

Author's Response

Biogeosciences Discuss., doi:10.5194/bg-2015-640, 2016

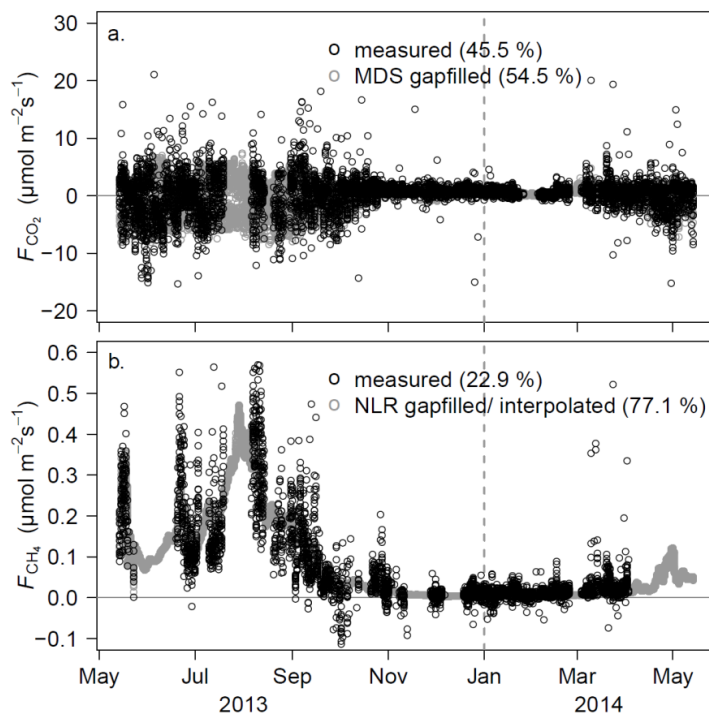
We first list the comments of the two referees followed by our respective responses, which are marked in blue. Page and line specifications refer to the reviewed discussion paper. Subsequently, we provide a marked-up manuscript version including our tracked changes within the manuscript.

Comments of referees and author's responses

Anonymous Referee #1

1. In the manuscript there are lengthy descriptions of gap-filling of the eddy covariance data, and the coverage of the actual data is presented in Table 1. However, there is very little information about the timing of these gaps, I was hoping for a bit more open policy about the shortcomings of the data. In row 310 there is a remark that data from April and May are missing from Figure 3 because the sensor was dismantled. Are there other similar longer gaps in the data? Where?

We added an appendix presenting the data coverage of CO₂ and CH₄ fluxes within the study period. We cross-refer to Fig. A1 on page 7 in line 185.



“Figure A1: Data coverage of a) CO₂ and b) CH₄ fluxes within the study period. Gapfilling results of the MDS_{CO₂nofoot} and NLR_{CH₄nofoot} approaches are added as grey circles. The percentages in brackets indicate the time series coverages of measurements and gapfilling values.”

26 2. The term “polytrophic” is not very commonly used in the lake science, I suppose it means a shallow,
27 polymictic and eutrophic lake. However, as the term is not very commonly known, I think the paper
28 would draw more interest if the title was “... polymictic and eutrophic lake ...” or “... a shallow
29 eutrophic lake ...”.

30 This comment is based on the very first submitted draft of this manuscript. However, this draft was
31 slightly changed according to the quick reports of the Referees, which was necessary to publish the
32 manuscript for interactive discussion. As suggested in the quick report, we changed the term
33 “polytrophic” to “eutrophic” and thank Referee #1 for this suggestion. We now further replaced
34 “eutrophic shallow lake” by “eutrophic and polymictic lake” in line 111 on page 4. In addition to the
35 suggestions in the quick reports, we applied few small changes to the very first draft to further improve
36 the manuscript. Thus, the lines mentioned by Referee #1 are shifted.

37
38 3. The writers stated that summer 2013 was exceptionally hot and dry and as a consequence the
39 water level dropped considerably rising again the next winter. As the lake is very shallow, I was
40 wondering how much the fluctuation of the water level affected the lake area (i.e. area covered
41 with water). Was the water area considerably larger in winter than in summer? One of the main
42 findings of this study is that open water and vegetated areas had very different gas fluxes. How
43 much did the fluctuating water level (or dry land versus water covered land) effect the results?

44 During summer particularly areas with a wintertime very shallow inundation of the soil were exposed,
45 pertaining especially parts of the emergent vegetation stands. We did not map the fluctuations of soil
46 inundation and aerial images, which could help to define the extent of inundation, are not available
47 for the periods with highest and lowest water table. Nevertheless, in summer the detection of
48 inundated and exposed areas would be hampered by the vegetation hiding the surface. We could not
49 observe a considerable decrease of the spatial extent of the open water body, as emergent vegetation
50 mainly covers the shallower edges of the water body. Water table modelling would require a digital
51 terrain model (DTM) with a very high height accuracy, as the study site itself is on average less than
52 0.5 m above sea level. The most accurate available DTM covering the site is the DTM5 with a height
53 accuracy of 0.25 to 1 m, which is not sufficient to represent the microtopography.

54 Changing coverages of exposed versus inundated soil most probably have an effect on the difference
55 of the surface type fluxes. However, for profound statements long-term measurements covering more
56 than one summer will be necessary. In addition, we expect the effect of water level changes to be very
57 variable within the open water body, as the bottom is characterised by a distinct microtopography (see
58 also response to comment 3 of Referee #2) and therefore different vulnerability to changes. Thereby,
59 eddy covariance measurements can only provide limited information.

60 We changed lines 476-479 on page 16 to the following: “Unusual warm and dry conditions and
61 associated water table lowering during summer 2013 might have triggered a shift from anaerobic to
62 aerobic decomposition due to the exposure of formerly only shallowly inundated soil and organic mud,
63 primarily in the emergent vegetation stands. We could not observe a considerable decrease of the
64 spatial extent of the open water body as emergent vegetation mainly covers the shallower edges of
65 the water body.”

66
67 4. One of the findings of this study is that convection brought about a diurnal fluctuation of CH₄ flux.
68 If this is true, most likely convection contributed also on the diurnal fluctuation of CO₂ flux. Have
69 you considered this when calculating e.g. NEE?

70 We did not consider convection within NEE modelling and the calculation of the surface type fluxes so
71 far. However, we agree that thermally induced convective mixing might also have an effect on the
72 diurnal fluctuations of NEE. Nevertheless, open water is characterised by remarkably lower CO₂
73 exchange rates than emergent vegetation.

74 According to our response we add the following paragraph to the discussion on the diurnal variability
75 of CH₄ emissions (page 14, line 398): “Apart from CH₄, thermally induced convection potentially
76 contributes also to the diurnal fluctuation of the CO₂ flux at our study site. According to Eugster et al.
77 (2003) penetrative convection might be the dominant mechanism yielding CO₂ fluxes during periods
78 of low wind speed, especially in case of a stratification of CO₂ concentrations in the water body.
79 Ebullition triggered by convective mixing might be less important for CO₂ than for CH₄, as
80 concentrations of CO₂ are most often low in gas bubbles (e.g. Casper et al. 2000, Poissant et al. 2007,
81 Repo et al. 2007, Sepulveda-Jauregui et al. 2015, Spawn et al. 2015). Further investigations should
82 focus on the controls of the diurnal patterns in CO₂ and CH₄ exchange based on additional
83 measurements, e.g. gas concentrations in the water, methane oxidation or plant-mediated transport.”

84

85 *Detailed comments:*

86

87 5. Page 11, row 310: Please add 2014 to avoid misunderstandings (April and May 2014 not shown ...)

88 We changed the paragraph according to our response to comment Nr. 5 of Referee #2 and added the
89 respective year to the months.

90

91 6. Page 15, row 432: Extra bracket at the end of the sentence.

92 A cross-reference to Table 4 was missing. We already corrected this prior to the publication of the
93 manuscript for interactive discussion as can be seen in line 435 on page 15 (for shifted lines see
94 response to comment 2).

95

96 7. Figure 2. It is not quite clear here if the fluxes are for the whole EC area or for the AOI.

97 Fig. 2 presents the daily fluxes for the EC source area. We added the missing information to the figure
98 caption: “Figure 2: Temporal variability of environmental variables and ecosystem CO₂ and CH₄
99 exchange within the EC source area. Seasonal course a) of water level (Wlevel), cumulative
100 precipitation (Cum. Precip) and air temperature (T_{air}), b) the daily CH₄ flux (gapfilled, NLR_{CH₄nofoot}) and
101 c) the daily NEE (gapfilled LUT_{CO₂nofoot}) and component fluxes (modelled R_{eco} and GPP, LUT_{CO₂nofoot}).”

102

103 8. Figure 6. It is not quite clear what does the density describe. Please clarify.

104 We thank the referee for this suggestion. We use a smoothed 2d kernel density estimate to illustrate
105 the abundance of the CO₂ and CH₄ fluxes dependent on the fractional coverage of open water within
106 the EC source area. The plot was created with the command smoothScatter of the R package graphics.

107 The graph is based on flux data from 15 May until 14 September 2013, as the dependence of the flux
108 variability on the source area coverage of open water is most pronounced during summer.

109 We changed the figure caption to the following: “Figure 6: Impact of the fractional coverage of open
110 water (Ω_{water}) within the EC source area on the measured fluxes of CO₂ and CH₄ (15 May to 14
111 September 2013). The abundances of CO₂ and CH₄ fluxes in dependence on Ω_{water} are illustrated by a
112 smoothed two-dimensional kernel density estimate. The variability of CO₂ flux rates decreased with
113 increasing Ω_{water} , whereas the variability of the CH₄ flux increased.”

114

115 **Anonymous Referee #2**

116

- 117 1. Line 218: What does 'enhanced' mean here – is this still simply a lookup table method or does it
118 include something else?

119 The “enhanced” Look-up Table (LUT) approach corresponds to the Marginal Distribution Sampling
120 (MDS) approach (see e.g. Moffat et al. 2007). The term “enhanced” indicates an essential modification
121 in comparison to the standard LUT: missing NEE is filled with the mean value of data under similar
122 meteorological conditions (radiation, air temperature and vapour pressure deficit) of a fixed margin
123 within a moving window. Thus, the temporal autocorrelation of NEE is exploited. The algorithm varies
124 in case of incomplete meteorological data (see Reichstein et al. 2005). To adapt to the common
125 terminology we replaced the abbreviation “LUT” by “MDS” at all occurrences in the manuscript and
126 changed page 8 lines 218-221 to: “A Marginal Distribution Sampling (MDS) approach proposed by
127 Reichstein et al. (2005), available as web tool based on the R package REddyProc ([http://www.bgc-
128 jena.mpg.de/REddyProc/brew/REddyProc.rhtml](http://www.bgc-jena.mpg.de/REddyProc/brew/REddyProc.rhtml)) was applied for gapfilling and partitioning of NEE
129 measurements (LUT_{CO2nofoot}), with air temperature as temperature variable.”

130

- 131 2. Line 251: The outer pair of brackets is not needed here.

132 We agree and deleted the outer pair of brackets.

133

- 134 3. Line 300: The statements about the water level are confusing when comparing them with line 112
135 in the site description. There the water depth was said to ‘range from 0.1 and 0.7 m’ (does this
136 refer to spatial or temporal variation?) and here the temporal fluctuations are shown to be 0.36
137 and 0.77 m as visible from Fig. 2. How do these two statements fit together?

138 We apologize for the confusion and the declaration of a rather misleading water level range. The range
139 “0.1 to 0.7 m” on page 4 line 112 and page 7 line 206 is the generously rounded range of the mean
140 annual water level 2008-2012 generated by measurement based water level modelling. For a long-
141 term range we refer to Zak et al. (2015) reporting water levels between 0.2 m and 1.2 m above the
142 surface at a specific gauge between 2004 and 2012. We replace the range “0.1 to 0.7 m” on page 4 line
143 112 and add in brackets “2004 to 2012; Zak et al. 2012”. We deleted the water level information on
144 page 7 line 206 as we declare the temporal range for our study period within the results part. This
145 range is measured at one single position close to the tower, including the snow cover on ice covering
146 the shallow lake. Both the long-term and our short-term water level measurements are not
147 representative for the whole shallow lake, as the study site is characterised by a distinct
148 microtopography due to previous shrinkage and subsidence of the peat in consequence of drainage
149 and degradation.

150

- 151 4. Line 304: Why were median fluxes instead of averages or totals given here? I think this is not very
152 common and should therefore be briefly explained.

153 We present median values for our flux measurements as this is the best measure of a central tendency
154 in a skewed dataset due to not evenly distributed gaps.

155

- 156 5. Line 309ff: Why were the CH₄ fluxes normalized but not the CO₂ fluxes?

157 By normalising the mean half-hourly CH₄ fluxes per month we can illustrate the diurnal pattern of CH₄
158 fluxes, which was hardly visible in the unnormalised fluxes during months with generally low CH₄
159 exchange rates. We did not normalise the CO₂ fluxes so far as we can detect a diurnal cycle for the
160 same months based on both normalised and unnormalised fluxes. However, to be consistent we now
161 also normalised the mean half-hourly CO₂ fluxes per month. In addition, we decided to also include

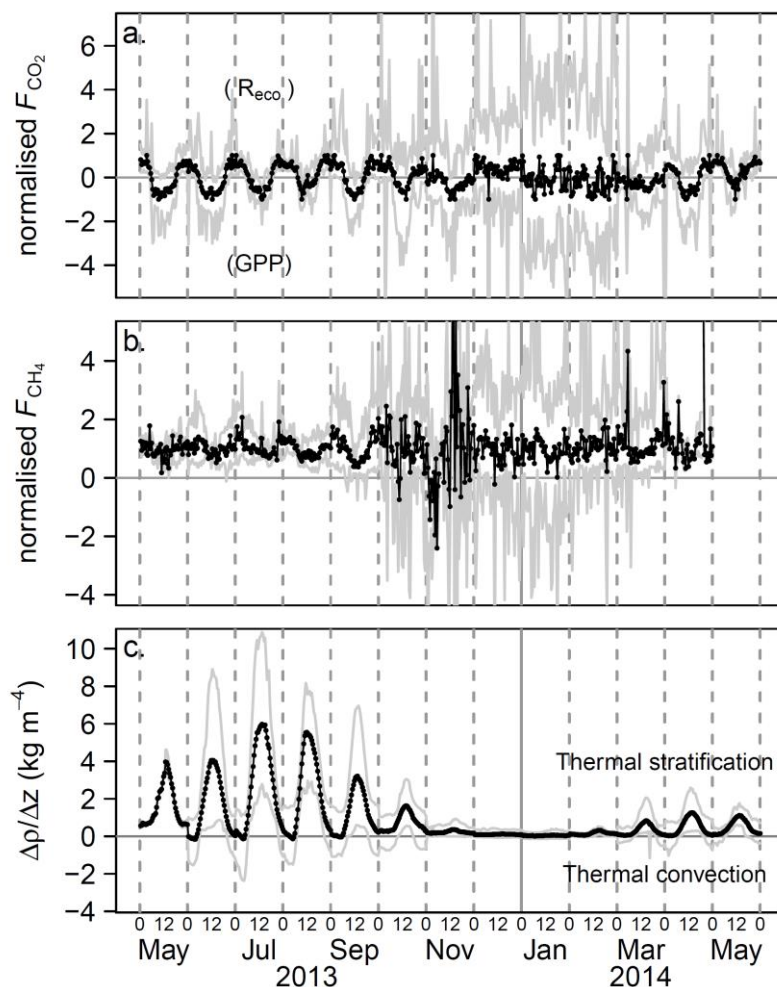
162 fluxes of days were less than five half-hourly flux values are available, thus including mean half-hourly
163 CH₄ fluxes for April 2014, which are based on three days only, due to the dismantling of the sensor.

164 We modified lines 307-314 on page 11 to:

165 "To investigate the potential presence of a diurnal cycle of CO₂ and CH₄ fluxes throughout the study
166 period we normalised the mean half-hourly CO₂ and CH₄ fluxes per month with the respective
167 minimum/ maximum and median of the half-hourly fluxes of the specific month (modified from Rinne
168 et al. 2007). A pronounced diurnal cycle of CO₂ fluxes with peak uptake around midday and peak
169 release around midnight was obvious until November 2013 and beginning in March 2014 (see Fig. 3),
170 although less pronounced in these two months. We found a clear diurnal cycle of CH₄ fluxes from June
171 to September 2013 and in March 2014 (April 2014 based on 3 days only and May 2014 not available
172 as the sensor was dismantled) with daily peaks during night-time (around midnight until early
173 morning)."

174 We changed Fig. 3 as follows:

175



176

177

178 "Figure 3: Average diurnal cycle of a) CO₂ flux, b) CH₄ flux and c) the water density gradient per
179 month. The numbers at the x-axis denote midnight (0) and midday (12) in UTC. Midnight is also
180 illustrated with a dashed line. Black and grey lines represent the mean and the range, respectively.
181 The CO₂ and CH₄ fluxes are normalised with the monthly minimum/ maximum and the median of
182 the half-hourly fluxes, respectively. Although the zero line is slightly shifted due to normalisation,
183 positive CO₂ fluxes roughly indicate the dominance of R_{eco} against GPP, negative fluxes the
184 dominance of GPP against R_{eco}. The period of ice-cover was excluded from the calculation of the
185 temperature gradient. A density gradient equal to or below zero indicates thermally induced

186 convective mixing down to the bottom of the open water body of the shallow lake, positive
187 gradients instead thermal stratification.”

188

189 6. Line 363: Insert “for the AOI” before “than”.

190 Done.

191

192 7. Lines 384ff: Would convection also affect the CO₂ emissions from the lake? Please discuss whether
193 this is possible – or why you think it’s not.

194 For our response to this comment we refer to our response to comment 4 of Referee #1.

195

196 8. Line 417: Replace “typically” with “typical”.

197 Done.

198

199 9. Line 451: Add “and a higher rate of CH₄ oxidation in the aerated top soil” after “CH₄”.

200 We agree and changed lines 448-451 on page 15: “Furthermore, the soil of emergent vegetation stands
201 is generally only temporarily and partly inundated and the water table decreased additionally during
202 the unusual warm and dry summer 2013, probably resulting in a lower rate of anaerobic
203 decomposition to CH₄ and a higher rate of CH₄ oxidation in the aerated top soil.”

204

205 10. Lines 495ff: This is one of the (few) weak points of this study: With only one year of data that
206 happened to be characterized by “unusual meteorological conditions” the question arises as to
207 what extent the observation of the wetland being a large GHG source can be transferred to other
208 sites and other years. Other studies have shown multi-year trends in GHG budgets following
209 wetland restoration. I suggest that the authors discuss this in more detail, taking for example the
210 papers by Waddington and Day (2007, JGR) or by Herbst et al. (2013, this journal) and/or the
211 respective references therein into account.

212 The unusual meteorological conditions during our study period might have caused a differing GWP
213 compared to years with usual meteorological conditions, highlighting the need of long-term
214 measurements. Moreover, based on the few existing studies a consistent picture and development of
215 the GHG exchange behaviour does not seem to exist for rewetted fens, probably due to a variety of
216 driving conditions and processes. We agree to extend our comparison with other studies and for that
217 refer to our response on comment 12 (changes for the paragraph of lines 495-504 on page 17).

218 In addition, we changed lines 491-494 on page 16f.: “Our results imply a delayed shift of the ecosystem
219 towards a C sink with reduced climate impact, which might be the result of the exceptional
220 characteristics represented by eutrophic conditions and lateral transport of organic matter within the
221 open water body.”

222 Within the conclusions we deleted the sentence “Our results show [...]” in lines 522f. and the sentences
223 in lines 525-528 starting with “In combination with [...]” and changed lines 534-536: “Interannual
224 comparisons are also necessary to verify what the results of this study imply: that the intended effects
225 of rewetting in terms of CO₂ emission reduction and C sink recovery are not yet achieved at this site.
226 In this context, the effect of unusual meteorological conditions needs further investigation. More
227 general statements for the climate impact of rewetted fens can only be provided by inclusion of
228 additional sites varying e.g. in groundwater table and plant composition.”

229

230 11. Line 514: I suggest adding a phrase like “... and the interannual variability if short-term studies like
231 this one are involved” to the end of this sentence.

232 We agree and changed the sentence to: “Inter-site comparisons (e.g. with other shallow lakes evolved
233 during fen rewetted) are challenging with regard to the site-specific spatial heterogeneity and their
234 interannual variability, if short-term studies like the present one are involved.” In addition we
235 continue: “Comparisons might be misleading in case the fractional coverages of the main surface types
236 are not considered. Furthermore, as shown by Wilson et al. (2007, 2008) and Minke et al. (2015)
237 vegetation composition has a remarkable effect on GHG emissions of rewetted peatlands and should
238 be considered within inter-site comparisons.”

239

240 12. Lines 517ff: What I miss in the conclusions is some statement or estimate that relates the finding
241 of this study to the situation of drained fen grasslands, at least on the basis of literature data. Does
242 the described method of rewetted (involving the flooding of substantial parts of the area) make
243 the GHG budget worse than that of a drained fen? Or just worse than that of a more cautiously
244 restored fen (with less surface inundation), but still better than that of the drained situation?

245 The climate impact of our study site is stronger than generally expected for rewetted peatlands, apart
246 from the CH₄ hot spot characteristic of newly rewetted sites. We mentioned in lines 459f. on page 15
247 that the net CO₂ budget for the EC source area at our study site was higher or similar to those of drained
248 and degraded peatlands under grassland management (e.g. Hatala et al. 2012, Schrier-Uijl et al. 2014).
249 In addition, CH₄ release was remarkably higher than for the referenced degraded sites, resulting in a
250 stronger climate impact of our study site. Time plays an important role for the climate impact after
251 rewetted and success is often achieved only several years or decades after rewetted (e.g. Hendriks et
252 al. 2007/ Schrier-Uijl et al. 2014). Minke et al. (2015) showed still strong GHG emissions even after 25
253 years of rewetted due to strong above-surface water level fluctuations. However, the effect of water
254 level does not seem to be consistent along different sites, especially for CO₂. Secondary plant
255 succession towards a peat forming vegetation (Zerbe et al. 2013) and terrestrialisation (Zak et al. 2015)
256 are reported to be requirements for peat formation and thus the revitalisation of the C sink function
257 in case of inundated conditions in consequence of rewetted (but e.g. Knox et al. 2015). At our study
258 site emergent vegetation, but especially non-peat forming *Typha latifolia*, is progressively entering and
259 organic mud is steadily filling up the open water body. Ongoing investigations will show how the GHG
260 exchange will develop.

261 Based on our response we added a statement on the CH₄ emissions of the degraded peatlands, whose
262 CO₂ emissions were compared to our results (see lines 459f. on page 15) and changed lines 407-409
263 on page 14 as follows: “However, natural (e.g. Bubier et al. 1993, Nilsson et al. 2001) and degraded
264 fens (Hatala et al. 2012, Schrier-Uijl et al. 2014, see also IPCC 2014) release most often less CH₄ than
265 the majority of rewetted fens, with some exceptions (e.g. Huttunen et al. 2003).”

266 In the conclusions we already mentioned the potentially special character of shallow lakes and changed
267 lines 538-540 as follows: “Our study shows that permanent (high) inundation in combination with
268 nutrient-rich conditions involves the risk of long-term high CH₄ emissions. They counteract the actually
269 intended lowering of the climate impact of drained and degraded fens and can result in an even
270 stronger climate impact than degraded fens, as also shown in previous studies.”

271 Furthermore, in combination with comment Nr. 10, we decided to extend our discussion in terms of
272 comparisons to other study sites with different degrees of rewetted, i.e. water table height. We
273 changed the paragraph of lines 495-504 on page 17 as follows: “However, the unusual meteorological
274 conditions during our study period might have caused a differing (lower or higher) GWP compared to
275 previous years. CH₄ emissions might have been lower at the expense of high net CO₂ release, whereas
276 under usual meteorological conditions e.g. CO₂ uptake could probably compensate the CH₄ emissions.
277 Inundation is often associated with high CH₄ emission. Thus, during rewetted the water table is
278 generally recommended to be held at or just below the soil surface to prevent inundation and the
279 formation of organic mud (Couwenberg et al. 2011, Joosten et al. 2012, Zak et al. 2015). In contrast to
280 CH₄, the influence of water level on net CO₂ release is not nearly consistent in the few existing studies
281 of rewetted peatlands. In comparison to our site, Knox et al. (2015) reported high net CO₂ uptake to

282 substantially compensate high CH₄ emissions for a site with mean water levels above the soil surface
283 after several years of rewetting (see Table 5). Similarly, Schrier-Uijl et al. (2014) reported high CO₂
284 uptake rates for a Dutch fen site 7 years after rewetting and even C uptake and a GHG sink function
285 after 10 years with water levels below or at the soil surface. Herbst et al. (2011) present a snapshot of
286 the GHG emissions of a Danish site after 5 years of rewetting with permanently and seasonally wet
287 areas, whereby high CO₂ uptake and moderate CH₄ emissions lead to substantial GHG savings. In
288 contrast, weak CO₂ uptake and decreasing, but still high CH₄ emissions were reported for another fen
289 site in NE Germany with mean water levels above the soil surface (Koebsch et al. 2013, 2015 and Hahn
290 et al. 2015), resulting in a decreasing climate impact after 3 years of rewetting. Interestingly, changes
291 of NEE due to flooding were negligible, although GPP and R_{eco} rates decreased considerable due to the
292 flooding (Koebsch et al. 2013). In comparison to the decreasing CH₄ emissions at this site, Waddington
293 and Day (2007) report enhancing CH₄ release for a Canadian peatland in the 3 three years after
294 rewetting. A third rewetted fen site in NE Germany with water levels close to the soil surface was
295 reported as weak GHG source 14-15 years after rewetting (Günther et al. 2015).”

296

297 Apart from the suggestions of the two referees we decided to slightly modify some other parts of the
298 manuscript for further improvement. In addition, we recognized a mistake in Table 4 due to the
299 erroneous line 7 (CH₄ emission from water) in Table 10 in Hendriks et al. (2007). In alignment with
300 Table 7 in Hendriks et al. (2007) the right value for CH₄ emission from water for 2005 has to be 37.3 g
301 C m⁻² a⁻¹, i.e. 46 g CH₄ m⁻² a⁻¹. We corrected the wrong value in Table 4 and also changed the study year
302 of this observation to “2005”. In addition, we added the annual net CH₄ exchange for 2006 according
303 to Table 7 in Hendriks et al. (2007): 49 g CH₄ m⁻² a⁻¹ at water levels above 0 m. Furthermore, we
304 corrected the water level specification for the study site described in Minke et al. (2015) to 0.13 m in
305 2011-2012 and < 0.13 m in the following year. We corrected a mistake in the emission factors derived
306 from IPCC (2014) and changed on page 14 line 402-404: “This rate is remarkably higher than the
307 emission factor of 28.8 g CH₄ m⁻² a⁻¹ that was assigned to rewetted temperate rich organic soils, which
308 is in turn more than twice the rate of the nutrient-poor complement (IPCC 2014).”

309 **Additional references:**

310

311 Koebisch, F., Glatzel, S., Hofmann, J., Forbrich, I. and Jurasinski, G.: CO₂ exchange of a temperate fen
312 during the conversion from moderately rewetting to flooding, *J. Geophys. Res.-Biogeo.*, 118, 940-
313 950, doi:10.1002/jgrg.20069, 2013.

314 Moffat, A. M., Papale, D., Reichstein, M., Hollinger, D. Y., Richardson, A. D., Barr, A. G., Beckstein, C.,
315 Braswell, B. H., Churkina, G., Desai, A. R., Falge, E., Gove, J. H., Heimann, M., Hui, D., Jarvis, A. J.,
316 Kattge, J., Noormets, A. and Stauch, V. J.: Comprehensive comparison of gap-filling techniques for
317 eddy covariance net carbon fluxes, *Agricultural and Forest Meteorology*, 147, 209-232,
318 doi:10.1016/j.agrformet.2007.08.011, 2007.

319 Poissant, L., Constant, P., Pilote, M., Canário, J., O'Driscoll, N., Ridal, J. and Lean, D.: The ebullition of
320 hydrogen, carbon monoxide, methane, carbon dioxide and total gaseous mercury from the
321 Cornwall Area of Concern, *Sci. Total Envir.*, 381, 256-262, doi:10.1016/j.scitotenv.2007.03.029,
322 2007.

323 Sepulveda-Jauregui, A., Walter Anthony, K. M., Martinez-Cruz, K., Greene, S. and Thalasso, F.: Methane
324 and carbon dioxide emissions from 40 lakes along a north-south latitudinal transect in Alaska,
325 *Biogeosciences*, 12, 3197-3223, doi:10.5194/bg-12-3197-2015, 2015.

326 Spawn, S. A., Dunn, S. T., Fiske, G. J., Natali, S. M., Schade, J. D. and Zimov, N. S.: Summer methane
327 ebullition from a headwater catchment in Northeastern Siberia, *Inland Waters*, 5, 224-230,
328 doi:10.5268/IW-5.3.845, 2015.

329

331

332 **High net CO₂ and CH₄ release at a eutrophic shallow lake**
333 **on a formerly drained fen**

334

335 **D. Franz¹, F. Koebsch¹, E. Larmanou¹, J. Augustin² -and T. Sachs¹**

336 [1] {Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg,
337 14473 Potsdam, Germany}

338 [2] {Institute for Landscape Biogeochemistry, Leibniz Centre for Agricultural Landscape Research
339 (ZALF), Eberswalder Str. 84, 15374 Müncheberg, Germany}

340 *Correspondence to:* D. Franz (daniela.franz@gfz-potsdam.de)

341

342 **Abstract**

343 Drained peatlands often act as carbon dioxide (CO₂) hotspots. Raising the groundwater table is
344 expected to reduce their CO₂ contribution to the atmosphere and revitalize their function as carbon
345 (C) sink in the long term. Without strict water management rewetting often results in partial flooding
346 and the formation of spatially heterogeneous, nutrient-rich shallow lakes. Uncertainties remain as to
347 when the intended effect of rewetting is achieved, as this specific ecosystem type has hardly been
348 investigated in terms of greenhouse gas ~~exchange~~-(GHG) exchange. In most cases of rewetting,
349 methane (CH₄) emissions increase under anoxic conditions due to a higher water table and in terms of
350 global warming potential (GWP) outperform the shift towards CO₂ uptake, at least in the short-term.

351 Based on eddy covariance measurements we studied the ecosystem-atmosphere exchange of CH₄ and
352 CO₂ (~~NEE~~) at a shallow lake situated on a former fen grassland in Northeast (NE) Germany. The lake
353 evolved shortly after flooding, 9 years previous to our investigation period. The ecosystem consists of
354 two main surface types: open water (inhabited by submerged and floating vegetation) and emergent
355 vegetation (particularly including the eulittoral zone of the lake, dominated by *Typha latifolia*). To
356 determine the individual contribution of the two main surface types to the net CO₂ and CH₄ exchange
357 of the whole lake ecosystem, we combined footprint analysis with CH₄ modelling and net ecosystem
358 exchange (NEE) partitioning.

359 The CH₄ and CO₂ dynamics were strikingly different between open water and emergent vegetation.
360 Net CH₄ emissions from the open water area were around 4-fold higher than from emergent vegetation
361 stands, accounting for 53 and 13 g CH₄ m⁻² a⁻¹, respectively. In addition, both surface types were net
362 CO₂ sources with 158 and 750 g CO₂ m⁻² a⁻¹, respectively. Unusual meteorological conditions in terms
363 of a warm and dry summer and a mild winter might have facilitated high respiration rates. In sum, even
364 after 9 years of rewetting the lake ecosystem exhibited a considerable C loss and global warming
365 impact, the latter mainly driven by high CH₄ emissions. We assume the eutrophic conditions in
366 combination with permanent high inundation as major reasons for the unfavourable GHG balance.

367

368 **1 Introduction**

369 Peatland ecosystems play an important role in global greenhouse gas (GHG) cycles, although they
370 cover only about 3 % of the earth's surface (Frolking et al. 2011). Peat growth depends on the
371 proportion of carbon (C) sequestration and release. Pristine peatlands act as long-term C sinks and are
372 near-neutral (slightly cooling) regarding their global warming potential (GWP; Frolking et al. 2011),
373 dependent on rates of C sequestration and methane (CH₄) emissions. However, many peatlands
374 worldwide are used e.g. for agriculture, as are more than 85% of the peatlands in Germany and the
375 Netherlands (Silvius et al. 2008). Drainage is associated with shrinkage and internal phosphor
376 fertilisation of the peat (Zak et al. 2008). Moreover, the hydrology of the area as well as physical and
377 chemical peat characteristics are changing (Holden et al. 2004, Zak et al. 2008). Above all, drained and
378 intensively managed peatlands are known as strong sources of carbon dioxide (CO₂; e.g. Joosten et al.
379 2010, Hatala et al. 2012, Beetz et al. 2013). On the other hand, lowering the water table is typically
380 accompanied with decreasing CH₄ emissions (Roulet et al. 1993). Emission factors of 1.6 g CH₄ m⁻² a⁻¹
381 and 2235 g CO₂ m⁻² a⁻¹ were assigned to temperate deep-drained nutrient-rich grassland in the 2013
382 wetland supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2014).

383 In the last decades rewetting of peatlands attracted attention in order to stop soil degradation, reduce
384 CO₂ emissions and to recover their functions as C and nutrient sink and ecological habitat (Zak et al.
385 2015). Large rewetting projects were initiated, e.g. the Mire Restoration Program of the federal state
386 of Mecklenburg-West Pomerania in Northeast (NE) Germany (Berg et al. 2000) starting in 2000 and
387 involving 20 000 ha of formerly drained peatlands, thereby especially fens (Zerbe et al. 2013) e.g. in
388 the Peene river catchment. However, uncertainties remain as to when the intended effects of
389 rewetting are achieved. Only few studies exist on the temporal development of GHG emissions of
390 rewetted fens, especially on longer time scales. Augustin and Joosten (2007) discuss three very
391 different states following peatland rewetting based on observations at Belarusian mires, though
392 without specifying the individual lengths of the phases. Broad agreement exists concerning the CH₄

393 hot spot characteristic of newly rewetted peatlands (e.g. Meyer et al. 2001, Hahn-Schöfl et al. 2011,
394 Knox et al. 2015). However, a rapid recovery of the net CO₂ sink function is not consistently reported
395 (e.g. Wilson et al. 2007).

396 Peatlands develop a ~~distinct~~pronounced microtopography after drainage and subsequent subsidence.
397 Rewetting e.g. in the Peene river catchment resulted in the formation of large-scale shallow lakes in
398 the lower parts of the fens, with water depths usually below 1 m (Zak et al. 2015, Steffenhagen et al.
399 2012). These new ecosystems are nutrient-rich and most often strikingly different from natural
400 peatlands. They experience a rapid secondary plant succession (Zak et al. 2015). Helophytes are
401 expected to progressively enter the open water body over the time leading to the terrestrialisation of
402 the shallow lake and in the best case peat formation. However, this new ecosystem type and its
403 progressive transformation have hardly been investigated in terms of GHG dynamics. The ecosystem-
404 inherent spatial heterogeneity suggests complex patterns of GHG emissions due to distinct GHG source
405 or sink characteristics of the involved surface types (generally open water and the littoral zone)
406 resulting in measurement challenges. Site-specific heterogeneity implicitly has to be considered for
407 the evaluation of ecosystem scale flux measurements (e.g. Barcza et al. 2009, Hendriks et al. 2010,
408 [Herbst et al. 2011](#), Hatala Matthes et al. 2014). The importance of small open water bodies in wetlands
409 as considerable GHG sources was highlighted in previous studies (e.g. by Schrier-Uijl et al. 2011, Zhu
410 et al. 2012, IPCC 2014) and in case of CH₄ even for landscape-scale budgets e.g. by Repo et al. (2007).
411 In addition, the littoral zone of lakes is often found to be a CH₄ hot spot (Juutinen et al. 2003, Wang et
412 al. 2006) with a contribution of up to 90 % to the whole-lake CH₄ release (Smith and Lewis 1992), albeit
413 depending on the lake size (Bastviken et al. 2004) and plant community. Rööhm et al. (2014) measured
414 the largest CH₄ (and CO₂) emissions of a temperate eutrophic lake at the helophyte zone within the
415 littoral.

416 The objectives of this study are 1) to investigate the ecosystem-atmosphere exchange of CH₄ and CO₂
417 (NEE) of a nutrient-rich lake ecosystem emerged at a former fen grassland and 2) particularly infer the
418 individual GHG dynamics of the main surface types within the ecosystem and quantify their
419 contribution to the annual exchange rates. Therefore, we applied the eddy covariance technique from
420 May 2013 to May 2014 and used an analytical footprint model to downscale the spatially integrated,
421 half-hourly fluxes to the main surface types “open water” and “emergent vegetation”. The resulting
422 source area (i.e. spatial origin of the flux) fractions were then included in a temperature response (CH₄)
423 and NEE partitioning model (CO₂) in order to quantify the source strength of the two surface types.

424

425 2 Material and methods

426 2.1 Study site

427 The study site “Polder Zarnekow” is a rewetted, rich fen (minerotrophic peatland) located in the Peene
428 river valley (Mecklenburg-West Pomerania, NE Germany, 53°52.5′ N 12°53.3′ E, see Fig. 1), with less
429 than 0.5 m a.s.l. elevation. It is part of the Terrestrial Environmental Observatories Network (TERENO).
430 The temperate climate is characterised by a long-term mean annual air temperature and mean annual
431 precipitation of 8.7 °C and 584 mm, respectively (German Weather Service, meteorological station
432 Teterow, 24 km SW of the study site; reference period 1981–2010). The geomorphological character
433 of the area is predominantly a result of the Weichselian glaciation as the last period of the Pleistocene
434 (Steffenhagen et al. 2012). The fen developed with continuous percolating groundwater flow (Succow
435 2001). Peat depth partially reaches 10 m (Hahn-Schöfl et al. 2011). Drainage was initialized in the 18th
436 century and strongly intensified between 1960 and 1990 within an extensive melioration program
437 (Höper et al. 2008). The decline of the water table to > 1 m below surface and subsequent
438 decomposition and mineralisation of the peat (especially in the upper 30 cm, Hahn-Schöfl et al. 2011)
439 caused phosphor fertilisation (Zak et al. 2008) and soil subsidence to levels below that of adjacent
440 freshwater bodies (Steffenhagen et al. 2012, Zerbe et al. 2013). The latter simplified the rewetting
441 process which was initiated in winter 2004/2005 by opening the dikes.

442 In consequence of flooding the drained fen was converted into a spatially heterogeneous site of
443 emergent vegetation (on temporarily inundated soil) and permanent open water areas. In this study
444 we focus on a eutrophic shallow-and polymictic lake (open water body about 7.5 ha) as part of the
445 rewetted area, with water depths ranging from 0.24 to 1.20-7 m (2004 to 2012; Zak et al. 2015). During
446 the study period the open water body of the lake was inhabited by submerged and floating
447 macrophytes, particularly *Ceratophyllum demersum*, *Lemna minor*, *Spirodela polyrhiza* (Steffenhagen
448 et al. 2012) and *Polygonum amphibium*, which rather corresponds to the sublittoral zone in a typical
449 lake zonation. *Ceratophyllum* and *Lemna* sp. were already reported to colonise the lake in the second
450 year of rewetting (Hahn-Schöfl et al. 2011). *Phalaris arundinacea*, that dominated the fen before
451 rewetting, died off in the first year of inundation (Hahn-Schöfl et al. 2011) and has been limited to the
452 non-inundated periphery of the ecosystem. Helophytes (e.g. *Glyceria*, *Typha*) started the colonisation
453 of lake margins and other temporarily inundated areas in the third year of rewetting. The eulittoral
454 zone of the lake is now dominated by *Typha latifolia* stands gradually colonising the open water in the
455 last years. Emergent vegetation stands also include sedges as *Carex gracilis* (Steffenhagen et al. 2012).
456 At the bottom of the shallow lake an up to 30 cm thick layer of organic sediment evolved, initially fed
457 by fresh plant material of the former vegetation and since then continuously replenished by recent
458 aquatic plants and helophytes after die-back (Hahn-Schöfl et al. 2011).

459 2.2 Eddy covariance and additional measurements

460 We conducted eddy covariance (EC) measurements of CO₂ and CH₄ exchange on a tower placed on a
461 stationary platform at the NE edge of the shallow lake (see Fig. 1). Thereby we ensured to frequently
462 catch the signal from both the open water body and the *Typha latifolia* dominated belt of the shallow
463 lake (eulittoral zone). We defined an area of interest (AOI) in order to focus on an ecosystem
464 dominated by a shallow lake and to avoid a possible impact of the farm and grassland to the north of
465 the shallow lake. The EC measurement setup included: an ultrasonic anemometer for the 3D wind
466 vector (u , v , w) and sonic temperature (HS-50, Gill, Lymington, Hampshire, UK), an enclosed-path
467 infrared gas analyser (IRGA) and an open-path IRGA for CO₂/H₂O and CH₄ concentrations, respectively
468 (LI-7200 and LI-7700, LI-COR Biogeosciences, Lincoln NE, USA). Flowrate was about 10-11 l min⁻¹.
469 Measurement height was on average 2.63 m above the water surface at the position of the tower,
470 depending on the water level. We recorded raw turbulence and concentration data with a LI-7550
471 digital data logger system (LI-COR Biogeosciences, Lincoln NE, USA) at 20 Hz in half-hourly files. The
472 dataset is shown in Coordinated Universal Time (UTC), which is 1 hour behind local time (LT).

473 We further equipped the tower with instrumentation for net radiation, air temperature/humidity, 2D
474 wind direction and speed, incoming and reflected photosynthetic photon flux density (PPFD/PPFD_r)
475 and water level. Additional measurements in close proximity to the tower included precipitation, soil
476 heat flux as well as soil and water temperature. Soil temperature was measured below the water
477 column in depths of 10 cm, 20 cm, 30 cm, 40 cm and 50 cm and water temperature at the sediment-
478 water-interface. All non-eddy covariance-related measurements were logged as 1 min averages/sums
479 (precipitation). Gaps were filled with measurements of the Leibniz Centre for Agricultural Landscape
480 Research (ZALF, Müncheberg, Germany) at the same platform and a nearby climate station (Climate
481 station Karlshof, GFZ German Research Centre for Geosciences, 14 km distance from study site, Itzerott
482 2015).

483 A water density gradient was calculated based on the temperature at the water surface and at the
484 sediment-water interface. The water surface temperature was calculated based on the Stefan-
485 Boltzmann law (see e.g. Foken et al. 2008):

$$486 \quad T_w = \sqrt[4]{\frac{I}{\varepsilon_w \sigma_{SB}}} \quad (1)$$

487

488 where T_w is the water surface temperature (K), I is the long-wave outgoing radiation (W m⁻²), ε_w is
489 the infrared emissivity of water (0.960) and σ_{SB} is the Stefan–Boltzmann constant (5.67·10⁻⁸ W m⁻² K⁻⁴).
490 We calculated the density of the air-saturated water at the water surface and the sediment-water
491 interface according to Bignell (1983):

492 $\rho_{as} = \rho_{af} - 0.004612 + 0.000106 * T$ (2)

493 where ρ_{as} is the density of the respective air-saturated water (kg m^{-3}), ρ_{af} is the density of the
494 respective air-free water (kg m^{-3} ; see Wagner and Pruß 2002) at atmospheric pressure (1013 hPa) and
495 T is the respective water temperature ($^{\circ}\text{C}$). The gradient of the two water densities (air-saturated)
496 $\Delta\rho/\Delta z$ was calculated as difference of the water density (air-saturated) at the sediment-water
497 interface and the surface water density (air-saturated), divided by the distance (m) between the two
498 basic temperature measurements. Changes of the distance due to the fluctuating water level were
499 considered. Positive and negative gradients indicate periods of stratification and thermally induced
500 convective mixing of the water column, respectively.

501 **2.3 Flux computation and further processing**

502 For this analysis we used data from 14 May 2013 to 14 May 2014. We calculated half-hourly fluxes of
503 CO_2 and CH_4 based on the covariances between the respective scalar concentration and the vertical
504 wind velocity using the processing package EddyPro 5.2.0 (LI-COR, Lincoln, Nebraska, USA). Sonic
505 temperature was corrected for humidity effects according to van Dijk et al. (2004). Artificial data spikes
506 were removed from the 20 Hz data following Vickers and Mahrt (1997). We used the planar fit method
507 (Finnigan et al. 2003, Wilczak et al. 2001) for axis rotation and defined the sector borders according to
508 Siebicke et al. (2012). Block averaging was used to detrend turbulent fluctuations. For time lag
509 compensation we applied covariance maximization (Fan et al. 1990). Spectral losses due to crosswind
510 and vertical instrument separation were corrected according to Horst and Lenschow (2009). The
511 methods of Moncrieff et al. (2004) and Fratini et al. (2012) were used for the correction of high-pass
512 filtering and low-pass filtering effects, respectively. For fluctuations of CH_4 density we corrected
513 changes in air density according to Webb et al. (1980), considering LI-7700-specific spectroscopic
514 effects (McDermitt et al. 2011). According to the micrometeorological sign convention, positive values
515 represent fluxes from the ecosystem into the atmosphere (emission) and negative values fluxes from
516 the atmosphere into the ecosystem (ecosystem uptake).

517 **2.4 Quality assurance**

518 We filtered the averaged fluxes according to their quality as follows (see Table 1, [for final measurement](#)
519 [data coverage see Fig. A1](#)):

- 520 - We rejected fluxes with quality flag 2 (QC 2, bad quality) based on the 0-1-2 system of Mauder
521 and Foken (2004).

- 522 - CH₄ fluxes were skipped if the signal strength (RSSI) was below the threshold of 14 %. This
523 threshold was estimated according to Dengel et al. (2011).
- 524 - Fluxes with friction velocity (u^*) < 0.12 m s⁻¹ and > 0.76 m s⁻¹ were not included due to
525 considerably high fluxes beyond these thresholds, which were estimated similar to the
526 procedure described in Aubinet et al. (2012) based on binned u^* classes. The storage term was
527 calculated as described in Béziat et al. (2009).
- 528 - Unreasonably high positive and negative fluxes (0.2 %/99.8 % percentile) were discarded from
529 the CO₂ and CH₄ flux dataset.

530 Quality control (apart from EddyPro internal steps) and the subsequent processing steps were
531 performed with the free software environment R (R Core Team 2012).

532 **2.5 Footprint modelling**

533 We applied footprint analysis to determine the source area including the fractions of the surface types
534 of each quality-controlled half-hourly flux using a footprint calculation procedure following Göckede
535 et al. (2004). The source area functions were calculated based on the analytical footprint model of
536 Kormann and Meixner (2001). Roughness length and vegetation height were estimated with an
537 iterative algorithm (see also Barcza et al. 2009). Based on an aerial image (GoogleEarth,
538 <http://earth.google.com/>) the surface of our study site was classified into two main types and
539 implemented in a land cover grid: “open water” including in particular the open water_body of the
540 shallow lake ~~with 0.1 to 0.7 m water depth~~ and “emergent vegetation” with a height up to 2 m and
541 including the eulittoral zone of the shallow lake dominated by *Typha latifolia*. The cumulative annual
542 footprint climatology was calculated following Chen et al. (2011). Fluxes were excluded where
543 footprint information was not available or more than 20 % of the source area was outside the AOI (see
544 Fig. 1 and Table 1). The fractional coverage within the AOI (A_i) was 21.7 % for open water.

545 Quasi-continuous source area information for the two surface types were achieved by gapfilling the
546 results of the footprint model with the means of the source area fractions of the surface types (Ω_i) for
547 1°-wind direction-intervals, separately for stable and unstable conditions. In case the sum of the Ω_i was
548 less than 100 %, when the source area exceeded the set borders, we assigned the remaining
549 contribution percentages to emergent vegetation, as the area beyond the borders is dominated by
550 emergent vegetation rather than open water.

551 2.6 Gapfilling

552 ~~A Marginal Distribution Sampling (MDS)~~~~An enhanced lookup table (LUT)~~ approach proposed by
553 Reichstein et al. (2005), available as web tool based on the R package REddyProc ([http://www.bgc-](http://www.bgc-jena.mpg.de/REddyProc/brew/REddyProc.rhtml)
554 [jena.mpg.de/REddyProc/brew/REddyProc.rhtml](http://www.bgc-jena.mpg.de/REddyProc/brew/REddyProc.rhtml)), was applied for gapfilling and partitioning of NEE
555 measurements (~~MDSLUT~~_{CO2nofoot}), with air temperature as temperature variable. For the gapfilling of
556 CH₄ measurements non-linear regression (NLR) was applied (NLR_{CH4nofoot}):

$$557 F_{CH_4} = \exp(a + b_1 \cdot X_1 + \dots + b_j \cdot X_j) \quad (3)$$

558 where a and $b_1 \dots b_j$ are fitting parameters and $X_1 \dots X_j$ are environmental parameters. Several
559 environmental parameters, which were reported to be correlated with CH₄ flux on different time
560 scales, were tested to find the best bi- or multivariate NLR model for the ecosystem CH₄ flux: pressure
561 change, u^* , PAR, air temperature, soil heat flux, soil/peat temperature in different heights and
562 waterlevel. Only fluxes of the best quality (QC 0) were used to fit the NLR model and the ~~MDSLUT~~.

563 2.7 Calculation of the annual CO₂ and CH₄ budget and the global warming 564 potential (GWP)

565 We used the continuous flux datasets derived from gapfilling for the calculation of annual CO₂ and CH₄
566 budgets. The ecosystem GHG balance was calculated by summation of the net ecosystem exchange of
567 CO₂ and CH₄ using the global warming potential (GWP) of each gas at the 100-year time horizon (IPCC,
568 2013). According to the IPCC AR5 (IPCC, 2013) CH₄ has a 28-fold global warming potential compared
569 to CO₂ (without inclusion of climate-carbon feedbacks).

570 The uncertainty of the annual estimates was calculated as the square root of the sum of the squared
571 random error (measurement uncertainty) and gapfilling error within the one-year observation period
572 (see e.g. Hommeltenberg et al. 2014, Shoemaker et al. 2015). An estimation of the random uncertainty
573 due to the stochastic nature of turbulent sampling according to Finkelstein and Sims (2001) is
574 implemented in EddyPro 5.2.0. In case of the ~~MDSLUT~~ approach the gapfilling error (standard error)
575 was calculated from the standard deviation of the fluxes used for gapfilling, provided by the web tool.
576 For budgets based on the NLR approach we used the residual standard error of the NLR model as
577 gapfilling error (following Shoemaker et al. 2001).

578 2.8 Estimation of surface type fluxes

579 To estimate the specific surface type fluxes, we combined footprint analysis with NEE partitioning
580 (using NLR) to assign gross primary production (GPP) and ecosystem respiration (R_{eco}) to the two main
581 surface types (NLR_{CO2foot}). R_{eco} and GPP were modelled as sum of the two surface type fluxes weighted

582 by Ω_i (analogous to Forbrich et al. 2011). Night-time R_{eco} (global radiation $< 10 \text{ W m}^{-2}$) was estimated
 583 by the exponential temperature response model of Lloyd and Taylor (1994) assuming that night-time
 584 NEE represents the night-time R_{eco} :

$$585 \quad R_{eco} = \sum_{i=1}^2 \Omega_i \cdot (R_{ref_i} \cdot \exp(E_{0_i} (\frac{1}{T_{ref}-T_0} - \frac{1}{T_{air}-T_0}))) \quad (4)$$

586 where R_{eco} is the half-hourly measured ecosystem respiration ($\mu\text{mol}^{-1}\text{m}^{-2}\text{s}^{-1}$), Ω_i is the source area
 587 fraction of the respective surface type, R_{ref} is the respiration rate at the reference temperature T_{ref}
 588 (283.15 K), E_0 defines the temperature sensitivity, T_0 is the starting temperature constant (227.13 K)
 589 and T_{air} the mean air temperature during the flux measurement. The model parameters achieved for
 590 night-time R_{eco} were applied for the modelling of day-time R_{eco} . GPP was calculated by subtracting day-
 591 time R_{eco} from the measured NEE. GPP was further modelled using a rectangular, hyperbolic light
 592 response equation based on the Michaelis–Menten kinetic (see e.g. Falge et al. 2001):

$$593 \quad GPP = \sum_{i=1}^2 \Omega_i \cdot \left(\frac{GP_{max_i} \cdot \alpha_i \cdot PAR}{\alpha_i \cdot PAR + GP_{max_i}} \right) \quad (5)$$

594 where GPP is the calculated gross primary production ($\mu\text{mol}^{-1}\text{m}^{-2}\text{s}^{-1}$), Ω_i is the source area fraction
 595 of the respective surface type, GP_{max} is the maximum C fixation rate at infinite photon flux density of
 596 the photosynthetic active radiation PAR ($\mu\text{mol}^{-1}\text{m}^{-2}\text{s}^{-1}$), α is the light use efficiency ($\text{mol CO}_2 \text{ mol}^{-1}$
 597 photons). We calculated one parameter set for R_{eco} and GPP per day based on a moving window of 28
 598 days (method [NLR_{nofoot}](#)). In order to avoid over-parameterization we introduced fixed values of 150 for
 599 E_0 and -0.03 and -0.01 for α of emergent vegetation and water bodies, respectively, to get reasonable
 600 parameter values for R_{ref} and GP_{max} . We excluded parameter sets for R_{eco} or GPP, if one of the two R_{ref}
 601 and GP_{max} parameter values was insignificant ($p\text{-value} \geq 0.05$), negative or zero. In addition, the 1 %/99
 602 % percentiles of GP_{max} were excluded. These gaps within the parameter set were filled by linear
 603 interpolation. Gaps remained in R_{eco} and GPP time series due to gaps in the environmental variables.
 604 Gaps up to 3 hours length were filled by linear interpolation. Larger gaps were filled with the mean of
 605 the flux during the same time of the day before and after the gap. Due to the moving window approach,
 606 we could not estimate model parameters for the first and last 14 days of our study period. Instead, we
 607 applied the first and last estimated parameter set, respectively. Modelled GPP and R_{eco} were summed
 608 up to half-hourly NEE fluxes and used for alternative NEE gapfilling ([NLR_{CO2foot}](#)).

609 As for NEE we expect different CH_4 emission rates of the two surface types. Thus, we extended the NLR
 610 model ([NLR_{CH4nofoot}](#)) in a way that the CH_4 flux is the sum of the two surface type fluxes weighted by Ω_i
 611 ([NLR_{CH4foot}](#)):

$$612 \quad F_{CH_4} = \sum_{i=1}^2 \Omega_i \cdot \exp(a_i + b_{1i} \cdot X_1 + \dots + b_{ji} \cdot X_j) \quad (6)$$

613

614 where Ω_1 is the source area fraction of the respective surface type. Considering the principle of
615 parsimony, we combined up to three parameters besides the contribution of the surface types.
616 Remaining gaps were filled by interpolation. Surface type CO₂ and CH₄ fluxes were derived based on
617 the fitted NLR parameters.

618 We calculated the annual budgets of CO₂ and CH₄ for the EC source area, the surface types (assuming
619 source area fraction of 100 % for the respective surface type) and the AOI, the latter following Forbrich
620 et al. (2011) by applying Eq. 4 and Eq. 5 for CO₂ as well as Eq. 6 for CH₄ with the fitted parameters, but
621 A_i instead of Ω_i as weighting surface type contribution. The gapfilling error for the NLR_{CO₂foot} model was
622 based on the residual standard error of both R_{eco} and GPP.

623

624 **3 Results**

625 **3.1 Environmental conditions and fluxes of CO₂ and CH₄**

626 Mean annual air temperature and annual precipitation for the study period were 10.1 °C and 416.5
627 mm, respectively, indicating an unusual dry and warm measurement period compared to the long-
628 term average. The summer 2013 was among the 10 warmest since the beginning of the measurements
629 in 1881 (German Weather Service DWD). From June to August monthly averaged air temperature was
630 0.2 up to 0.9 °C higher and precipitation was 9.1 up to 38.1 mm less than the long-term averages. The
631 open water area of the shallow lake was densely vegetated with submerged and floating macrophytes.
632 A summertime algae slick accumulated in the NE part of the shallow lake. Winter 2013/2014 was
633 characterised by exceptionally mild temperatures and very sparse precipitation. However, a short cold
634 period (see Fig. 2) resulted in ice cover on the shallow lake between 21 January and 16 February 2014.
635 The water level of the shallow lake fluctuated between 0.36 and 0.77 m (at the position of the sensor)
636 and had its minimum at the end of August/beginning of September and its maximum in January. We
637 observed the exposure of normally inundated soil surface at emergent vegetation stands during the
638 dry period in summer 2013.

639 Both CO₂ and CH₄ flux measurement time series showed a clear seasonal trend with a median CO₂ flux
640 of 0.57 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and a median CH₄ flux of 0.02 $\mu\text{mol m}^{-2} \text{s}^{-1}$. CH₄ emissions peaked in mid-August
641 2013 with 0.57 $\mu\text{mol m}^{-2} \text{s}^{-1}$. The highest net CO₂ uptake (-15.34 $\mu\text{mol m}^{-2} \text{s}^{-1}$) and release (21.04 μmol
642 $\text{m}^{-2} \text{s}^{-1}$) were both observed in June 2013. To investigate the potential presence of a diurnal cycle of
643 CO₂ and CH₄ fluxes throughout the study period we normalised the mean half-hourly CO₂ and CH₄
644 fluxes per month with the respective minimum/ maximum and median of the half-hourly fluxes of the
645 specific month (modified from Rinne et al. 2007). A pronounced diurnal cycle of CO₂ fluxes with peak
646 uptake around midday and peak release around midnight was obvious until November 2013 and

647 beginning in March 2014 (see Fig. 3), although less pronounced in these two months. We found a clear
648 diurnal cycle of CH₄ fluxes from June to September 2013 and in March 2014 (April 2014 based on 3
649 days only and May 2014 not available as the sensor was dismantled) with daily peaks during night-time
650 (around midnight until early morning). A diurnal cycle of CO₂ fluxes with peak uptake around midday
651 and peak release around midnight was obvious until November 2013 and beginning in March 2014
652 (see Fig. 3). To investigate the potential presence of a diurnal cycle of CH₄ fluxes we normalized the
653 mean half-hourly CH₄ fluxes per month with the respective median of the half-hourly fluxes of the
654 specific month (minimum five 30-min fluxes per day; method modified from Rinne et al. 2007). We
655 found a clear diurnal cycle of CH₄ fluxes from June to September 2013 and starting again in March 2014
656 (April and May not shown as the sensor was dismantled) with daily peaks during night time (around
657 midnight until early morning). The water density gradient indicates thermally induced convective
658 mixing of the whole water column during the night (around midnight until early morning) at the same
659 time of the day from May until October 2013 and from February to May 2014. In May 2014 the diurnal
660 pattern of the water density gradient was less pronounced than in May 2013.

661 **3.2 Gapfilling performance and annual budgeting of CO₂, CH₄, C and GWP**

662 The MDSLUT_{CO2nofoot} approach explained 74 % of the variance in NEE (see Table 2). Median NEE
663 accounted for 1.9 g CO₂ m⁻² d⁻¹. The annual budget of gapfilled NEE (MDSLUT_{CO2nofoot}) between 14 May
664 2013 and 14 May 2014 was 524.5 ± 5.6 g CO₂ m⁻² (see Table 3), characterising the site as strong CO₂
665 source with moderate rates of R_{eco} and GPP. We found a surprising CO₂ release strength during summer
666 2013, where already at the end of June daily R_{eco} often exceeded GPP. The highest daily CO₂ emission
667 and uptake rates of 24.8 g CO₂ m⁻² d⁻¹ and -27.9 g CO₂ m⁻² d⁻¹ were both observed-revealed in the
668 beginning of July 2013 (see Fig. 2). July 2013 accounted for 23.2 % and 25.8 % of the annual R_{eco} and
669 GPP, respectively. In addition, net CO₂ release outside the growing season (definition of the growing
670 season following Lund et al. 2010; until 19 November 2013 and starting 26 February 2014) was 203.7
671 g CO₂ m⁻² with a median of 2.2 g CO₂ m⁻² d⁻¹.

672 The environmental variable giving the best NLR model for CH₄ was soil temperature in 10 cm depth
673 (T_{s10}):

$$674 F_{CH_4} = \exp(-7.224 + 0.313 \cdot T_{s10}) \quad (7)$$

675 The model described 79 % of the variance in CH₄ flux (see Table 2). Including additional environmental
676 variables to the regression function did not increase the model performance significantly. Cumulative
677 CH₄ emissions were 40.5 ± 0.2 g CH₄ m⁻² a⁻¹ (see Table 3). Median CH₄ emissions were 41.9 mg m⁻² d⁻¹,
678 peaked at the end of July 2013 with 0.6415 g CH₄ m⁻² d⁻¹ and were at the minimum in January 2014
679 (see Fig. 2). The month with the highest proportion of annual CH₄ emissions was August 2013 (27.3 %).

680 Non-growing season CH₄ fluxes only accounted for a small proportion within the annual budget, about
681 0.8 g CH₄ m⁻².

682 The site was an effective C and GHG source, accounting for 173.4 ± 1.7 g C m⁻² a⁻¹ and 1658.5 ± 11.2 g
683 CO₂-Eq. m⁻² a⁻¹ for the EC source area (see Fig. 4). The proportion of CO₂ in the C and GWP budget was
684 82.5 % and 31.6 %, respectively. Components of the annual net C balance other than CO₂ and CH₄
685 fluxes, e.g. dissolved C, are not considered in this study. Our uncertainty estimates are within the range
686 of similar studies (e.g. Shoemaker et al. 2015).

687 **3.3 Source area composition and spatial heterogeneity of CO₂ and CH₄** 688 **exchange**

689 Footprint analysis revealed the peak contribution in an average distance of 18 m from the tower and
690 mainly from the open water area of the shallow lake (see Fig. 5). Open water covered on average 62.5
691 % of the EC source area. The two surface types showed different emission rates in terms of higher CH₄
692 fluxes and lower NEE rates with increasing Ω_{water} (see Fig. 6). Within the NLR_{CO₂foot} approach both
693 surface types were denoted as sources of CO₂, but with about 4-fold stronger rates of GPP, R_{eco} and
694 NEE for emergent vegetation compared to open water (see Fig. 7 and Table 3). The approach yielded
695 a similar cumulative annual NEE for the whole EC source area including both surface types as the
696 ~~LUFMDS~~_{CO₂nofoot} approach, but lower component fluxes (GPP and R_{eco}). As for CO₂, we implemented Ω_i
697 as weighting factors within the NLR model for CH₄ (NLR_{CH₄foot}) to get the surface type specific fluxes of
698 CH₄ and fitted the parameters as follows:

$$699 F_{CH_4} = \Omega_{veg} \cdot \exp(-10.076 + 0.415 \cdot T_{s10}) + \Omega_{water} \cdot \exp(-6.449 + 0.286 \cdot T_{s10}) \quad (8)$$

700 Open water accounted for more than 4-fold higher emissions than the vegetated areas (see Fig. 7 and
701 Table 3). The NLR_{CH₄foot} approach revealed a similar annual CH₄ budget as the NLR_{CH₄nofoot} approach.

702 Annual budgets of CO₂ (844 g CO₂ m⁻² a⁻¹) and CH₄ (22 g CH₄ m⁻² a⁻¹) for the AOI differed strongly from
703 the budgets for the EC source area due to the contrasting emission rates of open water and emergent
704 vegetation (see Table 3) and different fractional coverages of the surface types within the AOI and the
705 EC source area. This resulted in a higher C loss (246.5 g C m⁻² a⁻¹) and a lower GWP (1452.9 g CO₂-Eq.
706 m⁻² a⁻¹) for the AOI than for the EC source area. In the following we will primarily discuss the budgets
707 of the EC source area and the surface types.

708

709 4 Discussion

710 4.1 Diurnal variability of CH₄ emissions

711 In terms of its daily cycle, CH₄ exchange between wetland ecosystems and the atmosphere is not
712 generalisable, but rather dependent on the spatial characteristics of the wetland and thus, the impact
713 of the individual CH₄ emission pathways (diffusion, ebullition, plant-mediated transport). Our
714 measurements showed a diurnal cycle of CH₄ exchange from June to September 2013 and in March
715 2014, with the strongest emissions during night, as reported for shallow lakes (e.g. Podgrajsek et al.
716 2014) and wetland sites with a considerable fraction of open water (e.g. Godwin et al. 2013, ~~Koebisch~~
717 ~~et al. 2015~~). In comparison, wetland CH₄ emissions were also reported to show daily maxima at day-
718 time (e.g. Morrisey et al. 1993, Hendriks et al. 2010, Hatala Matthes et al. 2014), especially at sites with
719 high abundance of vascular plants. No diurnal pattern (e.g. Rinne et al. 2007, Forbrich et al. 2011,
720 Herbst et al. 2011) occurred especially at sites without large open water areas (Godwin et al. 2013).

721 We assume the process of convective mixing of the water column (e.g. Godwin et al. 2013, Poindexter
722 and Variano 2013, Podgrajsek et al. 2014, Sahlée et al. 2014, Koebisch et al. 2015) to be crucial for the
723 diurnal pattern of CH₄ emissions at our study site. This is indicated by the concurrent timing of
724 convective mixing and daily peak CH₄ emissions and a generally high fractional source area coverage
725 of the open water, which shows higher rates of CH₄ release than emergent vegetation. Furthermore,
726 closed chamber measurements likewise show night-time peak emissions on the shallow lake in
727 summer 2013 (Hoffmann et al. 2015). During the day, CH₄ is trapped in the lower (anoxic) layers of the
728 thermally stratified water column. Due to the heat release of the surface water to the atmosphere in
729 the night the surface water cools down, initiating convective mixing of the water column down to the
730 bottom. Diffusion is enhanced due to the buoyancy-induced turbulence, the associated increased gas
731 transfer velocity at the air-water interface (Eugster et al. 2003, MacIntyre et al. 2010, Podgrajsek et al.
732 2014) as well as the transport of CH₄ enriched bottom water to the surface (Godwin et al. 2013,
733 Podgrajsek et al. 2014). In addition, ebullition can be triggered by turbulence due to convective mixing
734 (~~Podgrajsek et al. 2014, Read et al. 2012). The daily pattern of the open water CH₄ release might~~
735 ~~superimpose the reverse diurnal cycle of plant-mediated transport with peak emissions during day-~~
736 ~~time, as the release of methane is dependent on the stomatal conductance of the plants (e.g. Morrisey~~
737 ~~et al. 1993). Apart from convective mixing, highest sediment and soil temperature in the night until~~
738 ~~early morning might play an important role for the peak emissions of CH₄ due to increased microbial~~
739 ~~activity. Furthermore, diurnal variability in CH₄ oxidation could contribute to the daily pattern of CH₄~~
740 ~~release. Oxygen is supplied to the water, sediment and soil during the day in consequence of~~
741 ~~photosynthesis and increases CH₄ oxidation. However, convective mixing of the water column during~~
742 ~~the night might supply oxygen to deeper water depths potentially increasing CH₄ oxidation. We assume~~

743 plant-mediated transport to be characterised by a reverse diurnal cycle with peak emissions during
744 day-time, as the release of methane is dependent on the stomatal conductance of the plants (e.g.
745 Morrisey et al. 1993). This pathway is limited to plants with aerenchymatic tissue like *Typha latifolia*,
746 which dominates the eulittoral zone at our study site. CH₄ is transported from the soil to the
747 atmosphere, bypassing potential oxidation zones above the rhizosphere (chimney effect). Unusually
748 for wetland plants (Torn and Chapin 1993), complete stomatal closure during night was observed for
749 *Typha latifolia* (Chanton et al. 1993). However, this temporal constraint seems to be superimposed by
750 more efficient CH₄ pathways during the night and early morning.

751 Apart from CH₄, thermally induced convection potentially contributes also to the diurnal fluctuation of
752 the CO₂ flux at our study site. According to Eugster et al. (2003) penetrative convection might be the
753 dominant mechanism yielding CO₂ fluxes during periods of low wind speed, especially in case of a
754 stratification of CO₂ concentrations in the water body. Ebullition triggered by convective mixing might
755 be less important for CO₂ than for CH₄, as concentrations of CO₂ are most often low in gas bubbles (e.g.
756 Casper et al. 2000, Poissant et al. 2007, Repo et al. 2007, Sepulveda-Jauregui et al. 2015, Spawn et al.
757 2015). Further investigations should focus on the controls of the diurnal patterns in CO₂ and CH₄
758 exchange based on additional measurements, e.g. gas concentrations in the water, methane oxidation
759 or plant-mediated transport.

760 **4.2 Annual CH₄ emissions**

761 The CH₄ emissions of our studied ecosystem were within the range of other temperate fen sites
762 rewetted for several years (up to 63 g CH₄ m⁻² a⁻¹; e.g. Hendriks et al. 2007, Wilson et al. 2008, Günther
763 et al. 2013, Schrier-Uijl et al. 2014). This rate corresponds to twice the emission factor of 21.6 g CH₄ m⁻²
764 a⁻¹, that was assigned to rewetted temperate rich organic soils, which is in turn more than twice the
765 rate of the nutrient-poor complement (IPCC 2014). This rate is remarkably higher than the emission
766 factor of 28.8 g CH₄ m⁻² a⁻¹ that was assigned to rewetted temperate rich organic soils, which is in turn
767 more than twice the rate of the nutrient-poor complement (IPCC 2014). In contrast, newly rewetted
768 fens emit its multiple. In the first year after flooding, Hahn et al. (2015) observed at a fen site in NE
769 Germany an average net release of 260 g CH₄ m⁻² a⁻¹, which is 186 times higher than before flooding,
770 at a fen site in NE Germany. Two years later the CH₄ emissions were significantly lower (40 g CH₄ m⁻²
771 per within the growing season; Koebisch et al. 2015). However, natural fens release most often less CH₄
772 than the majority of rewetted fens (e.g. Bubier et al. 1993, Nilsson et al. 2001), with some exceptions
773 (e.g. Huttunen et al. 2003). However, natural (e.g. Bubier et al. 1993, Nilsson et al. 2001) and degraded
774 fens (Hatala et al. 2012, Schrier-Uijl et al. 2014, see also IPCC 2014) release most often less CH₄ than
775 the majority of rewetted fens, with some exceptions (e.g. Huttunen et al. 2003).

776 The two main surface types open water and emergent vegetation differed substantially in their CH₄
777 exchange rates. Open water contributed overproportionally to the measured ecosystem fluxes and
778 showed remarkably higher CH₄ release rates (52.6 g CH₄ m⁻² a⁻¹) than the emergent vegetation stands
779 (13.2 g CH₄ m⁻² a⁻¹). However, closed-chamber measurements at the shallow lake show an even higher
780 long-term average annual CH₄ release rate (206 g CH₄ m⁻² a⁻¹) since rewetting with large interannual
781 variability and occasionally extreme high release rates (up to 400 g CH₄ m⁻² a⁻¹; Casares et al., in prep.).

782 We assume the permanent high inundation and high productivity due to eutrophic conditions, feeding
783 the organic mud deposited at the bottom of the open water body (which is typically for shallow lakes
784 in rewetted fens), to be of particular importance for high CH₄ emissions as substrate for
785 decomposition. The mud initially evolved as a mixture of sand and easily decomposable labile plant
786 litter from reed canary grass, which died-off after flooding and produced a large C pool for CH₄
787 production (Hahn-Schöfl et al 2011). During an incubation experiment with substrate from our study
788 site Hahn-Schöfl et al. (2011) observed that the new sediment layer has very high specific rates of
789 anaerobic CH₄ (and CO₂) production. In addition, Zak et al. (2015) emphasised the impact of litter
790 quality and reported a very high CH₄ production potential for litter of *Ceratophyllum demersum*, which
791 dominates the biomass in the open water at our study site. Due to the eutrophic character of the lake
792 and associated high productivity within the open water body and in the eulittoral zone, high amounts
793 of fresh labile organic matter continuously replenish the mud layer and thus the C pool. ~~As the C~~
794 ~~balance (CO₂ and CH₄) seems to be extremely unbalanced, we~~ Especially in case of strong winds we
795 further assume a lateral input of allochthonous organic matter into the NE "bay" of the shallow lake,
796 which is the area with the peak contribution of our EC derived fluxes, and thus an additional refill of
797 the C pool especially during strong winds. The importance of fresh labile organic matter provided by
798 the die-back of the former vegetation as driving force for high CH₄ emissions was also discussed in
799 Hahn et al. (2015). They measured the highest CH₄ emissions in sedge stands suffering from strongest
800 die-back.

801 For comparison annual budgets of CH₄-CO₂ and CH₄-CO₂ for other nutrient-rich lentic freshwater
802 ecosystems ~~in terms of~~ (pristine, anthropogenically influenced and transient ecosystems) are listed in
803 Table 4. Studies on nutrient-rich lakes generally revealed lower CH₄ release for open water. In contrast,
804 beaver ponds were partially reported to emit similar-comparable rates of CH₄. Similarly to our study
805 site beaver ponds are at least in the beginning disbalanced ecosystems due to a rapidly increased water
806 level with associated suffering and finally the die-back of former vegetation, which is not adapted to
807 higher water levels. A large C pool for CH₄ production develops. However, even for a beaver pond
808 existing more than 30 years CH₄ emissions still accounted ed for 40 g CH₄ m⁻² a⁻¹ (Yavitt et al. 1992).

809 ~~Annual~~The lower CH₄ emissions of the surface type emergent vegetation ~~were about 4-fold lower than~~
810 ~~for open water. This~~ might be the result of increased CH₄ oxidation in the soil, as plants with
811 aerenchymatic tissue release oxygen into the rhizosphere, in reverse to the emission of CH₄ into the
812 atmosphere (Bhullar et al. 2013). Minke et al. (2015) highlight the difference in net CH₄ release for
813 typical helophyte stands with moderate emissions for *Typha* dominated sites. Besides the effect of the
814 gas transport within plants, lower water and sediment temperatures due to shading by the emergent
815 vegetation might yield lower CH₄ production than for open water. Furthermore, the soil of emergent
816 vegetation stands is generally only temporarily and partly inundated and the water table decreased
817 additionally during the unusual warm and dry summer 2013, probably resulting in a lower rate of
818 anaerobic decomposition to CH₄ and a higher rate of CH₄ oxidation in the aerated top soil. This in turn
819 might be a reason, that in comparison to other sites dominated by *Typha* (rewetted wetlands, lake
820 shores and freshwater marshes; see Table 4) the emergent vegetation at our site is at the lower limit
821 of reported CH₄ release rates and best comparable to closed chamber measurements of *Typha latifolia*
822 microsites at another rewetted fen site in NE Germany (Günther et al. 2015).

823 **4.3 Annual net CO₂ release**

824 We observed high annual net release of CO₂ during the observation period, which is rather uncommon
825 for fens several years after rewetting (e.g. Hendriks et al. 2007, Schrier-Uijl et al. 2014, Knox et al.
826 2015). Surprisingly, the net CO₂ budgets were was higher or similar to those of drained and degraded
827 peatlands (e.g. Hatala et al. 2012, Schrier-Uijl et al. 2014, but IPCC 2014). Both surface types acted as
828 net sources, with emergent vegetation (750 g CO₂ m⁻² a⁻¹) showing a distinctively higher net budget
829 (158 g CO₂ m⁻² a⁻¹) as well as GPP and R_{eco} rates than open water ~~(158 g CO₂ m⁻² a⁻¹)~~. Only few NEE
830 rates are published for the open water body of eutrophic shallow lakes. Ducharme-Riel et al. (2015)
831 report 224 g CO₂ m⁻² a⁻¹ as annual NEE of a eutrophic lake in Canada (see Table 4). According to
832 Kortelainen et al. (2006) Finnish lakes, which are mainly small and shallow, continuously emit CO₂
833 during the ice-free period, positively correlated with their trophic state.

834 Our study revealed a high annual net CO₂ release for emergent vegetation, which is in the wide range
835 of NEE rates for *Typha* sites reported in other studies, including both net CO₂ sources and sinks (see
836 Table 5). GPP and R_{eco} are generally high (especially at rewetted fen sites; both component fluxes most
837 often > 3000 g CO₂ m⁻² a⁻¹), characterising *Typha* stands as high turnover sites, usually resulting in net
838 CO₂ uptake. In contrast, R_{eco} and GPP rates at our study site are in the lower part of the reported range.
839 We assume the continuously high R_{eco} rates during winter 2013/2014, contributing to the high annual
840 net CO₂ emissions, to be the result of mild and dry meteorological conditions. In summer 2013, R_{eco}
841 exceeded GPP already in late June, indicating a significant contribution of heterotrophic respiration to
842 the CO₂ production. However, Unusual warm and dry conditions and associated water table lowering

843 during summer 2013 might have triggered a shift from anaerobic to aerobic decomposition due to the
844 exposure of formerly only shallowly inundated soil and organic mud, primarily in the emergent
845 vegetation stands. We could not observe a considerable decrease of the spatial extent of the open
846 water body as emergent vegetation mainly covers the shallower edges of the water body. unusual
847 warm and dry conditions and associated water table lowering during summer 2013 might have
848 triggered a shift from anaerobic to aerobic decomposition. This includes the exposed organic mud at
849 former shallowly inundated soil of emergent vegetation stands, e.g. at the edge of the lake. Besides
850 CH₄, Hahn-Schöfl et al. (2011) showed that the new sediment layer at the bottom of inundated areas
851 exhibits very high rates of anaerobic CO₂ production. The effect of water table lowering at *Typha* sites
852 due to dry conditions is also shown by Günther et al. (2015) and Chu et al. (2015): relative increase of
853 R_{eco} rates, resulting in net CO₂ release. This might be of special interest in terms of climate change, as
854 a temperature increase and significantly less precipitation in summer are expected for NE Germany
855 and meteorological conditions are more frequently characterised as “unusually” warm and dry. In
856 addition, a considerable increase of microbial activity and thus, generally increased decomposition due
857 to high temperatures might be of importance. Besides CH₄, Hahn-Schöfl et al. (2011) showed that the
858 new sediment layer at the bottom of inundated areas exhibits very high rates of anaerobic CO₂
859 production. Allochthonous organic matter import into the NE bay due to lateral transport, as discussed
860 for CH₄, might have further enhanced decomposition (e.g. Chu et al. 2015). Longer data gaps in summer
861 2013 (see Fig. A1) increase the uncertainty of our annual CO₂ budget. However, the observed shift to
862 net CO₂ release starting in late June 2013 as well as its continuation later on are substantially based on
863 measurements.

864 **4.4 Global warming potential and the impact of spatial heterogeneity**

865 The lake ecosystem is characterised by a high-GWPstrong climate impact 9 years after rewetting,
866 mainly driven by high CH₄ emissions. Based on our results the site can hardly be classified into any
867 rewetting phase following of the peatland rewetting concept discussed by Augustin and Joosten
868 (2007). Our results imply a delayed shift of the ecosystem towards a C sink with reduced climate
869 impact, which might be the result of the exceptional characteristics represented by eutrophic
870 conditions and lateral transport of organic matter within the open water body. The slow development
871 and shift of the ecosystem to a C sink with reduced climate impact might be the result of the
872 exceptional characteristics represented by eutrophic conditions and lateral transport of organic matter
873 within the open water body. The trophic status of water and sediment is an important factor regulating
874 GHG emissions, as shown by Schrier-Uijl et al. (2011) for lakes and drainage ditches in wetlands.
875 However, the unusual meteorological conditions during our study period might have caused a differing
876 (lower or higher) GWP compared to previous years. CH₄ emissions might have been lower at the

877 expense of high net CO₂ release, whereas under usual meteorological conditions e.g. CO₂ uptake could
878 probably compensate the CH₄ emissions. Inundation is often associated with high CH₄ emission. Thus,
879 during rewetting the water table is generally recommended to be held at or just below the soil surface
880 to prevent inundation and the formation of organic mud (Couwenberg et al. 2011, Joosten et al. 2012,
881 Zak et al. 2015).

882 In contrast to CH₄, the influence of water level on net CO₂ release is not nearly consistent in the few
883 existing studies of rewetted peatlands. In comparison to our site Knox et al. (2015) reported high net
884 CO₂ uptake to substantially compensate high CH₄ emissions for a site with mean water levels above
885 the soil surface after several years of rewetting (see Table 5). Similarly, Schrier-Uijl et al. (2014)
886 reported high CO₂ uptake rates for a Dutch fen site 7 years after rewetting and even C uptake and a
887 GHG sink function after 10 years with water levels below or at the soil surface. Herbst et al. (2011)
888 present a snapshot of the GHG emissions of a Danish site after 5 years of rewetting with permanently
889 and seasonally wet areas, whereby high CO₂ uptake and moderate CH₄ emissions lead to substantial
890 GHG savings. In contrast, weak CO₂ uptake and decreasing, but still high CH₄ emissions were reported
891 for another fen site in NE Germany with mean water levels above the soil surface (Koebsch et al. 2013,
892 2015 and Hahn et al. 2015), resulting in a decreasing climate impact after 3 years of rewetting.
893 Interestingly, changes of NEE due to flooding were negligible, although GPP and R_{eco} rates decreased
894 considerable due to the flooding (Koebsch et al. 2013). In comparison to the decreasing CH₄ emissions
895 at this site, Waddington and Day (2007) report enhancing CH₄ release for a Canadian peatland in the
896 first three years after rewetting. A third rewetted fen site in NE Germany with water levels close to the
897 soil surface was reported as weak GHG source 14-15 years after rewetting (Günther et al.
898 2015). However, the unusual meteorological conditions during our study period might have caused a
899 comparable low GWP compared to previous years due to lower CH₄ emissions at the expense of high
900 net CO₂ release. In comparison, e.g. Schrier-Uijl et al. (2014) report C uptake and a GHG sink function
901 of a fen 10 years after rewetting with water levels below or at the soil surface. In a study by Knox et al.
902 (2015) a wetland with mean water level above the soil surface was characterised by a near-neutral
903 climate impact after 15 years of rewetting, where continued high CH₄ emissions were compensated by
904 strong net CO₂ uptake. In the course of rewetting the water table is recommended to be held at or just
905 below the soil surface to prevent inundation and thus, the formation of organic mud (Couwenberg et
906 al. 2011, Joosten et al. 2012, Zak et al. 2015).

907 We calculated the “true” fluxes of CO₂ and CH₄ for the AOI by weighting the ~~non-linear regression~~ NLR
908 functions for the two surface types with their fractional coverage inside the AOI. The inferred C budget
909 and global warming potential differs considerably from that of the EC source area, highlighting the
910 strikingly different emission rates of open water versus emergent vegetation. Thus, footprint analysis

911 providing the fractional coverage of the main surface types is imperative for the interpretation of
912 ecosystem flux measurements as provided by the EC technique at such a spatially heterogeneous site.
913 In addition, for an interannual comparison of EC derived budgets for such sites it is necessary to define
914 a fixed AOI, as the cumulative footprint climatology (representing the EC source area) changes
915 interannually. Inter-site comparisons (e.g. with other shallow lakes evolved during fen rewetting) are
916 challenging with regard to the site-specific spatial heterogeneity and their interannual variability, if
917 short-term studies like the present one are involved. Comparisons might be misleading in case the
918 fractional coverages of the main surface types are not considered. Furthermore, as shown by Wilson
919 et al. (2007, 2008) and Minke et al. (2015) vegetation composition has a remarkable effect on GHG
920 emissions of rewetted peatlands and should be considered within inter-site comparisons.

921

922 5 Conclusions

923 This study contributes to the understanding of eutrophic shallow lakes as a challenging ecosystem
924 often evolving during fen rewetting ~~in NE Germany~~. Within the study period the ecosystem was a
925 strong source of CH₄ and CO₂. Both open water and emergent vegetation, particularly including the
926 eulittoral zone, were net emitters of CH₄ and CO₂, but with strikingly different release rates. This
927 illustrates the importance of footprint analysis for the interpretation of the EC measurements on a
928 rewetted site with distinct spatial heterogeneity. ~~Our results show that the intended effects of~~
929 ~~rewetting in terms of CO₂ emission reduction and C sink recovery are not yet achieved at this site.~~ The
930 strong negative climate impact of the lake is dominated by considerable CH₄ release, particularly from
931 the open water section. ~~In combination with the high net CO₂ release the C budget seems to be~~
932 ~~extremely unbalanced. Measurements of lateral transport of organic substrate within the open water~~
933 ~~body and a full C budget could give indication on a potential allochthonous input into the NE bay.~~
934 ~~Furthermore, the effect of unusual meteorological conditions need further investigation.~~ A comparison
935 with existing chamber measurements at the open water body for the same time period will be helpful
936 for the evaluation of our measurements and estimation for the surface type fluxes. ~~The site is~~
937 ~~continuously changing, with *Typha latifolia* progressively entering the open water body in the course~~
938 ~~of terrestrialisation, probably resulting in peat formation and C uptake once the shallow lake is~~
939 ~~replenished by organic sediments.~~ The site is gradually changing, with helophytes (especially *Typha*
940 *latifolia*) progressively entering the open water body in the course of terrestrialisation. Peat formation
941 and C uptake might be initiated once the shallow lake is inhabited by peat-forming vegetation and
942 replenished by organic sediments. Therefore, long-term measurements are necessary to evaluate the
943 impact of future ecosystem development on GHG emissions. Interannual comparisons are also
944 necessary to verify what the results of this study imply: that the intended effects of rewetting in terms

945 of CO₂ emission reduction and C sink recovery are not yet achieved at this site. In this context, the
946 effect of unusual meteorological conditions needs further investigation. Moreover, More general
947 statements for the climate impact of rewetted fens can only be provided by inclusion of additional
948 sites varying e.g. in groundwater table and ~~vegetation type~~ plant composition. We assume that shallow
949 lakes represent a special case with regard to the GHG dynamics and climate impact, with exceptionally
950 high CH₄ release and occasionally high net CO₂ emissions. Our study shows that permanent (high)
951 inundation in combination with nutrient-rich conditions involves the risk of long-term high CH₄
952 emissions. They counteract the actually intended lowering of the climate impact of drained and
953 degraded fens and can result in an even stronger climate impact than degraded fens, as also shown in
954 previous studies. ~~Inundation involves the risk of unpredictable and long-term high CH₄ emissions,~~
955 ~~especially in case of nutrient-rich conditions, that counteract the actually intended lowering of the~~
956 ~~climate impact of drained and degraded fens.~~ We strongly recommend to consider this risk in future
957 rewetting projects and support the call of Lamers et al. (2015) for the need of well-conceived
958 restoration management instead of the trial-and-error approach, whereon restoration of wetland
959 ecosystem services was based ~~on~~ for a long time.

960

961 Appendix A

962 Measurement data coverage of CO₂ and CH₄ fluxes within the study period is shown in Fig. A1.

963

964 Data availability

965 Processed eddy covariance flux and meteorological data of this study site (site code DE-Zrk) are
966 available at <http://www.europe-fluxdata.eu>.

967

968 **Acknowledgements**

969 This work was supported by the Helmholtz Association of German Research Centres through a
970 Helmholtz Young Investigators Group to T.S. (grant VH-NG-821) and is a contribution to the Helmholtz
971 Climate Initiative REKLIM (Regional Climate Change). Infrastructure funding through the Terrestrial
972 Environmental Observatories Network (TERENO) is also acknowledged. We thank M. Hoffmann (ZALF,
973 Müncheberg, Germany) and C. Hohmann (GFZ Potsdam, Germany) for providing meteorological data.

974

975 **References**

- 976 Aubinet, M., Feigenwinter, C., Heinesch, B., Laffineur, Q., Papale, D., Reichstein, M., Rinne, J. and Van
977 Gorsel, E.: Nighttime flux correction, in: Eddy Covariance: A practical guide to measurement and
978 data analysis, Springer Atmospheric Sciences, edited by Aubinet, M., Vesala, T. and Papale, D.,
979 Springer Netherlands, Dordrecht, doi:10.1007/978-94-007-2351-1, 133-158, 2012.
- 980 Augustin, J. and Joosten, H.: Peatland rewetting and the greenhouse effect, International Mire
981 Conservation Group Newsletter, 3, 29-30, 2007.
- 982 Barcza, Z., Kern, A., Haszpra, L. and Kljun, N.: Spatial representativeness of tall tower eddy covariance
983 measurements using remote sensing and footprint analysis, Agr. Forest Meteorol., 149, 795-807,
984 doi: 10.1016/j.agrformet.2008.10.021, 2009.
- 985 Bastviken, D., Cole, J., Pace, M. and Tranvik, L.: Methane emissions from lakes: Dependence of lake
986 characteristics, two regional assessments, and a global estimate, Global Biogeochem. Cy., 18,
987 GB4009, doi: 10.1029/2004GB002238, 2004.
- 988 Beetz, S., Liebersbach, H., Glatzel, S., Jurasinski, G., Buczko, U. and Höper, H.: Effects of land use
989 intensity on the full greenhouse gas balance in an Atlantic peat bog, Biogeosciences, 10, 1067-
990 1082, doi:10.5194/bg-10-1067-2013, 2013.
- 991 Berg, E., Jeschke, L. and Lenschow, U.: Das Moorschutzkonzept Mecklenburg-Vorpommern, Telma, 30,
992 173-220, 2000.
- 993 Béziat, P., Ceschia, E. and Dedieu, G.: Carbon balance of a three crop succession over two cropland
994 sites in South West France, Agr. Forest Meteorol., 149, 1628-1645,
995 doi:10.1016/j.agrformet.2009.05.004, 2009.
- 996 Bhullar, G. S., Edwards, P. J. and Olde Venterink, H.: Variation in the plant-mediated methane transport
997 and its importance for methane emission from intact wetland peat mesocosms, J. Plant Ecol., 6,
998 298-304, doi: 10.1093/jpe/rts045, 2013.
- 999 Bignell, N.: The effect of dissolved air on the density of water, Metrologia, 19, 57-59, 1983.
- 1000 Bonneville, M.-C., Strachan, I. B., Humphreys, E. R. and Roulet, N. T.: Net ecosystem CO₂ exchange in a
1001 temperate cattail marsh in relation to biophysical properties, Agr. Forest Meteorol., 148, 69-81,
1002 doi:10.1016/j.agrformet.2007.09.004, 2008.
- 1003 Bubier, J. L., Moore, T. R. and Roulet, N. T.: Methane emissions from wetlands in the Midboreal Region
1004 of Northern Ontario, Canada, Ecology, 74, 2240-2254, 1993.

1005 Casper, P., Maberly, S. C., Hall, G. H. and Finlay, B. J.: Fluxes of methane and carbon dioxide from a
1006 small productive lake to the atmosphere, *Biogeochemistry*, 49, 1-19, doi:
1007 10.1023/A:1006269900174, 2000.

1008 Chanton, J. P., Whiting, G. J., Happell, J. D. and Gerard, G.: Contrasting rates and diurnal patterns of
1009 methane emission from different types of vegetation, *Aquat. Bot.*, 46, 111-128, 1993.

1010 Chen, B., Coops, N. C., Fu, D., Margolis, H. A., Amiro, B. D., Barr, A. G., Black, T. A., Arain, M. A., Bourque,
1011 C. P.-A., Flanagan, L. B., Lafleur, P. M., McCaughey, J. H. and Wofsy, S. C.: Assessing eddy-
1012 covariance flux tower location bias across the Fluxnet-Canada Research Network based on remote
1013 sensing and footprint modelling, *Agr. Forest Meteorol.*, 151, 87–100,
1014 doi:10.1016/j.agrformet.2010.09.005, 2011.

1015 Chu, H., Gottgens, J. F., Chen, J., Sun, G., Desai, A. R., Ouyang, Z., Shao, C. and Czajkowski, K.: Climatic
1016 variability, hydrologic anomaly, and methane emission can turn productive freshwater marshes
1017 into net carbon sources, *Glob. Change Biol.*, 21, 1165-1181, doi: 10.1111/gcb.12760, 2015.

1018 Couwenberg, J., Thiele, A., Tanneberger, F., Augustin, J., Bärtsch, S., Dubovik, D., Lishchynskaya, N.,
1019 Michaelis, D., Minke, M., Skuratovich, A. and Joosten, H.: Assessing greenhouse gas emissions
1020 from peatlands using vegetation as a proxy, *Hydrobiologia*, 674, 67-89, doi:10.1007/s10750-011-
1021 0729-x, 2011.

1022 Dengel, S., Levy, P. E., Grace, J., Jones, S. K. and Skiba, U. M.: Methane emissions from sheep pasture,
1023 measured with an open-path eddy covariance system, *Glob. Change Biol.*, 17, 3524-3533, doi:
1024 10.1111/j.1365-2486.2011.02466.x, 2011.

1025 Ducharme-Riel, V., Vachon, D., del Giorgio, P. A. and Prairie, Y. T.: The relative contribution of winter
1026 under-ice and summer hypolimnetic CO₂ accumulation to the annual CO₂ emissions from
1027 northern lakes, *Ecosystems*, 18, 547-559, doi:10.1007/s10021-015-9846-0, 2015.

1028 Eugster, W., Kling, G., Jonas, T., McFadden, J. P., Wüest, A., MacIntyre, S. and Chapin III, F. S.: CO₂
1029 exchange between air and water in an Arctic Alaskan and midlatitude Swiss lake: importance of
1030 convective mixing, *J. Geophys. Res.*, 108, 4362, doi: 10.1029/2002JD002653, 2003.

1031 Falge, E., Baldocchi, D., Olson, R. J., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R.,
1032 Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N.-O., Katul, G.,
1033 Keronen, P., Kowalski, A., Ta Lai, C., Law, B. E., Meyers, T., Moncrieff, J., Moors, E., Munger, J. W.,
1034 Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T.,
1035 Wilson, K. and Wofsy, S. C.: Gap filling strategies for defensible annual sums of net ecosystem
1036 exchange, *Agr. Forest Meteorol.*, 107, 43–69, doi:10.1016/S0168-1923(00)00225-2, 2001.

- 1037 Fan, S.-M., Wofsy, S. C., Bakwin, P. S., Jacob, D. J. and Fitzjarrald, D. R.: Atmosphere-biosphere
1038 exchange of CO₂ and O₃ in the Central Amazon Forest, *J. Geophys. Res.*, 95, 16851-16864, 1990.
- 1039 Finkelstein, P. L. and Sims, P. F.: Sampling error in eddy correlation flux measurements, *J. Geophys.*
1040 *Res.-Atmos.*, 106, 3503-3509, doi:10.1029/2000JD900731, 2001.
- 1041 Finnigan, J. J., Clement, R., Mahli, Y., Leuning, R. and Cleugh, H. A.: A re-evaluation of long-term flux
1042 measurement techniques. Part I: Averaging and coordinate rotation, *Bound.-Lay. Meteorol.*, 107,
1043 1-48, doi:10.1023/A:1021554900225, 2003.
- 1044 ~~Foken, T.: *Micrometeorology*. Springer, Berlin, 308 pp, doi:10.1007/978-3-540-74666-9, 2008.~~
- 1045 Forbrich, I., Kutzbach, L., Wille, C., Becker, T., Wu, J. and Wilmking, M.: Cross-evaluation of
1046 measurements of peatland methane emissions on microform and ecosystem scales using high-
1047 resolution landcover classification and source weight modelling, *Agr. Forest Meteorol.*, 151, 864-
1048 874, doi:10.1016/j.agrformet.2011.02.006, 2011.
- 1049 Fratini, F., Ibrom, A., Arriga, N., Burba, G. and Papale, D.: Relative humidity effects of water vapour
1050 fluxes measured with closed-path eddy-covariance systems with short sampling lines, *Agr. Forest*
1051 *Meteorol.*, 165, 53-63, 2012.
- 1052 Frolking, S., Talbot, J., Jones, M. C., Treat, C. C., Kauffman, J. B., Tuittila, E.-S. and Roulet, N. T.: Peatlands
1053 in the earth's 21st century climate system, *Environ. Rev.*, 19, 371-396, doi:10.1139/a11-014, 2011.
- 1054 Göckede, M., Rebmann, C. and Foken, T.: A combination of quality assessment tools for eddy
1055 covariance measurements with footprint modelling for the characterisation of complex sites, *Agr.*
1056 *Forest Meteorol.*, 127, 175-188, doi:10.1016/j.agrformet.2004.07.012, 2004.
- 1057 Godwin, C. M., McNamara, P. J. and Markfort, C. D.: Evening methane emission pulses from a boreal
1058 wetland correspond to convective mixing in hollows, *J. Geophys. Res.-Biogeo.*, 118, 994-1005, doi:
1059 10.1002/jgrg.20082, 2013.
- 1060 Günther, A. B., Huth, V., Jurasinski, G. and Glatzel, S.: Scale-dependent temporal variation in
1061 determining the methane balance of a temperate fen, *Greenhouse Gas Measurement and*
1062 *Management*, 4, 41-48, doi: 10.1080/20430779.2013.850395, 2013.
- 1063 Günther, A. B., Huth, V., Jurasinski, G. and Glatzel, S.: The effect of biomass harvesting on greenhouse
1064 gas emissions from a rewetted temperate fen, *GCB Bioenergy*, 7, 1092-1106, doi:
1065 10.1111/gcbb.12214, 2015.
- 1066 Hahn, J., Köhler, S., Glatzel, S. and Jurasinski, G.: Methane exchange in a coastal fen in the first year
1067 after flooding – A systems shift, *PLoS ONE*, 10, e0140657, doi:10.1371/journal.pone.0140657,
1068 2015.

1069 Hahn-Schöfl, M., Zak, D., Minke, M., Gelbrecht, J., Augustin, J. and Freibauer, A.: Organic sediment
1070 formed during inundation of a degraded fen grassland emits large fluxes of CH₄ and CO₂,
1071 Biogeosciences, 8, 1539-1550, doi:10.5194/bg-8-1539-2011, 2011.

1072 Hatala, J. A., Detto, M., Sonntag, O., Deverel, S. J., Verfaillie, J. and Baldocchi, D. D.: Greenhouse gas
1073 (CO₂, CH₄, H₂O) fluxes from drained and flooded agricultural peatlands in the Sacramento-San
1074 Joaquin Delta, Agr. Ecosyst. Environ., 150, 1-18, doi:10.1016/j.agee.2012.01.009, 2012.

1075 Hatala Matthes, J., Sturtevant, C., Verfaillie, J., Knox, S. and Baldocchi, D.: Parsing the variability in CH₄
1076 flux at a spatially heterogeneous wetland: Integrating multiple eddy covariance towers with high-
1077 resolution flux footprint analysis, J. Geophys. Res.-Biogeo., 119, 1322-1339,
1078 doi:10.1002/2014JG002642 2014.

1079 Hendriks, D. M. D., van Huissteden, J., Dolman, A. J. and van der Molen, M. K.: The full greenhouse gas
1080 balance of an abandoned peat meadow, Biogeosciences, 4, 411-424, doi:10.5194/bg-4-411-2007,
1081 2007.

1082 Hendriks, D. M. D., van Huissteden, J. and Dolman, A. J.: Multi-technique assessment of spatial and
1083 temporal variability of methane fluxes in a peat meadow, Agr. Forest Meteorol., 150, 757-774,
1084 doi:10.1016/j.agrformet.2009.06.017, 2010.

1085 Herbst, M., Friborg, T., Ringgaard, R. and Soegaard, H.: Interpreting the variations in atmospheric
1086 methane fluxes observed above a restored wetland, Agr. Forest Meteorol., 151, 841-853,
1087 doi:10.1016/j.agrformet.2011.02.002, 2011.

1088 Hoffmann, M., Schulz-Hanke, M., Garcia Alba, J., Jurisch, N., Hagemann, U., Sachs, T., Sommer, M. and
1089 Augustin, J.: Technical Note: A simple calculation algorithm to separate high-resolution CH₄ flux
1090 measurements into ebullition and diffusion-derived components, Biogeosciences Discussions, 12,
1091 12923-12945, doi:10.5194/bgd-12-12923-2015, 2015.

1092 Holden, J., Chapman, P. J. and Labadz, J. C.: Artificial drainage of peatlands: hydrological and
1093 hydrochemical process and wetland restoration, Prog. Phys. Geog., 28, 95-123,
1094 doi:10.1191/0309133304pp403ra, 2004.

1095 Hommeltenberg, J., Mauder, M., Drösler, M., Heidbach, K., Werle, P. and Schmid, H. P.: Ecosystem
1096 scale methane fluxes in a natural temperate bog-pineforest in southern Germany, Agr. Forest
1097 Meteorol., 198-199, 273-284, doi:10.1016/j.agrformet.2014.08.017, 2014.

1098 Höper, H., Augustin, J., Cagampan, J. P., Drösler, M., Lundin, L., Moors, E., Vasander, H., Waddington,
1099 J. M., and Wilson, D.: Restoration of peatlands and greenhouse gas balances, in: Peatlands and
1100 climate change, edited by Strack, M., International Peat Society, Jyväskylä, 182-210, 2008.

1101 Horst, T. W. and Lenschow, D. H.: Attenuation of scalar fluxes measured with spatially-displaced
1102 sensors, *Bound.-Lay. Meteorol.*, 130, 275-300, doi:10.1007/s10546-008-9348-0, 2009.

1103 Huttunen, J. T., Nykänen, H., Turunen, J. and Martikainen, P. J.: Methane emissions from natural
1104 peatlands in the northern boreal zone in Finland, Fennoscandia, *Atmos. Environ.*, 37, 147-151,
1105 doi:10.1016/S1352-2310(02)00771-9, 2003.

1106 IPCC: Climate Change 2013: The physical science basis. Contribution of Working Group I to the Fifth
1107 Assessment Report of the Intergovernmental Panel on Climate Change, edited by Stocker, T. F.,
1108 Qin, D., Plattner, G.-K., Tignor, M. M. B., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and
1109 Midgley, P. M., Cambridge University Press, Cambridge, New York, 1535 pp,
1110 doi:10.1017/CBO9781107415324, 2013.

1111 IPCC: 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories:
1112 Wetlands, edited by Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M.
1113 and Troxler, T.G., IPCC, Switzerland, 354 pp, 2014.

1114 Itzerott, S.: TERENO (Northeast), Climate station Karlshof, Germany. Deutsches
1115 GeoForschungsZentrum GFZ. <http://dx.doi.org/10.5880/TERENO.265>, 2015.

1116 Joosten, H.: The global peatland CO₂ picture – Peatland status and drainage related emissions in all
1117 countries of the world, *Wetlands International*, Ede, 36 pp, 2010.

1118 Joosten, H., Tapio-Biström, M.-L. and Tol, S. (Eds.): Peatlands – guidance for climate change mitigation
1119 through conservation, rehabilitation and sustainable use, 2nd edition, Food and Agriculture
1120 Organization of the United Nations and Wetlands International, 100 pp, 2012.

1121 Juutinen, S., Alm, J., Larmola, T., Huttunen, J. T., Morero, M., Martikainen, P. J. and Silvola, J.: Major
1122 implication of the littoral zone for methane release from boreal lakes, *Global Biogeochem. Cy.*,
1123 17, 1117, doi:10.1029/2003GB002105, 2003.

1124 Kankaala, P., Ojala, A. and Käki, T.: Temporal and spatial variation in methane emissions from a flodded
1125 transgression shore of a boreal lake, *Biogeochemistry*, 68, 297-311, doi:
1126 10.1023/B:BIOG.0000031030.77498.1f, 2004.

1127 Knox, S. H., Sturtevant, C., Hatala Matthes, J., Koteen, L., Verfaillie, J. and Baldocchi, D.: Agricultural
1128 peatland restoration: effects of land-use change on greenhouse gas (CO₂ and CH₄) fluxes in the
1129 Sacramento-San Joaquin Delta, *Glob. Change Biol.*, 21, 750-765, doi:10.1111/gcb.12745, 2015.

1130 [Koebisch, F., Glatzel, S., Hofmann, J., Forbrich, I. and Jurasinski, G.: CO₂ exchange of a temperate fen](#)
1131 [during the conversion from moderately rewetting to flooding, *J. Geophys. Res.-Biogeo.*, 118, 940-](#)
1132 [950, doi:10.1002/jgrg.20069, 2013.](#)

- 1133 Koebisch, F., Jurasinski, G., Koch, M., Hofmann, J. and Glatzel, S.: Controls for multi-scale temporal
1134 variation in ecosystem methane exchange during the growing season of a permanently inundated
1135 fen, *Agr. Forest Meteorol.*, 204, 94-105, doi:10.1016/j.agrformet.2015.02.002, 2015.
- 1136 Kormann, R. and Meixner, F. X.: An analytical footprint model for non-neutral stratification, *Bound.-*
1137 *Lay. Meteorol.*, 99, 207-224, doi:10.1023/A:1018991015119, 2001.
- 1138 Kortelainen, P., Rantakari, M., Huttunen, J. T., Mattsson, T., Alm, J., Juutinen, S., Larmola, T., Silvola, J.
1139 and Martikainen, P. J.: Sediment respiration and lake trophic state are important predictors of
1140 large CO₂ evasion from small boreal lakes, *Glob. Change Biol.*, 12, 1554-1567, doi: 10.1111/j.1365-
1141 2486.2006.01167.x. 2006.
- 1142 Lamers, L. P. M., Vile, M. A., Grootjans, A. P., Acreman, M. C., van Diggelen, R., Evans, M. G., Richardson,
1143 C. J., Rochefort, L., Koojiman, A. M., Roelofs, J. G. M. and Smolders, A. J. P. ~~(2015)~~: Ecological
1144 restoration of rich fens in Europe and North America: from trial and error to an evidence-based
1145 approach, *Biol. Rev.*, 90, 182-203, doi: 10.1111/brv.12102, 2015.
- 1146 Lloyd, J. and Taylor, J. A.: On the temperature dependence of soil respiration, *Funct. Ecol.*, 8, 315-323,
1147 doi:10.2307/2389824, 1994.
- 1148 Lund, M., Lafleur, P. M., Roulet, N. T., Lindroth, A., Christensen, T. R., Aurela, M., Chojnicki, B. H.,
1149 Flanagan, L. B., Humphreys, E. R., Laurila, T., Oechel, W., Olejnik, J., Rinne, J., Schubert, P. and
1150 Nilsson, M. B.: Variability in exchange of CO₂ across 12 northern peatland and tundra sites, *Glob.*
1151 *Change Biol.*, 16, 2436-2448, doi:10.1111/j.1365-2486.2009.02104.x, 2010.
- 1152 MacIntyre, S., Jonsson, A., Jansson, M., Aberg, J., Turney, D. E. and Miller, S. D.: Buoyancy flux,
1153 turbulence, and the gas transfer coefficient in a stratified lake, *Geophys. Res. Lett.*, 37, L24604,
1154 doi:10.1029/2010GL044164, 2010.
- 1155 Mauder, M. and Foken, T.: Documentation and instruction manual of the Eddy covariance software
1156 package TK2. Arbeitsergebnisse Nr. 26, University of Bayreuth, Department of Micrometeorology,
1157 42 pp, 2004.
- 1158 McDermitt, D., Burba, G., Xu, L., Anderson, T., Komissarov, A., Riensche, B., Schedlbauer, J., Starr, G.,
1159 Zona, D., Oechel, W., Oberbauer, S. and Hastings, S.: A new low-power, open-path instrument for
1160 measuring methane flux by eddy covariance, *Appl. Phys. B*, 102, 391-405, doi:10.1007/s00340-
1161 010-4307-0, 2011.
- 1162 Meyer, K., Höper, H. and Blankenburg, J.: Spurengashaushalt und Klimabilanz von Niedermooren unter
1163 dem Einfluß des Vernässungsmanagements, in: *Ökosystemmanagement für Niedermoore.*

- 1164 Strategien und Verfahren zur Renaturierung, edited by Kratz, R. and Pfadenhauer, J., Ulmer,
1165 Stuttgart, 104-111, 2001.
- 1166 Minke, M., Augustin, J., Burlo, A., Yarmashuk, T., Chuvashova, H., Thiele, A., Freibauer, A., Tikhonov, V.
1167 and Hoffmann, M.: Water level, vegetation composition and plant productivity explain
1168 greenhouse gas fluxes in temperate cutover fens after inundation, *Biogeosciences Discussions*,
1169 12, 17393-17452, doi:10.5194/bgd-12-17393-2015, 2015.
- 1170 Moffat, A. M., Papale, D., Reichstein, M., Hollinger, D. Y., Richardson, A. D., Barr, A. G., Beckstein, C.,
1171 Braswell, B. H., Churkina, G., Desai, A. R., Falge, E., Gove, J. H., Heimann, M., Hui, D., Jarvis, A. J.,
1172 Kattge, J., Noormets, A. and Stauch, V. J.: Comprehensive comparison of gap-filling techniques for
1173 eddy covariance net carbon fluxes, *Agr. Forest Meteorol.*, 147, 209-232,
1174 doi:10.1016/j.agrformet.2007.08.011, 2007.
- 1175 Moncrieff, J. B., Clement, R., Finnigan, J. and Meyers, T.: Averaging, detrending and filtering of eddy
1176 covariance time series, in: *Handbook of micrometeorology: a guide for surface flux*
1177 *measurements*, edited by Lee, X., Massman, W. J. and Law, B. E., Kluwer Academic, Dordrecht, 7-
1178 31, doi:10.1007/1-4020-2265-4, 2004.
- 1179 Morrissey, L. A., Zobel, D. B. and Livingston, G. P.: Significance of stomatal control on methane release
1180 from *Carex*-dominated wetlands, *Chemosphere*, 26, 339-355, doi:10.1016/0045-6535(93)90430-
1181 D, 1993.
- 1182 Naiman, R. J., Manning, T. and Johnston, C. A.: Beaver population fluctuations and tropospheric
1183 methane emissions in boreal wetlands, *Biogeochemistry*, 12, 1-15, doi: 10.1007/BF00002623,
1184 1991.
- 1185 Nilsson, M., Mikkilä, C., Sundh, I., Granberg, G., Svensson, B. H. and Ranneby, B.: Methane emission
1186 from Swedish mires: National and regional budgets and dependence on mire vegetation, *J.*
1187 *Geophys. Res.*, 106, 20847-20860, doi:10.1029/2001JD900119, 2001.
- 1188 Petrescu, A. M. R., Lohila, A., Tuovinen, J.-P., Baldocchi, D. D., Desai, A. R., Roulet, N. T., Vesala, T.,
1189 Dolman, A. J., Oechel, W. C., Marcolla, B., Friborg, T., Rinne, J., Hatala Matthes, J., Merbold, L.,
1190 Meijide, A., Kiely, G., Sottocornola, M., Sachs, T., Zona, D., Varlagin, A., Lai, D. Y. F., Veenendaal,
1191 E., Parmentier, F.-J. W., Skiba, U., Lund, M., Hensen, A., van Huissteden, J., Flanagan, L. B.,
1192 Shurpali, N. J., Grünwald, T., Humphreys, E. R., Jackowicz-Korczyński, M., Aurela, M. A., Laurila, T.,
1193 Grüning, C., Corradi, C. A. R., Schrier-Uijl, A. P., Christensen, T. R., Tamstorf, M. P., Mastepanov,
1194 M., Martikainen, P. J., Verma, S. B., Bernhofer, C. and Cescatti, A.: The uncertain climate footprint
1195 of wetlands under human pressure, *PNAS*, 112, 4594-4599, doi:10.1073/pnas.1416267112, 2015.

- 1196 Podgrajsek, E., Sahlée, E. and Rutgersson, A.: Diurnal cycle of lake methane flux, *J. Geophys. Res.-*
1197 *Biogeo.*, 119, 236-248, doi:10.1002/2013JG002327, 2014.
- 1198 Poindexter, C. M. and Variano, E. A.: Gas exchange in wetlands with emergent vegetation: the effects
1199 of wind and thermal convection at the air–water interface, *J. Geophys. Res.-Biogeo.*, 118, 1297–
1200 1306, doi:10.1002/jgrg.20099, 2013.
- 1201 [Poissant, L., Constant, P., Pilote, M., Canário, J., O’Driscoll, N., Ridal, J. and Lean, D.: The ebullition of](#)
1202 [hydrogen, carbon monoxide, methane, carbon dioxide and total gaseous mercury from the](#)
1203 [Cornwall Area of Concern, *Sci. Total Envir.*, 381, 256-262, doi:10.1016/j.scitotenv.2007.03.029,](#)
1204 [2007.](#)
- 1205 R Core Team: R: A Language and Environment for Statistical Computing. R Foundation for Statistical
1206 Computing, Vienna, Austria, 2012.
- 1207 Read, J. S., Hamilton, D. P., Desai, A. R., Rose, K. C., MacIntyre, S., Lenters, J. D., Smyth, R. L., Hanson,
1208 P. C., Cole, J. J., Staehr, P. A., Rusak, J. A., Pierson, D. C., Brookes, J. D., Laas, A. and Wu, C. H.: Lake-
1209 size dependency of wind shear and convection as controls on gas exchange, *Geophys. Res. Lett.*,
1210 39, L09405, doi:10.1029/2012GL051886, 2012.
- 1211 Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann,
1212 N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A.,
1213 Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M.,
1214 Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T.,
1215 Yakir, D. and Valentini, R.: On the separation of net ecosystem exchange into assimilation and
1216 ecosystem respiration: review and improved algorithm, *Glob. Change Biol.*, 11, 1424-1439,
1217 doi:10.1111/j.1365-2486.2005.001002.x, 2005.
- 1218 Repo, M. E., Huttunen, J. T., Naumov, A. V., Chichulin, A. V., Lapshina, E. D., Bleuten, W. and
1219 Martikainen, P. J.: Release of CO₂ and CH₄ from small wetland lakes in western Siberia, *Tellus*, 59B,
1220 788-796, doi:10.1111/j.1600-0889.2007.00301.x, 2007.
- 1221 Rinne, J., Riutta, T., Pihlatie, M., Aurela, M., Haapanala, S., Tuovinen, J.-P., Tuittila, E.-S. and Vesala, T.:
1222 Annual cycle of methane emission from a boreal fen measured by the eddy covariance technique,
1223 *Tellus*, 59B, 449-457, doi:10.1111/j.1600-0889.2007.00261.x, 2007.
- 1224 Rocha, A. V. and Goulden, M. L.: Large interannual CO₂ and energy exchange variability in a freshwater
1225 marsh under consistent environmental conditions, *J. Geophys. Res.*, 113, G04019,
1226 doi:10.1029/2008JG000712, 2008.

- 1227 Rõõm, E.-I., Nõges, P., Feldmann, T., Tuvikene, L., Kisand, A., Teearu, H. and Nõges, T.: Years are not
1228 brothers: Two-year comparison of greenhouse gas fluxes in large shallow Lake Võrtsjärv, Estonia,
1229 J. Hydrol., 519, 1594-1606, doi:10.1016/j.jhydrol.2014.09.011, 2014.
- 1230 Roulet, N. T., Ash, R. and Moore, T. R.: Low boreal wetlands as a source of atmospheric methane, J.
1231 Geophys. Res., 97, 3739-3749, 1992.
- 1232 Roulet, N.T., Ash, R., Quinton, W. and Moore, T. R.: Methane flux from drained northern peatlands:
1233 Effect of a persistent water table lowering on flux, Global Biogeochem. Cy., 7, 749-769,
1234 doi:10.1029/93GB01931, 1993.
- 1235 Sahlée, E., Rutgersson, A., Podgrajsek, E. and Bergström, H.: Influence from surrounding land on the
1236 turbulence measurements above a lake, Bound.-Lay. Meteorol., 150, 235-258,
1237 doi:10.1007/s10546-013-9868-0, 2014.
- 1238 Schrier-Uijl, A. P., Veraart, A. J., Leffelaar, P. A., Berendse, F. and Veenendaal, E. M.: Release of CO₂ and
1239 CH₄ from lakes and drainage ditches in temperate wetlands, Biogeochemistry, 102, 265-279,
1240 doi:10.1007/s10533-010-9440-7, 2011.
- 1241 Schrier-Uijl, A. P., Kroon, P. S., Hendriks, D. M. D., Hensen, A., van Huissteden, J., Berendse, F. and
1242 Veenendaal, E. M.: Agricultural peatlands: towards a greenhouse gas sink – a synthesis of a
1243 Dutch landscape study, Biogeosciences, 11, 4559-4576, doi:10.5194/bg-11-4559-2014, 2014.
- 1244 [Sepulveda-Jauregui, A., Walter Anthony, K. M., Martinez-Cruz, K., Greene, S. and Thalasso, F.: Methane](#)
1245 [and carbon dioxide emissions from 40 lakes along a north-south latitudinal transect in Alaska,](#)
1246 [Biogeosciences, 12, 3197-3223, doi:10.5194/bg-12-3197-2015, 2015.](#)
- 1247 Shoemaker, W. B., Anderson, F., Barr, J. G., Graham, S. L. and Botkin, D. B.: Carbon exchange between
1248 the atmosphere and subtropical forested cypress and pine wetlands, Biogeosciences, 12, 2285-
1249 2300, doi:10.5194/bg-12-2285-2015, 2015.
- 1250 Siebicke, L., Hunner, M. and Foken, T.: Aspects of CO₂ advection measurements, Theor. Appl. Climatol.,
1251 109, 109-131, doi:10.1007/s00704-011-0552-3, 2012.
- 1252 Silvius, M., Joosten, H. and Opdam, S.: Peatlands and people, in: Assessment on peatlands, biodiversity
1253 and climate change: Main Report, edited by Parish, F., Sirin, A., Charman, D., Joosten, H.,
1254 Minayeva, T., Silvius, M. and Stringer, L., Global Environment Centre, Kuala Lumpur, and Wetlands
1255 International, Wageningen, 20-38, 2008.
- 1256 Smith, L. K. and Lewis Jr., W. M.: Seasonality of methane emissions from five lakes and associated
1257 wetlands of the Colorado Rockies, Global Biogeochem. Cy., 6, 323-338, 1992.

- 1258 [Spawn, S. A., Dunn, S. T., Fiske, G. J., Natali, S. M., Schade, J. D. and Zimov, N. S.: Summer methane](#)
1259 [ebullition from a headwater catchment in Northeastern Siberia, *Inland Waters*, 5, 224-230,](#)
1260 [doi:10.5268/IW-5.3.845, 2015.](#)
- 1261 Steffenhagen, P., Zak, D., Schulz, K., Timmermann, T. and Zerbe, S.: Biomass and nutrient stock of
1262 submersed and floating macrophytes in shallow lakes formed by rewetting of degraded fens,
1263 *Hydrobiologia*, 692, 99-109, doi:10.1007/s10750-011-0833-y, 2012.
- 1264 Strachan, I. B., Nugent, K. A., Crombie, S. and Bonneville, M.-C.: Carbon dioxide and methane exchange
1265 at a cool-temperate freshwater marsh, *Environ. Res. Lett.*, 10, 065006, doi:10.1088/1748-
1266 9326/10/6/065006, 2015.
- 1267 Succow, M.: Durchströmungsmoore, in: *Landschaftsökologische Moorkunde*, edited by Succow, M.
1268 and Joosten, H., Schweizerbart, Stuttgart, 463-470, 2001.
- 1269 Torn, M. S. and Chapin III, F. S.: Environmental and biotic controls over methane flux from arctic tundra,
1270 *Chemosphere*, 26, 357-368, doi:10.1016/0045-6535(93)90431-4, 1993.
- 1271 van Dijk, A., Moene, A. F. and de Bruin, H. A. R.: The principles of surface flux physics: Theory, practice
1272 and description of the ECPack library, Meteorology and Air Quality Group, Wageningen University,
1273 Wageningen, 98 pp, 2004.
- 1274 Vickers, D. and Mahrt, L.: Quality control and flux sampling problems for tower and aircraft data, *J.*
1275 *Atmos. Ocean. Tech.*, 14, 512-526, 1997.
- 1276 Waddington, J. M. and Day, S. M.: Methane emissions from a peatland following restoration, *J.*
1277 *Geophys. Res.*, 112, G03018, doi:10.1029/2007JG000400, 2007.
- 1278 Wagner, W. and Pruß, A.: The IAPWS formulation 1995 for the thermodynamic properties of ordinary
1279 water substance for general and scientific use, *J. Phys. Chem. Ref. Data*, 31, 387-535, 2002.
- 1280 Wang, H., Lu, J., Wang, W., Yang, L. and Yin, C.: Methane fluxes from the littoral zone of hyper eutrophic
1281 Taihu Lake China, *J. Geophys. Res.*, 111, D17109, doi:10.1029/2005JD006864, 2006.
- 1282 Webb, E. K., Pearman, G. I. and Leuning, R.: Correction of flux measurements for density effects due
1283 to heat and water vapor transfer, *Q. J. Roy. Meteor. Soc.*, 106, 85-100,
1284 doi:10.1002/qj.49710644707, 1980.
- 1285 Whiting, G. J. and Chanton, J. P.: Greenhouse carbon balance of wetlands: methane emission versus
1286 carbon sequestration, *Tellus*, 53B, 521-528, doi: 10.1034/j.1600-0889.2001.530501.x, 2001.
- 1287 Wilczak, J. M., Oncley, S. P. and Stage, S. A.: Sonic anemometer tilt correction algorithms, *Bound.-Lay.*
1288 *Meteorol.*, 99, 127-150, doi:10.1023/A:1018966204465, 2001.

1289 Wilson, D., Tuittila, E.-S., Alm, J., Laine, J., Farrell, E. P. and Byrne, K. A.: Carbon dioxide dynamics of a
1290 restored maritime peatland, *Ecoscience* 14, 71-80, doi: 10.2980/1195-
1291 6860(2007)14[71:CDDOAR]2.0.CO;2, 2007.

1292 Wilson, D., Alm, J., Laine, J., Byrne, K. A., Farrell, E. P. and Tuittila, E.-S.: Rewetting of cutaway
1293 peatlands: are we re-creating hot plots of methane emissions?, *Restor. Ecol.*, 17, 796-806,
1294 doi:10.1111/j.1526-100X.2008.00416.x, 2008.

1295 Yavitt, J. B., Angell, L. L., Fahey, T. J., Cirimo, C. P. and Driscoll, C. T.: Methane fluxes, concentrations,
1296 and production in two Adirondack beaver impoundments, *Limnol. Oceanogr.*, 37, 1057-1066,
1297 1992.

1298 Zak, D., Gelbrecht, J., Wagner, C. and Steinberg, C. E. W.: Evaluation of phosphorus mobilisation
1299 potential in rewetted fens by an improved sequential chemical extraction procedure, *Eur. J. Soil.*
1300 *Sci.*, 59, 1191-1201, doi:10.1111/j.1365-2389.2008.01081.x, 2008.

1301 Zak, D., Reuter, H., Augustin, J., Shatwell, T., Barth, M., Gelbrecht, J. and McInnes, R. J.: Changes of the
1302 CO₂ and CH₄ production potential of rewetted fens in the perspective of temporal vegetation
1303 shifts, *Biogeosciences*, 12, 2455-2468, doi:10.5194/bg-12-2455-2015, 2015.

1304 Zerbe, S., Steffenhagen, P., Parakenings, K., Timmermann, T., Frick, A., Gelbrecht, J. and Zak, D.:
1305 Ecosystem service restoration after 10 years of rewetting peatlands in NE Germany, *Environ.*
1306 *Manage.*, 51, 1194-1209, doi:10.1007/s00267-013-0048-2, 2013.

1307 Zhu, D., Chen, H., Zhu, Q., Wu, Y. and Wu, N.: High Carbon Dioxide Evasion from an Alpine Peatland
1308 Lake: The Central Role of Terrestrial Dissolved Organic Carbon Input, *Water Air Soil Poll.*, 223,
1309 2563-2569, doi:10.1007/s11270-011-1048-6, 2012.

1310

1311 Table 1: Data loss and final data coverage during the observation period. ~~Percentage of~~ CO₂ and CH₄
 1312 flux data were lost by power and instrument failure and maintenance as well as quality control and
 1313 footprint analysis.

Filter criteria	Percentage of data [%]	
	CO ₂	CH ₄
Power and instrument failure, maintenance	15.0	46.4
Absence of sensor	-	11.2
QC 2	7.5	2.0
RSSI	-	2.1
u*	18.6	8.8
Unreasonably high fluxes	0.2	0.1
No footprint information/footprint > 20 % outside the AOI	13.2	6.5
Final data coverage	45.5	22.9

1314

1315 Table 2: Gapfilling model performance was estimated according to Moffat et al. (2007) with several
 1316 measures ($n_{\text{CO}_2} = 6193$, $n_{\text{CH}_4} = 3386$, fluxes of best quality QC 0): the adjusted coefficient of
 1317 determination R^2_{adj} for phase correlation (significant in all cases, $p\text{-value} < 2.2e^{-16}$), the absolute root
 1318 mean square index (RMSE_{abs}) and the mean absolute error (MAE) for the magnitude and distribution
 1319 of individual errors, as well as the bias error (BE) for the bias of the annual sums.

Method	R^2_{adj}	RMSE_{abs} ($\text{mg m}^{-2} 30\text{min}^{-1}$)	MAE ($\text{mg m}^{-2} 30\text{min}^{-1}$)	BE ($\text{g m}^{-2} \text{a}^{-1}$)
MDSLUT _{CO2no}	0.74	104.35	24.05	13.14
foot				
NLR _{CO2foot}	0.66	119.10	27.51	-2.12
NLR _{CH4nofoot}	0.79	1.36	0.83	-3.34
NLR _{CH4foot}	0.81	1.28	0.78	-2.54

1320

1321 Table 3: Annual balances of CO₂ and CH₄ derived by different methods for the whole EC source area,
 1322 the area of interest (AOI) and the two surface types: ~~LUT~~-MDS approach without footprint
 1323 consideration (~~MDS~~LUT_{CO2nofoot}), NLR approach without (NLR_{CH4nofoot}) and with (NLR_{CH4foot}, NLR_{CO2foot})
 1324 footprint consideration. Uncertainty was calculated as square root of the sum of squared random
 1325 uncertainty (measurement uncertainty) and gapfilling uncertainty.

Source area	Flux (g m ⁻² a ⁻¹)	Method			
		CO ₂		CH ₄	
		MDS LUT _{CO2nofoot}	NLR _{CO2foot}	NLR _{CH4nofoot}	NLR _{CH4foot}
Whole EC source area	NEE	524.5 ± 5.6	531.4 ± 13.0		
	GPP	-2380.5 ± 5.6	-2122.1 ± 16.7		
	R _{eco}	2863.6 ± 5.6	2603.6 ± 8.4		
	CH ₄			40.5 ± 0.2	39.8 ± 0.2
AOI	NEE		843.5 ± 13.0		
	GPP		-3192.2 ± 16.7		
	R _{eco}		4035.7 ± 8.4		
	CH ₄				21.8 ± 0.2
Emergent vegetation	NEE		750.3 ± 13.0		
	GPP		-4076.8 ± 16.7		
	R _{eco}		4827.2 ± 8.4		
	CH ₄				13.2 ± 0.2
Open water	NEE		158.2 ± 13.0		
	GPP		-1021.5 ± 16.7		
	R _{eco}		1179.7 ± 8.4		
	CH ₄				52.6 ± 0.2

1326

1327 Table 4: NEE and net CH₄ exchange at open water sites. The letters in parentheses indicate seasonal
 1328 (S; May to October) and annual (A) budgets. Positive water level indicates inundated conditions. GHG
 1329 flux measurement methods are denoted as: CH = chambers, CO = concentration profiles, TR = gas traps.

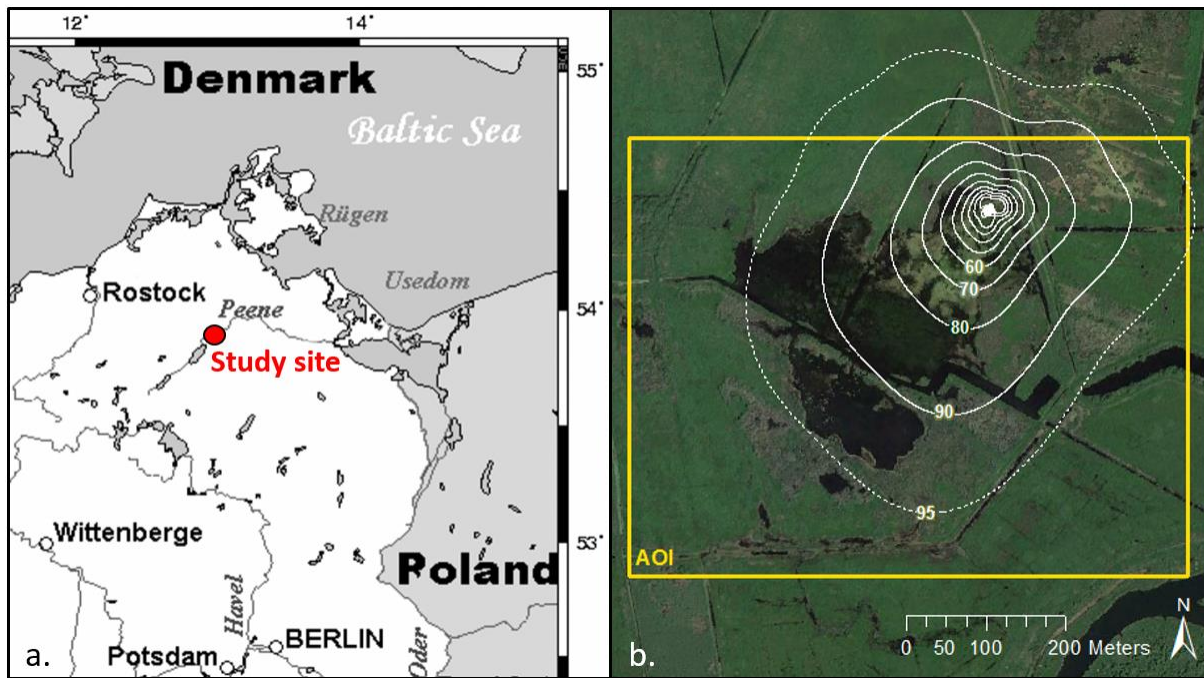
Reference	Location, ecosystem type	Dominant plant species	Study year	Average water depth (m)	NEE (g CO ₂ m ⁻² a ⁻¹)	CH ₄ (g CH ₄ m ⁻² a ⁻¹)
Huttunen et al. (2003), CH	Lake Postilampi, Finland: hypertrophic lake		1997	3.2		16 (A)
Casper et al. (2000), TR/CO	Priest Pot, UK: hypertrophic lake		1997	2.3		13 (A)
Ducharme-Riel et al. (2015), CO	Bran-de-Scie, Quebec: eutrophic lake		2007-2008	3.2	224 (A)	
Wang et al. (2006), CH	Taihu Lake, China, hypertrophic lake: - bare infralittoral zone - pelagic zone		2003-2004	0.5 to 1.8 1.8		3 (A) 4 (A)
Hendriks et al. (2007), CH	Horstermeer, The Netherlands: eutrophic ditches		2005-2006 2006	> 0 > 0		47.5 (A) 49 (A)
Waddington and Day (2007), CH	Bois-des-Bel peatland, Quebec: - ponds - ditches		2000-2002	> 0 > 0		0.3 (S) 2.9 (S)†
Naimann et al. (1991), CH	Kabetogama Peninsula, Minnesota, beaver pond: - submergent aquatic plants - deep water	<i>Utricularia spp.</i> , <i>Potamogeton spp.</i>	1988	0.45 1.25		14 (A) 12 (A)
Roulet et al. (1992), CH	Low forest region, Ontario: beaver ponds		1990	0.2 to 0.4		7.6 (A)
Bubier et al. (1993), CH	Clay Belt, Ontario: beaver pond		1991	0.5 to 1.5		44 (A)
Yavitt et al. (1992), CH	New York, beaver ponds: - 3 years old - > 30 years old		1990	≤ 2 ≤ 2		34 (A) 40 (A)

1330 Table 5: Annual (A)/seasonal (S) NEE, GPP, R_{eco} and net CH₄ exchange at *Typha* sites. Positive water
 1331 level indicates inundated soil. GHG flux measurement methods are denoted as: CH = chambers, EC =
 1332 eddy covariance.

Reference	Location, ecosystem type	Dominant plant species	Study year	Mean water level (m)	NEE (g CO ₂ m ⁻² a ⁻¹)	GPP (g CO ₂ m ⁻² a ⁻¹)	R _{eco}	CH ₄ (g CH ₄ m ⁻² a ⁻¹)
Kankaala et al. (2004), CH	Lake Vesijärvi, Finland: - inner cattail-reed zone	<i>Phragmites australis</i> , <i>Typha latifolia</i>	1997	< 0.1 to > 0.2				51 (S) ¹
			1998	< 0.1 to > 0.2				43 (S) ¹ , 6 (S) ²
Chu et al. (2015), EC	- outer cattail-reed zone	<i>Phragmites australis</i> , <i>Typha latifolia</i>	1997	< 0.1 to > 0.2				30 (S) ¹
			1998	< 0.1 to > 0.2				23 (S) ¹ , 7 (S) ²
			1999	< 0.1 to > 0.2				23 (S) ¹
			2011	0.3 to 0.6	-289 (A)	-3338 (A)	3049 (A)	58 (A)
Bonneville et al. (2008), EC Strachan et al. (2015), NEE: EC, CH4: CH	Lake Erie, Freshwater marsh	<i>Nymphaea odorata</i>	2012	0.3 to 0.6	109 (A)	-3490 (A)	3599 (A)	76 (A)
			2013	0.3 to 0.6	340 (A)	-2666 (A)	3006 (A)	70 (A)
			2005-2006 2005-2009	winter > summer ≈ 0	-967 (A) -462 to -1041 (A)	-3045 (A)	2078 (A)	170 (A)
Whiting and Chanton (2001), CH	Virginia, freshwater marsh	<i>Typha latifolia</i>	1992-1993	0.05 to 0.2	-3288 (A)			109 (A)
			1992 1993	0.05 to 0.2 0.05 to 0.2	-3587 (A) -4177 (A)			69 (A) 96 (A)
Rocha and Goulden (2008), EC	San Joaquin Freshwater Marsh Reserve, California: - freshwater marsh	<i>Typha latifolia</i>	1999 2000 2001 2012	winter +, midsummer - winter +, midsummer - winter +, midsummer - 1.07		-3994 (A) -6006 (A) -7717 (A)	4811 (A) 5980 (A) 6721 (A)	71 (A)
Knox et al. (2015), EC	- wetland (rewetted 2010)	<i>Schoenoplectus acutus</i> , <i>Typha</i> spp.	2012	0.26	-1455 (A)	-5519 (A)	4064 (A)	52 (A)
			2010	0.51	388 (A)			21 (A)
Petrescu et al. (2015), EC	- wetland (rewetted 2010)	?	2010	0.51	388 (A)			21 (A)
			2010-2011 2011-2012	40.13 < 0.130-7	553 (A) -414 (A)	-2825 (A) -3980 (A)	3375 (A) 3566 (A)	80 (A) 91 (A)
Minke et al. (2015), CH	Giel'cykau' kašy, Belarus, fen (rewetted 1985)	<i>Typha latifolia</i> , <i>Hydrocharis morsus-ranae</i>	2011	0.02	-156 (A)			13 (A)
			2012	-0.09	345 (A)			4 (A)
Günther et al. (2015), CH	Treibtal, Germany, fen (rewetted 1997)	<i>Typha latifolia</i>	2002	0.07	975 (A)	-3272 (A)	4064 (A)	39 (A)
			2003	0.03	1653 (A)	-4357 (A)	6010 (A)	29 (A)
Wilson et al. (2007, 2008), CH	Turraun, Ireland, cutover bog (rewetted 1991)	<i>Typha latifolia</i>	2002 2003	0.07 0.03	975 (A) 1653 (A)	-3272 (A) -4357 (A)	4064 (A) 6010 (A)	39 (A) 29 (A)

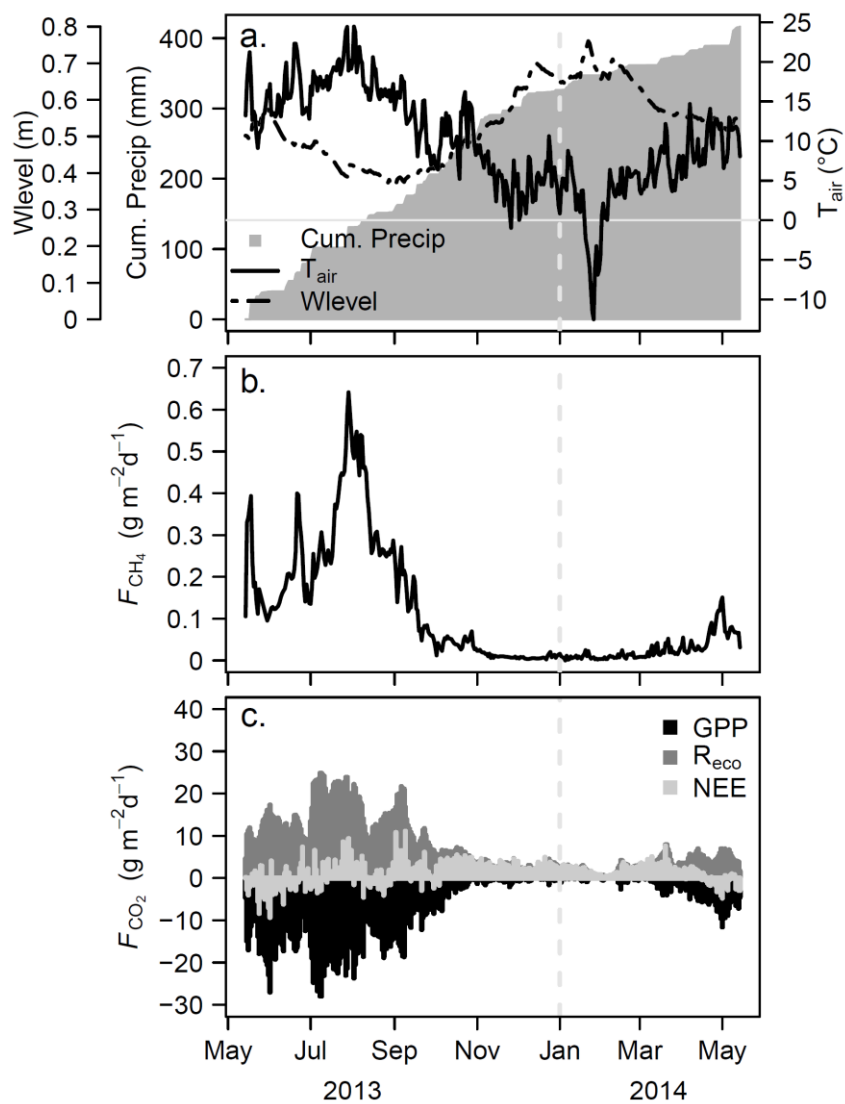
¹ open water period

² winter



1333
 1334 Figure 1: a) Polder Zarnekow is situated in NE Germany within the Peene River valley; map source and
 1335 copyright: <https://commons.wikimedia.org/wiki/File:Germanymap2.png> (modified). b) Footprint
 1336 climatology calculated according to Chen et al. (2011) on a Landsat image (6 Jun 2013, source: Google
 1337 Earth). White lines represent the isopleths of the cumulative annual footprint climatology, where the
 1338 area within the 95 isopleth indicates 95 % contribution to the annual flux. The white dot denotes the
 1339 tower position. The yellow box indicates the area of interest (AOI) as a filter criterion to focus on fluxes
 1340 of the shallow lake and to avoid the possible impact of a farm and grassland to the north of the shallow
 1341 lake. If the half-hourly flux source area exceeded the AOI by more than 20 % the flux was discarded.
 1342 The site is characterised by two main surface types: open water and emergent vegetation.

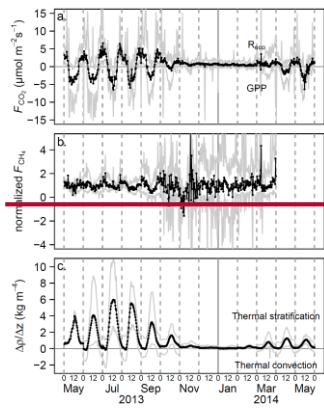
1343



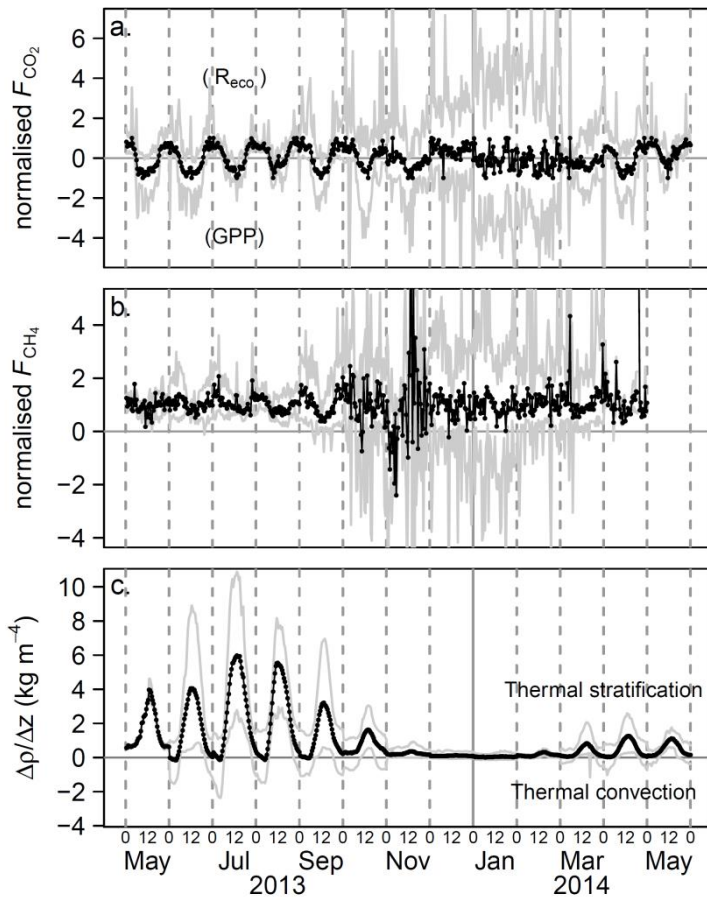
1344

1345 Figure 2: Temporal variability of environmental variables and ecosystem CO₂ and CH₄ exchange within
 1346 the EC source area. Seasonal course a) of water level (Wlevel), cumulative precipitation (Cum. Precip)
 1347 and air temperature (T_{air}), b) the daily CH₄ flux (gapfilled, NLR_{CH4nofoot}) and c) the daily NEE (gapfilled
 1348 LUTMDS_{CO2nofoot}) and component fluxes (modelled R_{eco} and GPP, LUTMDS_{CO2nofoot}).

1349



1350



1351

1352 Figure 3: Average diurnal cycle of a) CO₂ flux, b) CH₄ flux and c) the water density gradient per month.

1353 The numbers at the x-axis denote midnight (0) and midday (12). Midnight is also illustrated with a

1354 dashed line. Black and grey lines represent the mean and the range, respectively. ~~The CH₄ fluxes are~~

1355 ~~normalized with the monthly median of the half-hourly fluxes. Positive CO₂ fluxes represent the~~

1356 ~~dominance of R_{eco} against GPP, negative fluxes the dominance of GPP against R_{eco}. The CO₂ and CH₄~~

1357 ~~fluxes are normalised with the monthly minimum/ maximum and the median of the half-hourly fluxes,~~

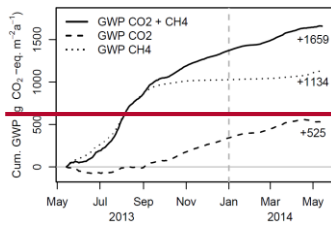
1358 ~~respectively. Although the zero line is slightly shifted due to normalisation, positive CO₂ fluxes roughly~~

1359 ~~indicate the dominance of R_{eco} against GPP, negative fluxes the dominance of GPP against R_{eco}. The~~

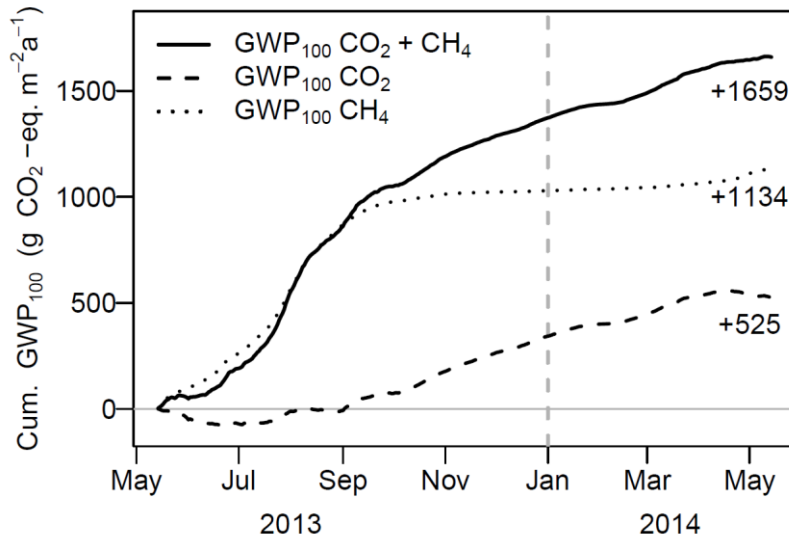
1360 period of ice-cover was excluded from the calculation of the temperature gradient. A density gradient

1361 equal to or below zero indicates thermally induced convective mixing down to the bottom of the open
1362 water body of the shallow lake, positive gradients instead thermal stratification.

1363



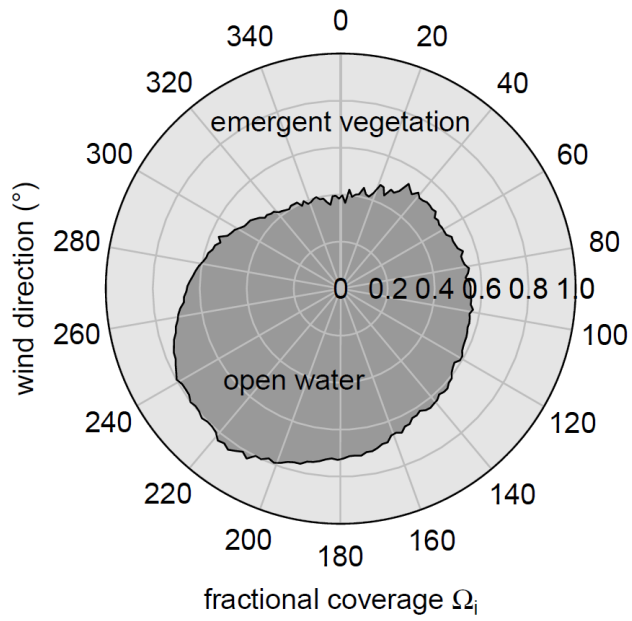
1364



1365

1366 Figure 4: Cumulative GWP_{100} budgets of CO_2 (based on $MDSLUT_{CO2nofoot}$), CH_4 (based on $NLR_{CH4nofoot}$) for
 1367 the EC source area and the sum of both for the EC source area during the observation period.

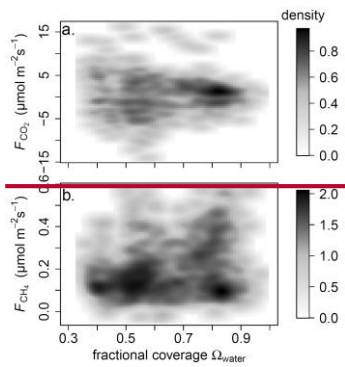
1368



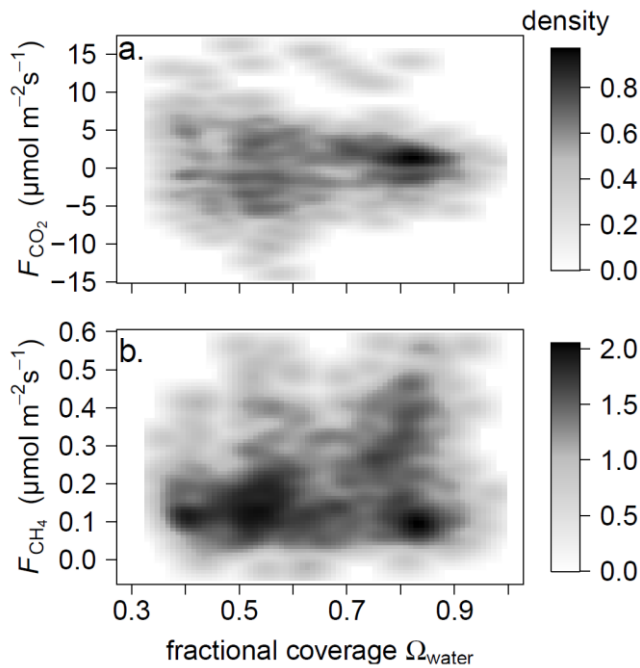
1369

1370 Figure 5: Source area fraction Ω_i of the two main surface types in dependence on the wind direction
 1371 (2° -bins).

1372



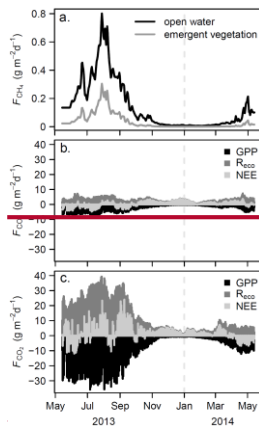
1373



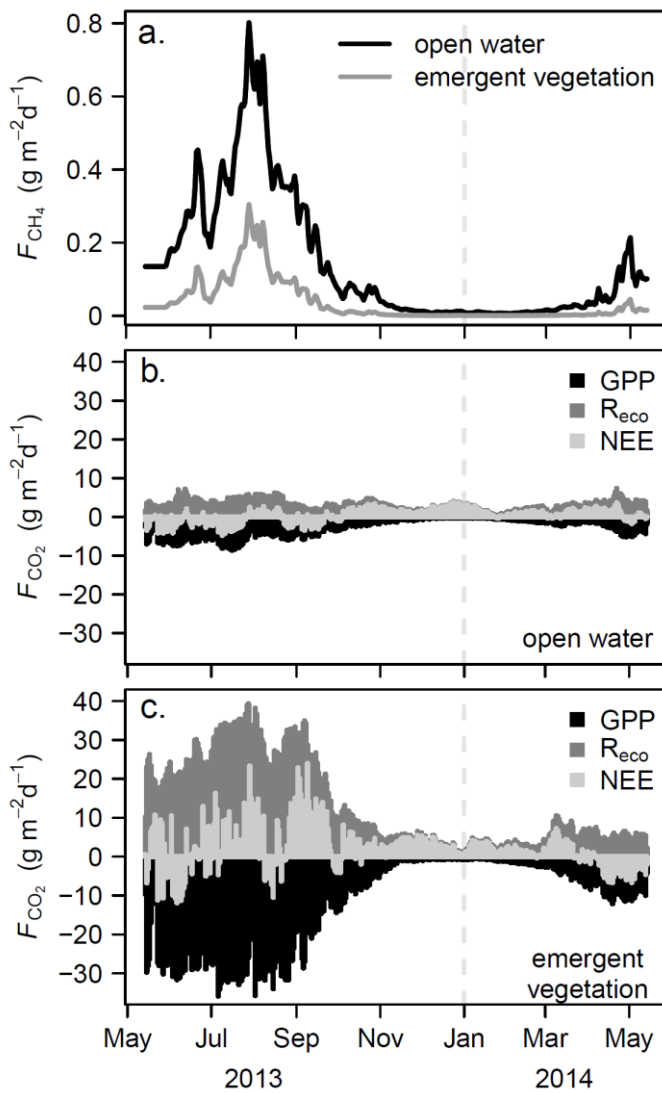
1374

1375 Figure 6: Impact of the fractional coverage of open water (Ω_{water}) within the EC source area on the
 1376 measured fluxes of CO_2 and CH_4 (15 May to 14 September 2013). The abundances of CO_2 and CH_4 fluxes
 1377 in dependence on Ω_{water} are illustrated by a smoothed two-dimensional kernel density estimate. The
 1378 variability of CO_2 flux rates decreased with increasing Ω_{water} , whereas the variability of the CH_4 flux
 1379 increased.

1380



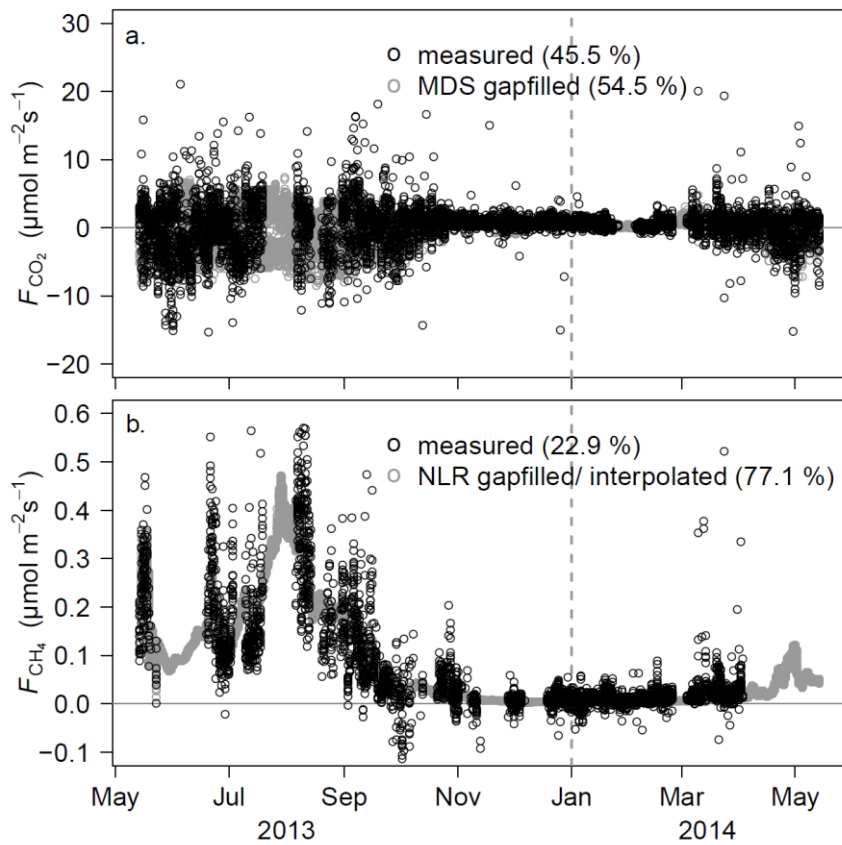
1381



1382

1383 Figure 7: Daily CH_4 , NEE and component fluxes (R_{eco} and GPP) for the surface types: a) daily CH_4 flux of
 1384 open water and emergent vegetation, b) daily NEE and component fluxes for open water, c) daily NEE
 1385 and component fluxes for emergent vegetation, derived by NLR with the source area fractions of the
 1386 surface types (Ω_i) as weighting factors ($\text{NLR}_{\text{CH}_4\text{foot}}$, $\text{NLR}_{\text{CO}_2\text{foot}}$).

1387



1388

1389 Figure A1: Data coverage of a) CO₂ and b) CH₄ fluxes within the study period. Gapfilling results of the
 1390 MDS_{CO2nofoot} and NLR_{CH4nofoot} approaches are added as grey circles. The percentages in brackets indicate
 1391 the time series coverages of measurements and gapfilling values.

1392