*Effect of water table management and elevated CO 2 on radish productivity and on CH 4 and CO 2 fluxes from peatlands converted to agriculture*.

**Article:**

Musarika, S., Atherton, C.E., Gomersall, T. et al. (6 more authors) (2017) Effect of water table management and elevated CO 2 on radish productivity and on CH 4 and CO 2 fluxes from peatlands converted to agriculture. Science of The Total Environment, 584-85. pp. 665-672. ISSN 0048-9697

https://doi.org/10.1016/j.scitotenv.2017.01.094

Science of the Total Environment 584–585 (2017) 665–672

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# Effect of water table management and elevated $CO_2$ on radish productivity and on $CH_4$ and $CO_2$ fluxes from peatlands converted to agriculture

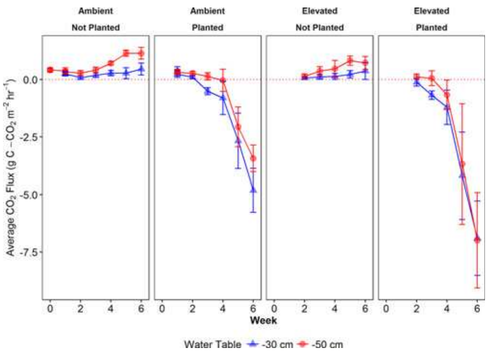
S. Musarika [a,1], C.E. Atherton [a,*,1], T. Gomersall [a], M.J. Wells [a], J. Kaduk [b], A.M.J. Cumming [b], S.E. Page [b], W.C. Oechel [c,d], D. Zona [a,d]

[a] *Department of Animal and Plant Sciences, University of Sheffield, Western Bank, Sheffield S10 2TN, United Kingdom*
[b] *Centre for Landscape & Climate Research, Department of Geography, University of Leicester, Leicester LE1 7RH, United Kingdom*
[c] *College of Environmental Sciences University of Exeter Exeter, EX4 4RU, United Kingdom*
[d] *Global Change Research Group, Dept. Biology, San Diego State University, San Diego, CA 92182, USA*

## HIGHLIGHTS

- Peat loss is a major issue affecting farmers in Europe, including the UK.
- A more sustainable farming should prevent peat loss while maintaining productivity.
- This experiment tested the impact of water table on productivity and peat loss.
- Raising the water table from −50 cm to −30 cm increases radish productivity.
- Increasing water table to −30 cm reduces peat loss.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

*Article history:*
Received 13 October 2016
Accepted 15 January 2017
Available online 30 January 2017

Editor: D. Barcelo

*Keywords:*
Carbon loss
Crop yield
Increased atmospheric $CO_2$
Land use change
Peat degradation
Sustainable agriculture

## ABSTRACT

Anthropogenic activity is affecting the global climate through the release of greenhouse gases (GHGs) e.g. $CO_2$ and $CH_4$. About a third of anthropogenic GHGs are produced from agriculture, including livestock farming and horticulture. A large proportion of the UK's horticultural farming takes place on drained lowland peatlands, which are a source of significant amounts of $CO_2$ into the atmosphere. This study set out to establish whether raising the water table from the currently used −50 cm to −30 cm could reduce GHGs emissions from agricultural peatlands, while simultaneously maintaining the current levels of horticultural productivity. A factorial design experiment used agricultural peat soil collected from the Norfolk Fens (among the largest of the UK's lowland peatlands under intensive cultivation) to assess the effects of water table levels, elevated $CO_2$, and agricultural production on GHG fluxes and crop productivity of radish, one of the most economically important fenland crops. The results of this study show that a water table of −30 cm can increase the productivity of the radish crop while also reducing soil $CO_2$ emissions but without a resultant loss of $CH_4$ to the atmosphere, under both ambient and elevated $CO_2$ concentrations. Elevated $CO_2$ increased dry shoot biomass, but not bulb biomass nor root biomass, suggesting no immediate advantage of future $CO_2$ levels to horticultural farming on peat soils.

---

* Corresponding author at: 231 Crookesmore Road, Sheffield S6 3FQ, United Kingdom.
*E-mail addresses:* musarika@icloud.com (S. Musarika), ceatherton1@sheffield.ac.uk (C.E. Atherton), tgomersall1@sheffield.ac.uk (T. Gomersall), mjwells1995@gmail.com (M.J. Wells), jk61@leicester.ac.uk (J. Kaduk), amjc1@leicester.ac.uk (A.M.J. Cumming), sep5@leicester.ac.uk (S.E. Page), w.oechel@exeter.ac.uk (W.C. Oechel), D.zona@sheffield.ac.uk (D. Zona).

[1] These authors equally contributed to this work

http://dx.doi.org/10.1016/j.scitotenv.2017.01.094

Overall, increasing the water table could make an important contribution to global warming mitigation while not having a detrimental impact on crop yield.

## 1. Introduction

Anthropogenically produced greenhouse gases such as carbon dioxide ($CO_2$) and methane ($CH_4$) represent the principle contributors to global warming (IPCC, 2013). $CO_2$ has been identified as the dominant greenhouse gas (GHG) driving climate change, while $CH_4$ is the second most potent GHG and has a radiative forcing 28 times greater than that of $CO_2$ over a hundred years (IPCC, 2013). Globally atmospheric concentration of $CO_2$ has risen from pre-industrial levels of ~260 ppm to over 400 ppm currently (Wigley, 1983; IPCC, 2014a, b), while atmospheric $CH_4$ have increased 150% over the same time period (IPCC, 2013). A significant proportion of these anthropogenic GHG emissions come from all aspects of agriculture (Foresight, 2011; Gilbert, 2012). The reduction of GHG emissions from agriculture is fraught with enormous challenges. Given the ever-increasing human population, which is estimated to reach around 10 billion in 30 years' time, it is important that any GHGs emission mitigation measures should not negatively affect food production and therefore food security (Godfray et al., 2010). On a global scale, close to 20% of the worlds' peatlands are exploited for agricultural use (Strack, 2008).

Drainage of peatlands for agriculture increases the oxygen content of the soil, promoting organic matter decomposition (Strack, 2008; Regina et al., 2015), which ultimately increases $CO_2$ emissions. A recent study by Evans et al. (2016) (SP1210) measured GHGs fluxes from both cultivated fen peat soils and a near intact peat fen in East Anglia, finding the cultivated soils to be a source of 25.34–28.45 t $CO_2$ $ha^{-1}$ $yr^{-1}$ while the near intact fen was a sink measuring −5.13 t $CO_2$ $ha^{-1}$ $yr^{-1}$. Peatlands cover 11% of England (14,185 $km^2$) but they are estimated to store more than half of total soil C in England (Natural England, 2015). While peatland drainage increases $CO_2$ loss into the atmosphere, natural peatlands are sources of $CH_4$ due to methanogenic activity under their prevalent waterlogged anoxic soil conditions. Consequently, while drainage increases $CO_2$ emissions, it reduces $CH_4$ losses (Petrescu et al., 2015) and can eventually lead to $CH_4$ consumption (Conrad, 1996).

More than half of European peatlands are no longer storing carbon (Zeitz and Velty, 2002) while in the UK about 1.3 million ha (40%) of peatland has been drained for farming purposes and only 20% (660,000 ha) is considered to be nearly natural, i.e. with minimal anthropogenic interference (Dixon et al., 2014). In combination with oxidation, peat is lost from drained peatlands due to physical changes in the soil structure (compression and compaction) and also wind erosion from the drained top layer of the peat soil (Levanon et al., 1987). A clear example of dramatic peat loss can be observed at the Holme Fen Post in Huntingdonshire, in southern England, where soil oxidation and compaction has resulted in subsidence of 4 m since 1848 (Eyre, 1968; Berglund and Berglund, 2011)

To reduce this C loss, it is necessary to raise the water table of cultivated peatlands, but excess water in the plant rooting zone and the associated anoxic soil conditions can negatively affecting root growth resulting in lower crop yields (Wang et al., 2004). Furthermore, a high water table can interfere with the use of heavy farm machinery and can encourage the prevalence of plant fungal diseases such as *Aphanomyces* (water mould), *Pythium*, and *Phytophthora* (Katan, 2000) further reducing crop yield. Only a few studies (e.g. Stanley and Harbaugh, 2002; Berglund and Berglund, 2011) have examined the effects of peatland water table manipulation on agricultural crop yield, especially of commercially important crops. The effect of water table depth on yields dependents on plant species, e.g. maize and sorghum under waterlogged conditions presented reduced yields compared to when soil was more aerated (Kahlown et al., 2005), and grasslands present a 10% loss in yield when water table is raised from −50 to −30 cm (Renger et al., 2002). On the other hand, an increase of water table could be beneficial for plant growth, especially for shallow rooting crops (Lambers et al., 2013), ryegrass (*Lolium perenne*) (Berglund and Berglund, 2011) and caladium (*Caladium xhortulanum*) tuber yields (Stanley and Harbaugh, 2002), and crop tuber yields (Stanley and Harbaugh, 2002). In the UK, farmers regularly use a rather cautious water table depth of −50 cm below the surface, and are concerned that a water table higher than −50 cm will negatively affect crop production (Martin Hammond - Manager at Rosedene Farm, one of the largest fenland farms in the UK, 2017). Overall, raising water table level should slow down peatland degradation and reduce GHGs emissions significantly improve the protection of the peat soil and reduce C loss (e.g. Renger et al., 2002), supporting more sustainable agricultural practices.

Increased atmospheric $CO_2$ affects plants by increasing their growth rate as the photosynthetic rate and water use efficiency are improved, leading to an increase in biomass (Idso et al., 1987; Poorter, 1993). Photosynthetic rate increases under elevated $CO_2$ levels (Sage et al., 1989; Poorter, 1993; Ainsworth and Long, 2005). To date, few studies have explored the impact that elevated $CO_2$ in combination with water table management has on crop productivity (Ainsworth and Long, 2005) and on the net $CO_2$ and $CH_4$ release from soil (Dijkstra et al., 2012), and thereby on the impact that agricultural practices will have on the climate.

In consultation with the farm manager of one of the largest farming groups in the UK, in eastern England, we undertook a multifactorial manipulation of water table and $CO_2$ concentration on peat cores collected from their field to test the response of $CO_2$ and $CH_4$ fluxes to current and future conditions. The final goal of this study was to explore the possibility of significantly reducing the rate of peat C loss by increasing the soil water table from a current position of −50 cm to a water table of −30 cm while maintaining a commercially acceptable crop yield. We hypothesised that increasing the water table to −30 cm from the currently adopted −50 cm would reduce $CO_2$ emissions but increase $CH_4$ emissions, and increase radish productivity. Finally, we expected that radish productivity would be higher with elevated $CO_2$.

## 2. Materials and methods

### 2.1. Study site

The soil samples used in the experiment were collected from Rosedene Farm in the East Anglian fens, west Norfolk (Fig. 1). The soils are formed from nutrient-rich fen peat, established after extensive post-war drainage that was ushered in by a large-scale agricultural expansion programme during the late 1930s and the early 1940s (Short, 2007). The core sampling was performed on the 24th September 2015, when no crops was present in the field. The different fields were separated by dykes, used for water table management separate all the fields, and these dykes are connected to water reservoirs used to manage the water table over the entire farm.

### 2.2. Experimental design

A total of 46 cores were successfully collected from the site and transported to the Sir David Read Controlled Environment Facility at the University of Sheffield, United Kingdom. The cores were collected using PVC pipes of 11 cm inner diameter and 50 cm depth. In order to preserve the soil structure, i.e. avoid compaction and horizons, the

**Fig. 1.** The field on Rosedene Farm in Methwold where the soil samples were collected. The farm's location is highlighted on the UK map in the insert.

PVC pipes were inserted into the soil until a −50 cm depth and then dug out to extract the soil cores intact. The multifactorial design required a total of 48 cores, but the PVC pipes of two cores were damaged during collection. Smaller PVC pipes (referred as water table depth pipes) of about 1.5 cm diameter with holes drilled every 1 cm were inserted into the extracted cores to monitor the depth of the water tables of the cores throughout the experiment. The pipes were protected with a fine mesh to prevent soil penetration and plugging of the holes. The bases of the cores were capped with pipe couplers and end caps to make a waterproof and airtight seal.

We planted radish (*Raphanus sativus*) in half the cores and left the other half without any crop. Radish is a crop of economic importance in the UK with around 5800 t grown in the UK each year (Agricultural and Horticultural Development Board, 2014). The multi-factorial experiment manipulated water table (with two levels −30 and −50 cm), and $CO_2$ concentration (400 and 800 ppm) and was designed to investigate i) the effects of atmospheric $CO_2$ concentration on growth of radish and fluxes of $CH_4$ and $CO_2$, ii) the effects of different water tables (−30 cm and −50 cm) on radish growth and fluxes of $CO_2$ and $CH_4$ and iii) the effects of the presence of radish on the fluxes of $CO_2$ and $CH_4$. The farm grows a variety of crops, including lettuce, celery, and potatoes, but radish was an ideal candidate for this study because of its relatively small size, which allowed us to perform this experiment in growth chambers.

The cores were evenly divided between two growth chambers (one maintained at ambient $CO_2$, 400 ppm and the other at elevated $CO_2$, 800 ppm) and the experiment was carried out over a period of 7 weeks. The selected $CO_2$ concentration of 800 ppm is consistent with the multi-model average of the Representative Concentration Pathways (RCP) that range from lows of 794 ppm to highs of 1142 ppm by the year 2100 (IPCC, 2013; IPCC, 2014a, b). The first week (Week 0) of the experiment was used as a baseline, and both chambers had the same atmospheric $CO_2$ concentrations (ambient at ~400 ppm), temperature of 10 °C, humidity of 70%, and the water table in all cores was maintained at −50 cm in all cores, and no crops were planted. During this time, the fluxes from the cores were nearly identical between the chambers ($0.404 \pm 0.078$ s.d. g C $CO_2$ $m^{-2}$ $h^{-1}$ and $0.424 \pm 0.092$ s.d. C $CO_2$ $m^{-2}$ $h^{-1}$, with not a significant statistical difference). In Week 1 in 12 of the cores of each chamber the water table was raised to −30 cm and in the other 11 the level was kept at −50 cm, as illustrated in Fig. 2. Six cores from each water table level were planted with three seeds of radish per core, while the other five or six cores were left unplanted (Fig. 2). This design allowed partitioning the response of the $CO_2$ and $CH_4$ fluxes in the presence and absence of crops for each treatment. To partition the impact of respiration and photosynthetic activity and estimate gross primary productivity (GPP) in the planted cores, $CO_2$ fluxes were measured under both dark and light conditions. The relative humidity was maintained constantly at 70% during the entire experiment while the air temperature was increased weekly from 10 °C (Week 0, Week 1, Week 2), to 12 °C (Week 3), to 15 °C (Week 4), and to 20 °C (Week 5, Week 6), mimicking the seasonal increase in the field. These temperatures were selected after analysis of available field data collected from a meteorology station for the years 2012–2015 (A. Cumming, 2017). During the experiment, the Photosynthetically Active Radiation (PAR) was on average 613.4 ± 165.2 s.d., $\mu$mol $m^{-2}$ $s^{-1}$ ($n = 10$) during the day (8:00–20:00) and off during the night.

The water table depths were checked daily to ensure that they remained at the required depths. If the water table dropped below the desired values, distilled water was carefully added to the cores. When the water table depth pipes were not used to record the water table levels, their extremity were plugged to prevent $CO_2$ or $CH_4$ release from deeper soil layers. Soil temperature at −10 cm below the soil surface, air temperature at 10 cm above the surface, and soil moisture in the upper 10–12 cm of soil were recorded twice a week. Air and soil temperatures were recorded using thermocouples, and soil moisture was measured using a CS616 (Campbell Scientific, Logan, Utah, USA) with 12 cm long probes, inserted into the soil at a slight angle. All these sensors were connected to a datalogger (CR1000, Campbell Scientific Logan, Utah, USA).

### 2.3. Gas flux measurement and calculation

During the experiment, $CH_4$ and $CO_2$ flux measurements were collected twice a week using a Los Gatos Research (LGR) Ultra-Portable Greenhouse Gas Analyzer (UGGA). A measuring chamber with a volume of 0.006059 $m^3$ and an area of 0.0034212 $m^2$ was connected to the LGR. The measuring chamber, a clear Plexiglas® cylinder, was placed over each core for 3 min, and was removed for a minute between each measurement. The $CO_2$ or $CH_4$ fluxes were estimated by the rate of increase in concentration within the chamber when the measuring chamber was placed above the cores as described in McEwing et al. (2015).

Respiration was measured by covering the measuring chamber with aluminium foil to block any light (and therefore inhibiting photosynthesis). Gross primary productivity (GPP) was estimated by adding the $CO_2$ fluxes under light conditions (i.e. the net ecosystem exchange, NEE) to respiration (RE). Net ecosystem exchange (NEE) indicate the net $CO_2$ fluxes collected with the clear chamber, with positive values indicating release of C into the atmosphere and negative values uptake of C.

### 2.4. Harvesting the crops

At the end of Week 6, the radish crops were harvested. To prevent damage to the roots, the soil was carefully poured out from each PVC pipe, then any excess soil was removed while retaining fine roots. The root, shoot and bulb fresh biomass were measured separately immediately after harvesting, inserted into individual paper bags and dried in an oven at 80 °C for over 48 h, and the measured again to estimate the dry biomass.

### 2.5. Statistical analysis

The $CO_2$ and $CH_4$ fluxes were separated between planted and unplanted cores and then analysed for statistical differences between the different treatments using R (version 3.2.3, R Developing Team). The diagnostic plots indicated an acceptable normality assumption of the $CO_2$ and $CH_4$ fluxes. Repeated measures ANOVA (three-way) was carried out using the lmerTest package (Kuznetsova et al., 2016), to test if $CH_4$ flux, $CO_2$ flux, respiration and GPP were different among the different treatments; water table (−30 cm and −50 cm), atmospheric $CO_2$ concentration (ambient and elevated) and the presence/absence of radish. This repeated measures design was chosen to account

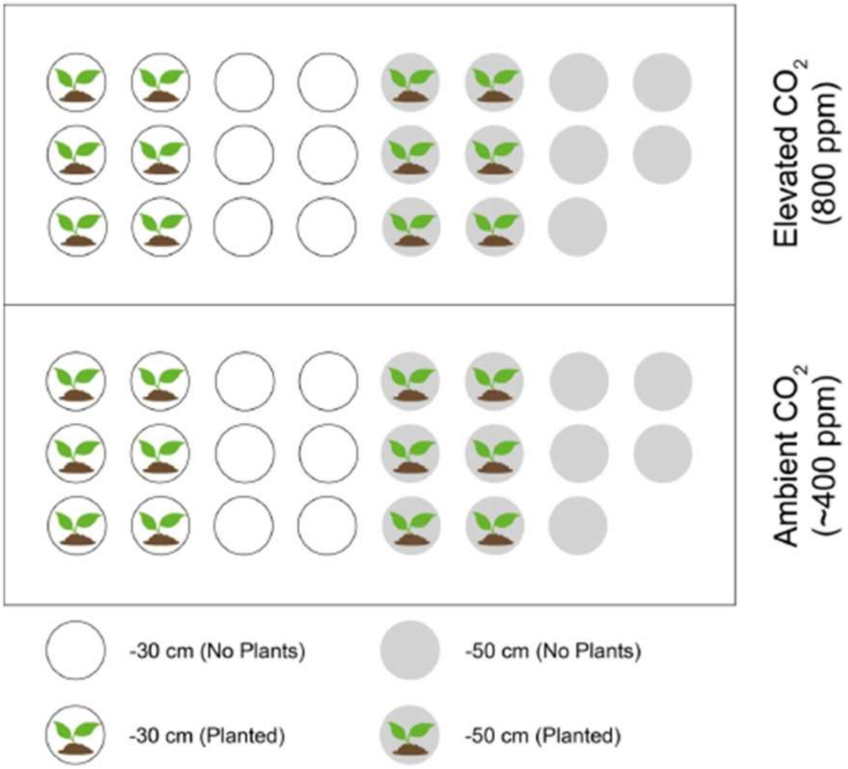


**Fig. 2.** The layout of the growth chambers, the elevated chamber top panel and the ambient chamber bottom panel. Both chambers had 23 cores. The shaded circles represent −50 cm unplanted cores and shaded circles with the illustrated plant represent −50 cm planted cores. The unshaded circles represent −30 cm water table unplanted and −30 cm planted with the illustrated plant.

for pseudo replication because the cores were measured multiple times throughout the experiment. Furthermore, a two-way ANOVA was used to test if plant wet and dry biomass collected at the end of the experiment were different among the water table levels and the atmospheric $CO_2$ concentrations.

## 3. Results

### 3.1. Ecosystem respiration (RE)

The initial $CO_2$ fluxes in Week 0 showed that the soil was losing $CO_2$, with a recorded average across the cores of 0.414 ± 0.085 (mean ± s.d.) g C $CO_2$ $m^{-2}$ $h^{-1}$. The average RE from the unplanted cores with −50 cm water table were higher for both atmospheric $CO_2$ concentrations than in the −30 cm (Fig. 3). Statistical analysis of RE, in the unplanted cores indicated a significant effect of water table ($t = 6.838$, $p < 0.001$). Atmospheric $CO_2$ concentration was not significant, neither was the interaction of water table and atmospheric $CO_2$ concentration. RE increased with increased temperature over the duration of the experiment (Fig. 4).

### 3.2. Net ecosystem exchange (NEE)

The planted cores showed on average an uptake of $CO_2$ (Fig. 3), and the cores in the elevated atmospheric $CO_2$ chamber sequestered on average more $CO_2$ than the cores in the ambient atmospheric $CO_2$ chamber (Fig. 3). Furthermore, there were marked differences in fluxes between the water tables, with the −30 cm water table resulting in more $CO_2$ uptake in the planted cores (Figs.s 3 and 4). Statistical analysis of NEE for the planted cores showed that there was a significant effect of the water table ($t = 2.150$, $p = 0.0344$), and atmospheric $CO_2$ concentration ($t = -2.100$, $p = 0.0387$). The interaction between the water table and atmospheric $CO_2$ concentration was however not statistically significant. As expected, the plant growth over the duration of the experiment increased the $CO_2$ uptake (Fig. 4).

### 3.3. Gross primary productivity (GPP)

Statistical analyses of the GPP in the planted cores showed that there was a significant effect of the water table ($t = -2.664$, $p = 0.0094$) but there was no significant effect of atmospheric $CO_2$ concentration ($t = 0.052$, $p = 0.9584$). Likewise, the interaction between water table and atmospheric $CO_2$ concentration was not significant.

### 3.4. $CH_4$ fluxes

During the entire experiment, an average $CH_4$ consumption was observed in all treatments (Fig. 6) with an overall average of −0.023 ± 0.044 s.d. mg C —$CH_4$ $m^{-2}$ $h^{-1}$. Lower $CH_4$ consumption was found in the −30 cm water table under both atmospheric $CO_2$ concentrations, and the presence of crops decreased $CH_4$ consumptions when water table was at −30 cm (Fig. 5). A small $CH_4$ emission was observed with the −30 cm water table, more pronounced under the warmest conditions in Week 6 (Fig. 6). The statistical analysis of the $CH_4$ fluxes shows that water table treatment has a statistically significant effect on $CH_4$ fluxes ($f = 14.4711$, $p \leq 0.001$). Conversely, atmospheric $CO_2$ concentration did not have a significant effect on the $CH_4$ fluxes, neither was the presence of crops by themselves. However, the interaction of the water table and the presence of crops had a significant effect on $CH_4$ fluxes ($f = 5.0772$, $p = 0.025$). The interaction between water table and atmospheric $CO_2$ concentration was not significant, neither was the interaction between the presence of crops and atmospheric $CO_2$ concentration.

### 3.5. Roots, shoots, and bulb biomass

The average entire plant (including roots, shoots, and bulb) fresh biomass at harvest was 89.5 g ± 28.03 (mean ± s.d.) at ambient $CO_2$ with −30 cm water table, and 67.5 g ± 13.73 at ambient $CO_2$ with −50 cm water table, 84.1 g ± 15.13 at elevated $CO_2$ with −30 cm water table and 87.9 g ± 12.37 at elevated $CO_2$ with −50 cm water table. The statistical analysis of the plant dry biomass showed a significant effect of water table level ($f = 4.4507$, $p = 0.048$) and atmospheric $CO_2$ concentration ($f = 4.2541$, $p = 0.052$), while the interaction between water table level and atmospheric $CO_2$ concentration was not significant. The effect of the water table on the dry bulb biomass was significant ($f = 6.1600$, $p = 0.02207$), but the effect of atmospheric $CO_2$ concentration was not significant, neither was the interaction between the water table and atmospheric $CO_2$ concentration. For root dry biomass, there was no significant effect of water table, and neither

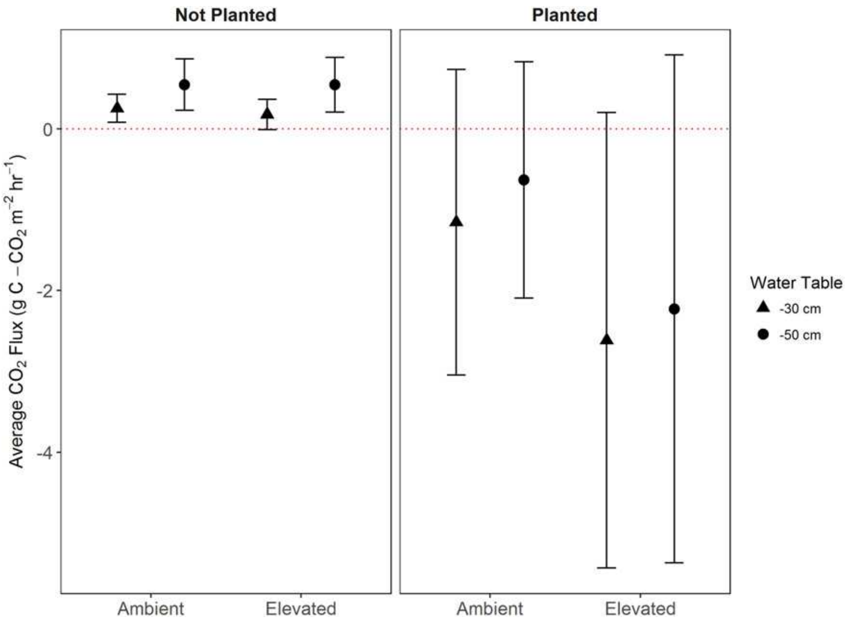


**Fig. 3.** $CO_2$ averages (RE for the not planted cores, and NEE for the planted cores) taken using the transparent chamber for all the growing weeks for all the in each of the two chambers (ambient and elevated $CO_2$). Displayed are means and st. deviations.

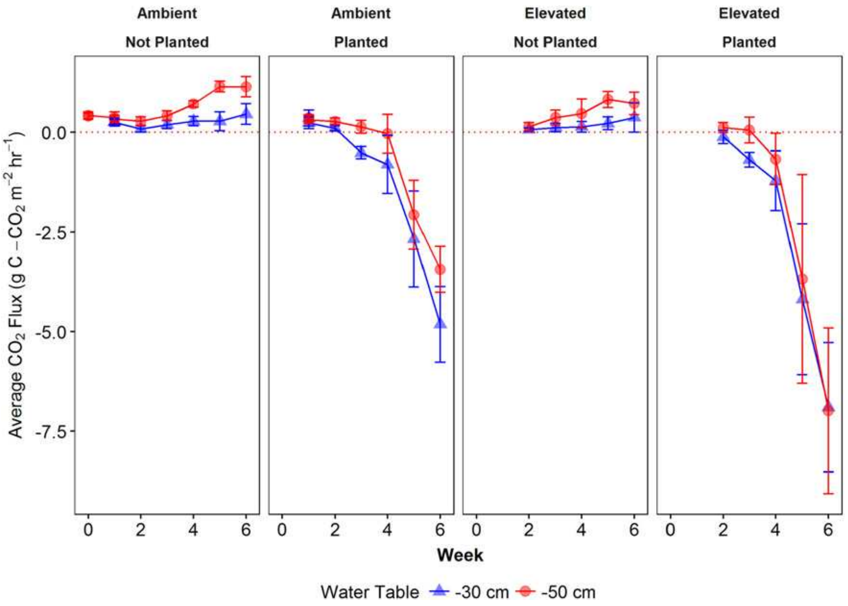


**Fig. 4.** Weekly averaged $CO_2$ fluxes, in each of the indicated treatments (RE for the not planted cores, and NEE for the planted cores). These panels display only the measurements using the transparent measuring chamber (equivalent to the net ecosystem exchange in planted cores, and the respiration in the not-planted cores). Displayed are mean and st. deviations.

atmospheric $CO_2$ concentration, nor the interaction between water table and atmospheric $CO_2$ concentration. The effect of the water table on the shoot dry biomass was not significant effect, but atmospheric $CO_2$ concentration did have a significant effect on the shoot dry biomass (*f* = *6.5723*, *p* = *0.01852*). The interaction between the water table and atmospheric $CO_2$ concentration was likewise significant for the shoot dry biomass (*f* = *5.2786*, *p* = *0.03251*).

## 4. Discussion

This study showed that a −30 cm water table has the potential to improve the productivity of radish bulbs, while decreasing $CO_2$ loss from the peat soil, without resulting in a $CH_4$ loss into the atmosphere. This is in contrast to the observed reduction in optimum plant productivity with increased water table (Renger et al., 2002; Kahlown et al., 2005), and in agreement with the observed increase in yield with higher water table from shallow rooting and tubers (Stanley and Harbaugh, 2002; Berglund and Berglund, 2011; Lambers et al., 2013). The dry radish bulbs weight was in fact higher at −30 cm water table than at −50 cm water table, suggesting that increasing the water table favours crop productivity, at least in the case of radish. This result is also consistent with the higher GPP in the high (−30 cm) water table level. Given that farmers are concerned that increasing the water table during the growing season will negatively affect productivity, this is a very important finding that should support more responsible agricultural practices.

While radish bulbs grew better with increased water availability, they were not affected by elevated atmospheric $CO_2$ concentration. This result was surprising, as raising atmospheric $CO_2$ concentration increase the photosynthetic rate and biomass accumulation (e.g. Idso et al., 1987; Poorter, 1993; Smith et al., 2000; Reddy et al., 2010). On the

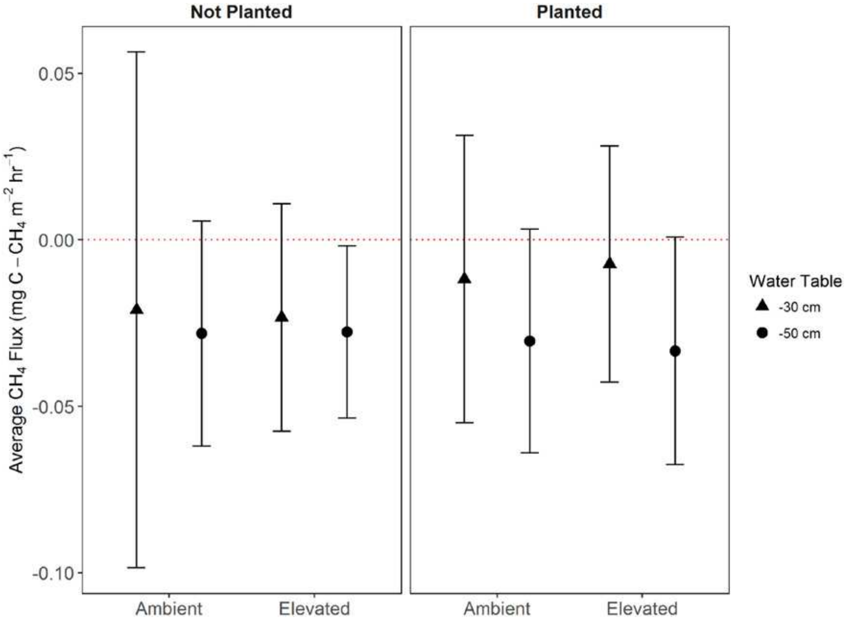


**Fig. 5.** Average $CH_4$ fluxes for the whole experiment for each of the treatments of the water table, atmospheric $CO_2$ concentration and the presence of crops. Displayed are means and st. deviations.

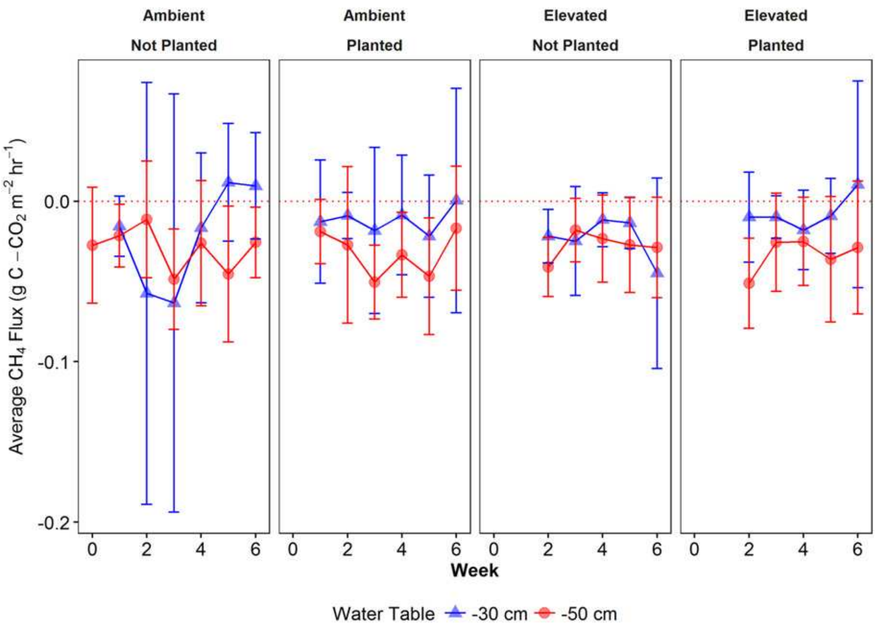


**Fig. 6.** Weekly $CH_4$ flux averages. The top four panels were in the ambient $CO_2$ chamber, the first two had a 50 cm water table while the other two had a −30 cm water table. The bottom four panels are from the elevated chamber, the first two had a −50 cm water table, and the other two had a 30 cm water table. The panels show only fluxes measured using the transparent measuring chamber. Displayed are means and standard deviation.

other hand, shoots did respond to elevated atmospheric $CO_2$ concentration. Further research should be performed to investigate the potential changes in carbon allocation under elevated $CO_2$.

Overall, we showed that a modest increase of the water table from −50 cm to −30 cm not only improved radish productivity, but also decreased $CO_2$ loss from the peatland, and therefore reduced peat loss. In this study, increasing the water table from −50 to −30 cm more than halved the soil $CO_2$ loss, and therefore could present an important mitigation strategy for climate change. Nonetheless, there are concerns that reducing aerobic respiration and consequently $CO_2$ loss can instead lead to an increase in $CH_4$ emissions, because $CH_4$ is produced under anoxic conditions (Moore and Dalva, 1993) and might be particularly relevant in these rich peatland soils (IPCC, 2014a, 2014b). Generally, $CH_4$ emissions from peatlands should not be ignored given the significantly greater radiative forcing of $CH_4$ compared to that of $CO_2$ and its higher global warming potential (GWP). Nevertheless, the increase in the water table during this experiment average $CH_4$ consumption was generally observed during the entire duration of the experiment. A higher water table (−30 cm) resulted in less $CH_4$ consumption than the −50 cm water table, and only a minor $CH_4$ emission only during the end of the experiment, under the warmest conditions. The lower consumption in the higher water table treatment could be due to the combination of higher production in the anoxic soil layers combined with the lower consumption in the narrower near surface soil layer (e.g. Munir and Strack, 2014). Higher temperatures have been shown to increase methanogen abundance and substrate availability, resulting in a higher $CH_4$ emission (Inglett et al., 2012).

In conclusion, the results of this study indicate that increasing the water table in lowland fen peatland used for agriculture can make a sizeable contribution to the mitigation of soil-derived GHG emissions, while potentially maintaining (or even increasing) current levels of crop production. As previously shown by Kahlown et al. (2005), the effects of water table depth on crop productivity depends on the crop species, thus experimentation using other commercially important crops, in addition to radish, should be undertaken so that farmers can be better informed, and decide to use a higher water table in their fields. Given the current scale of GHG emissions from drained horticultural peat soils in the UK there is an urgent need to identify economically feasible mitigation measures. The significant improvements in C sequestration and reduced C losses revealed in this study as a result of a modest increase in the water table indicate that farmers could implement relatively simple measures to assist in reducing GHG, emissions and decrease their peat loss while simultaneously maintaining, and possibly increasing, crop yields.

## Authors' contributions

WCO and SP are the PIs of the Leverhulme Visiting Professorship that supported this research, DZ is the PI of the Royal Society International Exchange that co-funded this project. DZ supervised the students that performed this experiment with the support of WCO and SP. SM, CEA, TG, BB, MJW performed the experiment; JK, and AMJC helped with the soil cores collection and provided feedback on the data analysis and interpretation. All authors contributed to writing the paper.

## Acknowledgements

We thank Martin Hammond and his son Alexander Hammond from Rosedene Farm for their help and for allowing us to take soil samples from the farm, Simon Benson and David Ackerley were also crucial in the collection of the cores. The staff at the University of Sheffield that helped with the experiment and Ben O Boxall for assisting with data collection. WO and SP are grateful for the award of a Leverhulme Visiting Professorship (grant number VP2-2012-028) which enabled them to undertake collaborative research, a part of which is reported in this paper and by a Royal Society International Exchange grant awarded to D Zona (R/2013), and by a NERC grant (award number NE/P002552/1). We thank the Grantham Centre for Sustainable Futures for the support to the students helping with the project.

## References

Agricultural and Horticultural Development Board, 2014. Use of Plant Defence Elicitors to Provide Induced Resistance Protection in Brassica and Allium Crops. (Available: http://horticulture.ahdb.org.uk/sites/default/files/research_papers/FV%20417_GS_Annual_2014.pdfLast accessed 24th September 2016).

Ainsworth, E.A., Long, S.P., 2005. What have we learned from 15 years of free-air $CO_2$ enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising $CO_2$. New Phytol. 165, 351–372.

Berglund, Ö., Berglund, K., 2011. Influence of water table level and soil properties on emissions of greenhouse gases from cultivated peat soil. Soil Biol. Biochem. 43, 923–931.

Conrad, R., 1996. Soil microorganisms as controllers of atmospheric trace gases H-2, CO, $CH_4$, OCS, $N_2O$, and NO. Microbiol. Rev. 60, 609–640.

Cumming, A., 2016. (Personal communication). University of Leicester (2017).

Dijkstra, F.A., Prior, S.A., Runion, G.B., Torbert, H.A., Tian, H., Lu, C., Venterea, R.T., 2012. Effects of elevated carbon dioxide and increased temperature on methane and nitrous oxide fluxes: evidence from field experiments. Front. Ecol. Environ. 1, 520–527.

Dixon, S.D., Qassim, S.M., Rowson, J.G., Worrall, F., Evans, M.G., Boothroyd, I.M., Bonn, A., 2014. Restoration effects on water table depths and $CO_2$ fluxes from climatically marginal blanket bog. Biogeochemistry 118, 159–176.

Evans, J., Gauci, V., Grayson, R., Haddaway, N., He, Y., Heppell, K., Holden, J., Hughes, S., Kaduk, J., Jones, D., Matthews, R., Menichino, N., Misselbrook, T., Page, S., Pan, G., Peacoak, M., Rayment, M., Ridley, L., Robinson, I., Rylett, D., Scowen, M., Stanley, K., Worrall, F., 2016. Lowland peatland systems in England and Wales - evaluating greenhouse gas fluxes and carbon balances. Final report to Defra on Project SP1210. Centre for Ecology and Hydrology, Bangor.

Eyre, S.R., 1968. Vegetation and Soils: A World Picture. Edward Arnold, London.

Foresight, 2011. The Future of Food and Farming. The Government Office for Science, London.

Gilbert, N., 2012. One-third of our Greenhouse Gas Emissions Come From Agriculture. (Avaliable: http://www.nature.com/news/one-third-of-our-greenhouse-gas-emissions-come-from-agriculture-1.11708 Last accessed 29th April 2016).

Godfray, H.C., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327 (5967), 812–818.

Hammond, M., 2016. (Personal communication). Rosedene Farm (2017).

Idso, S.B., Kimball, B.A., Anderson, M.G., Maunder, J.R., 1987. Effects of atmospheric $CO_2$ enrichment on plant growth: the interactive role of air temperature. Agric. Ecosyst. Environ. 20, 1–10.

Inglett, K.S., Inglett, P.W., Reddy, K.R., Osborne, T.Z., 2012. Temperature sensitivity of greenhouse gas production in wetland soils of different vegetation. Biogeochemistry 108 (1), 77–90.

IPCC, 2013. Climate change 2013. The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

IPCC, 2014a. Climate change 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Cambridge.

IPCC, 2014b. Climate change 2014. Synthesis Report - Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Geneva.

Kahlown, M.A., Ashraf, M., Zia-ul-Haq, 2005. Effect of shallow groundwater table on crop water requirements and crop yields. Agric. Water Manag. 76 (1), 24–35.

Katan, J., 2000. Physical and cultural methods for the management of soil-borne pathogens. Crop. Prot. 19 (8–10), 725–731.

Kuznetsova, A., Brockhoff, P.B., Christensen, R.H., 2016. lmerTest: Tests in Linear Mixed Effects Models. R Package Version 2.0-30. (Available: http://CRAN.R-project.org/package=lmerTest Last accessed 17th March 2016).

Lambers, H., Chapin III, F.S., Pons, T.L., 2013. Plant water relations. In: Lambers, H., Chapin III, F.S., Pons, T.L. (Eds.), Plant Physiological Ecology. Springer, New York, pp. 154–209.

Levanon, D., Levin, I.K., Cohen, U., 1987. The effect of high yielding perennial herbage crops on biological degradation and nitrate accumulation in peat soil. Exp. Agric. 23 (1), 69–74.

McEwing, K.R., Fisher, J.P., Zona, D., 2015. Environmental and vegetation controls on the spatial variability of $CH_4$ emission from wet-sedge and tussock tundra ecosystems in the Arctic. Plant Soil 288, 37–52.

Moore, T.R., Dalva, M., 1993. The influence of temperature and water table position on carbon dioxide and methane emissions from laboratory columns of peatland soils. Eur. J. Soil Sci. 44 (4), 651–664.

Munir, T.M., Strack, M., 2014. Methane flux influenced by experimental water table drawdown and soil warming in a dry boreal continental bog. Ecosystems 17 (7), 1271–1285.

Natural England, 2015. Summary of evidence: Soils EIN012. (Available: http://publications.naturalengland.org.uk/publication/6432069183864832. Last accessed 25th September 2016).

Petrescu, A.M.R., Lohila, A., Tuovinen, J.P., Baldocchi, D.D., Desai, A.R., Roulet, N.T., Vesala, T., Dolman, A.J., Oechel, W.C., Marcolla, B., Friborg, T., Rinne, J., Matthes, J.H., Merbold, L., Meijide, A., Kiely, G., Sottocornola, M., Sachs, T., Zona, D., Varlagin, A., Lai, D.Y.F., Veenendaal, E., Parmentier, F.J.W., Skiba, U., Lund, M., Hensen, A., van Huissteden, J., Flanagan, L.B., Shurpali, N.J., Grünwald, T., Humphreys, E.R., Jackowicz-Korczyński, M., Aurela, M.A., Laurila, T., Grüning, C., Corradi, C.A.R., Schrier-Uijl, A.P., Christensen, T.R., Tamstorf, M.P., Mastepanov, M., Martikainen, P.J., Verma, S.B., Bernhofer, C., Cescatti, A., 2015. The uncertain climate footprint of wetlands under human pressure. Proc. Natl. Acad. Sci. 112 (15), 4594–4599.

Poorter, H., 1993. Interspecific variation in the growth response of plants to an elevated ambient $C0_2$ concentration. Vegetatio 104 (1), 77–97.

Reddy, A.R., Rasineni, G.K., Raghavendra, A.S., 2010. The impact of global elevated $CO_2$ concentration on photosynthesis and plant productivity. Curr. Sci. 99 (1), 46–57.

Regina, K., Sheehy, J., Myllys, M., 2015. Mitigating greenhouse gas fluxes from cultivated organic soils with raised water table. Mitig. Adapt. Strateg. Glob. Chang. 20 (8), 1529–1544.

Renger, M., Wessolek, G., Schwärzel, K., Sauerbrey, R., Siewert, C., 2002. Aspects of peat conservation and water management. J. Plant Nutr. Soil Sci. 165 (4), 487–493.

Sage, R.F., Sharkey, T.D., Seemann, J.R., 1989. Acclimation of photosynthesis to elevated CO2 in five C3 species. Plant Physiol. 89, 590–596.

Short, B., 2007. War in the fields and villages: the county war agricultural committees in England, 1939–45. Rural. Hist. 18 (2), 217–244.

Smith, S.D., Huxman, T.E., Zitzer, S.F., Charlet, T.N., Housman, D.C., Coleman, J.S., Nowak, R.S., 2000. Elevated $CO_2$ increases productivity and invasive species success in an arid ecosystem. Nature 408, 79–82.

Stanley, C.D., Harbaugh, B.K., 2002. Water table depth effect on water use and tuber yield for subirrigated caladium production. HortTechnology 12 (4), 679–681.

Strack, M., 2008. Peatlands and Climate Change. International Peat Society, Jyväskylä.

Wang, X., Hollanders, P.H., Wang, S., Fang, S., 2004. Effect of field groundwater table control on water and salinity balance and crop yield in the Qingtongxia Irrigation District, China. Irrig. Drain. 53 (3), 263–275.

Wigley, T.M., 1983. The pre-industrial carbon dioxide level. Climate Change 5 (4), 315–320.

Zeitz, J., Velty, S., 2002. Soil properties of drained and rewetted fen soils. J. Plant Nutr. Soil Sci. 165 (5), 618–626.