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Raising the groundwater table in the non-growing season can reduce greenhouse gas emissions and maintain crop productivity in cultivated fen peats

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Abstract

Fen peatlands represent a globally important carbon (C) store, while also providing highly productive agricultural land. Drainage of these organic soils is required to create conditions suitable for crop growth, but this results in substantial greenhouse gas (GHG) emissions. One potential GHG mitigation option is to raise the groundwater table to reduce the duration and volume of peat exposure to aerobic conditions. However, the trade-off between maintaining food production and securing ecosystem function under a high water table (WT) presents a serious challenge for both land managers and policy makers. Therefore, we conducted a controlled mesocosm experiment to investigate the effects of WT elevation (from -50 cm to -30 cm) under three contrasting scenarios: (i) WT raised throughout the year, (ii) WT raised in the winter only, and (iii) WT raised in the growing season only. We measured GHG emissions, nitrate, ammonium and dissolved organic C concentrations in soil solution, alongside the yield of a commercially important crop (lettuce). Raising the WT throughout the year reduced lettuce yields by 37% and reduced CO_2 emissions by 36% without changing the loss rates of N_2O or CH_4. Raising the WT only in the winter did not significantly reduce crop yield, but still suppressed CO_2 emissions during the fallow period (by 30%). Raising the WT only in the growing season reduced root growth and CO_2 emissions (by 27%), but had no major effect on lettuce yield. In conclusion, the present study shows that raising the groundwater table in the non-growing season reduced GHG emissions without negatively affecting lettuce yields, and may therefore represent a viable GHG mitigation option for agricultural peatlands.

Key words: food security, Histosol, hydrological regime, nutrient cycling, sustainable agriculture

1. Introduction

Peatland soils store >600 Gt carbon (C) globally and constitute the largest natural terrestrial C pool (Limpens et al., 2008; Yu et al., 2010). Therefore, changes in the peatland C pool can have substantial effects on atmospheric carbon dioxide (CO_2) levels, and thus the global climate (IPCC, 2013). At present, extensive areas of peatlands are drained and cultivated for agriculture (Leifeld and Menichetti, 2018; Wijedasa et al., 2018). Lowering of groundwater tables by drainage aerates peat soils, stimulating microbial mineralisation of soil organic matter (SOM) and increasing losses of both CO_2 and dissolved organic C (DOC) (Dawson et al., 2010; Evans et al., 2016). Oxidation of soil C in cultivated peatlands generates an estimated 0.9 to 1.9 Gt CO_2-eq yr^{-1}, accounting for 2.5 to 5% of all anthropogenic greenhouse gas (GHG) emissions (IPCC, 2013; Leifeld and Menichetti, 2018). Given the extent of peatland drainage, there is an urgent need for information on how management practices can be modified to decrease drainage-induced GHG emissions whilst maintaining the current horticultural productivity in these economically important areas.

Raising the groundwater table could be an effective strategy for minimizing C losses from nutrient-rich cultivated peat soils (Musarika et al., 2017; Leifeld and Menichetti, 2018; Wijedasa et al., 2018; Wen et al., 2019a,b). This strategy can reduce oxygen diffusivity in soil pores, and subsequently suppress aerobic catabolism, limit rates of SOM mineralisation and reduce CO_2 emissions (Dinsmore et al., 2009; Fenner and Freeman, 2011). However, the more anaerobic soil conditions created may increase the potential for denitrification and methanogenesis, leading to increased production of nitrous oxide (N_2O) and methane (CH_4) (Turetsky et al., 2011; Lee et al., 2017). For example, Wen et al. (2019a) reported a significant pulse of N_2O emissions when groundwater tables were raised alongside incorporation of a highly nitrogenous cover crop (Vetch; *Vicia sativa*). Elevated groundwater tables are also liklely to favour denitrification and thus produce substantial N_2O emissions in the immediate period following rewetting (Taft et al., 2018). However, N_2O emissions might also decrease under saturated conditions due to the reduction of N_2O by complete denitrification (Wen et al., 2016). CH_4 emissions can be very high when groundwater tables are close to or above the peat surface, but methanotrophy in aerobic surface peat generally limits CH_4 emissions to negligible levels when groundwater table depths are maintaned below 20 cm (Dias et al., 2010; Couwenberg et al., 2011; Evans et al., 2017). Overall, it remains unknown to what extent the groundwater table elevation can mitigate net GHG emissions in cultivated peatland soils.

For groundwater table management to be a viable option to decrease GHG emissions in intensive arable areas, it would need to be adopted by land managers. Raising groundwater tables too far is likely to produce anoxic conditions around the root zone, which can negatively impact root growth and thus lower crop yields (Wen et al., 2019b). A high groundwater table could also reduce the supply or availability of nutrients (e.g. N and P) due to the reduced rates of peat mineralisation (and the subsequent release of ammonium and inorganic P) under anaerobic conditions. This would also limit the conversion of ammonium (NH_4^+) to nitrate (NO_3^-) via nitrification. Thus, crop growth is likely to be restricted unless it can be offset by additional fertilisation. The effects of groundwater depth on the growth and yield of crops will depend on plant species and root architecture. The cover crops rye and vetch showed a 22% and 29% loss in yield, respectively, when the groundwater table was increased from -50 cm to -30 cm (Wen et al., 2019b). In addition, the yield of celery was 19% lower in mesocosms with a groundwater table maintained at -30 cm in comparison to -50 cm (Matysek et al., 2019). However, no change or even an increase of productivity has been reported for radish (Musarika et al., 2017) and ryegrass (Berglund and Berglund, 2011) under an elevated groundwater table regime. As impacts on yield vary between species, and relatively few studies have examined commercially important crops at different groundwater table depths, there is a need for further work to inform land managers and policy makers on the influence of groundwater table adjustment on crop production.

Previous studies of GHG mitigation in agricultural peatlands have to a large extent been limited to the growing season only, and/or carried out under constant light and temperature in a laboratory setting or have focused on one GHG only, ignoring the potential trade-offs between CO_2, N_2O and CH_4 (e.g. Musarika et al., 2017; Matysek et al., 2019). The effects of seasonal variations in climate, hydrology and management on GHG emissions under field conditions thus represent a key knowledge gap. To address these issues, this study quantified the impacts of groundwater table management on GHG emissions and lettuce yield from peat mesocosms maintained under ambient climatic conditions. We examined four groundwater table management scenarios to investigate the effects of raising water levels for different periods. We hypothesised that an annual high groundwater table would decrease CO_2 emissions, but might stimulate N_2O emissions by favouring denitrification. Annual high groundwater table would also be expected to decrease root biomass and thus lettuce yield, by creating anaerobic root-zone conditions (hypothesis I). We also hypothesised that maintaining a high groundwater table only in winter would reduce GHG emissions during the winter period, whilst not significantly affecting crop yield (hypothesis II), as aerobic conditions would prevail in the rhizosphere during the growing period. However, for the treatments with a high groundwater table in summer, we hypothesised that this would produce a smaller GHG mitigation than annual high groundwater table, but a similar yield reduction (hypothesis III).

2. Materials and methods

2.1. Study site and experimental design

Our study site was located on a commercial farm at Southery, Nofolk, UK (52°31'N, 0°23'E). The site is comprised of drained lowland fen that has been under intensive horticultural/arable production for ca. 75 years (Musarika et al., 2017). Typically, the winter water table lies 1.5-2.0 m below the soil surface in the winter, and is then raised up to ca. 0.5 m during the growing season to provide an optimal water supply for salad crop production. Perforated pipes buried at ca. -1 m depth and spaced at 10 m horizontal intervals drain into a network of ditches and allow active management of groundwater at the site. Detailed soil properties are described in Wen et al. (2019a).

We collected 16 intact soil cores in September 2017 and then transported them to Bangor University, UK (53°13'N, 4°07'W). The cores were collected in plastic pipes from 4 independent field blocks located 50 m apart. These blocks represented the replicates for the experimental treatments. The cores were 55 cm high and 16 cm diameter. They were placed in modified outer containers in order to control water table depth, and maintained outdoors during the measurement period. The groundwater table was raised to -30 cm in eight cores, whilst the remainder were left at -50 cm. We selected these water table depths because -50 cm depth is standard management during the growing season, and -30 cm depth has been demonstrated to mitigate GHG emissions whilst maintaining crop productivity on fen peat soil (Musarika et al., 2017). No crop was planted between November-April, to mimic the fallow period at the field site. In the middle of May, the water table treatments were reversed for half of the cores at each depth to simulate seasonal management changes. Four cores with -50 cm water table depth were rewetted to -30 cm (summer high WT) and four cores with -30 cm water table depth were drained to -50 cm (winter high WT). The remaining cores were maintained at their previous water table depths to simulate continuously high (annual high WT) and low (annual low WT) groundwater treatments. In the third week of June, three seeds of little gem lettuce (*Lactuca sativa* L.) were sown in each mesocosm. After ten days growth, this was thinned to one seedling per mesocosm. No fertiliser was applied to the mesocosms throughout the experiment, as fertilisation may offset crop uptake to some extent and potentially reduce the effects of groundwater table management.

2.2. Greenhouse gas flux measurements and calculations

Ecosystem respiration, N_2O, and CH_4 flux measurements were conducted fortnightly during the winter fallow period (Nov-April; 6 months), using cylindrical opaque PVC chambers that fitted onto the top of the mesocosms. The chambers were 12 cm high and 16 cm diameter, and the top was fitted with a Suba-Seal® (Sigma-Aldrich Poole, UK) for gas collection via a syringe and needle. During the period when water tables were changed (May-June; 1 month), we increased our sampling frequency to twice per week, in order to capture any transient changes in GHG emissions. We then sampled weekly throughout the crop growth period (June-July; 2 months). On each sampling occasion, three gas samples were collected from the 2.3 litre headspace of each chamber at 0, 20 and 40 minutes, and placed in pre-evacuated 20 ml glass vials. Gas samples were analysed using a gas chromatograph equipped with ECD and FID detectors and a TurboMatrix 110 auto sampler (PerkinElmer Inc., Shelton, CT, USA). Gaseous fluxes were calculated from changes in headspace gas concentrations, accounting for air temperature, headspace volume and soil area (Wen et al., 2019a,b). The linearity of headspace GHG concentrations ($R^2 \geq 0.90$) within the duration of chamber closure were checked. Cumulative fluxes of CO_2, N_2O and CH_4 were calculated for the fallow period by linear interpolation of measured flux rates (Wen et al., 2017). To compare total global warming impact, all cumulative fluxes were converted to CO_2 equivalents based on 100-year Global Warming Potentials (GWPs) of 265 for N_2O and 28 for CH_4 (IPCC, 2013).

2.3. Soil solution measurements

At each sampling event, soil solutions were collected non-destructively using Rhizon-MOM® samplers (Rhizosphere Research Products B.V., Wageningen, The Netherlands). These samplers were inserted horizontally into the soil through the side of the cores at the beginning of the experiment and remained *in situ* throughout. Soil solution was collected from topsoil (15 cm depth) and subsoil (40 cm depth) in the mesocosms. These samples were stored at -20 °C in sterile Vacutainers® (BD Life Sciences, Franklin Lakes, NJ) and later analysed for DOC, NO_3^- and NH_4^+, as described in Wen et al. (2019a,b).

2.4. Lettuce crop biomass measurements

The lettuce plants were harvested eight weeks after planting and fresh biomass was measured immediately. To measure plant root biomass, we destructively sampled the cores by separating the soil into five depth layers (0-10, 10-20, 20-30, 30-40 and 40-50 cm) and carefully removing roots from each layer by hand. Dry root and shoot biomass were measured by oven drying (48 h, 80 °C).

2.5. Statistical analysis

The data sets were tested for normal distribution using the Shapiro-Wilk test, and equality of variance using Levene's test. For data with non-normal distributions or unequal variances, either square root or logarithmically transformation were conducted. Treatment effects were analysed using one-way analysis of variance (ANOVA). Treatment means were compared pairwise using Tukey's post hoc tests with correction for multiple testing. Spearman's *rho* was used to explore correlations between GHG fluxes and soil properties. All differences were considered significant at $P \leq 0.05$. SPSS Statistics 24 (IBM Corp., NY, USA) was used to conduct all statistical analyses.

3. Results

3.1. Ecosystem respiration

Ecosystem respiration rates were relatively low and stable during the fallow period. Rewetting/drainage slightly increased the variability in respiration. CO_2 fluxes were continuously elevated following the germination of lettuce plants (Fig. 2a). Over the fallow period, average CO_2 fluxes were 33% greater from low groundwater table mesocosms than from high groundwater table mesocosms ($P < 0.05$; Table 1). Following groundwater table adjustment, summer high WT and winter high WT treatments had lower ecosystem respiration rates than the annual low WT treatment, but higher rates than the annual high WT treatment ($P < 0.05$). During the lettuce growth period, the CO_2 flux was average 23% lower in the cores with elevated growing season groundwater tables (annual high WT and summer high WT) than in the seasonally low treatments (annual low WT and winter high WT; $P < 0.05$).

3.2. N_2O fluxes

Average N_2O fluxes of 172 ± 70 μg N m^{-2} h^{-1} were observed during the first sampling event in November 2017. There was a rapid decrease by the next sampling event and fluxes thereafter remained low throughout the winter fallow period. No clear trend was observed during the groundwater table change or lettuce growth periods (Fig. 2b). No significant differences were found between groundwater table treatments during the fallow period (Table 1). During the groundwater table adjustment phase, raising the groundwater table decreased the soil N_2O flux rate by 25% (relative to annual low WT), whilst drainage increased the soil N_2O flux rate by 17% (relative to annual high WT). However, these differences did not prove significant. The highest fluxes during the groundwater table adjustment period were from the annual low WT treatment and these were significantly higher than both annual high WT and winter high WT treatments ($P < 0.05$). Although N_2O emissions from the annual low WT treatment were 35-64% higher than from the other treatments during the lettuce growth period, these differences were not statistically significant.

3.3. CH_4 fluxes

In the fallow period, there was a small net uptake of CH_4 from the atmosphere for all but the annual high WT treatment, which showed very low emissions (Fig. 2c). From the groundwater table adjustment period onwards, the soil became a slight CH_4 source for the remainder of the experiment across all treatments. However, no significant differences in CH_4 fluxes were observed between treatments in any measurement period, and fluxes were invariably low.

3.4. Soil solution DOC, NO_3^- and NH_4^+ concentrations

DOC concentrations slightly increased in all treatments over the course of the measurement period (Fig. 3). In the fallow period, the DOC concentrations in the topsoil were elevated in the seasonally higher water table treatments (Table 2). During the groundwater table adjustment period, DOC concentrations in the topsoil were significantly lower in the annual low WT treatment ($P < 0.05$), but no significant differences were observed between treatments in the lettuce growth period. No significant differences in DOC concentration were found between treatments during any measurement period (Table 2).

In the topsoil, soil NO_3^- concentrations decreased substantially, levelled off thereafter, and then gradually increased in mesocosms with seasonally low water tables from spring (March) onwards (Fig. 4a). NO_3^- concentrations converged on zero during the lettuce growth period. The NO_3^- concentrations were statistically higher in annual low WT than any other treatment during the groundwater table adjustment and lettuce growth phases of the experiment ($P <$ 0.05; Table 2). In the subsoil, NO_3^- concentrations gradually decreased throughout the experiment period (Fig. 4b). There were no significant differences between treatments for NO_3^- concentrations in the subsoil in any phase of the experiment (Table 2).

Soil NH_4^+ concentrations in the topsoil were very low, approaching zero, throughout the experiment, and no significant differences were observed between groundwater table treatments in any measurement period (Fig. 5a; Table 2). NH_4^+ concentrations in the subsoil were higher in seasonally high WT treatments during the fallow period ($P < 0.05$; Table 2). Rewetting of the summer high WT cores increased soil NH_4^+ concentrations in the subsoil, whilst drainage of the winter high WT mesocosms decreased the concentration thereafter (Fig. 5b).

3.5. Correlation of soil GHG fluxes with measured environmental parameters

GHG fluxes (ecosystem respiration, N_2O and CH_4) were positively correlated with air temperature and soil temperature over the entire measurement period and negatively correlated with soil moisture (Table 3). Ecosystem respiration was positively correlated with DOC concentration and negatively correlated with mineral N concentrations. Soil N_2O flux was positively correlated with NO_3^- concentration in the topsoil but no correlation was observed with NO_3^- concentration in the subsoil. Additionally, no correlation was found between soil N_2O flux and NH_4^+ concentration in either layer. Soil CH_4 flux was significantly correlated with DOC concentration in the subsoil and NO_3^- concentration in both layers.

3.6. Lettuce shoot and root biomass

Biomass of lettuce shoots and roots were significantly influenced by groundwater table management (Table 4). The annual low WT treatment had a higher shoot biomass compared to the annual high WT treatment ($P < 0.05$). The seasonally adjusted groundwater table treatments (summer high WT and winter high WT) had shoot biomass intermediate between the two continuous depth treatments. Shallow (0-10 cm) root biomass was higher in the annual low

WT treatment than in either of the treatments with elevated water table during the lettuce growth period (annual high WT and summer high WT) treatment (*P* < 0.05; Table 4). The winter high WT treatment was intermediate between the others. No significant differences in root biomass were observed between treatments in the 10-20 and 20-30 cm layers. Whilst lettuce root biomass was low in the annual low WT and winter high WT treatments below 30 cm, no roots were detected at all in the annual high WT and summer high WT treatments beyond this depth. Shoot N content was significantly higher in annual low WT than in the other treatments (*P* < 0.05; Table 4). Root N content and the C contents of both roots and shoots showed no significant differences between water table treatments.

4. Discussion

4.1. Effect of groundwater table management on CO_2 fluxes

The generally low CO_2 fluxes during the fallow winter period are likely a result of lower temperatures limiting microbial metabolic rates (Evans et al., 2017; Taft et al., 2017). However, the relatively long duration of this period means cumulative emissions can still be substantial (3.3-5.5 t CO_2 ha^{-1}), which is up to 42% of cumulative annual CO_2 fluxes when compared with a previous field study (Taft et al., 2017). The 33% lower ecosystem respiration rates of mesocosms with high groundwater tables (i.e. annual high WT and winter high WT) clearly demonstrate that groundwater management can mitigate winter CO_2 emissions from cultivated peatlands compared to the low WT treatments (i.e. annual low WT and summer high WT). This reduction in ecosystem respiration corresponds with the decreasing volume of the oxic soil layer, which constrains relatively quicker and more efficient aerobic decomposition processes.

During the lettuce growth period, CO_2 losses were much larger and clearly increased with time. We attributed this to lettuce-derived CO_2 emissions (autotrophic respiration), which increases with plant growth. Taft et al. (2017) indicated that root respiration contributed ca. 30-32% to total annual soil respiration at cultivated deep peat sites. As we only obtained total ecosystem respiration data in the current study, we could not separate the autotrophic and heterotrophic components. Consequently, we attribute lower ecosystem respiration rates under elevated groundwater tables to a combination of inhibited heterotrophic respiration and lower autotrophic respiration due to lettuce growth inhibition (ca. 19-38% reduction in biomass). This interpretation is supported by a strong positive correlation between ecosystem respiration and lettuce biomass ($R = 0.67$, $P < 0.001$). Future studies separating autotrophic respiration and heterotrophic respiration and the potential for SOM priming will help us obtain a better understanding of the complex interaction between roots and rhizosphere microorganisms under different groundwater table scenarios.

The DOC concentrations observed in this study agree well with the ecosystem respiration rates. DOC concentrations can be elevated under conditions favouring anaerobic decomposition processes as these are less efficient than aerobic processes and so result in accumulation of water-soluble intermediate metabolites in soil solution (Kalbitz et al., 2003). Anaerobic conditions can also lead to decreased DOC adsorption and slower conversion of released DOC to CO_2 (Moore and Dalva, 2001; Karki et al., 2016). This agrees with our observations that DOC concentrations were higher in seasonally elevated water table treatments.

4.2. Effect of groundwater table management on N_2O fluxes

The lack of N_2O flux measurements from recent studies of groundwater table elevation on lowland peat soils (e.g. Musarika et al., 2017; Matysek et al., 2019) leaves a substantial and critical knowledge gap due to the relatively greater global warming potential of N_2O than CO_2 and CH_4. Field observations suggest that N_2O emissions can constitute a substantial proportion (20-50%) of total GHG emissions in agricultural peatlands (Couwenberg et al., 2011; Evans et al., 2017; Taft et al., 2017). The low N_2O emissions we observed through the winter fallow period and positive correlation with temperature suggest low winter temperatures may play a key role in limiting N_2O producing processes. However, the length of the fallow period means that the contribution of N_2O from this period to the overall GHG budget is significant. As we did not apply N fertiliser throughout the measurement period, the total N_2O emissions (0.5-0.8 t CO_2-eq ha^{-1} yr^{-1}) was lower compared to the field study (5.0-13.9 t CO_2-eq ha^{-1} yr^{-1}; Taft et al., 2017). In this study, groundwater table management did not appear to affect winter N_2O emissions. Soil NO_3^- concentrations began to increase in the low groundwater table treatments from March onwards as temperatures began to rise. This suggests that increased temperature induced an increase in nitrification rates as the soil became drier soil and may explain the brief pulse in N_2O emissions observed in these treatments at the end of the fallow period (Rochette et al., 2010).

Groundwater table fluctuation has been found to be a key predictor of N_2O emissions from cultivated lowland peats (Tiemeyer et al., 2016). Changes in groundwater table will directly alter soil redox potential and thus the soil's capacity for nitrification and denitrification. As nitrification produces substrate (NO_3^-) for denitrification, sudden wetting after prolonged dry periods can rapidly shift soil conditions to favour denitrification in the presence of a large substrate pool and has the potential to produce N_2O emission pulses (Butterbach-Bahl and Wolf, 2017). In the groundwater table adjustment period, N_2O emissions were elevated substantially in summer high WT treatment but not statistically significantly above annual high WT and winter high WT treatments. The lack of statistical significance could result from the combination of the short-lived nature of denitrification pulses and our non-continuous GHG measurement approach. Additionally, the substantial reduction of N_2O to N_2 under anaerobic condition (Wen et al., 2017) may also lead to lower N_2O emissions.

During lettuce growth, soil N_2O emissions were low and no difference was found between treatments. This results from the crop taking up available N from the soil and thus temporarily removing the substrate for denitrification and nitrification (Sepehri et al., 2020). However, in this study we did not follow farmer practice to apply a small amount (top-dressing) of fertiliser in the spring, which could potentially reduce the net effect of water table management on soil N_2O flux.

4.3. Effect of groundwater table management on CH_4 fluxes

Carbon losses from CH_4 emissions (0.002 – 0.02 t CO_2-eq ha^{-1} yr^{-1}) were much smaller than from CO_2 emissions. This is consistent with both field and mesocosm studies at the same site (-0.02 – 0.04 t CO_2-eq ha^{-1} yr^{-1}; Musarika et al., 2017; Taft et al., 2017, 2018; Matysek et al., 2019). It has been found that CH_4 emissions from UK lowland peat soils are usually negligible when the groundwater table is more than 20 cm below the surface (Evans et al., 2017). In this study, although average CH_4 fluxes were negative or near zero during the winter period, they became positive from around early summer (May) onwards even with a low (-50 cm) groundwater table. This is likely due to the combined effect of temperature and vegetation. Matysek et al. (2019) also found low rates of CH_4 emission from celery planted peat cores with -50 cm water table. The relatively low levels of CH_4 emissions from cultivated peats and their resilience to management changes suggest that they are unlikely to increase problematically under the elevated water tables proposed for mitigation of either CO_2 or N_2O.

4.4. Effect of groundwater table management on lettuce yield

Lettuce yield was decreased under a continuously elevated groundwater table, consistent with findings on celery yield in another study on the same soil (Matysek et al., 2019). The reduced lettuce yields in high groundwater table treatments can be attributed to partial flooding of the root system. Elevation of the groundwater table could submerge active roots and create anoxic conditions hostile to root development (Armstrong and Drew, 2002). Therefore, lettuce roots did not extend below the groundwater table in this study. Nutrient limitation may lower above and belowground biomass under raised groundwater tables, because (i) plants and associated symbionts cannot access deeper nutrient pools (Oomes et al., 1996), and (ii) the supply of nutrients from peat mineralisation is reduced. Matysek et al. (2019) found that fertiliser addition mitigated the effects on celery yield of groundwater table elevation from -50 cm to -30 cm. Our experiment did not involve fertiliser addition, which may have exacerbated the negative effects of raised groundwater table on yields.

The seasonal adjustment of groundwater tables also influenced lettuce shoot and root biomass. The relatively low yield from the winter high WT treatment indicates that the preceding groundwater table conditions can have a negative effect on later crop growth. SOM mineralisation and nitrification would be constrained under high groundwater table conditions (i.e. N mineralisation was ca. 80 and 48 kg N ha^{-1} for annual low WT and annual high WT treatments, respectively) as evidenced by the low NO_3^- concentrations in this treatment at the start of the growing period. The lower N content of lettuce shoots under all elevated groundwater table treatments further confirms that reduced soil NO_3^- concentrations limits plant N availability. Reductions in soil N content following elevated groundwater table periods could require farmers to increase fertilisation rates to support economically viable yields. This has the potential to increase N_2O emissions, especially during the heavily irrigated and warm growth period (Evans et al., 2017). However, if this increase is smaller (in climate impact terms) than the accompanying reduction in CO_2 emissions demonstrated in our experiment (or if N_2O emissions could be mitigated through the use of slow-release fertilisers or nitrification inhibitors), then higher groundwater tables combined with compensatory fertilisation could represent a viable management strategy to reduce GHG emissions without an accompanying yield penalty.

Winter elevation of groundwater tables creates several issues for farm management, which can negatively impact crops. Low trafficability under wet winter conditions can restrict access for vehicles to cultivate fields. Soil worked when wet can become heavily compacted and this damages the structure, preventing creation of fine-grained planting beds required for salad crops and creating potentially anaerobic conditions (Chamen et al., 2015). This could be overcome, however, with a new generation of autonomous robotic vehicles with low ground pressures (Hameed, 2018). These considerations do not rule out groundwater table management as a GHG mitigation option for lowland peats, but they do highlight the complexity and scale of the challenges involved.

5. Conclusions

Raising the groundwater table from -50 cm to -30 cm was effective at reducing rates of ecosystem respiration in cultivated drained peatland soil. However, permanently elevated water tables can reduce crop yield and this is likely to be major economic obstacle preventing farmer adoption of this strategy. Raising groundwater levels during fallow periods could substantially reduce overall GHG emissions (especially CO_2), without reducing yields during cropping periods. Thus, it represents a viable alternative strategy. A number of practical risks, however, are also associated with elevated winter water tables. Here we observed a reduction in soil NO_3^- concentrations (reducing N availability to crops), which would necessitate increased fertilisation rates with associated emission risks. The complexity of the system means that if winter water table elevation is to be seriously considered as a GHG mitigation option then field scale experimental studies under working farm conditions will be required to identify and address challenges.

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Figure captions

Fig. 1 Temporal variation of air temperature and precipitation at the experimental site (a), and water-filled pore space in the soil mesocosms (b). Management events (rewetting/drainage, lettuce planting) are indicated by arrows. Values represent means ± standard errors (*n* = 4).

Fig. 2 Temporal variation of ecosystem respiration (a), soil N_2O flux (b), and soil CH_4 flux (c) from the mesocosms in response to water table management. Management events (rewetting/drainage, lettuce planting) are indicated by arrows. Values represent means ± standard errors (*n* = 4).

Fig. 3 Temporal variation of dissolved organic C in soil solution sampled from topsoil (a) and subsoil (b) in the mesocosms. Management events (rewetting/drainage, lettuce planting) are indicated by arrows. Values represent means ± standard errors (*n* = 4).

Fig. 4 Temporal variation of NO_3^--N concentration in soil solution sampled from topsoil (a) and subsoil (b) in the mesocosms. Management events (rewetting/drainage, lettuce planting) are indicated by arrows. Values represent means ± standard errors (*n* = 4).

Fig. 5 Temporal variation of NH_4^+-N concentration in soil solution sampled from topsoil (a) and subsoil (b) in the mesocosms. Management events (rewetting/drainage, lettuce planting) are indicated by arrows. Values represent means ± standard errors (*n* = 4).

Table 1: Mean GHG fluxes from different groundwater table treatments during the three measurement periods.

Variables	Treatments	Fallow period Phase I (6 months)	Groundwater table adjustment Phase II (1 months)	Lettuce growth Phase III (2 months)	Global warming impact Phase I+II (7 months)
		(mg C m^{-2} h^{-1})	(µg N m^{-2} h^{-1})	(µg C m^{-2} h^{-1})	(t CO_2-eq ha^{-1})
CO_2 flux	Annual low WT	21.7±2.4 a	67.3±6.3 a	456.7±50.1 a	5.50±0.44 a
	Annual high WT	15.5±2.2 b	20.9±5.4 c	312.8±29.6 b	3.28±0.40 b
	Summer high WT	23.9±0.7 a	56.9±6.7 ab	311.0±32.6 b	5.37±0.19 a
	Winter high WT	15.1±1.3 b	42.1±6.3 b	355.4±19.5 ab	3.66±0.32 b
N_2O flux	Annual low WT	25.8±1.1	68.8±9.8 a	28.3±12.8	0.68±0.07
	Annual high WT	26.0±9.5	21.4±4.8 b	18.2±5.7	0.40±0.11
	Summer high WT	32.8±8.0	51.6±16.1 ab	10.3±5.1	0.72±0.14
	Winter high WT	29.2±9.5	25.1±5.0 b	16.1±8.3	0.43±0.11
CH_4 flux	Annual low WT	-2.5±2.0	6.9±5.3	12.4±3.5	-0.002±0.005
	Annual high WT	0.7±1.8	13.2±5.1	23.6±9.3	0.004±0.003
	Summer high WT	-5.9±0.7	15.0±11.8	6.1±5.5	-0.006±0.003
	Winter high WT	-3.5±3.4	11.6±4.8	16.4±3.4	<0.001±0.005

Annual low WT, constant groundwater table at -50 cm depth; Annual high WT, constant groundwater table at -30 cm; Summer high WT, groundwater table altered from -50 cm to -30 cm before cropping; Winter high WT, groundwater table level altered from -30 cm to -50 cm before cropping. Values represent means ± standard errors (n = 4). Lower case letters indicate significant differences between treatment means ($P \leq 0.05$).

Table 2: Mean soil solution concentrations of DOC, NO_3^- and NH_4^+ in the topsoil and subsoil under different water table treatments during the three measurement periods.

Variable	Treatment	Fallow	Water table adjustment	Lettuce growth
Dissolved organic C	Annual low WT	80±3 b	75±1 b	132±7
in the topsoil	Annual high WT	98±7 a	119±9 a	115±14
(mg C L^{-1})	Summer high WT	93±2 ab	109±8 a	130±12
	Winter high WT	102±4 a	117±4 a	139±9
Dissolved organic C	Annual low WT	96±13	153±18	164±17
in the subsoil	Annual high WT	86±5	145±13	155±18
(mg C L^{-1})	Summer high WT	96±12	148±12	181±23
	Winter high WT	85±5	133±10	116±16
NO_3^--N	Annual low WT	21±2	58±5 a	15±3 a
in the topsoil	Annual high WT	19±6	2.7±2.5 c	1.1±1.4 b
(µg N L^{-1})	Summer high WT	21±3	31±9 b	0.4±0.4 b
	Winter high WT	21±2	13±5 bc	16.4±3.4 b
NO_3^--N	Annual low WT	39±6	0.3±0.3	<0.01
in the subsoil	Annual high WT	39±13	0.7±0.7	<0.01
(µg N L^{-1})	Summer high WT	37±3	0.1±0.0	<0.01
	Winter high WT	37±4	0.2±0.2	<0.01
NH_4^+-N	Annual low WT	0.2±0.0	0.1±0.0	0.1±0.0
in the topsoil	Annual high WT	0.2±0.0	0.1±0.0	0.1±0.0
(µg N L^{-1})	Summer high WT	0.2±0.0	0.1±0.0	0.1±0.0
	Winter high WT	0.3±0.0	0.2±0.1	0.1±0.0
NH_4^+-N	Annual low WT	0.2±0.1 b	0.4±0.2 b	0.6±0.4 b
in the subsoil	Annual high WT	1.4±0.4 a	3.0±0.6 a	4.0±0.6 a
(µg N L^{-1})	Summer high WT	0.2±0.0 b	1.1±0.2 b	2.4±0.3 ab

Winter high WT	1.3±0.1 a	1.7±0.5 ab	1.4±0.7 b

Annual low WT, constant groundwater table at -50 cm depth; Annual high WT, constant groundwater table at -30 cm; Summer high WT, groundwater table altered from -50 cm to -30 cm before cropping; Winter high WT, groundwater table level altered from -30 cm to -50 cm before cropping. Values represent means ± standard errors (n = 4). Lower case letters indicate significant differences between treatment means ($P \leq 0.05$).

Table 3: Spearman correlations of ecosystem respiration, N_2O and CH_4 fluxes with measured environmental variables.

	Ecosystem respiration	Soil N_2O flux	Soil CH_4 flux
T_{air}	0.84***	0.25*	0.27**
T_{5cm}	0.81***	0.42***	0.24*
WFPS	-0.43***	-0.27**	-0.05
DOC_topsoil	0.38**	0.18	0.14
DOC_subsoil	0.72***	0.07	0.33**
NO_3^-_topsoil	-0.24*	0.25*	-0.25*
NO_3^-_subsoil	-0.62***	-0.05	-0.37**
NH_4^+_topsoil	-0.55***	0.06	-0.22
NH_4^+_subsoil	0.17	0.03	0.17

Correlations represented by Spearman's *rho* statistic. *, $P \leq 0.05$; **, $P \leq 0.01$; and ***, $P \leq 0.001$. Environmental variables: T_{air}, air temperature; T_{5cm}, soil temperature at 5 cm depth; WFPS, water-filled pore space; DOC_topsoil and DOC_subsoil, dissolved organic carbon content of soil solution at -15 cm and -40 cm depths, respectively; NO_3^-_topsoil and NO_3^-_subsoil means soil solution nitrate concentration at indicated depths; NH_4^+_topsoil and NH_4^+_subsoil means soil solution ammonium concentration at indicated depths.

Table 4: Lettuce plant dry biomass, C and N contents for both shoots and roots under different water table treatments.

	Annual low WT	Annual high WT	Summer high WT	Winter high WT
Total plant biomass (g)	10.7±0.7 a	6.6±0.8 b	8.6±0.7 ab	8.6±0.4 ab
Shoot biomass (g)	8.1±0.7 a	5.1±0.6 b	6.7±0.6 ab	6.4±0.4 ab
0-10 cm root biomass (g)	2.28±0.26 a	1.41±0.22 b	1.63±0.08 b	2.02±0.08 ab
10-20 cm root biomass (g)	0.16±0.08	0.12±0.02	0.23±0.12	0.08±0.02
20-30 cm root biomass (g)	0.06±0.02	0.05±0.01	0.05±0.01	0.05±0.00
30-40 cm root biomass (g)	0.04±0.01	N.a.	N.a.	0.05±0.01
40-50 cm root biomass (g)	0.01±0.01	N.a.	N.a.	0.02±0.01
Shoot C content (%)	41.3±2.4	40.5±1.9	40.3±1.8	40.7±21.9
Shoot N content (%)	2.4±0.2 a	1.9±0.1 b	1.8±0.1 b	1.9±0.0 b
Root C content (%)	43.2±0.1	43.0±0.3	42.9±0.2	43.5±0.1
Root N content (%)	1.2±0.1	1.3±0.1	0.7±0.2	0.9±0.1
Lettuce C (t C ha^{-1})	2.2±0.2 a	1.4±0.2 b	1.8±0.2 b	1.8±0.1 ab
Lettuce N (t N ha^{-1})	0.11±0.01 a	0.06±0.01 b	0.07±0.01 b	0.07±0.004 b

Annual low WT, constant groundwater table at -50 cm depth; Annual high WT, constant groundwater table at -30 cm; Summer high WT, groundwater table altered from -50 cm to -30 cm before cropping; Winter high WT, groundwater table level altered from -30 cm to -50 cm before cropping. Values represent means ± standard errors (n = 4). Lower case letters indicate significant differences between treatment means. N.a. indicates roots were not detectable.

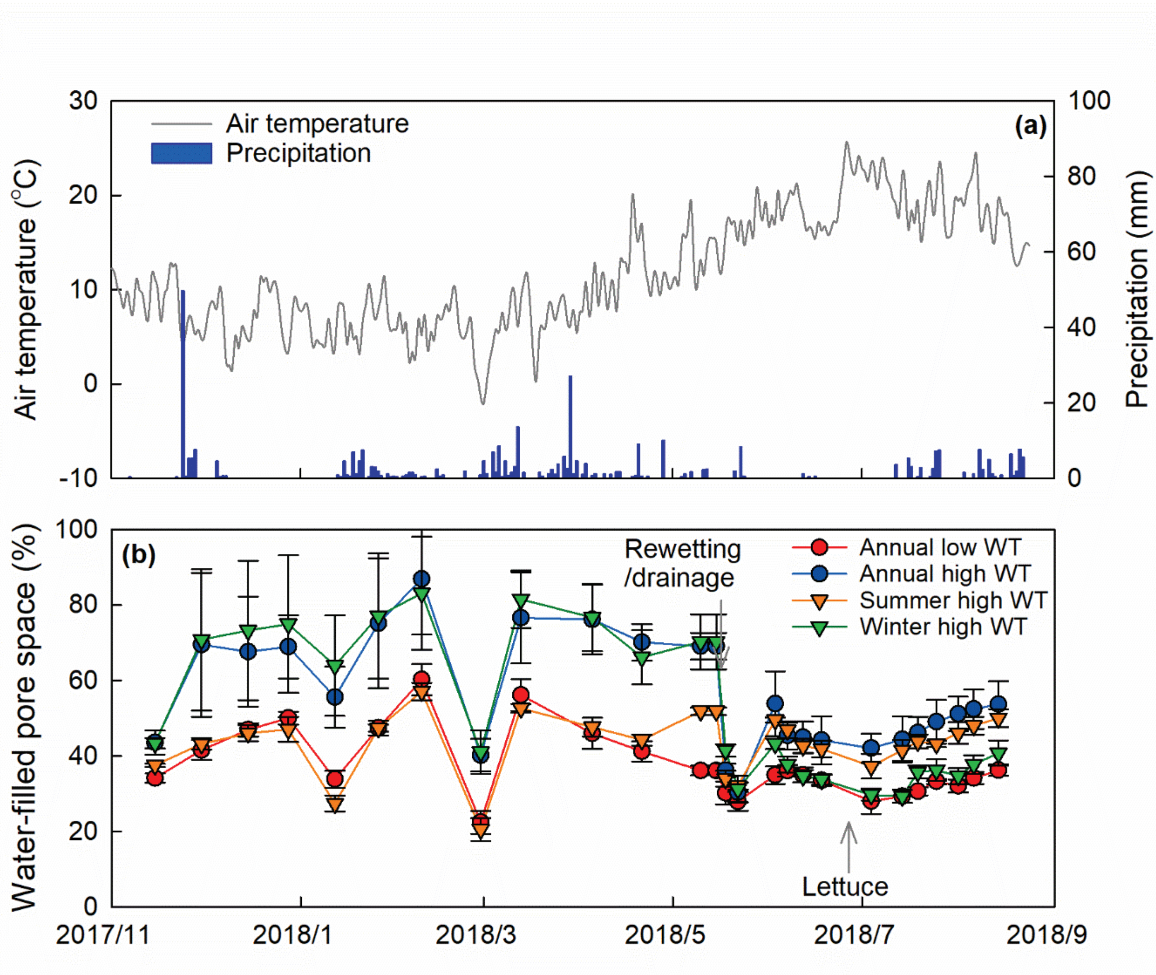
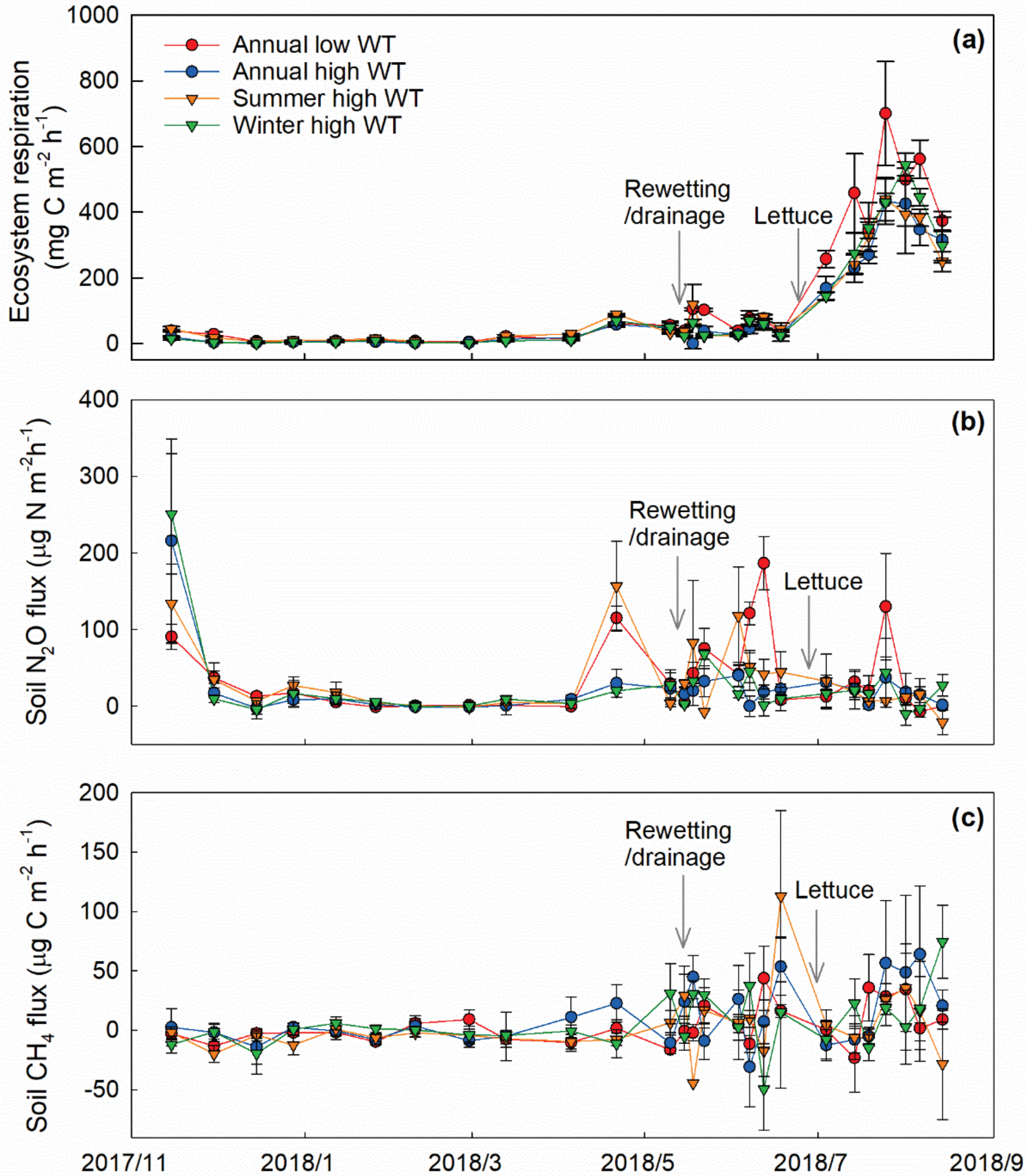
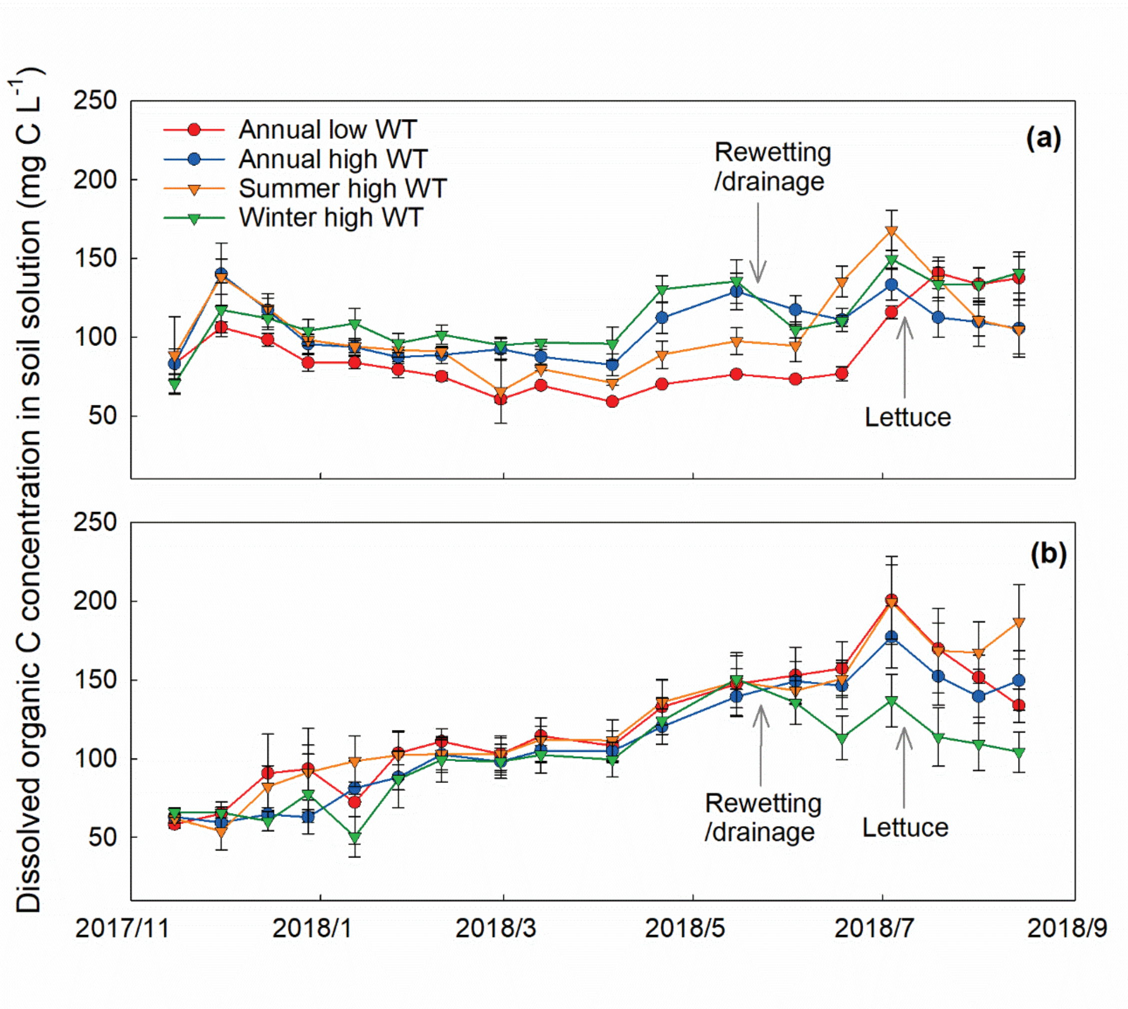

Air temperature
Precipitation
(a)
Air temperature (°C)
Precipitation (mm)
(b)
Rewetting
/drainage
Annual low WT
Annual high WT
Summer high WT
Winter high WT
Lettuce
Water-filled pore space (%)
2017/11
2018/1
2018/3
2018/5
2018/7
2018/9

Fig. 1



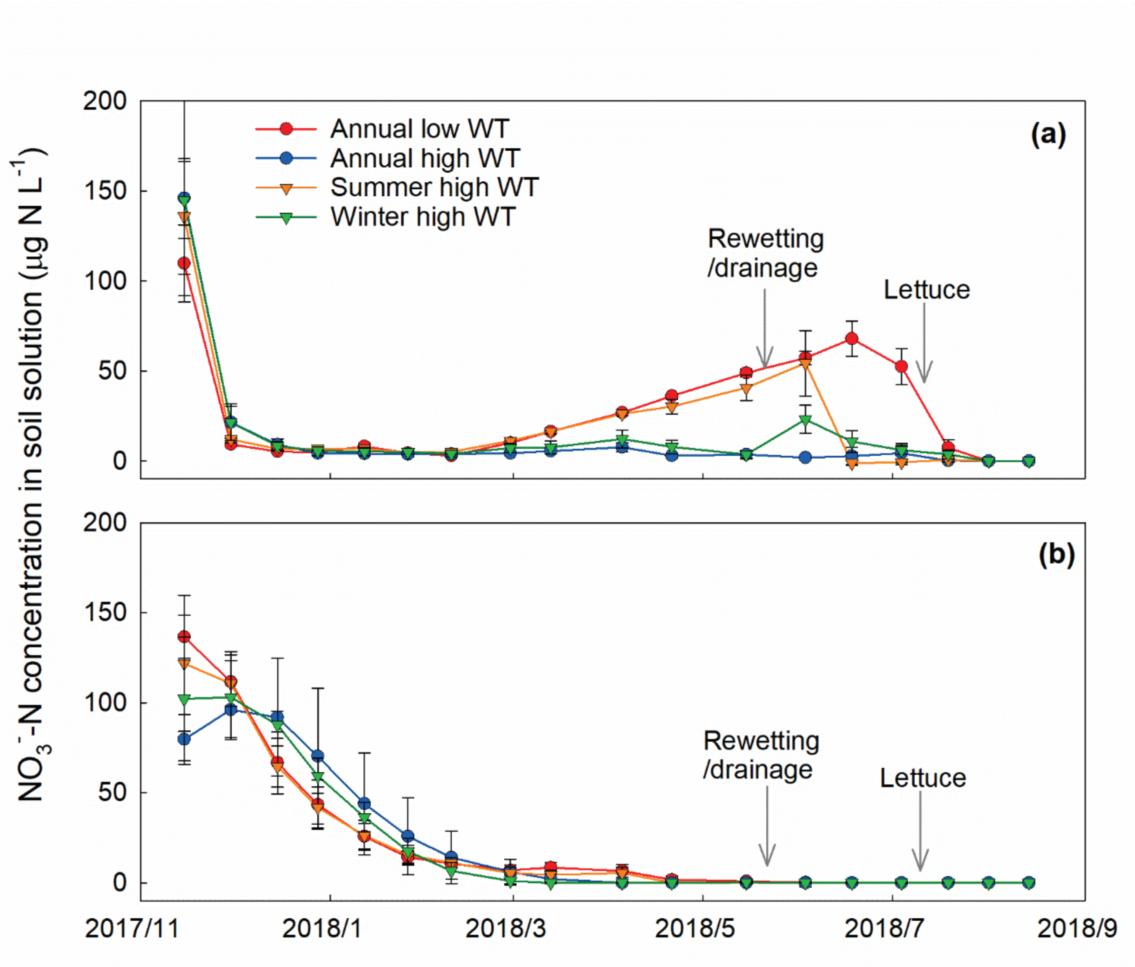
(a)
Annual low WT
Annual high WT
Summer high WT
Winter high WT
Rewetting /drainage
Lettuce
Ecosystem respiration (mg C m-2 h-1)
(b)
Rewetting /drainage
Lettuce
Soil N2O flux (µg N m-2h-1)
(c)
Rewetting /drainage
Lettuce
Soil CH4 flux (µg C m-2 h-1)
2017/11
2018/1
2018/3
2018/5
2018/7
2018/9

Fig. 2


Dissolved organic C concentration in soil solution (mg C L-1)
250
200
150
100
50
Annual low WT
Annual high WT
Summer high WT
Winter high WT
(a)
Rewetting
/drainage
Lettuce
(b)
Rewetting
/drainage
Lettuce
2017/11
2018/1
2018/3
2018/5
2018/7
2018/9

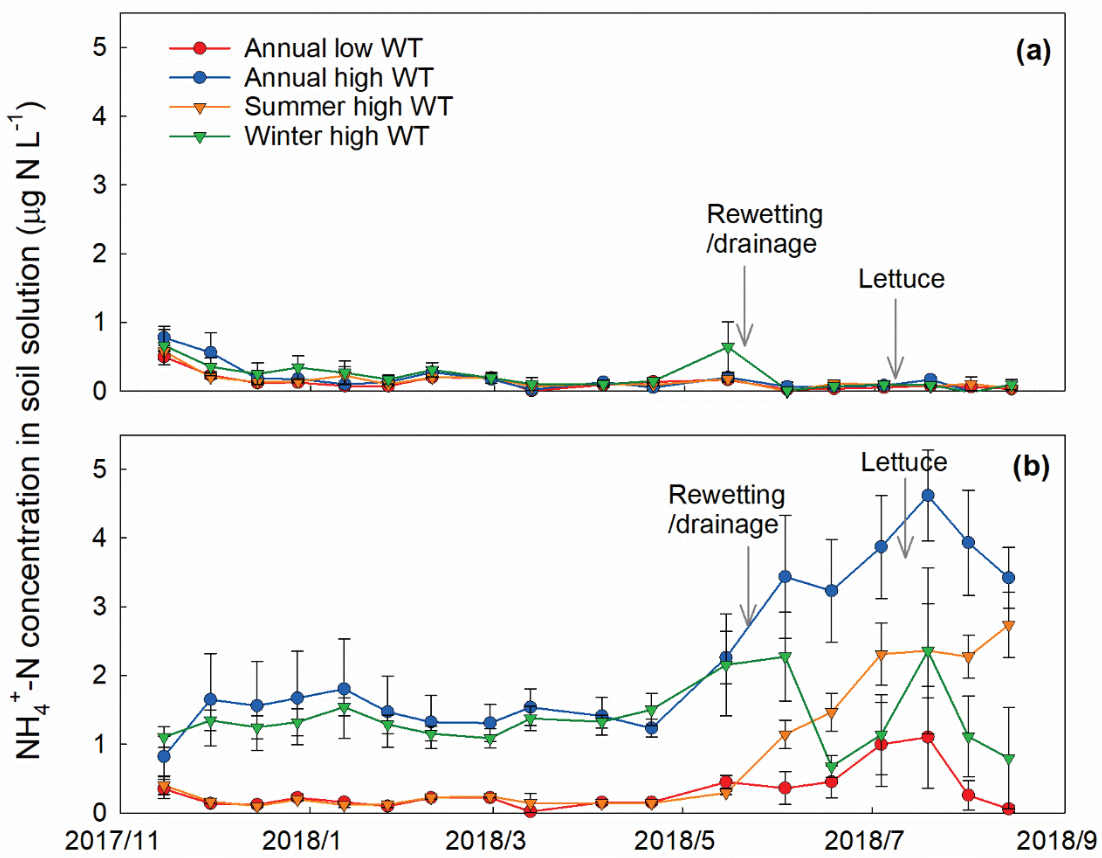
557

558 **Fig. 3**



NO_3^--N concentration in soil solution (μg N L^{-1})
Annual low WT
Annual high WT
Summer high WT
Winter high WT
(a)
(b)
Rewetting /drainage
Lettuce
200
150
100
50
0
2017/11
2018/1
2018/3
2018/5
2018/7
2018/9

Fig. 4


Annual low WT
Annual high WT
Summer high WT
Winter high WT
(a)
Rewetting
/drainage
Lettuce
(b)
Lettuce
Rewetting
/drainage
NH4+-N concentration in soil solution (μg N L-1)
0
1
2
3
4
5
2017/11
2018/1
2018/3
2018/5
2018/7
2018/9

561

562 **Fig. 5**