

**Impact of fertilizer, water table, and warming on celery yield and CO<sub>2</sub> and CH<sub>4</sub> 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 (CO<sub>2</sub>) and methane (CH<sub>4</sub>))  
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 CO<sub>2</sub> loss by 31%. A 5°C temperature  
35    increase enhanced ecosystem emissions of CO<sub>2</sub> 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.

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

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

## 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 km<sup>2</sup> 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<sup>-1</sup> (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 ( $> 1\text{m}$ ) at a  
81 rate of about  $2.1\text{ cm yr}^{-1}$  and of thin peat ( $< 1\text{m}$ ) at a rate of  $1.3\text{ cm yr}^{-1}$  (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).

Mineralization of organic matter also affects the climate by increasing the emission of greenhouse gases (GHG) such as CO<sub>2</sub> and CH<sub>4</sub>. The majority of studies on the impact of the water table on GHG emissions in temperate and northern peatlands demonstrate that a rise in the position of the water table decreases emissions of CO<sub>2</sub> while increasing release of CH<sub>4</sub> (Nykanen et al., 1995, Dinsmore et al., 2009, Wilson et al., 2016, Karki et al., 2016 Strack et al., 2004, Hou et al., 2013, Poyda et al., 2016, Regina et al., 2015, Yrjälä et al., 2011). However, in several studies no link has been found between the water table level and GHG emissions (Regina et al., 2007, Lafleur et al., 2005; Schrier-Uijl et al., 2010, Muhr et al., 2016; Dirks et al., 2000). Despite the importance of preserving agricultural peats and reducing GHG emissions, there is a lack of studies testing more sustainable water table levels which could both maintain current crop yield and minimise GHG emissions (Regina et al., 2015; Taft et al., 2017; Taft et al., 2018). While a deeper water table (-40 to -50 cm) could maximize yield, a shallower water table (e.g. -30 cm) might be able to maintain 90% of the productivity whilst reducing peat mineralisation by 30-40% (Renger et al., 2002) thereby substantially extending the future potential numbers of years of cropping before complete peat wastage.

The carbon loss from the Fens can also be stimulated by increases in temperature. The average global temperature increase expected for this region is expected to be within the range of 0.3-4.8°C by the end of this century (relative to 1986-2005) (IPCC, 2014). It is estimated that under the highest greenhouse gas emission scenario, temperatures in 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

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

To address these critical issues discussed above, in this study we explored the impacts of water table, fertilization and warming, on mineralisation of Fen peat, the yield of celery as well as the emissions of CO<sub>2</sub> and CH<sub>4</sub>, and the carbon leaching out of the system as dissolved organic carbon (DOC). We hypothesise that increasing the water table from a field depth of -50 cm to -30 cm would not affect celery yield, would decrease emission of CO<sub>2</sub> while only slightly increasing CH<sub>4</sub> flux, and would increase DOC concentration in drainage water. We expect that increasing the temperature (by 5°C) would increase celery yield and increase DOC in the soil water, raise CO<sub>2</sub> respiration but only slightly affect CH<sub>4</sub> emission. Finally, we hypothesize that fertilization would increase celery yield, increase GHG emissions and increase DOC loss.

## **Methodology**

Sample area and soil collection

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



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

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

#### Treatment design

We tested the hypotheses in a multifactorial experiment that varied the water table (two levels -30 cm, and -50 cm below the surface), the air temperature (ambient and ambient + 5°C), and two fertilization levels (liquid fertilizer -see details below, and without any fertilisation) on peat cores incubated in controlled environment chambers for a simulated growing season. Celery was chosen as the study species as it is one of the most profitable crops according to the farmer (Martin Hammond, pers. comm.), and it is a marshland plant and therefore should be well-adapted to conditions of an elevated water table (Seale, 1975). Celery was planted in half of the 64 cores collected from the field, while the other half of the cores were left unplanted. The full combination of experimental factors (water table, air temperature, fertilizer and crop) 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  $\pm 0.5$  °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

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

The fertilised cores were treated with the same fertiliser that is used by the farmer on the celery crop: liquid CHAFER 6-6-12 ( $[\text{NH}_4\text{PO}_3]_n$  - ammonium polyphosphate), which has the following composition: N – 6% w/v,  $\text{K}_2\text{O}$  – 12% w/v, and  $\text{P}_2\text{O}_5$  – 6% w/v. It was applied at the same rate that the farmer uses for the celery crop: 800 l ha<sup>-1</sup>. The fertiliser was dissolved in 25 ml DI water before application by watering of the cores. The PVC pipe used in this experiment has a cross-sectional area of 94.99 cm<sup>2</sup>, therefore each core from the fertilised treatment was enriched with 0.8 ml CHAFER 6-6-12, which was diluted in 25 ml distilled water prior to addition.

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

Crop planting and biomass measurements

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

#### Greenhouse gas fluxes

CO<sub>2</sub> and CH<sub>4</sub> concentrations were measured once a week for 11 weeks using an LGR Ultra Portable Gas Analyser GGA-30p (Los Gatos Research, Mountain View, CA, USA), with a measurement frequency of one hertz (one measurement per second). Two custom-made PVC chambers both with a volume of 2.8 L were used to record fluxes, one transparent for light measurements (e.g. net ecosystem exchange, NEE) and an opaque chamber for dark measurements (indicated as ecosystem respiration, (ER) in the cores with celery presence, and soil respiration (Rh) in the cores with the absence of the crop). The autotrophic respiration was estimated as the difference between 1) the ecosystem respiration in the planted cores, and 2) the ecosystem respiration in the cores where no crops were planted. The chambers were placed on the top of pipes as shown in Figure 3. The gross primary production (GPP) was estimated as the sum of ER

and NEE. The rates of change in gas concentration in the chambers were used to estimate the CO<sub>2</sub> and CH<sub>4</sub> fluxes as described in McEwing et al. (2015). We also used flux tower data collected at Methwold (Morrison et al., 2013), close to our sampled field, for comparison with chamber GHG measurements. The flux tower data covered 60 days of crop cycle from 22 June to 20 August 2012, and a 60 day fallow period to 19 October 2012 (Morrison et al., 2013).

#### Dissolved organic carbon (DOC) in water samples

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

#### Statistical analysis

Statistical analysis was performed using the open source programme R version 3.3.1 (R Development Core Team, 2017). The CH<sub>4</sub>, NEE and ecosystem respiration fluxes were

log-transformed, to meet the assumptions of linear models, and ANOVA. We used both linear models and linear mixed models as described in the following paragraphs. Linear mixed effects models were used to test the effects of water table level, temperature and fertiliser use on celery biomass and emissions of CO<sub>2</sub> and CH<sub>4</sub> for the entire dataset including weekly measurements, with 'week' and 'core' as random effects, to take into account the temporal and spatial pseudoreplication. Linear models were used on the fluxes averaged over the entire experiment. The linear mixed models and the linear models were then compared to test if the averaging removed some important information. Outliers, as determined by the Cook's distance which affected the CH<sub>4</sub> flux models, were removed. For the linear mixed models analyses we used the lme4 package (Bates, Maechler and Bolker, 2014) and reported  $\chi^2$  in the place of the F-value. The linear models were estimated using the "lm" function in R. The DOC values were averaged across weeks. The biomass and DOC data sets were analysed using ANOVA. The adequacy of all models was assessed by visual inspection of residual plots. When mixed effects models were used, the statistical significance of each factor was determined by likelihood ratio tests performed with the Anova () function between the full model and a model that only included the random effects (weeks and cores). The statistical significance levels used were P-value <0.05 and >0.01 (\*); P-value < 0.01 and > 0.001 (\*\*), and P-value <0.001 (\*\*\*).

## Results

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

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

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

differences in ER between the two water table levels and the fertiliser treatments

(Table 2; Figure 5c).

Gross Primary Production (GPP) was greatest in cores under elevated temperature

(Table 2), while water table depth and fertiliser addition did not appear to have a

significant influence on these values (Table 2; Figure 5d). None of the interactions

among factors was significant for GPP. Net Ecosystem Exchange was not significantly

affected by any of the factors (Table 2).

While the statistical results were fairly consistent for NEE, RE or Rh and GPP, there was

a difference in the outcomes between the two statistical approaches employed for the

CH<sub>4</sub> fluxes (Table 2). The linear model (Table 2, left columns) showed that the water

table and fertiliser treatments had no effect on the CH<sub>4</sub> flux, however, the presence of

the crops and temperature showed significant effects on CH<sub>4</sub> fluxes (Table 2; Figure 6).

In the linear mixed model (Table 2, right columns) CH<sub>4</sub> fluxes were unaffected by

temperature, water table, and fertiliser use, however, there was an effect of the

presence of the crops. Based on the linear model, the elevated temperature resulted

in more than doubling in the averaged emissions compared to ambient conditions, and

a shift from CH<sub>4</sub> consumption to CH<sub>4</sub> loss into the atmosphere. On average, planted

cores had more than twice the rate of CH<sub>4</sub> emissions when compared to the unplanted

cores, but the planted cores with a -50 cm water table showed both CH<sub>4</sub> consumption



and emission. Soil moisture did not influence CH<sub>4</sub> flux in either the linear model (Table 2, left columns) or the linear mixed model (Table 2, right columns).

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

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

## Discussion

### Celery biomass

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

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

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

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

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

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

the overall carbon loss of these ecosystems. Therefore, raising the water table may be a viable option for expanding the lifespan of agricultural peat and possibly the only one as emissions of GHG were reported to be unaffected by practices such as no- and minimum tillage (Taft et al., 2018). Nevertheless, due to negative effects on crop biomass as noted in this study, raising the water table for the duration of the growing season is unlikely to be adopted by farmers. Higher Rh from the elevated (+5°C) temperature treatment indicates increased rates of organic matter oxidation by soil microorganisms. Elevated temperatures can accelerate the decomposition of organic matter by increasing microbial metabolic rate (Ziegler et al., 2013). Such rates have been shown to rise in an exponential manner until 45-50°C before declining (Yiqi and Zhou, 2006). This has profound implications for climate change and lifespan of peat as temperature increases enhance soil CO<sub>2</sub> emission and thus generates a positive feedback mechanism, which results in more atmospheric warming and more peat loss - an effect increasingly seen across large areas of global peatlands.

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

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

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

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

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

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

#### CH<sub>4</sub> emissions

As CH<sub>4</sub> emissions from agricultural soils are usually much smaller than those of CO<sub>2</sub> (Zona et al., 2013; Maljanen et al., 2007; Karki et al., 2016) an increase in CH<sub>4</sub> release might not negate the benefit of the decreased CO<sub>2</sub> loss with a raised water table.

Differences in the outcomes between the two statistical approaches used for analysing the CH<sub>4</sub> data complicate the interpretation of the results. These results suggest that once the time-series element is removed, the patterns in the flux become more visible, and that temperature is a dominant control on these fluxes (see Table 3 for the linear model), consistent with the high temporal variability in the fluxes potentially confounding the statistical results. Emissions of CH<sub>4</sub> are governed by the interplay of two processes: CH<sub>4</sub> production by methanogens (which requires anoxic conditions) and consumption by methanotrophs (which occurs in oxic conditions) (Aerts and Ludwig, 1997). The position of the water table seems to be crucial in determining whether a

site becomes a source of CH<sub>4</sub>. A number of studies demonstrate that in the agricultural soils a water table of -20 cm or lower is enough for complete oxidation of CH<sub>4</sub> by methanotrophs. Regina et al. (2015) only found CH<sub>4</sub> emissions if the water table was shallower than -20 cm, which is consistent with our study where we mostly found CH<sub>4</sub> uptake (except for the planted cores where we detected CH<sub>4</sub> emissions even with -50 cm water table). In a mesocosm experiment on grassland peat, Karki et al. (2016) showed that CH<sub>4</sub> emissions were negligible at water tables of -30 cm and -40 cm and were significantly higher at 0 cm, -10 cm and -20 cm. Nykanen et al. (1995) reported low emissions or uptake of CH<sub>4</sub> from a fen utilised as a grassland whose water table varied between -20 cm and -117 cm. Poyda et al. (2016) reported insignificant CH<sub>4</sub> emissions from cultivated peat soil (grassland and cropland) for mean water table levels of -25 cm or deeper. Renou-Wilson et al. (2014) noted the lack of CH<sub>4</sub> emissions from a peat utilised as grassland on sites where the water table was below -30 cm.

The absence of a relationship between water table fluctuations and CH<sub>4</sub> emissions is likely due to the fact that deeper water tables have no or negligible effect on topsoil water content once the water table level is deeper than -30 cm (Juszczak et al., 2013).

The moisture level in the near surface soil layers is the key factor controlling methanogenic and methanotrophic activity and therefore CH<sub>4</sub> production and consumption (Tiemeyer et al., 2016; Stiehl-Braun et al., 2011).

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



extent than that of methanotrophs, however, the optimum temperature for both groups was found to be 25 °C (Dunfield et al., 1993). Increasing CH<sub>4</sub> emissions with rising temperatures (treatments: 5 °C, 10 °C, 15 °C, 20 °C, 25 °C) were found in a mesocosm experiment on peat soil (van Winden et al. (2012). Interactions between water table position and temperature may also occur as the response of CH<sub>4</sub> emissions from peat to temperature increases can depend on the position of the water table (Dinsmore et al., 2009). In the shallow water table treatment (0 to -5 cm) the increase in temperature led to higher CH<sub>4</sub> emissions, whereas in the low water table treatment (-30 to -35 cm) the CH<sub>4</sub> flux decreased with increasing temperature, which is consistent with the CH<sub>4</sub> consumption being stimulated more under drier conditions.

In the present study, there was no difference in the CH<sub>4</sub> flux between the ambient and the elevated (+5 °C) temperature treatments in the linear mixed model. However, the linear model showed that CH<sub>4</sub> emissions were significantly higher in the elevated temperature treatments. The discrepancy in these results might be linked to the high variability in the impact of temperature, which was not consistent throughout the measurement period, increasing the within-groups variability in the data (and decreasing the statistical significance of temperature). Once the data were averaged, the impact of temperature was lost, while it appeared significant once the data were modelled taking week and core into account.

The presence of celery was associated with higher CH<sub>4</sub> efflux – this was most likely caused by the addition of substrates in the form of decaying roots and root exudates stimulating methanogenic activity (Segers, 1998; Green et al., 2014). The increased

CH<sub>4</sub> loss in the presence of plants is also species-dependent as shown by peat mesocosms with *Molinia caerulea* which had higher CH<sub>4</sub> loss than those with *Sphagnum* and may reflect direct transfer of CH<sub>4</sub> from soil through plant tissues and out of stomata (Leroy et al., 2017). However, unlike *M. caerulea* celery does not have aerenchymous tissue which would allow for CH<sub>4</sub> transportation from the root zone to the atmosphere. Despite this, new root material can increase labile carbon compounds in the soil, supporting CH<sub>4</sub> production (Saarnio et al., 2004).

Although the level of the water table by itself did not affect CH<sub>4</sub> fluxes, it did influence the way CH<sub>4</sub> fluxes were influenced by the presence of crops and temperature (e.g. the interaction term between water table level and temperature was significant in the linear model and marginally significant in the linear mixed model, see Table 1). The increase in CH<sub>4</sub> fluxes between ambient and elevated temperature conditions is greater in the -50 cm water table, and it is also more pronounced in the planted cores (e.g. the difference in emissions between planted and unplanted cores is the highest at -50 cm).

#### Dissolved Organic Carbon

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

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

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

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

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

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

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

## Conclusion

Raising the water table from -50 cm to -30 cm on Fenland peats could decrease yields of celery by 19%, which is likely to be challenging for farmers to accept. However, in the absence of crops, a water table of -30 cm would decrease the rate of peat mineralisation to CO<sub>2</sub> by 31% without affecting CH<sub>4</sub> emissions. This presents an alternative solution to decrease peat loss while potentially maintaining crop yield by increasing the water table level outside of the growing periods of crops, which would at least reduce some of the peat loss before or after cultivation. We recommend replicating the study on a larger scale, as the limited growth space of the cores may not fully represent field conditions. Larger scale in-situ water table manipulations should test our findings under commercial farming conditions in order to validate the

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

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