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1 **Impact of fertilizer, water table, and warming on celery yield and CO₂ and CH₄**
2 **emissions from fenland agricultural peat.**

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19 **Abstract**

20 Peatlands are globally important areas for carbon preservation; although covering only
21 3% of global land area, they store 30% of total soil carbon. Lowland peat soils can also
22 be very productive for agriculture, but their cultivation requires drainage as most crops
23 are intolerant of root-zone anoxia. This leads to the creation of oxic conditions in
24 which organic matter becomes vulnerable to mineralisation. Given the demand for
25 high quality agricultural land, 40% of the UK's peatlands have been drained for
26 agricultural use.

27 In this study we present the outcomes of a controlled environment experiment
28 conducted on agricultural fen peat to examine possible trade-offs between celery
29 growth (an economically important crop on the agricultural peatlands of eastern
30 England) and emissions of greenhouse gases (carbon dioxide (CO₂) and methane (CH₄))
31 at different temperatures (ambient and ambient + 5°C), water table levels (-30 cm, and
32 -50 cm below the surface), and fertilizer use.

33 Raising the water table from -50 cm to -30 cm depressed yields of celery, and at the
34 same time decreased the entire ecosystem CO₂ loss by 31%. A 5°C temperature
35 increase enhanced ecosystem emissions of CO₂ by 25% and increased celery dry shoot
36 weight by 23% while not affecting the shoot fresh weight. Fertilizer addition increased
37 both celery yields and soil respiration by 22%. Methane emissions were generally very
38 low and not significantly different from zero.

39 Our results suggest that increasing the water table can lower emissions of greenhouse
40 gases and reduce the rate of peat wastage, but reduces the productivity of celery. If
41 possible, the water table should be raised to -30 cm before and after cultivation, and
42 only decreased during the growing season, as this would reduce the overall
43 greenhouse gas emissions and peat loss, potentially not affecting the production of
44 vegetable crops.

45 **Keywords:** agriculture, peatland, carbon loss, land use change, mitigation

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57 **Introduction**

58 Peatlands cover only 3% of the world's land area, but store 30% of total soil carbon
59 (Global Environmental Centre, 2008). At the same time, peat soils are widely utilised in
60 agriculture: in Europe 14% of the peatland area is under cultivation (Global
61 Environmental Centre, 2008), whilst in the UK, 40% of peatlands have been drained for
62 agricultural use (Dixon et al., 2014) and 24% of the deep peat area in England is being
63 farmed (Natural England, 2010). One of the most important regions for crop
64 production on lowland peats in the UK is the East Anglian Fenlands (the Fens): an area
65 of approximately 3800 km² of drained peat in England covering parts of
66 Cambridgeshire, Norfolk, West Suffolk and Lincolnshire (Darby, 1956) (Figure 1). Of this
67 Fenland area, 88% is cultivated, sustaining around 4000 farms and supplying 37% of
68 total vegetable production in England (NFU, 2018). An estimated 89% of the Fens are
69 classified as either Grade 1 or 2 agricultural land: the best scores on a five grade scale,
70 which describes suitability for cultivation in England and Wales, where more valuable
71 crops with higher nutritional and water demands such as vegetables are cultivated
72 (NFU, 2018). The fenland soils are especially fertile and account for nearly half of the
73 Grade 1 agricultural land in England. Cultivation of peat soil requires drainage as most
74 crops are intolerant of root-zone anoxia. This leads to the creation of oxic conditions in
75 the upper part of the peat column, resulting in increased vulnerability of the organic
76 matter to mineralisation by aerobic microorganisms and therefore peat wastage
77 (Global Environmental Centre, 2008). It is estimated that Fenland peats store 41 Tg of
78 carbon, which is being lost from the ecosystem at a rate of 0.4 Tg C yr⁻¹ (Holman and

79 Kechavarzi, 2011). The drainage-induced volume loss of the peat layer via shrinkage
80 results in soil compaction and oxidation, which cause wastage of thick peat (> 1m) at a
81 rate of about 2.1 cm yr⁻¹ and of thin peat (< 1m) at a rate of 1.3 cm yr⁻¹ (Holman and
82 Kechavarzi, 2011). This rate of loss means that most of this important area for UK
83 vegetable production will have less than 100 years of cultivation left before the peat is
84 depleted with potential substantial impact on food security.

85 Shrinkage, compaction and oxidation could be reduced by raising the water table; this
86 has the potential to extend the lifespan of the fertile soil of the Fens. Furthermore,
87 since large areas of the Fens have already sunk below sea level, maintaining drainage
88 requires expensive pumping of water and thus the Fens are increasingly threatened by
89 sea level rise. It is, therefore, crucial to explore the possibility of using a water table
90 level that minimises current peat loss and reduces the need to pump water, while at
91 the same time maintaining economically viable crop growth.

92 Although the position of the water table is often credited with being of key importance
93 in determining the rate of mineralisation of organic matter, there is insufficient
94 information to guide farmers and farm managers as to the optimal water table
95 position for each specific crop: the majority of studies focus on examining the yield of
96 cereals under different drainage scenarios – for example, wheat (Xu et al., 2013), and
97 maize (Florio et al., 2014). Very little work has been published on the performance of
98 horticultural field crops grown under varying water table levels, with studies offering
99 conflicting results (Dodds et al., 1997; Stanley and Harbaugh, 2002; Musarika et al.,
100 2017).

101 Mineralization of organic matter also affects the climate by increasing the emission of
102 greenhouse gases (GHG) such as CO₂ and CH₄. The majority of studies on the impact of
103 the water table on GHG emissions in temperate and northern peatlands demonstrate
104 that a rise in the position of the water table decreases emissions of CO₂ while
105 increasing release of CH₄ (Nykanen et al., 1995, Dinsmore et al., 2009, Wilson et al.,
106 2016, Karki et al., 2016 Strack et al., 2004, Hou et al., 2013, Poyda et al., 2016, Regina
107 et al., 2015, Yrjälä et al., 2011). However, in several studies no link has been found
108 between the water table level and GHG emissions (Regina et al., 2007, Lafleur et al.,
109 2005; Schrier-Uijl et al., 2010, Muhr et al., 2016; Dirks et al., 2000). Despite the
110 importance of preserving agricultural peats and reducing GHG emissions, there is a
111 lack of studies testing more sustainable water table levels which could both maintain
112 current crop yield and minimise GHG emissions (Regina et al., 2015; Taft et al., 2017;
113 Taft et al., 2018). While a deeper water table (-40 to -50 cm) could maximize yield, a
114 shallower water table (e.g. -30 cm) might be able to maintain 90% of the productivity
115 whilst reducing peat mineralisation by 30-40% (Renger et al., 2002) thereby
116 substantially extending the future potential numbers of years of cropping before
117 complete peat wastage.

118 The carbon loss from the Fens can also be stimulated by increases in temperature. The
119 average global temperature increase expected for this region is expected to be within
120 the range of 0.3-4.8°C by the end of this century (relative to 1986-2005) (IPCC, 2014). It
121 is estimated that under the highest greenhouse gas emission scenario, temperatures in
122 Eastern England would rise by 1.4°C to 5.7°C in winter and by 1.3°C to 7.5°C in summer

123 by 2080 (IPCC, 2014). Rising temperatures are predicted to accelerate the rate of
124 organic matter mineralisation, which will lead to higher emissions of greenhouse gases
125 as well as increased plant growth due to enhanced availability of nutrients which are
126 released during mineralisation (Rustad et al., 2001). The effects of higher temperatures
127 on both crop growth and GHG emissions are still highly uncertain.

128 To address these critical issues discussed above, in this study we explored the impacts
129 of water table, fertilization and warming, on mineralisation of Fen peat, the yield of
130 celery as well as the emissions of CO₂ and CH₄, and the carbon leaching out of the
131 system as dissolved organic carbon (DOC). We hypothesise that increasing the water
132 table from a field depth of -50 cm to -30 cm would not affect celery yield, would
133 decrease emission of CO₂ while only slightly increasing CH₄ flux, and would increase
134 DOC concentration in drainage water. We expect that increasing the temperature (by
135 5°C) would increase celery yield and increase DOC in the soil water, raise CO₂
136 respiration but only slightly affect CH₄ emission. Finally, we hypothesize that
137 fertilization would increase celery yield, increase GHG emissions and increase DOC
138 loss.

139

140

141 **Methodology**

142 Sample area and soil collection

143 Peat cores were sampled from a typical fen peatland at Rosedene Farm in Methwold
144 Hythe, Norfolk, that has been drained after World War II, intensively cultivated,
145 fertilized and used to grow vegetables including celery. The crops are rotated each
146 year, most common crops includes celery, lettuce, Chinese leaf, bulb onions, potatoes,
147 red beet, radish, carrots, and leeks. Although we sampled from a single field, these flat
148 peatlands are highly homogeneous, having undergone the same oxidative processes to
149 the same depths, as the water-tables are fixed to standard depths over large areas,
150 and similar high-value crops are widely grown on these soils. The historical studies of
151 Methwold peat close to the sampled field in our study have shown that across 12 sites
152 more than 20 years of intensive agriculture on drained peat has led to homogenization
153 of the top 50 cm into uniformly amorphous humified peat irrespective of earlier
154 differences in the peat which ranged from semi-fibrous to fibrous in the early 1980's
155 (Dawson et al., 2010). The sampling site is within 1-2 km of a flux tower measuring CO₂
156 fluxes from these agricultural peatlands at Methwold (Morrison et al., 2013). Rainfall in
157 the Fens is below 600 mm a year and the soil of the area is predominately peat, which
158 can be as deep as 2-3 m (Evans et al., 2016). The C:N ratios for the site are presented in
159 Evans et al., (2016), and are low (15:1) due to management practices such as nitrogen
160 fertilizer additions. Moreover, bulk density varied with location and depth depending
161 on the time of year. In particular the surface bulk density was measured to range from
162 0.3 – 0.5 g cm⁻³ and with depth (0-1 m) between 0.3 – 0.7 g cm⁻³ (Evans et al., 2016).
163 In the typical field at Rosedene Farm selected for sampling, the farmer maintains the
164 water table position at about -50 cm for crop production, mainly as a higher water

165 table might affect the use of machinery on site (Martin Hammond, pers. comm.). A
166 total of 64 peat cores with a diameter of 11 cm were randomly sampled to a depth 60
167 cm from across the field in April 2015 (Figure 1), using a sampling design reported in
168 Musarika et al. (2017).

169 The soil core collection was performed using PVC pipes, which were inserted into the
170 soil. The PVC pipes were excavated out of the ground, preserving the existing soil
171 structure of intact cores within the pipes. The pipes were capped at the bottom to
172 retain the field soil moisture.

173

174 Treatment design

175 We tested the hypotheses in a multifactorial experiment that varied the water table
176 (two levels -30 cm, and -50 cm below the surface), the air temperature (ambient and
177 ambient + 5°C), and two fertilization levels (liquid fertilizer -see details below, and
178 without any fertilisation) on peat cores incubated in controlled environment chambers
179 for a simulated growing season. Celery was chosen as the study species as it is one of
180 the most profitable crops according to the farmer (Martin Hammond, pers. comm.),
181 and it is a marshland plant and therefore should be well-adapted to conditions of an
182 elevated water table (Seale, 1975). Celery was planted in half of the 64 cores collected
183 from the field, while the other half of the cores were left unplanted. The full
184 combination of experimental factors (water table, air temperature, fertilizer and crop)
185 were replicated four times as shown in Figure 2.

186

187 The two water table levels represent the current conditions in the field (-50 cm) and
188 the level (-30 cm) which has been proposed to reduced greenhouse gas emissions and
189 retain productivity of a grassland (Renger et al., 2002), and radish (Musarika et al.,
190 2017). The water table in each core was monitored with the use of 20 mm diameter
191 drainage pipes with holes every 1 cm wrapped in fine nylon mesh to prevent clogging
192 of the holes with soil. The water table was measured once a day in the drainage pipe
193 with a marked stick and distilled water was added in the pipe if necessary to maintain
194 the water table at the set level. Towards the end of the experiment, the water table
195 was measured and adjusted twice a day to compensate for higher evaporation which
196 resulted from the elevated temperatures.

197 In order to regulate temperature conditions, the cores were placed in two CONVIRON
198 BDW 40 growth chambers (CONVIRON Controlled Environments Ltd., Winnipeg,
199 Manitoba, Canada). Inside the chambers the air temperature was regulated in real
200 time with an accuracy of ± 0.5 °C.

201 The ambient temperature was set to the weekly average daytime temperature
202 collected from a meteorological station in the field over a three year period (2013-
203 2015, Cumming et al. unpublished data). This resulted in an ambient temperature
204 equal to 17 °C at the beginning of the experiment, which was then raised to 18 °C in
205 week 4, to 19 °C in week 5, and to 20 °C from week 6 until the end of the experiment
206 reflecting the field conditions in June, July and August. The elevated temperatures
207 followed this same pattern – i.e. commencing at 22 °C and rising to 25 °C. The elevated

208 temperature of + 5 °C was chosen as it represents IPCC's most extreme global warming
209 scenario: RCP 8.5, which predicts a global temperature rise of 4.8 °C by the end of this
210 century (IPCC, 2014).

211 The fertilised cores were treated with the same fertiliser that is used by the farmer on
212 the celery crop: liquid CHAFER 6-6-12 ($[\text{NH}_4\text{PO}_3]_n$ - ammonium polyphosphate), which
213 has the following composition: N – 6% w/v, K_2O – 12% w/v, and P_2O_5 – 6% w/v. It was
214 applied at the same rate that the farmer uses for the celery crop: 800 l ha⁻¹. The
215 fertiliser was dissolved in 25 ml DI water before application by watering of the cores.
216 The PVC pipe used in this experiment has a cross-sectional area of 94.99 cm²,
217 therefore each core from the fertilised treatment was enriched with 0.8 ml CHAFER 6-
218 6-12, which was diluted in 25 ml distilled water prior to addition.

219 The air humidity in both chambers was kept constant at 70% and the PAR (Photo-
220 synthetically Active Radiation) varied between 670-740 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Air humidity and
221 PAR settings of this experiment are based on the average June, July and August
222 conditions recorded from the field in years 2013, 2014 and 2015 and are consistent
223 with a previous experiment on radish using soil cores from this site (Musarika et al.,
224 2017). In both chambers the daylight conditions lasted 12 h (12 h for night conditions)
225 throughout the growth period. Soil water content was measured in the top 12 cm
226 every week with a Campbell Scientific CS655 probe.

227

228 Crop planting and biomass measurements

229 The experiment lasted for a total of 14 weeks. In week one pre-germinated three-
230 weeks-old celery seedlings were planted into half of the peat cores. Fertiliser was
231 added only once, one day before planting. In week 14 the celery was harvested and
232 separated into shoots (leaves and stems) and roots. The cores were excavated and the
233 roots were extracted by washing the peat with tap water under a 1 mm sieve (initial
234 separation) and a 600 µm sieve (final separation). Afterwards the root samples were
235 dried at 80°C for 3 days and weighed to a precision of 0.01 g (dry root biomass). The
236 shoots were also weighed before drying (wet biomass) and after drying for 3 days at 80
237 °C (dry biomass).

238

239 Greenhouse gas fluxes

240 CO₂ and CH₄ concentrations were measured once a week for 11 weeks using an LGR
241 Ultra Portable Gas Analyser GGA-30p (Los Gatos Research, Mountain View, CA, USA),
242 with a measurement frequency of one hertz (one measurement per second). Two
243 custom-made PVC chambers both with a volume of 2.8 L were used to record fluxes,
244 one transparent for light measurements (e.g. net ecosystem exchange, NEE) and an
245 opaque chamber for dark measurements (indicated as ecosystem respiration, (ER) in
246 the cores with celery presence, and soil respiration (Rh) in the cores with the absence
247 of the crop). The autotrophic respiration was estimated as the difference between 1)
248 the ecosystem respiration in the planted cores, and 2) the ecosystem respiration in the
249 cores where no crops were planted. The chambers were placed on the top of pipes as
250 shown in Figure 3. The gross primary production (GPP) was estimated as the sum of ER

251 and NEE. The rates of change in gas concentration in the chambers were used to
252 estimate the CO₂ and CH₄ fluxes as described in McEwing et al. (2015). We also used
253 flux tower data collected at Methwold (Morrison et al., 2013), close to our sampled
254 field, for comparison with chamber GHG measurements. The flux tower data covered
255 60 days of crop cycle from 22 June to 20 August 2012, and a 60 day fallow period to 19
256 October 2012 (Morrison et al., 2013).

257

258 Dissolved organic carbon (DOC) in water samples

259 Samples for DOC analysis were collected from the bottom of cores at -50 cm into 20 ml
260 vials with a syringe connected to a pipe, filtered through Fisherbrand M300 0.7 µm
261 glass fibre filters within 8 hours of collection and refrigerated at 6 °C in plastic vials.
262 The vials were previously washed in a solution of 10% nitric acid and 10% hydrochloric
263 acid to remove easily-released carbon. Afterwards the samples were analysed on a
264 Sievers 5310C Total Organic Carbon (TOC) Analyser. Potassium hydrogen phthalate
265 TOC calibration standards at concentrations of 1, 5, 10 and 30 mg l⁻¹ were run with
266 each batch of samples. Samples were diluted with ultrapure (18 MΩ) deionised water
267 to bring them within the analytical range. The detection limit was 4 µg l⁻¹.

268

269 Statistical analysis

270 Statistical analysis was performed using the open source programme R version 3.3.1 (R
271 Development Core Team, 2017). The CH₄, NEE and ecosystem respiration fluxes were

272 log-transformed, to meet the assumptions of linear models, and ANOVA. We used
273 both linear models and linear mixed models as described in the following paragraphs.
274 Linear mixed effects models were used to test the effects of water table level,
275 temperature and fertiliser use on celery biomass and emissions of CO₂ and CH₄ for the
276 entire dataset including weekly measurements, with 'week' and 'core' as random
277 effects, to take into account the temporal and spatial pseudoreplication. Linear models
278 were used on the fluxes averaged over the entire experiment. The linear mixed models
279 and the linear models were then compared to test if the averaging removed some
280 important information. Outliers, as determined by the Cook's distance which affected
281 the CH₄ flux models, were removed. For the linear mixed models analyses we used the
282 lme4 package (Bates, Maechler and Bolker, 2014) and reported χ^2 in the place of the F-
283 value. The linear models were estimated using the "lm" function in R. The DOC values
284 were averaged across weeks. The biomass and DOC data sets were analysed using
285 ANOVA. The adequacy of all models was assessed by visual inspection of residual plots.
286 When mixed effects models were used, the statistical significance of each factor was
287 determined by likelihood ratio tests performed with the Anova () function between the
288 full model and a model that only included the random effects (weeks and cores). The
289 statistical significance levels used were P-value <0.05 and >0.01 (*); P-value < 0.01 and
290 > 0.001 (**), and P-value <0.001 (***)).

291

292

293 **Results**

294 The fresh weight of celery shoots was on average 19% lower with the water table at -
295 30 cm compared to the normal depth of -50 cm (Table 1; Figure 4a). The same trend
296 was followed by the dry weight of celery shoots (Table 1), which were also on average
297 19% lower in the -30 cm water table treatment (Figure 4b). Celery shoot fresh weight
298 was not significantly affected by temperature (Table 1; Figure 4a), while the dry weight
299 was 23% higher in the elevated temperature treatment (Table 1; Figure 4b). Fertiliser
300 use increased the shoot fresh weight by 22% (Table 1; Figure 4a) and the dry weight by
301 21% (Table 1) (Figure 4b). Root dry weight was 33% lower in the -30 cm water table
302 treatment (Table 1) and remained unaffected by temperature (Table 1; Figure 4b).
303 Fertilized cores had 18% higher root dry weight than the unfertilized cores (Table 1;
304 Figure 4b). There were no statistically significant interactions among any of the
305 treatment factors (temperature, water table level, fertiliser treatment) on shoot and
306 root biomass. The root:shoot dry weight ratio was 18% lower (Table 1) in the -30 cm
307 water table treatment and was 24% higher (Table 1) in the ambient temperature
308 treatment (Figure 4c). There was no significant effect of fertiliser addition on the
309 root:shoot ratio (Table 1; Figure 4c).

310 Soil respiration (Rh) was 25% higher in the elevated temperature treatment (Table 2)
311 than in the ambient conditions and also 31% higher in the -50 cm water table
312 treatment (Table 2) (Figure 5a) than with a -30 cm water table. The Rh was 22% higher
313 in the fertilised cores as compared with those not fertilised (Table 2) (Figure 5a).

314 Ecosystem respiration (ER) was also affected by temperature, being higher in the
315 elevated temperature treatment (Table 2; Figure 5c), but there were no significant

316 differences in ER between the two water table levels and the fertiliser treatments
317 (Table 2; Figure 5c).

318 Gross Primary Production (GPP) was greatest in cores under elevated temperature
319 (Table 2), while water table depth and fertiliser addition did not appear to have a
320 significant influence on these values (Table 2; Figure 5d). None of the interactions
321 among factors was significant for GPP. Net Ecosystem Exchange was not significantly
322 affected by any of the factors (Table 2).

323 While the statistical results were fairly consistent for NEE, RE or Rh and GPP, there was
324 a difference in the outcomes between the two statistical approaches employed for the
325 CH₄ fluxes (Table 2). The linear model (Table 2, left columns) showed that the water
326 table and fertiliser treatments had no effect on the CH₄ flux, however, the presence of
327 the crops and temperature showed significant effects on CH₄ fluxes (Table 2; Figure 6).
328 In the linear mixed model (Table 2, right columns) CH₄ fluxes were unaffected by
329 temperature, water table, and fertiliser use, however, there was an effect of the
330 presence of the crops. Based on the linear model, the elevated temperature resulted
331 in more than doubling in the averaged emissions compared to ambient conditions, and
332 a shift from CH₄ consumption to CH₄ loss into the atmosphere. On average, planted
333 cores had more than twice the rate of CH₄ emissions when compared to the unplanted
334 cores, but the planted cores with a -50 cm water table showed both CH₄ consumption

335 and emission. Soil moisture did not influence CH₄ flux in either the linear model (Table
336 2, left columns) or the linear mixed model (Table 2, right columns).

337 DOC concentrations were 45% higher in the elevated temperature treatment, and 22%
338 higher in the -30 cm water table treatment (these differences were statistically
339 significant, Table 3). DOC concentrations were 40% lower in cores with crop presence
340 and were not affected by fertiliser addition (Table 3). There was a statistically
341 significant interaction between water table and crop presence on DOC concentration
342 (Table 3).

343 Soil water content was significantly affected by the presence of the crops and water
344 table level, but there was no effect of temperature (Table 3).

345

346

347 **Discussion**

348

349 Celery biomass

350 A higher water table increases the risk of root waterlogging, which may have a
351 negative impact on yield. In our experiment celery roots extended until they reached
352 the water table and the deeper (-50 cm) water table treatment resulted in greater root
353 expansion, explaining the differences in root weight between the two treatments. This
354 indicates that nutrient limitation might be a possible cause of lower root and
355 aboveground biomass from the -30 cm water table treatment (Oomes et al., 1996),
356 which is also consistent with the observed higher biomass with fertiliser addition in our
357 experiment. Our findings are consistent with those of Dodds et al. (1997) who found
358 reduced tomato fruit biomass when a water table was maintained at -30 cm as
359 compared to -60 cm. In contrast, Musarika et al. (2017), who used a similar design to
360 the present study to observe how raising the water table from -50 to -30 cm affected
361 the yield of radish, found improved growth with the shallower water table. This could
362 be due to a higher tolerance to waterlogged conditions of radish and to its shallower
363 and less dense rooting system, and possibly lower nutrient limitation. Similarly, Stanley
364 and Harbaugh (2002) also found increased biomass of *Caladium* under a shallower
365 water table (i.e. -30 to -45 cm vs -60 cm).

366

367 The higher shoot biomass in cores exposed to elevated temperatures and deeper
368 water table shows that celery growth will be favoured by warming temperatures and
369 well-drained soils. The maximum temperature used during this experiment (20 °C and
370 25 °C) and the result of our study are similar to the temperature treatments (19 °C and
371 24 °C) used by Heißner et al. (2006) which also showed higher asparagus fresh-biomass
372 in the elevated temperature treatment. It has to be noted, however, that differences
373 in the biomass of crops grown at different temperatures may be affected by plant
374 water limitation due to higher evaporative demand at higher temperatures, rather
375 than being the direct effect of temperature (Carter et al., 2016). For example, Shaw et
376 al. (2014) showed that temperature increases above 29 °C resulted in lower yields of
377 rainfed maize, however, they found no effect on maize biomass when the plants were
378 irrigated, which points to moisture stress as a potential confounding variable in field
379 studies. For this reason, laboratory experiments (such as this one), where conditions
380 can be better controlled, can provide improved estimations of temperature effects on
381 plant properties allowing a separating moisture from other environmental controls. It
382 has been shown that in conditions of unlimited soil water supply, temperature
383 increases result in higher stomatal conductance (Urban et al., 2017; Marchin et al.,
384 2016) and higher carbon assimilation.

385 Few studies have examined the effects of soil warming on root development in
386 peatlands converted into agriculture. The results of our study are consistent with
387 findings even from very different ecosystems (e.g. arctic tundra), where increased root
388 production with warming was observed in hollows (depressions below the water

389 table), but not in hummocks (raised areas in between hollows) indicating that
390 microtopography and the position of the water table may play an important role in
391 root dynamics in peatlands (Sullivan et al., 2008). Steinaker and Wilson (2008)
392 reported that the production of roots in grassland and forest ecosystems increases
393 with higher soil temperatures. Similarly, to aboveground yield, effects of temperature
394 increases on roots may be confounded by soil moisture changes. In a grassland study
395 Xu et al. (2015) noted that soil water content in the upper soil layers decreased as a
396 result of warming and a greater portion of the rooting system was allocated to deeper
397 soil layers. Generally, a trade-off is expected between production of roots and
398 aboveground biomass as both compete for photosynthates (Radville et al., 2016), and
399 conditions which favour root development could also decrease aboveground crop
400 yield. In this study, the root dry weight was not significantly different between the
401 ambient and the elevated temperature treatments. Our results suggest that water
402 table depth is the dominant control on root development in these systems, and that
403 higher temperatures do not significantly stimulate root biomass when soil water
404 content is maintained as a constant.

405

406 Ecosystem respiration (ER) and soil respiration (Rh)

407 The higher Rh from the -50 cm water table treatment indicates that a statistically
408 significant portion of microbial decomposition occurred in the zone between -30 cm
409 and -50 cm. This indicates that the organic matter from the soil layers to a depth of -50
410 cm are still relatively easy to decompose, and can result in a significant contribution to

411 the overall carbon loss of these ecosystems. Therefore, raising the water table may be
412 a viable option for expanding the lifespan of agricultural peat and possibly the only one
413 as emissions of GHG were reported to be unaffected by practices such as no- and
414 minimum tillage (Taft et al., 2018). Nevertheless, due to negative effects on crop
415 biomass as noted in this study, raising the water table for the duration of the growing
416 season is unlikely to be adopted by farmers. Higher Rh from the elevated (+5°C)
417 temperature treatment indicates increased rates of organic matter oxidation by soil
418 microorganisms. Elevated temperatures can accelerate the decomposition of organic
419 matter by increasing microbial metabolic rate (Ziegler et al., 2013). Such rates have
420 been shown to rise in an exponential manner until 45-50°C before declining (Yiqi and
421 Zhou, 2006). This has profound implications for climate change and lifespan of peat as
422 temperature increases enhance soil CO₂ emission and thus generates a positive
423 feedback mechanism, which results in more atmospheric warming and more peat loss
424 - an effect increasingly seen across large areas of global peatlands.

425 Unlike Rh, ER was not influenced by the position of the water table. This result is
426 consistent with Lafleur et al. (2005), Dimitrov et al. (2010) and Updegraff et al. (2001);
427 however, others found higher rates of ER to be related to deeper water tables
428 (Juszczak et al., 2013; Riutta et al., 2007; Bubier et al., 2003). In our study we estimated
429 the autotrophic respiration to contribute to about 70% of ER, which is a higher value
430 than reported in Moore et al. (2002) (50%), Frohking et al. (2002) (50%), Shurpali et al.
431 (2008) (55%), Crow and Wieder (2005) (35 to 57%). Therefore, it is likely that the water

432 table-induced changes in heterotrophic respiration were offset by the effects on plant-
433 derived respiration.

434

435 Gross Primary Production (GPP) and Net Ecosystem Exchange (NEE)

436 The temperature, fertilizer and water level treatments did not affect the NEE of the
437 planted cores, which indicates that any increases in carbon loss from respiration were
438 offset by increased carbon sequestration by the celery plants. This would imply that
439 crops temporarily compensate the carbon losses by peat oxidation. However, once the
440 crops are removed the peat becomes a substantial net carbon source to the
441 atmosphere.

442 Net ecosystem exchange in disturbed peats might result in either a carbon loss or a
443 carbon storage. Site drainage history and water table level may act as factors in
444 determining NEE, however, this is not always the case. Aslan-Sungur et al. (2016)
445 reported a drained temperate peatland used in agriculture and peat mining as being a
446 strong carbon source, with NEE varying between 244 and 663 g C m⁻² yr⁻¹. On the other
447 hand, in some cases abandoned temperate peatlands can be a stronger CO₂ sink than
448 natural bogs (e.g. -128 ± 60 g C m⁻² yr⁻¹ as compared to -46 ± 36 g C m⁻² yr⁻¹) as a result
449 of greater biomass production and GPP in a drained agricultural peatland which
450 became grassland (Wang et al., 2018). In other cases drained peatlands show no
451 difference in carbon uptake after being restored (Järveoja et al., 2016). The flux tower
452 study conducted at Methwold, close to our sampled field, revealed net CO₂ release

453 from the drained agricultural fen peat to be $61.9 \pm 12.7 \text{ g C m}^{-2}$ for 120 days, covering
454 the cropping season and early autumn post-cropping (Morrison et al., 2013). This flux
455 rate is equivalent to about $0.021 \pm 0.00441 \text{ g C m}^{-2}$, similar to the ER measured in our
456 study (Figure 4). In our study, GPP was only stimulated by increased temperature,
457 suggesting that celery growth is temperature limited in this environment. However,
458 given that NEE was not significantly affected by temperature increase (Table 3), the
459 rise in carbon uptake from enhanced plant production is nullified by the increased ER.

460

461 CH₄ emissions

462 As CH₄ emissions from agricultural soils are usually much smaller than those of CO₂
463 (Zona et al., 2013; Maljanen et al., 2007; Karki et al., 2016) an increase in CH₄ release
464 might not negate the benefit of the decreased CO₂ loss with a raised water table.

465 Differences in the outcomes between the two statistical approaches used for analysing
466 the CH₄ data complicate the interpretation of the results. These results suggest that
467 once the time-series element is removed, the patterns in the flux become more visible,
468 and that temperature is a dominant control on these fluxes (see Table 3 for the linear
469 model), consistent with the high temporal variability in the fluxes potentially
470 confounding the statistical results. Emissions of CH₄ are governed by the interplay of
471 two processes: CH₄ production by methanogens (which requires anoxic conditions) and
472 consumption by methanotrophs (which occurs in oxic conditions) (Aerts and Ludwig,
473 1997). The position of the water table seems to be crucial in determining whether a

474 site becomes a source of CH₄. A number of studies demonstrate that in the agricultural
475 soils a water table of -20 cm or lower is enough for complete oxidation of CH₄ by
476 methanotrophs. Regina et al. (2015) only found CH₄ emissions if the water table was
477 shallower than -20 cm, which is consistent with our study where we mostly found CH₄
478 uptake (except for the planted cores where we detected CH₄ emissions even with -50
479 cm water table). In a mesocosm experiment on grassland peat, Karki et al. (2016)
480 showed that CH₄ emissions were negligible at water tables of -30 cm and -40 cm and
481 were significantly higher at 0 cm, -10 cm and -20 cm. Nykanen et al. (1995) reported
482 low emissions or uptake of CH₄ from a fen utilised as a grassland whose water table
483 varied between -20 cm and -117 cm. Poyda et al. (2016) reported insignificant CH₄
484 emissions from cultivated peat soil (grassland and cropland) for mean water table
485 levels of -25 cm or deeper. Renou-Wilson et al. (2014) noted the lack of CH₄ emissions
486 from a peat utilised as grassland on sites where the water table was below -30 cm.

487 The absence of a relationship between water table fluctuations and CH₄ emissions is
488 likely due to the fact that deeper water tables have no or negligible effect on topsoil
489 water content once the water table level is deeper than -30 cm (Juszczak et al., 2013).

490 The moisture level in the near surface soil layers is the key factor controlling
491 methanogenic and methanotrophic activity and therefore CH₄ production and
492 consumption (Tiemeyer et al., 2016; Stiehl-Braun et al., 2011).

493 Although warming increases the activity of both methanogenic and methanotrophic
494 communities, it does not affect the two groups to the same extent: at low temperature
495 (0-10°C) values, the activity of methanogens is reported to be inhibited to a greater

496 extent than that of methanotrophs, however, the optimum temperature for both
497 groups was found to be 25 °C (Dunfield et al., 1993). Increasing CH₄ emissions with
498 rising temperatures (treatments: 5 °C, 10 °C, 15 °C, 20 °C, 25 °C) were found in a
499 mesocosm experiment on peat soil (van Winden et al. (2012). Interactions between
500 water table position and temperature may also occur as the response of CH₄ emissions
501 from peat to temperature increases can depend on the position of the water table
502 (Dinsmore et al., 2009). In the shallow water table treatment (0 to -5 cm) the increase
503 in temperature led to higher CH₄ emissions, whereas in the low water table treatment
504 (-30 to -35 cm) the CH₄ flux decreased with increasing temperature, which is consistent
505 with the CH₄ consumption being stimulated more under drier conditions.

506 In the present study, there was no difference in the CH₄ flux between the ambient and
507 the elevated (+5 °C) temperature treatments in the linear mixed model. However, the
508 linear model showed that CH₄ emissions were significantly higher in the elevated
509 temperature treatments. The discrepancy in these results might be linked to the high
510 variability in the impact of temperature, which was not consistent throughout the
511 measurement period, increasing the within-groups variability in the data (and
512 decreasing the statistical significance of temperature). Once the data were averaged,
513 the impact of temperature was lost, while it appeared significant once the data were
514 modelled taking week and core into account.

515 The presence of celery was associate with higher CH₄ efflux – this was most likely
516 caused by the addition of substrates in the form of decaying roots and root exudates
517 stimulating methanogenic activity (Segers, 1998; Green et al., 2014). The increased

518 CH₄ loss in the presence of plants is also species-dependent as shown by peat
519 mesocosms with *Molinia caerulea* which had higher CH₄ loss than those with
520 *Sphagnum* and may reflect direct transfer of CH₄ from soil through plant tissues and
521 out of stomata (Leroy et al., 2017). However, unlike *M. caerulea* celery does not have
522 aerenchymous tissue which would allow for CH₄ transportation from the root zone to
523 the atmosphere. Despite this, new root material can increase labile carbon compounds
524 in the soil, supporting CH₄ production (Saarnio et al.,2004).

525 Although the level of the water table by itself did not affect CH₄ fluxes, it did influence
526 the way CH₄ fluxes were influenced by the presence of crops and temperature (e.g. the
527 interaction term between water table level and temperature was significant in the
528 linear model and marginally significant in the linear mixed model, see Table 1). The
529 increase in CH₄ fluxes between ambient and elevated temperature conditions is
530 greater in the -50 cm water table, and it is also more pronounced in the planted cores
531 (e.g. the difference in emissions between planted and unplanted cores is the highest at
532 -50 cm).

533

534 Dissolved Organic Carbon

535 Site hydrology strongly influences DOC concentration in peat water. Peatlands
536 subjected to drainage (such as agricultural peats) leach more DOC than undisturbed
537 ones (Frank et al., 2014). Nevertheless, studies on peatland restoration present mixed

538 results of rewetting on the concentration of DOC (Tiemeyer and Kahle, 2014; Frank et
539 al., 2014; Preston et al., 2011; Schwalm and Zeitz, 2015).

540 In this study the DOC concentration in the -30 cm water table treatment was 1.2 times
541 higher than the one in the -50 cm treatment. In peat soil used in agriculture the
542 majority of DOC is estimated to originate close to the surface due to the greater
543 presence of easily decomposable plant residues (Chow et al., 2006). For this reason,
544 the higher DOC concentration in drainage water of the -30 cm cores could be explained
545 not only by higher volume of peat available for leaching, but also leaching through a
546 layer that is richer in organic compounds. Therefore, raising the water table could
547 increase the loss of carbon as DOC, at least in the short period following rewetting.

548 Rising temperatures are expected to accelerate microbial decomposition of peat and
549 hence the production of DOC (Preston et al., 2011). In a peat incubation study, Moore
550 and Dalva (2001) report a 2.4-fold increase in DOC release following a temperature rise
551 from 4°C to 22°C. In our study, increasing the temperature by 5°C resulted in an almost
552 doubling of DOC concentrations in the drainage water, adding to the higher carbon
553 loss through Rh and ER.

554 DOC concentration was 1.5 times higher in the unplanted cores than in planted ones.
555 Vegetation can control production of DOC by affecting hydraulic properties of peat and
556 also by excretion of root exudates (Armstrong et al., 2012). Changes between
557 vegetation forms may also play a role as shown by Leroy et al. (2017) in a peat
558 mesocosm experiment. They found the presence of *Molinia caerulea* to have negative
559 effects on DOC content when compared to *Sphagnum*-only plots. Armstrong et al.

560 (2012) report the highest DOC values in *Calluna* dominated peatlands and the lowest
561 in *Sphagnum*. In this study, the presence of celery plants might have also affected DOC
562 concentration indirectly, by reducing peat water content and increasing microbial or
563 wetting-drying cycle release of DOC as moisture content was lower in the planted
564 cores.

565 The interaction between the presence of crops and water table level on DOC could be
566 linked to the water absorption by roots slowing down the leaching of carbon
567 compounds into the drainage water.

568

569 Conclusion

570 Raising the water table from -50 cm to -30 cm on Fenland peats could decrease yields
571 of celery by 19%, which is likely to be challenging for farmers to accept. However, in
572 the absence of crops, a water table of -30 cm would decrease the rate of peat
573 mineralisation to CO₂ by 31% without affecting CH₄ emissions. This presents an
574 alternative solution to decrease peat loss while potentially maintaining crop yield by
575 increasing the water table level outside of the growing periods of crops, which would
576 at least reduce some of the peat loss before or after cultivation. We recommend
577 replicating the study on a larger scale, as the limited growth space of the cores may
578 not fully represent field conditions. Larger scale in-situ water table manipulations
579 should test our findings under commercial farming conditions in order to validate the

580 applicability of our results from laboratory experiments into the more complex field
581 conditions.

582

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