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Optimizing fen peatland water-table depth for romaine lettuce growth to reduce peat wastage under future climate warming

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Summary

Forty percentage of UK peatlands have been drained for agricultural use, which has caused serious peat wastage and associated greenhouse gas emissions (carbon dioxide (CO_2) and methane (CH_4)). In this study, we evaluated potential trade-offs between water-table management practices for minimizing peat wastage and greenhouse gas emissions, while seeking to sustain romaine lettuce production: one of the most economically relevant crop in the East Anglian Fenlands. In a controlled environment experiment, we measured lettuce yield, CO_2, CH_4 fluxes and dissolved organic carbon (DOC) released from an agricultural fen soil at two temperatures (ambient and +2°C) and three water-table levels (−30 cm, −40 cm and −50 cm below the surface). We showed that increasing the water table from the currently used field level of −50 cm to −40 cm and −30 cm reduced CO_2 emissions, did not affect CH_4 fluxes, but significantly reduced yield and increased DOC leaching. Warming of 2°C increased both lettuce yield (fresh leaf biomass) and peat decomposition through the loss of carbon as CO_2 and DOC. However, there was no difference in the dry leaf biomass between the intermediate (−40 cm) and the low (−50 cm) water table, suggesting that romaine lettuce grown at this higher water level should have similar energetic value as the crop cultivated at −50 cm, representing a possible compromise to decrease peat oxidation and maintain agricultural production.

KEYWORDS

agriculture, CH_4 emissions, climate change, CO_2 emissions, crop, peat

1 | INTRODUCTION

Global emissions of greenhouse gases (GHGs) from croplands are estimated to be 1.994 ± 2.172 Pg carbon dioxide (CO_2)equivalent, with 32% coming from peatland cultivation (Carlson et al., 2017), despite peatlands being a small part of the total cultivated area. Peatlands, however, store 30% of global soil carbon (C) (Global Environmental Centre, 2008). In the UK, 40% of peatlands have been drained for agricultural use (Dixon et al., 2014), such as in the East Anglian Fenlands (i.e. the Fens; Figure 1). Soils of the Fens are characterized by high fertility: around 90% of the land is classified as Grade 1 or Grade 2 (the highest fertility values) (Natural England, 2015). This area supplies 37% of total vegetable production in England (NFU, 2019). Drainage, fertilizer application and intensive cultivation for crop production result in high rates of peat wastage by microbial aerobic decomposition (Global Environmental Centre, 2008), turning the Fens into a national hot spot of GHG emissions (Figure 1). It has been predicted that two thirds of the peat in the Fens will be lost by 2050 because of oxidative degradation (Burton & Hodgson, 1987), threatening the future production of food crops in this region. Recent estimates of rates of peat subsidence from the East Anglian Fens range from 0.33- to 0.75-cm depth per year (Taft et al., 2017), with rates generally increasing in agricultural land from 0.44 cm per year in shallow peat to 0.62 cm per year in deep peat (Evans et al., 2016).

The position of the water table determines the extent of the trade-off between emissions of CO_2 and methane (CH_4): at high water-table levels, anoxic conditions dominate, creating a favourable environment for methanogenesis, whereas production of CO_2 is suppressed because of the oxygen requirement of decomposing microorganisms (Karki et al., 2016; Poyda et al., 2016). Conversely, at low water tables oxygen can more freely access soil organic carbon, which leads to CH_4 consumption by methanotrophs and increased activity of microorganisms that respire CO_2 (Couwenberg, 2009; Maljanen et al., 2004). In a fen grassland, maximal yield was achieved with the water-table depths of between −40 cm and −50 cm, while raising the level to −30-cm reduced peat decomposition by 30%–40%, with only a 10% fall in grass productivity (Renger et al., 2002). However, water-table manipulation has given mixed results on horticultural yields, depending on the crop studied. Soya bean yields were 5% lower with the water table at −30 cm compared with −50 to −60 cm (Matsuo et al., 2017), and Ferreira et al. (2017) found that water-table position (two depths: −36 and −76 cm) affected potato root distribution, but did not impact tuber mass. Previous studies by our research team on high value horticultural crops, with a high water content and water requirements, showed that raising the water table of fenland peat from −50 to −30 cm increased total fresh biomass of radish by 33% (Musarika et al., 2017), but lowered fresh biomass of celery by 19% (Matysek et al., 2019). Given the crop-specific responses, the impact of different water-table levels on yields should be investigated across the most economically relevant crops.

Because of climate change, the average temperature in the East of England is expected to increase between 1.3°C and 7.5°C in summer (Jenkins et al., 2008). Rising temperatures can enhance peat decomposition and emissions of GHG (Ziegler et al., 2013), but also accelerate plant growth and CO_2 absorption by plants (Adaptation Sub-Committee, 2016; Ostberg et al., 2018).

Few studies that document GHG emissions from agriculturally used areas of the Fens exist. Evans et al. (2016) and Peacock et al. (2019) took field GHG measurements from semi-natural and cultivated areas of the Fens. Taft et al. (2018) measured GHG emissions from cores taken from agricultural land of the Fens. None of these studies examined crop growth under changing water-table and temperature conditions.

In the present study, we investigated the effects of three water-table levels (−30, −40 and −50 cm) on romaine lettuce

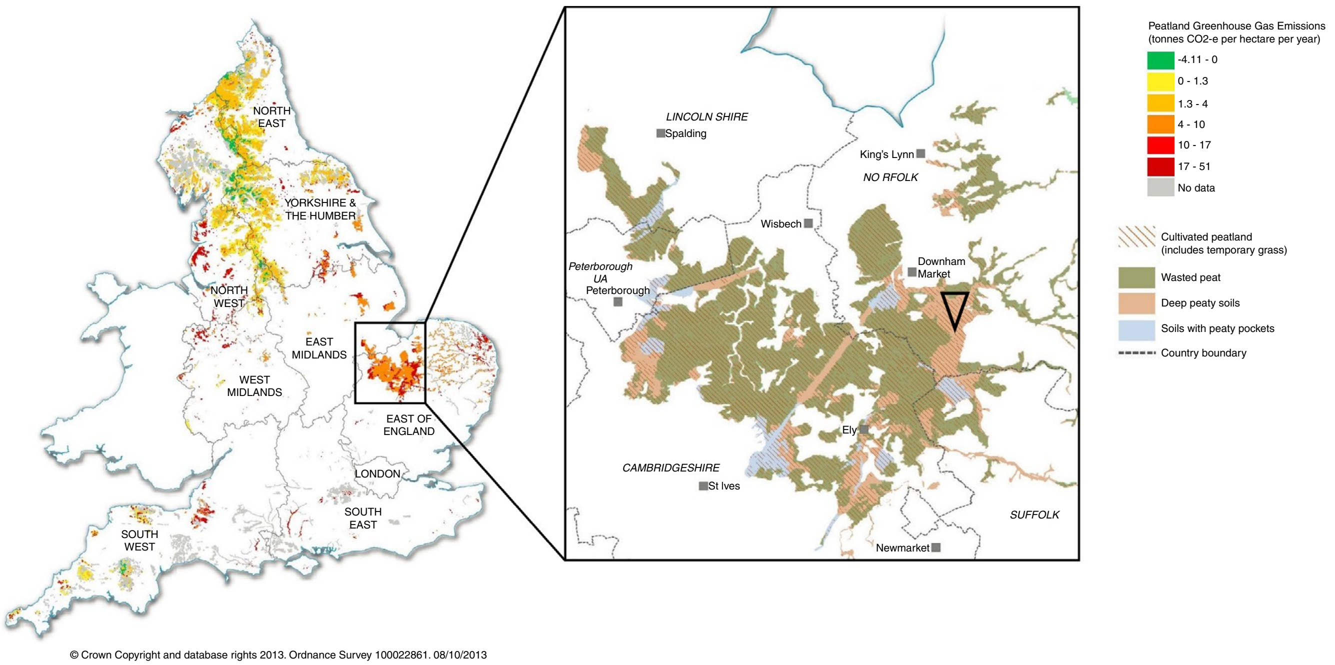

FIGURE 1 Sampling site location (black triangle), peat quality and estimated GHG emissions from the East Anglian Fenlands. Permission to use this map has been granted by Defra

(one of the most profitable crops grown in this region—Martin Hammond, pers. Comm; Defra, 2016) yield and peat C loss. We hypothesized that raising the water table would decrease ecosystem respiration (Rh), net ecosystem exchange of CO_2 (NEE) and gross primary production (GPP), and increase CH_4 emissions and that the intermediate water table of −40 cm would provide a good compromise between limiting peat wastage and maintaining lettuce yield. We also hypothesized that warming of 2°C would not only raise emissions of the two GHGs (i.e. CO_2 and CH_4) and soil water dissolved organic carbon (DOC) concentration, but would also enhance lettuce growth.

2 | METHODS

2.1 | Field site, peat core sampling and incubation conditions

A total of 64 peat cores of diameter 11 cm and up to 60 cm deep were collected in March 2017 at Rosedene Farm in Methwold Hythe, Norfolk, in the Fens (Figure 1), where the water table is normally maintained at −50 cm by pumping. The PVC pipes were hammered into the ground and excavated to preserve the existing soil structure. Caps were installed to bottoms of the pipes in order to keep the field soil moisture (Figure 2).

The cores were transported and placed in CONVIRON BDW-40 growth chambers (Controlled Environments Ltd., Winnipeg, Manitoba, Canada) at the Sir David Read Controlled Environment Facility, University of Sheffield, UK, under two different temperature treatments (see below). The photosynthetically active radiation (PAR) in both chambers varied between 670 and 740 µmol m^{-2} s^{-1} because of small differences in the geometry of the light bulbs between the chambers. Relative humidity inside the chambers was maintained at 70%, similar to the relative humidity observed at the field site (Cumming, 2018). The CO_2 level in both chambers was maintained at the ambient concentration of around 440 ppm.

Inside these chambers, the cores were subjected to a multifactorial manipulation (Figure 3) of:

- Water table at three levels: −30, −40 and −50 cm below the surface
- Temperature: ambient and elevated (+2°C)
- Cropping: planted and fallow

The water-table depth was measured once a day with a marked stick, and distilled water was added to maintain the required water level (usually every 1–2 days). Soil water content was measured in the top 12 cm every week with a Campbell Scientific soil moisture probe (model CS655; Campbell Scientific, Logan, Utah, USA).

The ambient temperature used was based on average daytime temperatures collected from a meteorological station in the field over three years (Cumming, 2018), during the time of the year when lettuce crops are established (February and March) (Figure 4). The elevated temperature treatment was +2°C higher, to approximate the average of the RCP (Representative Concentration Pathway) 4.5 scenario that predicts a temperature rise of 1.7°C to 3.2°C before the end of this century relative to years 1850–1900 (IPCC, 2014a; Palmer et al., 2018).

FIGURE 2 Peat cores with romaine lettuce grown with different water-table depths (a) after 5 weeks; (b) after 8 weeks; (c) after 12 weeks; and (d) mesh-covered pipe inserted into each core used for water-table measurement

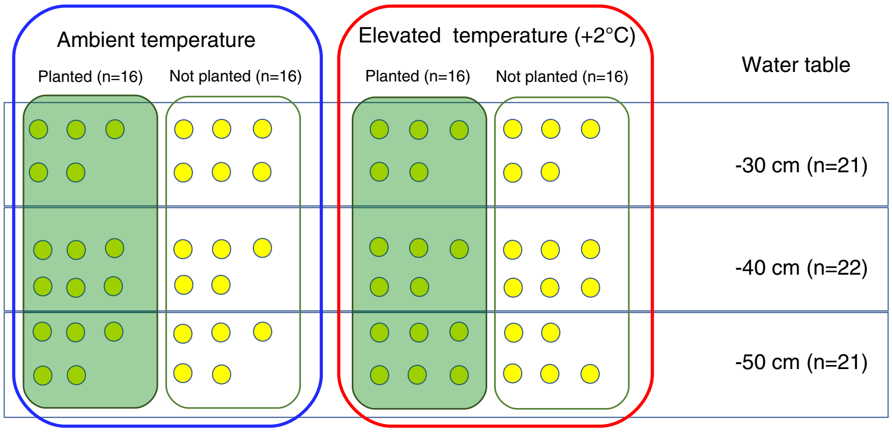

FIGURE 3 Multifactorial design of the experiment including two temperature treatments (ambient and elevated), two planting treatments (planted, not planted) and three water-table treatments (−30, −40 and −50 cm below the surface). Each dot represents one peat core. Total number of cores is 64

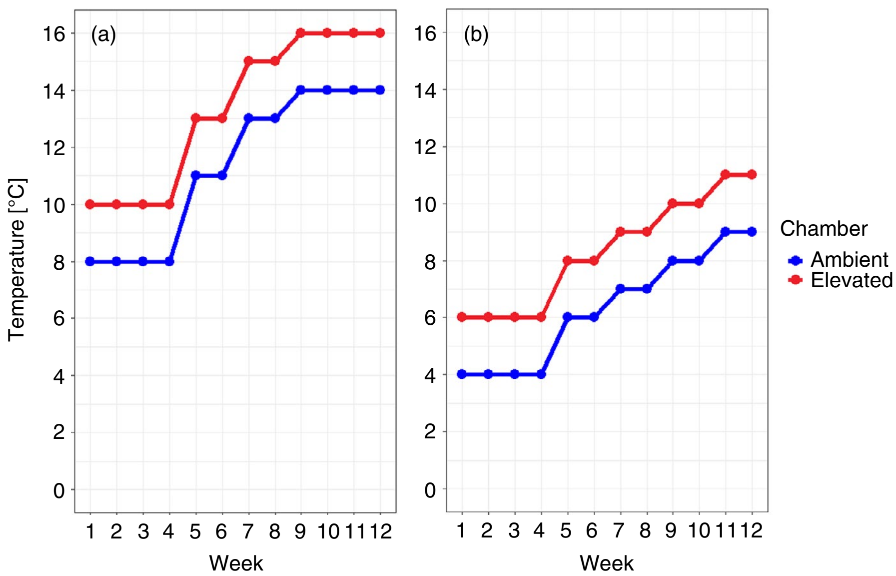

FIGURE 4 Daytime (a) and night-time (b) temperature settings for ambient and elevated (ambient +2°C), each of 12-hr duration

Seedlings of romaine lettuce were germinated over 3 weeks in the growth chambers on peat collected from the sampling site. At the start of the experiment, single seedlings were planted into half of the peat cores (Figure 3). The cores were allocated to randomized positions within the growth chambers and were re-randomized each week to avoid the within-chamber environmental gradient effects. We applied the same type and dose of the fertilizer used by the farmer for romaine lettuce (liquid Chafer 15-5-10; N:P:K mass ratio of 15:5:10, on a w/v basis [g/100 ml]) at a rate of 1000 L ha^{-1} (0.95 ml per core), which is 150 kg N ha^{-1}, 50 kg P_2O_5 ha^{-1} and 100 kg K_2O ha^{-1}, a day before planting the seedlings, and the starter solution Chafer Starter Solution Plus 11-38-3 (NPK +trace elements of copper (Cu), manganese (Mn) and zinc (Zn)) at a rate of 0.19 ml per core when the seedlings were transferred into the cores.

2.2 | Greenhouse gas fluxes

CO_2 and CH4 concentrations in the headspace of the cores were collected once a week for 11 weeks using an LGR Ultra-Portable Gas Analyser GGA-30p (Los Gatos Research, Mountain View, CA, USA). Two custom-made PVC chambers, both with a volume of 2.8 L, were used to record changes in gas concentration over time (McEwing et al., 2015). The measurements were taken over two minutes. A transparent chamber was used to measure Rh in the unplanted cores and NEE in the planted cores (and to estimate gross primary productivity, GPP) and an opaque chamber for dark measurements to measure ER in the planted cores. GPP in the planted cores was estimated as:

$$GPP = NEE - ER. \quad (1)$$

The fluxes of CO2 and CH4 were calculated as described in McEwing et al. (2015).

2.3 | DOC in the soil water

Water samples were collected in weeks 4, 6, 8 and 11 from two sources: the drainage pipe used for the water-table measurements (using a syringe) and directly from soil pores using Rhizon soil moisture samplers (Rhizosphere Research

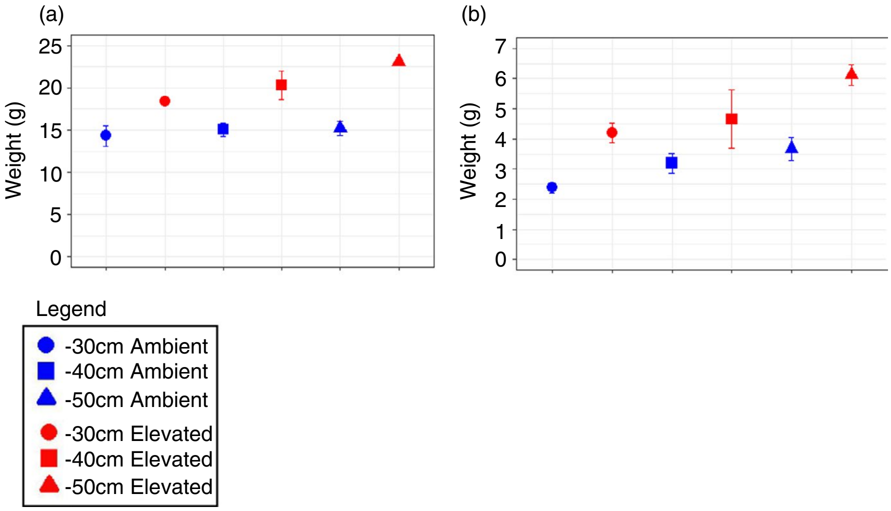

FIGURE 5 Romaine lettuce biomass (mean ±1 standard error) responses to temperature and water-table manipulations. There are two temperature settings: ambient and elevated (ambient +2°C). Water-table levels are −30, −40 and −50 cm. In all cases, $n = 5$ apart from: '−40 cm ambient' and '−50 cm elevated', where $n = 6$. (a) Shoot dry weight; (b) root dry weight

Products), which had been inserted in the top 10 cm of soil at the beginning of the experiment. This allowed for estimating DOC content in both pore water and drainage water. Samples for DOC analysis were filtered on Whatman 0.7 µm GD/X glass fibre syringe filters and analysed on a Sievers 5310C carbon analyser. The detection limit of this carbon analyser is 4 ppb, and the calibration standards were 1,000 mg C L^{-1} or 500 mg C L^{-1} potassium hydrogen phthalate.

2.4 | Lettuce harvest and root extraction

After 12 weeks of growth, the lettuce plants were harvested and fresh and dry weights (dried at 80°C for 24 hr) determined. The soil columns were frozen to prevent root decomposition and to facilitate peat extraction. On partial defrosting, the peat cores were extruded from the PVC pipes and cut into 10-cm depth increments. Roots were cleaned on a 425-µm sieve, with tap water, and dry weight (80°C for 24 hr) was determined.

2.5 | Statistical analysis

Statistical analysis was performed using the open source program R, version 3.3.1 (R Development Core Team, 2017). A two-way ANOVA was employed to determine the effects of water-table and temperature treatments on lettuce biomass. Given the complex data set, we used two model types to analyse the GHG data: linear models and linear mixed-effects models. The linear mixed models were applied using the lme4 package (Bates, Maechler, & Bolker, 2014), including 'week' and 'core' as random effects to avoid temporal and spatial pseudoreplication (i.e. sampling the same core multiple times during the experiment). These linear mixed models were used for testing the effects of water-table level, crop presence, temperature (categorical factors) and soil water content (continuous factor) on DOC concentrations in water and emissions of CO_2 and CH_4, with 'week' and 'core' as random effects. Outliers, as determined by the Cook's distance, were removed from the CH_4 data. In the analyses in which the lme4 package was used, χ^2 is reported in the place of the F-value. We also averaged CO_2 and CH_4 fluxes for the entire experiment and applied a simple linear model, as the averaging removed pseudoreplication. The linear mixed models and the linear models were then compared to test for consistency in the results with the two approaches. The adequacy of all models was assessed by visual inspection of the residual plots. The CH_4 flux data used in the linear modelling were log-transformed, since its distribution did not meet the assumptions of linear models. When the mixed-effects models were used, the statistical significance of each factor was determined by the likelihood-ratio tests performed with the Anova function between the full model and the model without the fixed factor. When the water-table level factor was significant across treatment groups, the difference in Rh, ER, NEE, GPP, CH_4 and DOC between the three water-table treatments was estimated using a *post hoc* Tukey test.

3 | RESULTS

The summary of results is presented in Figure 5. Romaine lettuce fresh and dry weights were significantly higher (by 38% and 42%, respectively) under elevated temperature than under ambient temperature (Table 1, Figure 5). The fresh leaf biomass was significantly affected by the water table: the highest yields were in the −50-cm treatment (Figure 5). The dry biomass weight showed no significant difference between −50 and −40 cm, although it was higher in the −50-cm treatment when compared to the −30-cm water table (Figure 5).

Root biomass responses were similar to those of the shoots, with the dry root weight being 40% higher in the elevated

TABLE 1 ANOVA test results for effects of environmental variables (three water-table positions, ambient and elevated temperature, and their interactions) on different components of lettuce biomass at harvest using linear models

	df	*F*-value	*p*-value
Shoot fresh weight			
Water table	2,24	12.33	**<.001*****
Temperature	1,24	28.66	**<.001*****
Water table*Temperature	2,24	0.81	.456
Shoot dry weight			
Water table	2,24	5.01	**.015***
Temperature	1,24	58.19	**<.001*****
Water table*Temperature	2,24	2.3	.121
Tap root dry weight			
Water table	2,24	8.62	**.002****
Temperature	1,24	43.28	**<.001*****
Water table*Temperature	2,24	0.85	.44
Total root dry weight			
Water table	2,21	6.36	**.007****
Temperature	1,21	33.98	**<.001*****
Water table*Temperature	2,21	0.77	.477
Root dry weight in top 10 cm			
Water table	2,22	6.84	**.005****
Temperature	1,22	31.54	**<.001*****
Water table*Temperature	2,22	0.8	.46
Root dry weight 10–30 cm			
Water table	2,22	15.13	**<.001*****
Temperature	1,22	58.4	**<.001*****
Water table*Temperature	2,22	5.19	**.014***
Root dry weight below 30 cm			
Water table	2,22	4.89	**.018***
Temperature	1,22	0.55	.467
Water table*Temperature	2,22	0.83	.452
Root dry weight in bottom 40 cm			
Water table	2,23	5.43	**.012***
Temperature	1,23	1.64	.212
Water table*Temperature	2,23	1.43	.26
Root:shoot ratio			
Water table	2,21	1.09	.354
Temperature	1,21	0	.998
Water table*Temperature	2,21	2.02	.158

Note: Tap root is the thickest root, with lateral roots removed. The root:shoot ratio was calculated on dry biomass.

Abbreviation: *df*, degrees of freedom.

*May be significant.; **Significant.; ***Highly significant.

temperature treatment than in the ambient one (Figure 5) and being reduced by raising the water-table level (e.g. 27% lower in the −30-cm water-table treatment than in the −50-cm treatment; Figure 5). There were no statistically significant differences in the total root biomass between −30-cm and −40-cm and between −40-cm and −50-cm water-table levels (Table 2). The dry root biomass in the top 10 cm of soil layer was significantly higher (by 60%) in the elevated temperature treatment (Table 1) and differed only between the −30-cm and −50-cm water tables (Table 2), being lower at −30 cm. The root biomass below −30 cm was not affected by temperature (Table 1). The root:shoot ratio was not affected by any of the treatments (Table 2). There were no significant interactions between temperature and water table in explaining variations in the biomass.

TABLE 2 Post hoc Tukey's test results for the significance of effects of water-table levels on romaine lettuce shoot and root biomass at harvest

	t-value	*p*-value
Shoot fresh weight		
WT (−30 cm) and WT (−40 cm)	2.166	.0979
WT (−30 cm) and WT (−50 cm)	4.906	<.001***
WT (−40 cm) and WT (−50 cm)	2.690	.0329*
Shoot dry weight		
WT (−30 cm) and WT (−40 cm)	1.467	.3242
WT (−30 cm) and WT (−50 cm)	3.082	.0136*
WT (−40 cm) and WT (−50 cm)	1.583	.2720
Tap root dry weight		
WT (−30 cm) and WT (−40 cm)	1.485	.3155
WT (−30 cm) and WT (−50 cm)	4.004	.00149**
WT (−40 cm) and WT (−50 cm)	2.478	.0519
Total root dry weight		
WT (−30 cm) and WT (−40 cm)	1.705	.2266
WT (−30 cm) and WT (−50 cm)	3.961	.002**
WT (−40 cm) and WT (−50 cm)	2.387	.0652
Root dry weight in top 10 cm		
WT (−30 cm) and WT (−40 cm)	1.604	.2648
WT (−30 cm) and WT (−50 cm)	3.658	.0038**
WT (−40 cm) and WT (−50 cm)	2.111	.1107
Root dry weight below 30 cm		
WT (−30 cm) and WT (−40 cm)	−0.216	.9747
WT (−30 cm) and WT (−50 cm)	2.687	.0345*
WT (−40 cm) and WT (−50 cm)	2.866	.0233*
Root dry weight 10 cm −30 cm		
WT (−30 cm) and WT (−40 cm)	3	.017*
WT (−30 cm) and WT (−50 cm)	5.9	<.001***
WT (−40 cm) and WT (−50 cm)	3.264	.01**

Note: Displayed are *t*-values and *p*-values of the tests. Tap root dry weight is for the thickest root, with lateral roots removed.

*May be significant.; **Significant.; ***Highly significant.

Soil water content was significantly lower in the elevated than the ambient temperature treatment (by 8%), in planted compared with unplanted cores (by 11%) and was affected by the water-table position (Table 3, Figure S2). As expected, soil water content was significantly lower in the −50-cm treatment when compared to −30-cm (by 19%) and −40-cm (by 14%) treatments (Table 4).

Soil respiration was higher (by 18%) under the elevated temperature and was affected by the water table, both of these variables having significant effects in the linear mixed models and the linear models (Table 3; Figure 6). The Rh flux was 39% lower in the −40-cm than in the −50 cm water-table level and 59% lower in the −30-cm than in the −50-cm water level (Table 4, Figure 6). Ecosystem respiration was 46% (and significantly) higher in the elevated temperature treatment than in the ambient temperature and was affected by the water table in the linear model, but not in the linear mixed model (Table 3, Figure 6). The *post hoc* test showed no significant differences in Rh between water-table levels −30 and −40 cm, but significant differences in Rh between water-table levels −30 and −50 cm and between −40 and −50 cm (Table 4, Figure 6). NEE was 20% lower in the elevated temperature treatment than in the ambient one and was unaffected by the water-table level in both the linear and the linear mixed model (Table 3, Figure 6). GPP was lower by a third in the elevated temperature treatment (compared with the ambient conditions) and unaffected by the water-table position (Table 3, Figure 6).

Consumption dominated CH_4 fluxes while CH_4 emissions were only detected in 11% of all samples. The rate of CH_4 consumption was one-third lower from the elevated temperature treatment as compared to the ambient temperature and significantly higher (by 50%) in the unplanted cores than in the planted cores (Table 3, Figure 6). Methane oxidation was 38% lower at the −40-cm than at the −50-cm water level, and 75% lower at the −30-cm than at the −50-cm treatment, and these differences were all statistically significant (Table 4, Figure 6). There were no statistically significant interactions between any of the dependent variables.

Dissolved organic carbon concentration in peat pore water and drainage water was higher in the planted cores (in pore water by 23% and in drainage water by 19%) (Figure S1, Table 5) and was not affected by temperature. Raising the water table increased DOC concentrations in the −40-cm (in pore water by 34% and in drainage water by 31%) and the −30-cm (in pore water by 31% and in drainage water by 40%) treatments compared with the −50-cm water level (Figure S1, Table 6). There was a statistically significant interaction between crop presence and temperature in explaining DOC concentration in pore water, with higher values associated with the elevated temperature conditions, and between water table and temperature in drainage samples, with lower concentrations from the elevated temperature treatment (Table 5). The DOC concentration values in molar units are presented in Table 7.

4 | DISCUSSION

4.1 | Lettuce production

Romaine lettuce was more adversely affected by lowering the water table from −50 to −30 cm than celery in our previous study (a 32% decrease compared with 19% for celery; Matysek et al., 2019), which indicates greater sensitivity of lettuce to waterlogging. Romaine lettuce growing at the −40-cm water table produced as much dry biomass as the plants at the −50-cm water level; however, the −40-cm

TABLE 3 Effects of environmental variables and their interactions on gas fluxes using both the linear mixed model (lmer) (which included 'week' and 'core' as random effects, to take into account the temporal and spatial pseudoreplication) and linear models (lm) (which were applied to the fluxes averaged over the entire experiment)

	Lmer			lm		
	df	χ^2	*p*-value	*df*	*F*-value	*p*-value
CH_4 fluxes						
Planting	1	2.76	.1	1, 49	4.34	.042*
Temperature	1	9.64	.002**	1, 49	4.53	.038*
Water table	2	4.33	.115	2, 49	22.17	<.001***
Soil water content	1	3.34	.06741	1, 59	4.61	.036*
Water table*Temperature	2	2.32	.313	2, 49	1.31	.278
Temperature*Planting	1	1.71	.191	1, 49	2.07	.156
Water table*Planting	2	0.93	.628	2, 49	1.9	.16
Soil respiration (Rh)						
Temperature	1	5.23	.022*	1, 25	4.87	.037*
Water table	2	18.2	<.001***	2, 25	21.94	<.001***
Water table*Temperature	2	0.02	.989	2, 25	0.05	.95
Soil water content	1	1.52	.2181	1, 29	28.64	<.001**
Net ecosystem exchange (NEE)						
Temperature	1	5.37	.02*	1, 26	9.23	.005**
Water table	2	5.08	.079	2, 26	1.92	.167
Soil water content	1	0.19	.665	1, 30	0.06	.812
Water table*Temperature	2	0.18	.913	2, 26	0.1	.909
Gross primary production (GPP)						
Temperature	1	24.58	<.001***	1, 26	31.97	<.001***
Water table	2	0.39	.822	2, 26	0.35	.709
Soil water content	1	0.23	.6343	1, 30	2.64	.115
Water table*Temperature	2	0.44	.805	2, 26	0.48	.63
Ecosystem respiration (ER)						
Temperature	1	13.4	<.001***	1, 26	35.35	<.001***
Water table	2	1.94	.379	2, 26	4.26	.025*
Soil water content	1	0.53	.4674	1, 30	8.49	.007**
Water table*Temperature	2	2.51	0.286	2, 26	2	0.155
Soil water content						
Temperature	1	18.86	<.001***	1, 59	12.33	<.001***
Water table	2	25.13	<.001***	2, 59	30.61	<.001***
Planting	1	8.39	<.001***	1, 59	26.87	<.001***

Note: The experiment lasted 12 weeks, and the GHG was measured eight times (every week or every 2 weeks). The total number of measurements used in the lmer model was $n = 512$ (for CH_4, Rh and soil water content) and $n = 256$ (for GPP, ER and NEE).

Abbreviations: Rh, soil respiration; NEE, net ecosystem exchange; GPP, gross primary production; ER, ecosystem respiration.

*May be significant.; **Significant.; ***Highly significant.

plants absorbed and stored less water, suggesting that the caloric value of romaine lettuce is similar between these different water levels. Rh at the −40-cm water table was significantly lower than at the −50-cm one, suggesting that this water level might be a good compromise to reduce peat wastage. Still, fresh lettuce biomass was lower by one-fifth in the −40-cm water level than in the −50-cm one, and this might influence the farmer to choose a deeper water table. Excessive soil water content leads to root hypoxia, which reduces stomatal conductance and photosynthetic rate (Rood et al., 2010; Yordanova, 2005). Total root biomass was significantly lower at the −30-cm compared with the −50-cm water table; leaf dry and fresh biomass were correspondingly lower as well. It is likely that the decrease

TABLE 4 Post hoc Tukey's test results for effects of water-table levels on GHG emissions and the water content of soil

	t-value	*p*-value
CH_4		
WT (−30 cm) and WT (−40 cm)	−1.426	.3356
WT (−30 cm) and WT (−50 cm)	−3.976	<.001***
WT (−40 cm) and WT (−50 cm)	−2.547	.0368*
Soil respiration (Rh)		
WT (−30 cm) and WT (−40 cm)	1.859	.172
WT (−30 cm) and WT (−50 cm)	6.437	<.001***
WT (−40 cm) and WT (−50 cm)	4.716	<.001***
Ecosystem respiration (ER)		
WT (−30 cm) and WT (−40 cm)	−0.071	.997
WT (−30 cm) and WT (−50 cm)	2.030	.125
WT (−40 cm) and WT (−50 cm)	2.148	.1
Soil water content		
WT (−30 cm) and WT (−40 cm)	−2.121	.0942
WT (−30 cm) and WT (−50 cm)	−7.266	<.001***
WT (−40 cm) and WT (−50 cm)	−5.237	<.001***

Note: Displayed are *t*-values and *p*-values of the test.

*May be significant.; **Significant.; ***Highly significant.

in root biomass was driven by inhibition of rooting depth by the higher water position, since the root presence below −30 cm was negligible in the −30-cm treatment. In a more drained soil, greater root production may improve nutrient access and therefore increase shoot production (Wang et al., 2015). Our study showed that even a moderate temperature increase of 2°C can raise both fresh and dry leaf biomass. In our study, the higher temperature raised the rate of photosynthesis (as also seen from the GPP values). Warming can increase stomatal conductance, thus enhancing atmospheric carbon uptake (Marchin et al., 2016; Urban et al., 2017). Moreover, higher temperatures may stimulate expansion of the rooting system (Batts et al., 1998; Hu et al., 2018), and the resulting increased resource uptake can then enhance aboveground growth. As we reported here, the higher total root mass in the elevated temperature treatment was largely driven by the roots in the topsoil layer and there was no effect of the elevated temperature on the root biomass below the depth of −30 cm. This phenomenon, also reported by other studies (Ma et al. 2017; Arndal et al., 2018), could improve fertilizer use efficiency, increasing the aboveground biomass.

4.2 | Greenhouse gas emissions

The lower Rh with the shallower water table is consistent with lower diffusion of oxygen and decreased aerobic decomposition (Taft et al., 2017; Wickland & Neff, 2008). The lack of significant difference in Rh between the −30-cm and the −40-cm water levels suggests that soil C decomposition in the shallower soil layer is more advanced than deeper in the soil, which is consistent with Kechavarzi et al., (2007), who found lower CO_2 loss with a water-table drawdown from 0 to −30 cm than with a decrease from −30 to −50 cm. Peats that have been subjected to prolonged exposure to aerobic conditions may show low Rh flux simply because the majority of easily decomposable compounds have already been oxidized (Bridgham & Richardson, 1992). The dry (but not the fresh) leaf biomass was significantly different only between two water-table levels (−30 and −50 cm), suggesting no net change in total C accumulation in the ecosystem following the water-table rise to −40 cm. The discrepancy between the dry biomass data (which showed a significant difference between the −30-cm and the −50-cm treatment) and the gas fluxes (which showed similar NEE and GPP between the different water levels) may be related to the nature of these different data sets: the NEE and GPP fluxes were measured on a weekly basis (and are therefore more sensitive to the time element), whereas the biomass at harvest represents the cumulative absorption of atmospheric C over 12 weeks, amplifying the differences between the treatments.

The temperature increase likely enhanced Rh by accelerating metabolism of organic matter decomposer microbes (Ziegler et al., 2013) and by raising evapotranspiration, which stimulated aerobic respiration (Gill et al., 2017).

The higher CH_4 consumption from the unplanted cores indicates that even though soil water content was lower in the planted cores, the lettuce either increased CH_4 production or reduced its consumption in soil. Methane emission rates from agricultural peatlands vary between different crops (Norberg et al., 2016), although bare soils are typically associated with lower CH_4 uptake than soils where crops are grown (Maljanen et al., 2004), as root exudates stimulate microbial activity (Girkin et al., 2018; Laanbroek, 2010). In this experiment, lettuce root secretions likely enhanced CH_4 production (Girkin et al., 2018; Serrano-Silva et al., 2014) given the higher DOC content in soil pore water of the planted cores. The dominance of CH_4 consumption over production in all treatments of this experiment

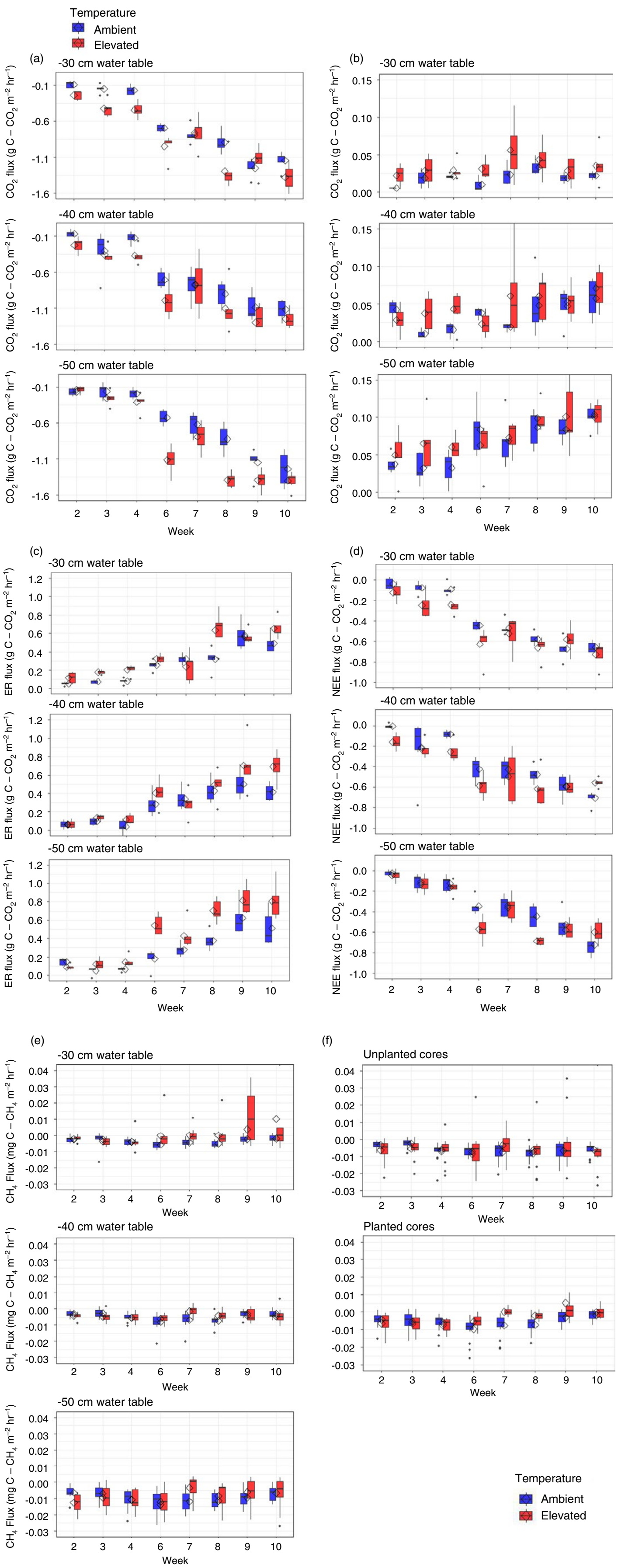

FIGURE 6 GHG emissions from peat cores at the three water-table levels (−30, −40 and −50 cm) for the ambient and elevated (ambient +2°C). Values are means from each week. (a) Gross primary production (GPP); (b) soil respiration (Rh); (c) ecosystem respiration (ER); (d) net ecosystem exchange (NEE); (e) methane flux (CH4) from the three water-table levels; and (f) methane flux (CH4) from planted and unplanted cores

TABLE 5 Effects of temperature, water-table position and cropping treatments and their interactions on DOC in topsoil water and drainage water

	df	χ^2	*p*-value
DOC topsoil			
Temperature	1	3.81	.051
Planting	1	20.75	<.001***
Water table	2	25.6	<.001***
Water table:Temperature	2	1.34	.511
Water table:Planting	2	1.96	.375
Planting:Temperature	1	6.41	.011*
DOC drainage			
Temperature	1	3.43	.064
Planting	1	8.35	.004**
Water table	2	10.98	.004**
Water table:Temperature	2	6.26	.044*
Water table:Planting	2	3.54	.17
Planting:Temperature	1	1.06	.304

The analysis was done with linear mixed model (lmer) (which included 'week' and 'core' as random effects, to take into account the temporal and spatial pseudoreplication). The total number of drainage samples was $n = 127$ (two collection campaigns) and the topsoil samples was $n = 250$ (four collection campaigns).

*May be significant.; **Significant.; ***Highly significant.

is expected as research shows that a water table of −30 to −40 cm should be enough for full oxidation (degradation of CH_4) to occur in cultivated peats (Karki et al., 2016; Poyda, 2016). This is attributable to the high potential of oxygen to penetrate down the soil profile; for example, Thomas et al. (1995) noted that oxygen was present in peat cores at −5-cm depth when the water table was kept within 1 cm to the surface, whereas McDonald et al. (1996) detected CH_4 oxidation at −30 cm in a peat core when the water table was at the surface.

TABLE 6 Post hoc Tukey's test of effect of water-table levels on DOC collected from topsoil water and drainage water

	z-value	*p*-value
DOC topsoil		
WT (−30 cm) and WT (−40 cm)	0.26	.963
WT (−30 cm) and WT (−50 cm)	−4.56	<.001***
WT (−40 cm) and WT (−50 cm)	−4.83	<.001***
DOC drainage		
WT (−30 cm) and WT (−40 cm)	−0.4	.914
WT (−30 cm) and WT (−50 cm)	−3.11	.005**
WT (−40 cm) and WT (−50 cm)	−2.68	.02*

Displayed are z-values and *p*-values of the test.

*May be significant.; **Significant.; ***Highly significant.

TABLE 7 Mean DOC values from all treatment combinations in mmol/L

Treatment	Pore water	Drainage water
Ambient −30 cm planted	5,6566	3,9804
Ambient −30 cm not planted	6,0395	4,2864
Ambient −40 cm planted	6,8943	4,5095
Ambient −40 cm not planted	5,5592	4,6166
Ambient −50 cm planted	5,2830	3,3168
Ambient −50 cm not planted	4,2469	4,5037
+2°C −30 cm planted	7,7525	4,1698
+2°C −30 cm not planted	5,8314	4,7177
+2°C −40 cm planted	7,5770	3,3914
+2°C −40 cm not planted	5,8484	4,2092
+2°C −50 cm planted	5,8649	1,9298
+2°C −50 cm not planted	3,6965	3,6139

4.3 | DOC

The highest concentrations of DOC in peat soils are often found close to the surface, during periods of waterlogging (Chow et al., 2006; Frank et al., 2017), probably because of more easily decomposable organic matter being present in the upper soil layers (Chow et al., 2006; Thibodeaux & Aguilar, 2005). We found that increasing the water-table level from −50 to −30 cm raised DOC concentrations in topsoil pore water, which could stimulate further organic matter decomposition (Morling et al., 2017; Qiu et al., 2016). DOC exported in drainage water will eventually degrade into CO_2, contributing to 'offsite emissions' of GHG (Moran & Zepp, 1997; Shen & Benner, 2018). Oxidation of DOC contributes 2% to CO_2 emissions from agricultural peats in the UK (Evans et al., 2016), and 90% of the DOC exported to oceans eventually oxidizes to CO_2 (IPCC, 2014b).

In peat soils, production of DOC depends on the type of vegetation cover and presence or absence of plants (Basiliko et al., 2012; Clay et al., 2012). Addition of organic matter from vegetation provides a pool from which DOC is produced and root exudates stimulate activity of decomposing microbes. The elevated temperature and planting resulting in higher DOC concentrations in pore water as found in our study is also reported by Fenner et al. (2007) and Harrison et al. (2008). The higher dry root weight in the top 20 cm in the warmer treatment suggests that the elevated temperature led to increased root production and, correspondingly, greater exudate decay and rates of organic matter decomposition via priming (Basiliko et al., 2012; Leroy et al., 2017). For this reason, the predicted future 2°C warming by early next century will likely contribute to higher DOC production and losses to water bodies from agriculturally used fields of the Fens.

5 | CONCLUSION

The findings of this study indicate that raising the water table from −50 to −40 cm decreases fresh leaf biomass by one-fifth. Increasing the water table from the field level to −40 cm was shown to reduce CO_2 emissions, while keeping CH_4 fluxes negative (oxidation), at the same time creating conditions that facilitate greater leaching of DOC, without a significant difference in lettuce leaf dry biomass. Climate warming of 2°C would increase romaine lettuce fresh yields and root biomass, pointing to the important role played by roots in nutrient acquisition. It would also inevitably lead to higher rates of peat decomposition and loss of C as CO_2 and DOC; however, more C would also be sequestered in the romaine lettuce crop. This temperature increase could offset C losses as CO_2, since the rise in soil respiration (by 18%) is lower than the absolute increase in GPP (one-third); however, the final C balance would depend on the complex equilibrium between C uptake, plant productivity and respiratory loss under the changing climate.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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