology*, 81, 3464-3478, 2000.
- 939 Weltzin, J. F., Harth, C., Bridgham, S. D., Pastor, J., and Vonderharr, M.: Production and  
940 microtopography of bog bryophytes: response to warming and water-table manipulations, *Oecologia*,  
941 128, 557-565, 2001.
- 942 Weltzin, J. F., Bridgham, S. D., Pastor, J., Chen, J., and Harth, C.: Potential effects of warming and  
943 drying on peatland plant community composition, *Global Change Biology*, 9, 141-151, 2003.
- 944 Wieder, R. K., Scott, K. D., Kamminga, K., Vile, M. A., Vitt, D. H., Bone, T., Xu, B., Benscoter, B.  
945 W., and Bhatti, J. S.: Postfire carbon balance in boreal bogs of Alberta, Canada, *Global Change  
946 Biology*, 15, 63-81, 2009.
- 947 Yu, Z.: Northern peatland carbon stocks and dynamics: A review, *Biogeosciences*, 9, 4071-4085, 2012.
- 948
- 949
- 950
- 951
- 952
- 953

Table 1. Mean seasonal air temperatures ( $T_{\text{air}}$ ), soil temperatures at 5 cm depth ( $T_{\text{soil } 5\text{cm}}$ ) and soil temperatures at 30 cm depth ( $T_{\text{soil } 30\text{cm}}$ ) at all the sites, measured during growing seasons (May to October) of 2011-2013 <sup>a</sup>.

Air / Soil Temperature	Treatment	<u>CONTROL</u>		<u>EXPERIMENTAL</u>		<u>DRAINED</u>	
		Hummock	Hollow	Hummock	Hollow	Hummock	Hollow
$T_{\text{air}}$ (°C)	Ambient	13.6 ± 0.3 <sup>A</sup>	13.5 ± 0.2 <sup>A</sup>	13.8 ± 0.1 <sup>A</sup>	13.9 ± 0.1 <sup>A</sup>	14.3 ± 0.3 <sup>A</sup>	14.3 ± 0.2 <sup>A</sup>
	Warmed	14.4 ± 0.5 <sup>B</sup>	14.4 ± 0.4 <sup>B</sup>	14.7 ± 0.3 <sup>B</sup>	14.7 ± 0.6 <sup>B</sup>	14.6 ± 0.2 <sup>A</sup>	15.2 ± 0.8 <sup>B</sup>
$T_{\text{soil } 5 \text{ cm}}$ (°C)	Ambient	12.3 ± 0.2 <sup>A</sup>	12.3 ± 0.0 <sup>A</sup>	13.1 ± 0.0 <sup>A</sup>	13.1 ± 0.1 <sup>A</sup>	13.7 ± 0.0 <sup>A</sup>	13.7 ± 0.1 <sup>A</sup>
	Warmed	12.9 ± 0.2 <sup>B</sup>	13.6 ± 0.6 <sup>B</sup>	13.8 ± 0.9 <sup>B</sup>	13.7 ± 0.6 <sup>B</sup>	14.1 ± 0.6 <sup>A</sup>	14.6 ± 0.4 <sup>B</sup>
$T_{\text{soil } 30 \text{ cm}}$ (°C)	Ambient	10.8 ± 2.5 <sup>A</sup>	11.0 ± 2.8 <sup>A</sup>	9.9 ± 2.7 <sup>A</sup>	11.2 ± 3.2 <sup>A</sup>	12.0 ± 3.7 <sup>A</sup>	13.2 ± 3.8 <sup>A</sup>
	Warmed	11.7 ± 2.3 <sup>A</sup>	12.4 ± 2.5 <sup>A</sup>	11.2 ± 2.7 <sup>A</sup>	12.2 ± 3.8 <sup>A</sup>	12.3 ± 3.8 <sup>A</sup>	12.7 ± 3.8 <sup>A</sup>

<sup>a</sup> All temperatures are mean (± SD). At each site, all the OTC-equipped hummocks ( $n = 3$ ) and hollows ( $n = 3$ ) were instrumented with HOBOs to log OTC warming of air ( $T_{\text{air}}$ ) and 5 cm deep soil ( $T_{\text{soil } 5\text{cm}}$ ). The 30 cm deep soil temperatures ( $T_{\text{soil } 30\text{cm}}$ ) were measured using thermocouple, during the measurement of CO<sub>2</sub> fluxes in the growing seasons of the study years. Means sharing same letters do not differ significantly. Letters should be compared only within one column separately for  $T_{\text{air}}$ ,  $T_{\text{soil } 5\text{cm}}$  and  $T_{\text{soil } 30\text{cm}}$ .

954  
955  
956  
957  
958  
959  
960  
961  
962  
963  
964  
965  
966

Table 2. Ground-layer and tree biomass ( $\text{g m}^{-2}$ ) at control, experimental and drained sites <sup>a</sup>.

Site/ Microforms	<u>ABOVE-GROUND</u>			<u>BELOW-GROUND</u>			<u>TREES</u>	<u>TOTAL</u>
	<u>Moss</u>	<u>Vascular</u>	<u>Lichen</u>	<u>Total</u>	<u>Fine</u>	<u>Coarse</u>	<u>Total</u>	
					< 2 mm	> 2 mm		Ambient/ Warmed
<b><u>CONTROL</u></b>								
<b>AMBIENT</b>							2142 ± 376	3168 ± 604
Hummock	208 ± 51 <sup>A</sup>	191 ± 62 <sup>A</sup>	0 ± 0 <sup>A</sup>	399 ± 24 <sup>A</sup>	335 ± 15	233 ± 61	568 ± 48	
Hollow	134 ± 17 <sup>A</sup>	216 ± 11 <sup>A</sup>	0 ± 0 <sup>A</sup>	350 ± 82 <sup>A</sup>	486 ± 67	266 ± 102	751 ± 332	
<b>WARMED</b>								3150 ± 578
Hummock	113 ± 46 <sup>A</sup>	172 ± 97 <sup>A</sup>	0 ± 0 <sup>A</sup>	285 ± 140 <sup>A</sup>	477 ± 118	71 ± 36	548 ± 147	
Hollow	269 ± 98 <sup>A</sup>	166 ± 32 <sup>A</sup>	0 ± 0 <sup>A</sup>	435 ± 130 <sup>A</sup>	418 ± 68	378 ± 84	796 ± 122	
<b><u>EXPERIMENTAL</u></b>								
<b>AMBIENT</b>							1986 <sup>b</sup>	2836 ± 540
Hummock	63 ± 24 <sup>A</sup>	185 ± 68 <sup>A</sup>	3 ± 2 <sup>B</sup>	251 ± 78 <sup>A</sup>	329 ± 148	112 ± 176	441 ± 96	
Hollow	138 ± 29 <sup>A</sup>	190 ± 24 <sup>A</sup>	0 ± 0 <sup>A</sup>	327 ± 51 <sup>A</sup>	385 ± 112	330 ± 188	715 ± 116	
<b>WARMED</b>								3048 ± 731
Hummock	178 ± 69 <sup>A</sup>	238 ± 37 <sup>A</sup>	0 ± 0 <sup>A</sup>	416 ± 80 <sup>A</sup>	581 ± 313	138 ± 70	719 ± 169	
Hollow	88 ± 89 <sup>A</sup>	139 ± 44 <sup>A</sup>	2 ± 1 <sup>B</sup>	228 ± 89 <sup>A</sup>	495 ± 119	250 ± 118	745 ± 171	
<b><u>DRAINED</u></b>								
<b>AMBIENT</b>							1964 ± 381	3429 ± 639
Hummock	143 ± 95 <sup>A</sup>	462 ± 91 <sup>B</sup>	38 ± 49 <sup>BC</sup>	643 ± 18 <sup>B</sup>	625 ± 220	300 ± 154	925 ± 247	
Hollow	146 ± 70 <sup>A</sup>	152 ± 51 <sup>A</sup>	80 ± 39 <sup>C</sup>	378 ± 6 <sup>A</sup>	631 ± 194	344 ± 409	975 ± 301	
<b>WARMED</b>								3970 ± 767
Hummock	38 ± 12 <sup>B</sup>	870 ± 66 <sup>C</sup>	12 ± 03 <sup>B</sup>	919 ± 63 <sup>C</sup>	895 ± 242	397 ± 58	1292 ± 249	
Hollow	24 ± 33 <sup>B</sup>	226 ± 99 <sup>A</sup>	200 ± 91 <sup>C</sup>	450 ± 23 <sup>A</sup>	999 ± 266	335 ± 219	1334 ± 332	

<sup>a</sup> Values are means ± SE ( $n = 3$  for each of above-ground, below-ground and trees biomasses). Means sharing same letters do not differ significantly. Letters should be compared only within one column. Total biomass was determined by weighting ground-layer by the proportion of hummocks and hollows at each site (control = 56% hummocks, experimental = 55% hummocks, drained = 52% hummocks).<sup>b</sup>  $n = 1$  (only one quadrat was available due to limited size of experimental site).

968

969

970

971

972

973

974

975

Table 3. Mixed-effects ANOVA  $F$  and  $p$ -values for the fixed effects of water level treatments (control, experimental, drained), warming treatments (non-OTC, OTC), microform types (hummock, hollow) and years (2011, 2012, 2013) with repeated measures of year, on CO<sub>2</sub> fluxes at the peatland surface <sup>a</sup>.

Effect	df	CO <sub>2</sub> Flux Components					
		<u>GPP<sub>max</sub></u>		<u>R</u>		<u>NE<sub>max</sub></u>	
		<i>F</i>	<i>P</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>
Water Level	2, 108	57.78	<b>0.000</b>	12.61	<b>0.000</b>	53.87	<b>0.000</b>
Microform	1, 108	56.71	<b>0.000</b>	12.60	<b>0.001</b>	92.55	<b>0.000</b>
Warming	1, 108	0.21	0.651	37.68	<b>0.000</b>	19.52	<b>0.000</b>
Year	2, 108	31.43	<b>0.000</b>	5.77	<b>0.004</b>	33.15	<b>0.000</b>
Water Level * Microform	2, 108	12.85	<b>0.000</b>	19.42	<b>0.000</b>	22.26	<b>0.000</b>
Water Level * Warming	2, 108	11.79	<b>0.000</b>	0.88	0.420	11.33	<b>0.000</b>
Water Level * Year	4, 108	8.11	<b>0.000</b>	4.75	<b>0.001</b>	2.86	<b>0.027</b>
Microform * Warming	1, 108	7.57	<b>0.007</b>	1.39	0.242	2.26	0.136
Microform * Year	2, 108	1.51	<b>0.003</b>	3.88	<b>0.024</b>	1.61	0.205
Warming * Year	2, 108	8.96	<b>0.000</b>	5.25	<b>0.007</b>	6.45	<b>0.002</b>
Water Level * Microform * Warming	2, 108	0.60	0.519	0.83	0.441	1.58	0.211
Water Level * Microform * Year	4, 108	0.17	0.954	2.17	0.077	1.02	0.400
Water Level * Warming * Year	4, 108	0.31	0.871	0.31	0.873	0.37	0.831
Microform * Warming * Year	2, 108	1.57	0.213	3.72	<b>0.027</b>	0.27	0.768
Water Level * Microform * Warming * Year	4, 108	2.63	<b>0.039</b>	0.54	0.710	3.30	<b>0.014</b>

<sup>a</sup> GPP<sub>max</sub> and NE<sub>max</sub> represent GPP<sub>ff</sub> and NE<sub>ff</sub> when the photon flux density of PAR was  $\geq 1000 \mu\text{mol m}^{-2} \text{s}^{-1}$ .  $R$  represents  $R_{\text{ff}}$  (forest floor respiration).

976

977

978

979

980

981

982

983

984

985

986

987

988



Table 4. Growing season CO<sub>2</sub>-C flux estimates ( $\pm$  SE; g CO<sub>2</sub>-C m<sup>-2</sup>)<sup>a</sup>.

Year	Site / Microforms	GPP <sub>ff</sub>	R <sub>ff</sub>	NE <sub>ff</sub>	R <sub>r</sub>	L <sub>tree</sub>	IC <sub>tree_ag</sub>	IC <sub>tree_bg</sub>	NEE <sup>b</sup>	C <sub>w</sub>		
2011	<b>CONTROL</b>											
		Ambient Hummock	-190 ± 29	225 ± 18	35 ± 30	63 ± 05						
		Ambient Hollow	-178 ± 29	130 ± 21	-48 ± 09	2 ± 00	-6 ± 1	-38 ± 08	-8 ± 1	-92 ± 12	-13	
		Warmed Hummock	-206 ± 41	251 ± 63	45 ± 21	70 ± 06						
		Warmed Hollow	-207 ± 37	134 ± 52	-74 ± 22	12 ± 03	-6 ± 1	-38 ± 08	-8 ± 1	-105 ± 16		
		<b>EXPERIMENTAL</b>										
		Ambient Hummock	-106 ± 44	182 ± 75	76 ± 12	53 ± 14						
		Ambient Hollow	-102 ± 52	349 ± 89	246 ± 55	115 ± 68	-7 ± 0	-42 ± 15	-9 ± 3	14 ± 05	105	
		Warmed Hummock	-104 ± 04	422 ± 83	317 ± 94	122 ± 56						
		Warmed Hollow	-136 ± 13	435 ± 95	299 ± 83	144 ± 55	-7 ± 0	-42 ± 15	-9 ± 3	119 ± 48		
		<b>DRAINED</b>										
		Ambient Hummock	-280 ± 21	295 ± 10	15 ± 07	62 ± 05						
		Ambient Hollow	-116 ± 19	536 ± 09	420 ± 23	123 ± 01	-11 ± 1	-66 ± 09	-15 ± 2	26 ± 14	-34	
		Warmed Hummock	-333 ± 91	343 ± 86	10 ± 09	72 ± 17						
	Warmed Hollow	-118 ± 19	468 ± 95	350 ± 92	108 ± 24	-11 ± 1	-66 ± 09	-15 ± 2	-8 ± 05			
2012	<b>CONTROL</b>											
		Ambient Hummock	-228 ± 43	216 ± 33	-12 ± 11	60 ± 05						
		Ambient Hollow	-181 ± 08	241 ± 45	60 ± 33	21 ± 00	-6 ± 1	-33 ± 07	-7 ± 1	-70 ± 10	-19	
		Warmed Hummock	-226 ± 99	222 ± 87	-04 ± 02	62 ± 19						
		Warmed Hollow	-197 ± 29	201 ± 88	04 ± 00	18 ± 17	-6 ± 1	-33 ± 07	-7 ± 1	-89 ± 27		
		<b>EXPERIMENTAL</b>										
		Ambient Hummock	-33 ± 23	165 ± 53	132 ± 12	48 ± 14						
		Ambient Hollow	-89 ± 77	351 ± 96	261 ± 67	116 ± 55	-7 ± 2	-39 ± 11	-9 ± 0	57 ± 44	100	
		Warmed Hummock	-119 ± 44	443 ± 88	324 ± 87	129 ± 17						
		Warmed Hollow	-77 ± 12	459 ± 59	382 ± 64	151 ± 82	-7 ± 2	-39 ± 11	-9 ± 0	157 ± 90		
		<b>DRAINED</b>										
		Ambient Hummock	-333 ± 75	359 ± 18	26 ± 13	75 ± 05						
		Ambient Hollow	-118 ± 20	507 ± 35	390 ± 47	116 ± 01	-10 ± 2	-60 ± 10	-13 ± 2	23 ± 15	-52	
		Warmed Hummock	-391 ± 44	356 ± 79	-36 ± 12	75 ± 27						
	Warmed Hollow	-136 ± 16	478 ± 63	342 ± 98	110 ± 29	-10 ± 2	-60 ± 10	-13 ± 2	-29 ± 11			
2013	<b>CONTROL</b>											
		Ambient Hummock	-233 ± 82	217 ± 59	-17 ± 01	61 ± 09						
		Ambient Hollow	-195 ± 29	248 ± 41	53 ± 14	22 ± 07	-6 ± 0	-33 ± 07	-7 ± 1	-76 ± 38	-6	
		Warmed Hummock	-259 ± 92	203 ± 56	-56 ± 23	57 ± 12						
		Warmed Hollow	-232 ± 97	322 ± 46	90 ± 22	29 ± 20	-6 ± 1	-33 ± 07	-7 ± 1	-82 ± 40		
		<b>EXPERIMENTAL</b>										
		Ambient Hummock	-51 ± 18	288 ± 22	237 ± 15	84 ± 18						
		Ambient Hollow	-93 ± 55	486 ± 58	394 ± 67	161 ± 56	-7 ± 2	-39 ± 11	-9 ± 0	135 ± 44	10	
		Warmed Hummock	-81 ± 34	330 ± 55	249 ± 69	96 ± 19						
		Warmed Hollow	-104 ± 16	535 ± 51	431 ± 99	177 ± 81	-7 ± 2	-39 ± 11	-9 ± 0	145 ± 90		
		<b>DRAINED</b>										
		Ambient Hummock	-347 ± 65	365 ± 84	17 ± 18	77 ± 21						
		Ambient Hollow	-123 ± 22	502 ± 33	380 ± 74	116 ± 61	-10 ± 2	-60 ± 10	-13 ± 2	13 ± 15	-73	
		Warmed Hummock	-517 ± 42	398 ± 58	-120 ± 11	83 ± 25						
	Warmed Hollow	-122 ± 36	513 ± 33	391 ± 91	118 ± 25	-10 ± 2	-60 ± 10	-13 ± 2	-58 ± 11			

<sup>a</sup> Negative values represent uptake of carbon by the peatland from the atmosphere. The forest floor respiration ( $R_{ff}$ ) includes tree root respiration ( $R_r$ ).  $C_w$  (NEE warmed - NEE ambient) represents warming induced net ecosystem exchange at site. <sup>b</sup> NEE (net ecosystem exchange) is calculated using equation 3 ( $NEE = NE_{ff} + IC_{tree\_ag} + IC_{tree\_bg} + L_{tree} - R_r$ ). Forest floor carbon exchange was determined by weighting  $NE_{ff}$  measured at each microform by the proportion of hummocks and hollows at each site (control = 56% hummocks, experimental = 55%, drained = 52% hummocks).

Appendix A. Estimated parameter values ( $\pm$  SE), standard error of the estimate (SEE) and goodness of fit ( $r^2$ ) for the gross primary production of forest Floor (GPP<sub>ff</sub>) model (Eq. 1) <sup>a</sup>.

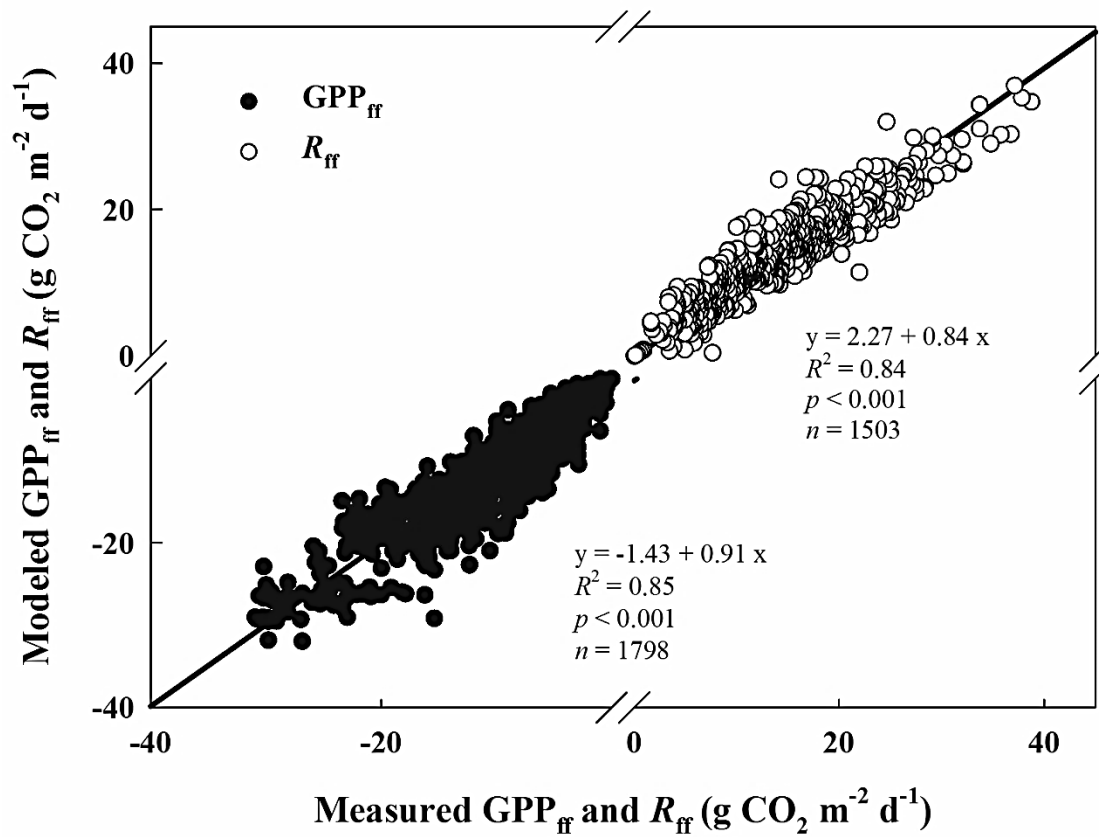
Year	Site / Microforms	GPP <sub>ff</sub> vs. PAR		GPP <sub>ff</sub> vs. WT		GPP <sub>ff</sub> vs. T		SEE	$r^2$
		$P_{\max}$	$k$	WT <sub>opt</sub>	WT <sub>tol</sub>	T <sub>opt</sub>	T <sub>tol</sub>		
		g CO <sub>2</sub> m <sup>-2</sup> d <sup>-1</sup>	μmol m <sup>-2</sup> s <sup>-1</sup>	cm	cm	°C	°C		
2011	<b>CONTROL</b>								
	Ambient Hummock	-22.2 ± 04	900 ± 422	-56 ± 13	30 ± 16	16 ± 04	10 ± 05	2.3	0.83
	Warmed Hummock	-27.2 ± 06	999 ± 468	-48 ± 04	15 ± 11	9 ± 15	20 ± 16	3.4	0.77
	Ambient Hollow	-19.4 ± 07	950 ± 601	-28 ± 10	23 ± 21	14 ± 08	10 ± 13	2.0	0.63
	Warmed Hollow	-15.7 ± 04	500 ± 318	-36 ± 02	11 ± 03	17 ± 13	18 ± 30	3.0	0.54
	<b>EXPERIMENTAL</b>								
	Ambient Hummock	-26.2 ± 24	999 ± 805	-64 ± 04	18 ± 09	30 ± 07	16 ± 02	3.2	0.75
	Warmed Hummock	-23.0 ± 15	999 ± 994	-57 ± 15	30 ± 11	30 ± 05	17 ± 16	5.4	0.54
	Ambient Hollow	-40.5 ± 15	999 ± 729	-58 ± 01	7 ± 01	13 ± 00	3 ± 00	3.3	0.82
	Warmed Hollow	-26.1 ± 18	999 ± 753	-82 ± 06	30 ± 08	15 ± 09	20 ± 06	5.0	0.62
	<b>DRAINED</b>								
	Ambient Hummock	-35.9 ± 09	950 ± 440	-118 ± 08	30 ± 11	12 ± 02	10 ± 03	1.0	0.82
	Warmed Hummock	-35.6 ± 14	999 ± 398	-111 ± 03	30 ± 06	15 ± 08	20 ± 08	1.0	0.80
	Ambient Hollows	-29.2 ± 17	850 ± 639	-71 ± 32	30 ± 17	11 ± 03	10 ± 10	0.9	0.68
	Warmed Hollow	-19.4 ± 27	998 ± 779	-124 ± 06	21 ± 10	9 ± 02	2 ± 02	3.2	0.56
	Warmed Hummock	-35.6 ± 14	999 ± 398	-111 ± 03	30 ± 06	15 ± 08	20 ± 08	1.0	0.80
2012	<b>CONTROL</b>								
	Ambient Hummock	-24.8 ± 05	900 ± 286	-35 ± 11	30 ± 14	15 ± 02	10 ± 04	1.8	0.86
	Warmed Hummock	-32.9 ± 05	999 ± 335	-54 ± 10	30 ± 17	21 ± 01	9 ± 01	1.9	0.85
	Ambient Hollow	-21.8 ± 04	950 ± 299	-42 ± 14	30 ± 20	15 ± 01	10 ± 02	1.1	0.85
	Warmed Hollow	-38.8 ± 12	999 ± 382	-25 ± 43	30 ± 09	17 ± 01	10 ± 02	1.2	0.85
	<b>EXPERIMENTAL</b>								
	Ambient Hummock	-28.4 ± 10	998 ± 638	-29 ± 12	30 ± 12	20 ± 04	12 ± 11	2.2	0.75
	Warmed Hummock	-27.8 ± 26	500 ± 463	-42 ± 31	30 ± 12	17 ± 21	20 ± 05	3.4	0.74
	Ambient Hollow	-40.1 ± 18	999 ± 574	-73 ± 03	30 ± 04	11 ± 00	3 ± 01	2.4	0.74
	Warmed Hollow	-12.6 ± 05	738 ± 679	-48 ± 13	23 ± 11	20 ± 02	5 ± 03	7.4	0.50
	<b>DRAINED</b>								
	Ambient Hummock	-50.0 ± 14	950 ± 416	-105 ± 03	30 ± 03	10 ± 02	10 ± 02	0.9	0.82
	Warmed Hummock	-50.0 ± 19	950 ± 444	-107 ± 02	30 ± 04	11 ± 03	12 ± 01	0.9	0.83
	Ambient Hollow	-31.3 ± 10	850 ± 246	-100 ± 11	23 ± 07	10 ± 06	10 ± 05	1.6	0.83
	Warmed Hollow	-18.5 ± 28	999 ± 779	-125 ± 06	21 ± 13	8 ± 01	1 ± 01	4.1	0.55
	2013	<b>CONTROL</b>							
Ambient Hummock		-32.1 ± 05	837 ± 219	-51 ± 07	30 ± 12	11 ± 07	20 ± 04	1.8	0.68
Warmed Hummock		-38.7 ± 10	500 ± 136	-45 ± 06	30 ± 20	20 ± 09	20 ± 04	1.1	0.85
Ambient Hollow		-46.8 ± 05	554 ± 121	-31 ± 01	12 ± 01	9 ± 01	6 ± 01	5.4	0.85
Warmed Hollow		-45.5 ± 24	500 ± 157	-24 ± 08	23 ± 09	19 ± 05	11 ± 10	1.2	0.85
<b>EXPERIMENTAL</b>									
Ambient Hummock		-38.0 ± 13	634 ± 292	-63 ± 03	30 ± 04	14 ± 05	10 ± 17	3.1	0.85
Warmed Hummock		-28.3 ± 28	500 ± 314	-67 ± 02	13 ± 02	15 ± 07	20 ± 10	3.4	0.85
Ambient Hollow		-26.3 ± 14	500 ± 156	-64 ± 09	30 ± 08	15 ± 07	13 ± 09	2.1	0.85
Warmed Hollow		-16.9 ± 14	557 ± 461	-74 ± 05	11 ± 05	20 ± 26	17 ± 12	0.4	0.85
<b>DRAINED</b>									
Ambient Hummock		-50.0 ± 37	500 ± 180	-102 ± 03	26 ± 07	30 ± 26	9 ± 05	0.6	0.82
Warmed Hummock		-50.0 ± 41	500 ± 241	-115 ± 05	28 ± 07	21 ± 18	9 ± 11	2.0	0.85
Ambient Hollow		-40.0 ± 41	820 ± 591	-76 ± 02	2 ± 01	18 ± 05	2 ± 02	1.5	0.83
Warmed Hollow		-28.0 ± 43	500 ± 456	-89 ± 17	7 ± 29	16 ± 01	1 ± 00	1.6	0.85

<sup>a</sup> The models were developed for each microform type ( $n = 3$ ) at the control, experimental and drained sites separately for growing seasons of 2011, 2012 and 2013. PAR, WT and  $T$  represent photosynthetically active radiation, water table (negative values show belowground water level) and 5 cm soil temperature, respectively.  $P_{\max}$  denotes potential maximum rate of GPP<sub>ff</sub> and  $k$  is level of PAR at which half of GPP<sub>ff</sub> occurs. WT<sub>opt</sub> and  $T_{opt}$  are Gaussian response parameters for optimum GPP<sub>ff</sub> while WT<sub>tol</sub> and  $T_{tol}$  are Gaussian response parameters describing the width of the curve. All modeled parameters are significant at  $p = 0.05$  level.

Appendix B. Estimated regression coefficient values ( $\pm$  SE), standard error of the estimate (SEE) and goodness of fit ( $r^2$ ) for the forest floor respiration ( $R_{ff}$ ) model (Eq. 2) <sup>a</sup>.

Year	Site / Microforms	<i>a</i>	<i>b</i>	<i>c</i>	SEE	$r^2$
		dimensionless			g CO <sub>2</sub> m <sup>-2</sup> d <sup>-1</sup>	
2011	<b>CONTROL</b>					
	Ambient Hummock	1.30 $\pm$ 0.3	-0.21 $\pm$ 0.1	-18.3 $\pm$ 6.8	0.8	0.81
	Warmed Hummock	0.49 $\pm$ 0.1	-0.16 $\pm$ 0.0	-1.8 $\pm$ 2.5	3.8	0.37
	Ambient Hollow	1.70 $\pm$ 0.3	-0.61 $\pm$ 0.2	-32.3 $\pm$ 9.7	0.7	0.79
	Warmed Hollow	0.54 $\pm$ 0.1	-0.38 $\pm$ 0.1	-8.1 $\pm$ 2.0	1.8	0.75
	<b>EXPERIMENTAL</b>					
	Ambient Hummock	1.32 $\pm$ 0.1	-0.07 $\pm$ 0.0	-5.7 $\pm$ 2.0	2.0	0.83
	Warmed Hummock	0.71 $\pm$ 0.1	-0.06 $\pm$ 0.1	-3.9 $\pm$ 3.6	2.8	0.56
	Ambient Hollow	0.67 $\pm$ 0.2	-0.37 $\pm$ 0.1	-17.1 $\pm$ 4.7	5.5	0.51
	Warmed Hollow	1.65 $\pm$ 0.3	-0.15 $\pm$ 0.1	-18.5 $\pm$ 5.1	5.3	0.60
	<b>DRAINED</b>					
	Ambient Hummock	0.31 $\pm$ 0.3	-0.02 $\pm$ 0.0	-2.62 $\pm$ 7.3	0.4	0.49
	Warmed Hummock	0.66 $\pm$ 0.1	-0.09 $\pm$ 0.0	-7.2 $\pm$ 4.2	3.4	0.45
	Ambient Hollow	0.55 $\pm$ 0.1	-0.02 $\pm$ 0.0	-2.3 $\pm$ 3.6	0.2	0.85
Warmed Hollow	1.80 $\pm$ 0.1	-0.10 $\pm$ 0.1	-20.7 $\pm$ 4.7	3.6	0.84	
2012	<b>CONTROL</b>					
	Ambient Hummock	0.39 $\pm$ 0.2	-0.25 $\pm$ 0.1	-10.7 $\pm$ 5.3	0.6	0.53
	Warmed Hummock	0.57 $\pm$ 0.1	-0.20 $\pm$ 0.1	-1.3 $\pm$ 2.2	2.9	0.57
	Ambient Hollow	0.93 $\pm$ 0.1	-0.25 $\pm$ 0.1	-12.8 $\pm$ 1.8	0.4	0.81
	Warmed Hollow	0.90 $\pm$ 0.1	-0.16 $\pm$ 0.1	-2.8 $\pm$ 2.0	3.1	0.71
	<b>EXPERIMENTAL</b>					
	Ambient Hummock	0.61 $\pm$ 0.1	-0.22 $\pm$ 0.1	-9.4 $\pm$ 2.9	3.2	0.68
	Warmed Hummock	1.08 $\pm$ 0.1	-0.15 $\pm$ 0.1	-13.5 $\pm$ 4.9	4.6	0.62
	Ambient Hollow	1.56 $\pm$ 0.2	-0.18 $\pm$ 0.1	-19.6 $\pm$ 9.4	6.0	0.67
	Warmed Hollow	0.63 $\pm$ 0.1	-0.25 $\pm$ 0.0	-12.4 $\pm$ 1.4	3.2	0.85
	<b>DRAINED</b>					
	Ambient Hummock	0.65 $\pm$ 0.1	-0.03 $\pm$ 0.1	-3.4 $\pm$ 8.1	0.3	0.91
	Warmed Hummock	0.89 $\pm$ 0.1	-0.00 $\pm$ 0.0	-4.4 $\pm$ 4.5	4.4	0.60
	Ambient Hollow	1.07 $\pm$ 0.1	-0.15 $\pm$ 0.0	-17.3 $\pm$ 5.6	0.9	0.80
Warmed Hollow	1.27 $\pm$ 0.1	-0.00 $\pm$ 0.0	-1.5 $\pm$ 3.7	5.0	0.67	
2013	<b>CONTROL</b>					
	Ambient Hummock	1.74 $\pm$ 0.1	-0.01 $\pm$ 0.1	-5.3 $\pm$ 3.1	3.0	0.67
	Warmed Hummock	2.02 $\pm$ 0.2	-0.03 $\pm$ 0.0	-8.3 $\pm$ 3.4	4.2	0.56
	Ambient Hollow	1.18 $\pm$ 0.1	-0.15 $\pm$ 0.1	-3.8 $\pm$ 1.7	3.1	0.68
	Warmed Hollow	1.56 $\pm$ 0.2	-0.18 $\pm$ 0.1	-5.4 $\pm$ 2.1	3.7	0.71
	<b>EXPERIMENTAL</b>					
	Ambient Hummock	0.75 $\pm$ 0.5	-0.53 $\pm$ 0.1	-10.3 $\pm$ 3.3	3.5	0.70
	Warmed Hummock	1.29 $\pm$ 0.3	-0.47 $\pm$ 0.1	-45.9 $\pm$ 7.5	6.2	0.53
	Ambient Hollow	0.48 $\pm$ 0.3	-0.61 $\pm$ 0.1	-29.8 $\pm$ 2.5	2.5	0.83
	Warmed Hollow	0.96 $\pm$ 0.3	-0.19 $\pm$ 0.1	-10.3 $\pm$ 5.5	6.9	0.38
	<b>DRAINED</b>					
	Ambient Hummock	1.44 $\pm$ 0.2	-0.17 $\pm$ 0.0	-27.5 $\pm$ 2.7	2.8	0.82
	Warmed Hummock	2.17 $\pm$ 0.2	-0.17 $\pm$ 0.0	-32.1 $\pm$ 3.2	2.9	0.80
	Ambient Hollow	1.70 $\pm$ 0.3	-0.32 $\pm$ 0.0	-41.5 $\pm$ 5.5	6.5	0.61
Warmed Hollow	0.77 $\pm$ 0.2	-0.20 $\pm$ 0.0	-23.2 $\pm$ 4.8	3.5	0.63	

<sup>a</sup> The models were developed for each microform type ( $n = 3$ ) at the control, experimental and drained sites separately for growing seasons of 2011, 2012 and 2013. *a*, *b* and *c* are regression coefficients. Negative values of *b* represent greater respiration with deeper water table values (below-ground WT having negative values). All modeled parameters are significant at  $p = 0.05$  level.



996

997 Figure 1. Goodness of fit ( $R^2$ ) between modeled and measured  $GPP_{ff}$  and modeled and measured  $R_{ff}$   
 998 values. The figure presents all data for control, experimental and drained sites for the study years (2011-  
 999 2013). Lines represent the 1:1 fit.

1000

1001

1002

1003

1004

1005

1006

1007

1008

1009

1010

1011

1012

1013

1014

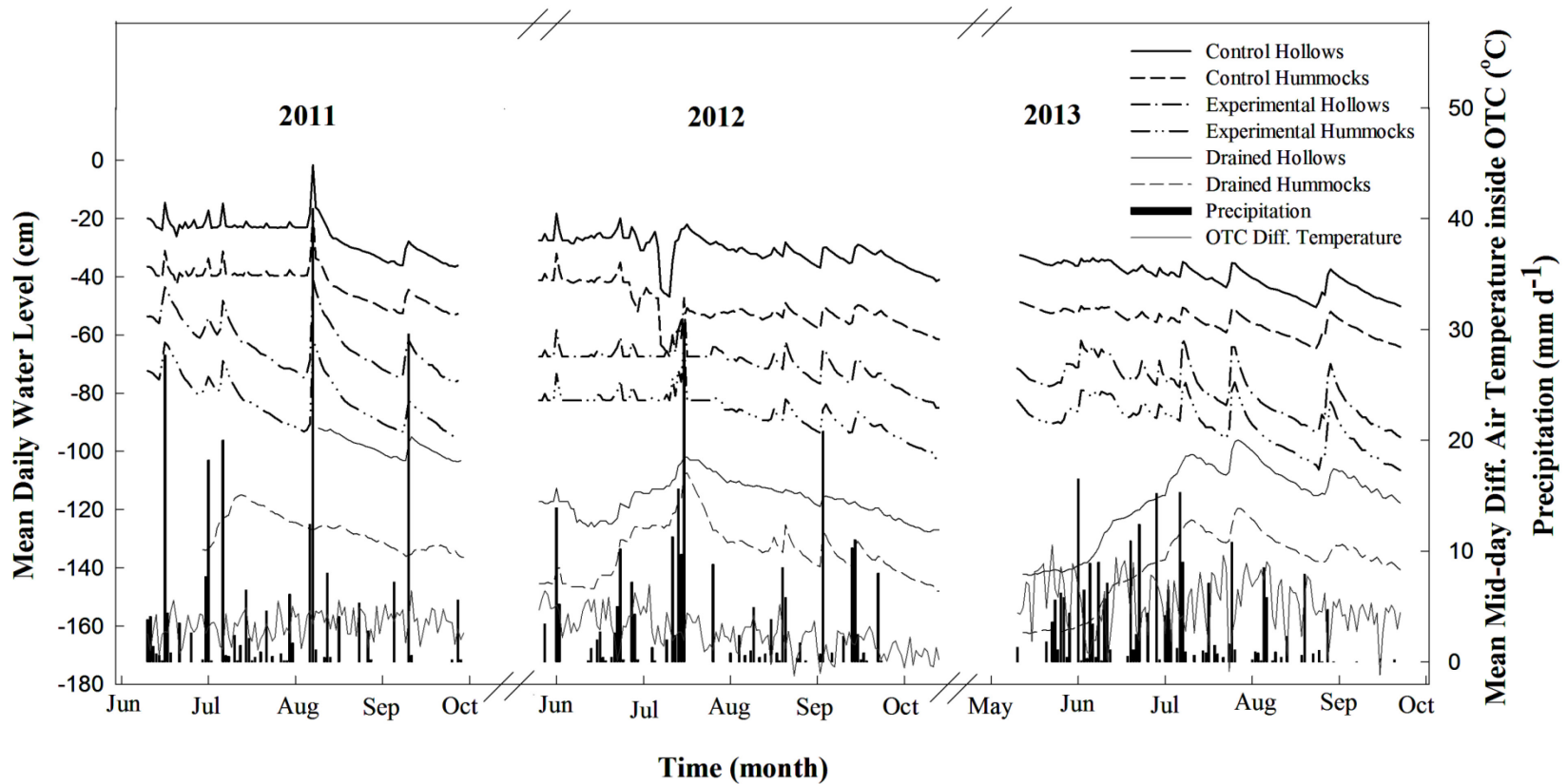
1015

1016

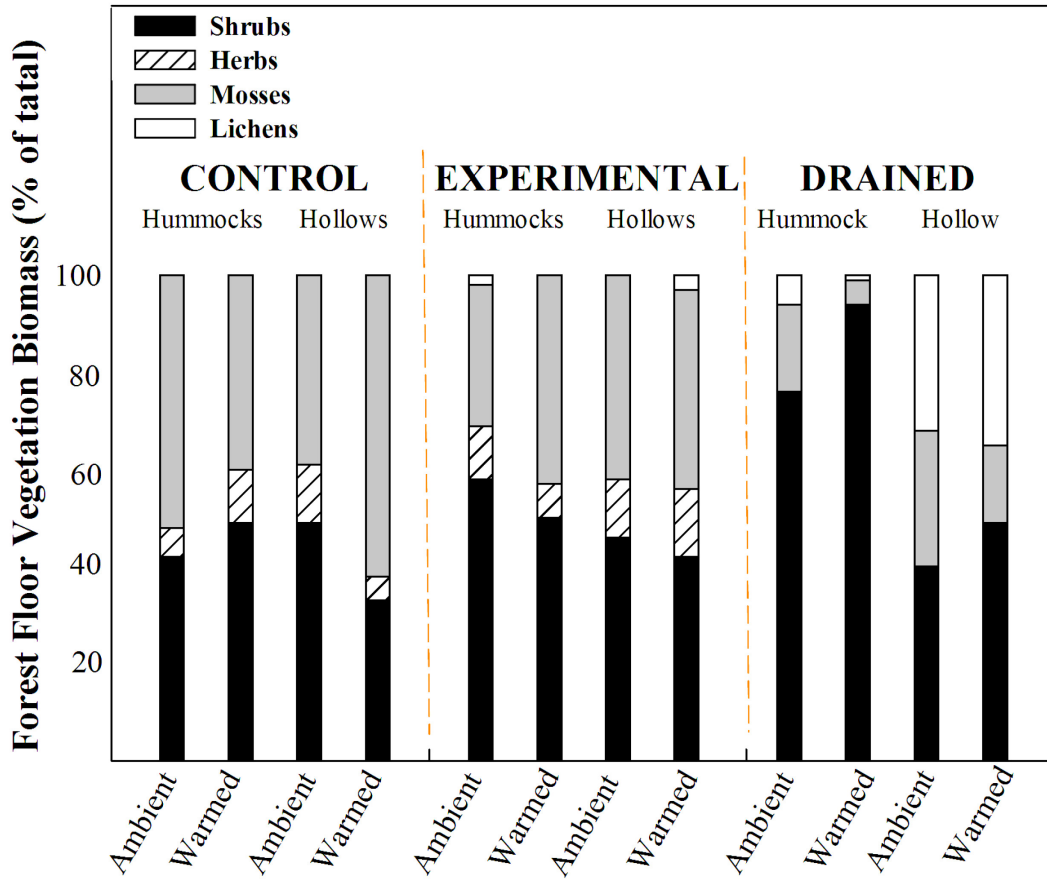
1017

1018

1019



1020  
 1021 Figure 2. Mean daily water level, mid-day differential (warmed – Ambient) air temperature and precipitation at hummock and hollow microforms  
 1022 during growing seasons of 2011, 2012 and 2013. Note the right y-axis has two values using the same scale: mean mid-day differential air  
 1023 temperature and daily precipitation. The x-axis breaks separate 2011, 2012 and 2013. The partially missing water level data at drained hummocks  
 1024 in 2011 was due to levellogger’s malfunction. The cumulative seasonal precipitation during 2012 and 2013 was 30.0% and 35.3% lesser  
 1025 respectively than that in 2011.

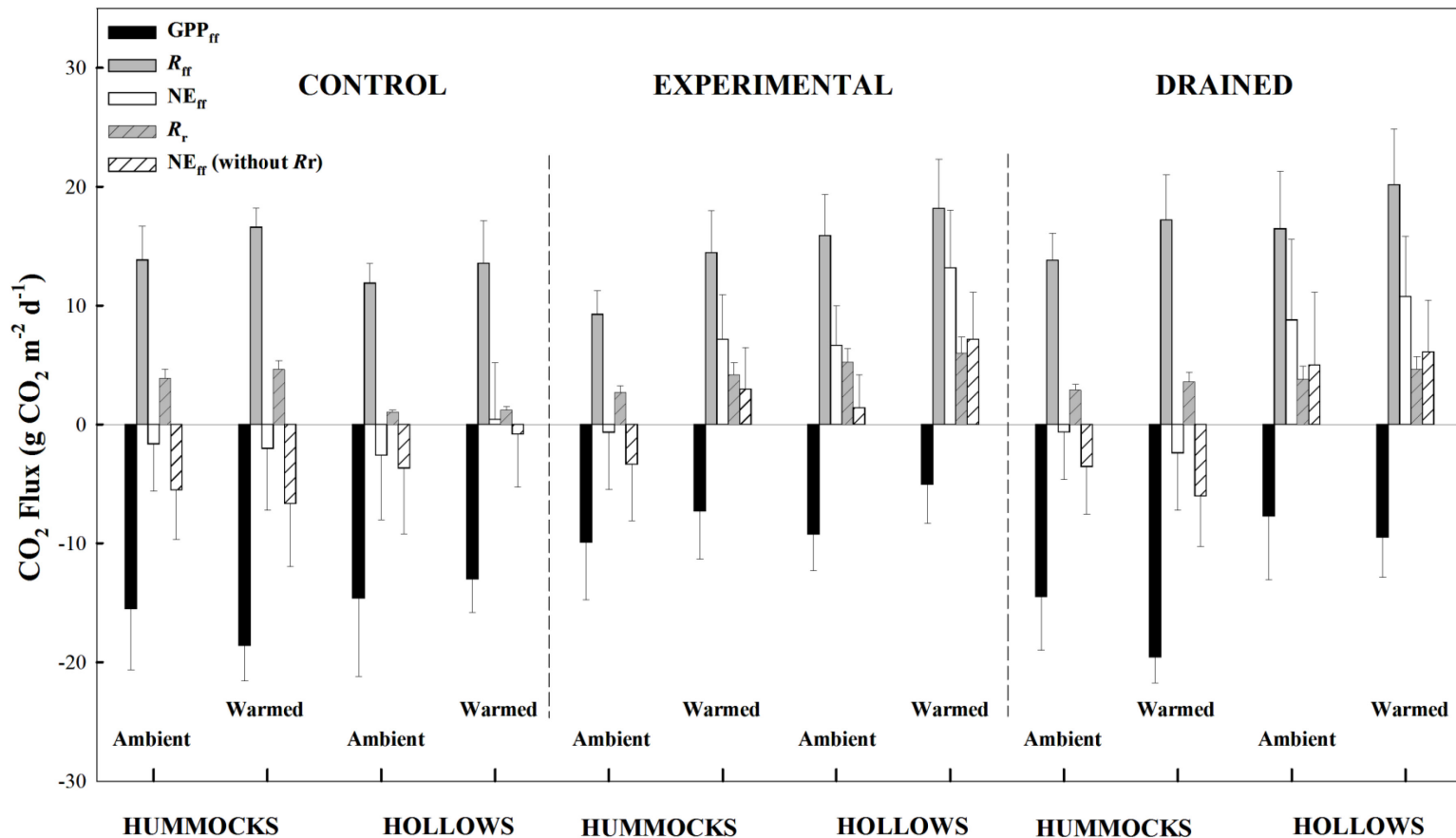


1026

1027

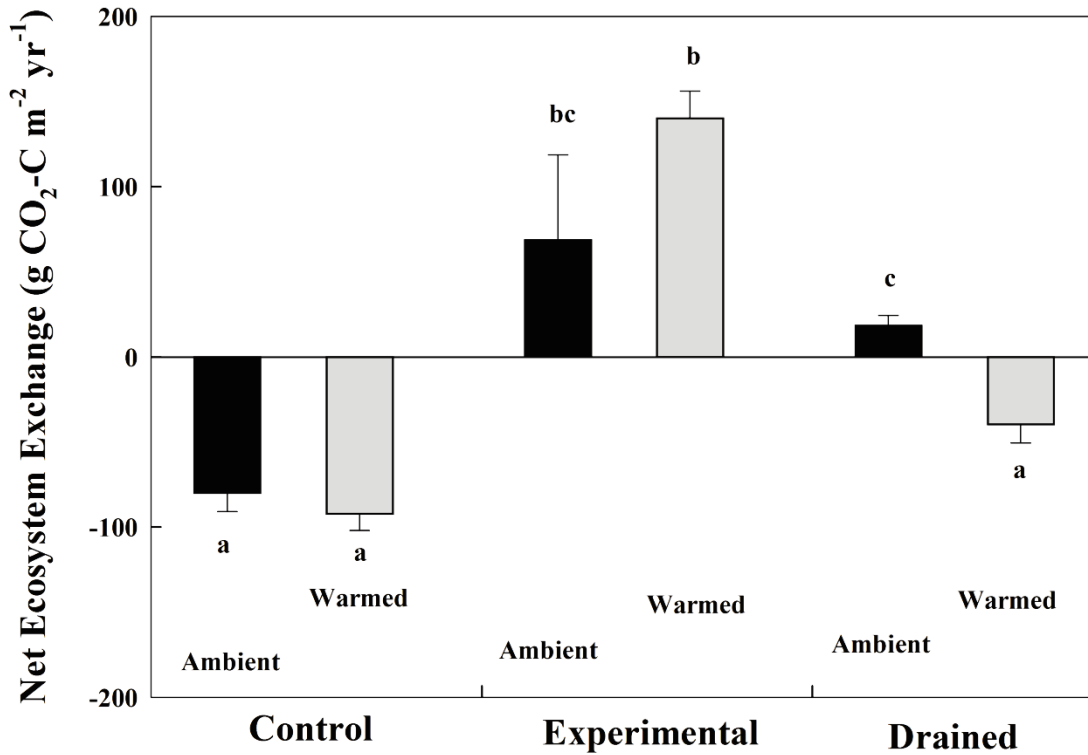
1028

Figure 3. Relationship between drainage, warming and microform scenario and ground layer above-ground biomass by category as a percentage of total.



1029

1030 Figure 4. GPP<sub>max</sub>, R<sub>fr</sub> and NE<sub>max</sub> and R<sub>r</sub> at control, experimental and drained sites averaged across 2011-2013. NE<sub>max</sub> (without above  
 1031 and below-ground parts of trees) was calculated by subtracting R<sub>r</sub> from NE<sub>max</sub> and represents net exchange of CO<sub>2</sub> of the ground-layer  
 1032 vegetation (including peat). Error bars indicate ± standard deviation. Results are from linear mixed-effects model with water table,  
 1033 OTC (warming) and microform and year as fixed effects and year as repeated measures. Only averaged fluxes across all study years  
 1034 are being graphed as the impacts of treatments were consistent in all growing seasons.



1035

1036

1037

1038

1039

1040

Figure 5. CO<sub>2</sub>-C balance averaged across study years (2011-2013). Error bars indicate ± standard deviation. Differences were evaluated between ambient and warmed sites (microforms) indicated by letters at each bar. Sites are significantly different at  $p < 0.05$  if they have no letters in common.