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Impact of water table levels and winter cover crops on greenhouse gas emissions from cultivated peat soils

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Abstract

Drainage and cultivation have turned peatlands from carbon (C) sinks into hotspots for greenhouse gas (GHG) emissions. Raising the water table and planting of winter cover crops are potential strategies to help reduce peat oxidation and re-initiate net C accumulation during the non-cropping period. However, the effects of these practices as well as their interactions on GHG emissions remain unclear. Here, we carried out an outdoor mesocosm experiment to elucidate the effect of water table levels (-30 cm and -50 cm) and winter cover crop cultivation (vetch, rye, no plant) on carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) fluxes during the winter period (November-April). Soil-atmosphere GHG exchange, GHG concentrations within the peat profile and soil water solute concentrations were monitored. Our results showed that high water table significantly reduced ecosystem respiration, while it had no net effect on N_2O and CH_4 fluxes. Uptake of available N by the cover crop significantly reduced nitrate in soil solution, thereby lowering the potential for leaching and both direct and indirect N_2O emissions. No interactive effects between water table levels and cover crops were detected for any of the measured GHG fluxes. Seasonal variations of GHG fluxes were positively correlated with soil air concentrations at -15 cm and -40 cm depths, which were further regulated by dissolved organic C, nitrate concentration, and anaerobic conditions in the soil. This study suggests that there is great potential to raise water table levels and introduce green cover crops to reduce GHG emissions. Further studies are needed to achieve a complete evaluation of these strategies outside of the growing season, which may provide a significant mitigation benefit in C-rich cultivated peatlands.

Keywords: Histosol, Groundwater level, Vetch, Rye, Sustainable agriculture

1. Introduction

Peatlands are estimated to contain 455 Gt of carbon (C), representing approximately 30% of the estimated total global soil C pool (Gorham 1991). Natural peatland ecosystems act as long-term C sinks, which is mainly attributed to the incomplete decomposition of plant materials under waterlogged, anoxic conditions. In the last century, 10%-20% of the original peatland area worldwide has been drained for agricultural use (Maljanen et al., 2010), turning these peatlands from C sinks into hotspots for carbon dioxide (CO_2) emissions (Meyer et al., 2013). These changes have aroused considerable environmental and political concern and new ways are being sought to preserve C in these cultivated peatland areas (Kløve et al., 2017; Taft et al., 2018). Thus, some agricultural practices, e.g. water table management and use of cover crops, are being promoted for the mitigation of greenhouse gas (GHG) emissions and nutrient leaching (Hobbs et al., 2008; Musarika et al., 2017; Taft et al., 2018).

Water table is a major driver of GHG emissions as it determines the amount of oxygen present in the pore space and thus the intensity of mineralization (Dinsmore et al., 2009), and potential for methanogenesis, methanotrophy and denitrification (Kliewer and Gilliam, 1995; Wang et al., 2017). Raising the water table is generally considered an effective way to reduce C loss in cultivated peatlands, as it decreases soil aeration and limits organic matter decomposition (Wang et al., 2004; Webster et al., 2013). However, there is a lack of quantitative information on how much mitigation could be achieved within cultivated systems in particular, as the responses of gross primary production, litter input, and priming of soil organic matter (SOM) decomposition are complex. Additionally, a few studies in cultivated systems have also shown little effect (e.g. Nieveen et al., 2005) or in a few cases an increase in CO_2 emissions following a raise in the water table (e.g. Berglund and Berglund, 2011). These uncertainties are mainly attributed to the large variations in soil properties and independent responses of constituent autotrophic and heterotrophic respiration (Berglund and

Berglund, 2011; Olefeldt et al., 2017). Moreover, water table level can also strongly influence methane (CH_4) emissions, as the balance between anaerobic CH_4 production and aerobic oxidation is shifted. A higher water table is generally associated with higher CH_4 emissions, which is a powerful heat-trapping gas that affects the climate system (Olefeldt et al., 2017; Turetsky et al., 2011). Given the uncertainty of CO_2 emissions as well as the positive response of CH_4 fluxes to anaerobic conditions, it remains unclear to what extent raising water table levels can reduce C loss and mitigate global warming potential from cultivated peatlands. Moreover, water table level may have a significant effect on nitrous oxides (N_2O), which is a potent GHG with a 100-year global warming potential 298 times that of CO_2 (IPCC, 2007) and the main ozone depleting substance in the twenty-first century (Ravishankara et al., 2009). Soil moisture is a major regulator of N_2O emissions as it controls the oxygen content to soil microbes, with optimum N_2O emissions occurring at ca. 70-80% water-filled pore space (Butterbach-Bahl et al., 2013). At higher soil moisture, N_2O production may decrease, possibly due to the terminal step of denitrification being triggered (i.e. the reduction of N_2O to N_2) under strictly anaerobic conditions. Understanding the influence of water table depth on GHG emissions is thus important for a complete assessment of this mitigation practice. Cover cropping involves growing crops over winter periods after harvest of the main crop, leading to reduced leaching losses of nitrate (NO_3^-) and gaseous nitrogen (N) emissions as available N can be immobilised in plant tissues (Cherr et al., 2006; Crews and Peoples, 2004; Vos and Van Der Putten, 2004). Leguminous cover crops can supply additional N through converting dinitrogen gas into soil N via biological N fixation (Askegaard and Eriksen, 2008). As cover crops are able to affect the quantity and quality of organic substrate availability, soil N content as well as the aerobic capacity by transporting O_2 to the rhizosphere, they may strongly influence not only N_2O but also CO_2 and CH_4 fluxes (Ström et al., 2003). However, little is known about how GHG emissions in a cultivated peat soil respond to cover cropping. Additionally, if the water table is raised too far it may induce anoxic or hypoxic conditions to prevail in the rhizosphere, which may affect root growth and biomass, as well as root exudation and respiration (Wang et al., 2004; Jones et al., 2009). The effect of raised water table on crop yield is variable, with either a decrease (Kahlown et al., 2005; Renger et al., 2002) or increase being observed (Berglund and Berglund, 2011; Musarika et al., 2017). This response may strongly depend on plant species and root architecture.

In the UK, fertile fen peatlands occur mainly in lowland areas of England, where they had an original extent of around 290,000 ha (Natural England, 2010). Since the initiation of large-scale pumped drainage of these areas in the 17th century, an estimated 90% of the original area has been converted to cropland or grasslands (Evans et al., unpublished), leading to widespread C loss and peat degradation, to the extent that around two thirds of the original lowland fen area now has less than 40 cm of peat remaining (Natural England, 2010). At a global scale, oxidation of cultivated peatlands is estimated to generate around 0.9 Gt CO_2-eq yr^{-1}, representing 2.5% of all anthropogenic GHG emissions (IPCC, 2013). Given this major contribution to global temperature forcing, there is an urgent need to develop more timely and appropriate management regimes in order to reduce drainage-induced peatland loss and contributions to atmospheric GHG concentrations.

Previous studies have highlighted the substantial contribution of CO_2 emission during the winter period in lowland peatland systems in England and Wales, which accounts for ca. 23-41% of total CO_2 emissions for the whole year (Evans et al., 2017). Hence, mitigation measures for CO_2 emission reduction during the winter fallow period may provide a significant benefit for GHG mitigation. However, the effects of water table and cover crop management outside of growing season as well as their interactions with GHG emissions from peat soils remain unclear. Although the agricultural practices of cover cropping have been used to reduce nitrate leaching overwinter, their effectiveness when integrated into nutrient-rich cultivated peatlands have not yet been satisfactorily investigated. Thus, this study aimed to investigate the effects of water table level on GHG fluxes and cover crop growth, and elucidate the ability of cover crops to accumulate and retain N over winter and concomitantly reduce GHG emissions. We hypothesised that a higher water table would decrease CO_2 and N_2O emissions, because anaerobic conditions limit organic matter decomposition and thus also provide less available N for nitrification and denitrification (hypothesis I). Because CH_4 emissions are rarely observed from peatlands unless water tables are higher than -20 cm (e.g. Dias et al., 2010; Couwenberg et al., 2011), we hypothesised that our high water table treatment (-30 cm) would not lead to increased CH_4 emissions (hypothesis II). Finally, we hypothesised that cover crop cultivation would increase net CO_2 uptake but decrease N_2O emissions, since cover crops will consume CO_2 from the atmosphere and available N from soil for photosynthesis and plant growth, respectively (hypothesis III).

2. Materials and methods

2.1. Study site and experimental design

The study site was located in East Anglia, UK (52°31'N, 0°23'E). It has a mean annual temperature of 13°C (range -6 to 25°C) and mean annual rainfall of 612 mm (Taft et al., 2017). The site is a flat, drained lowland fen (ca.1.5-m depth organic layer), and has been used for long-term, intensive crop production (e.g. lettuce, celery, sugar beet, wheat) since 1940 (Musarika et al., 2017). Pipe and ditch systems are used to regulate water table levels at this site. The soil is classified as an Earthy Sapric Fen Soil (Avery, 1990) with a humification score of H9 on the von Post scale. Soil properties are shown in Table 1.

To quantify the potential synergies between hydrological regime and cover crop, we conducted an outdoor mesocosm experiment to accurately control water table levels. Soil core sampling was performed in September 2017, when no crops were present in the field. Twenty-eight mesocosm cores were collected from the site using PVC pipes of 16 cm inner diameter and 55 cm height. To preserve soil structure and avoid compaction, the PVC pipes had a sharpened bevel edge at the base and were inserted into the soil to -52 cm depth and then excavated vertically to extract the soil cores intact. Subsequently, the cores were transported to Bangor University, UK, and remained outdoors during the entire measurement period. Once the cores arrived at Bangor, four of them were destructively harvested for analysis of soil properties at different soil depths (0-10, 10-30 and 30-50 cm depth). The remaining cores were placed in modified outer containers, to which rain/tap water was added to maintain a specific water table level within the cores throughout the entire measurement period. The base of the soil cores was open to allow water exchange with the surrounding water. After two-week acclimation, the water table in half of the cores was raised to -30 cm and in other cores the level was kept at -50 cm. These two water table depths were selected because they either represent the highest water table level used commercially under field conditions (-50 cm) or the conditions which have been reported to optimally reduce GHG emissions while maintaining productivity of an agricultural peatland (-30 cm; Musarika et al., 2017).

For each water table level treatment, four cores were planted with vetch (*Vicia sativa* L.) and four cores with rye (*Secale cereale* L.), while the other four cores were left unplanted (bare controls). In October 2017, 6 seeds of vetch or 12 seeds of rye were sown in each core to simulate real field sowing densities of 180 kg ha^{-1}, respectively. We selected vetch and rye as they are the most common cover crop species in UK, and represent legume and non-legume species, respectively. Moreover, rye is usually expected to have a deeper rooting system than vetch. The cover crops were harvested in May 2018, and aboveground biomass as well as C and N contents were quantified.

2.2. Soil properties

Soil pH was measured from 1:2.5 (w/v) soil-to-distilled water suspensions using a pH meter (Hanna Instrument Ltd., Leighton Buzzard, UK). Electrical conductivity (EC) was analysed from the same supernatant using a standard electrode. Bulk density of each layer was measured using the core method (Blake and Hartge, 1986). Soil water content was expressed as WFPS (water-filled pore space) calculated using particle density of 1.40 g cm^{-3} for the organic soil and the measured soil bulk density (Wen et al., 2017). Total organic C and N were measured from oven-dried and ground samples using a TruSpec® CN Analyzer (Leco Corp., St. Joseph, MI). Air temperature was recorded using an ibutton (Maxim Integrated Products, CA, USA) suspended one meter above the cores. Soil temperature at 5 cm was measured using a temperature probe (Hanna Instruments Ltd., Leighton Buzzard, UK). Precipitation data for the measurement period were obtained from the weather station at Bangor University's Henfaes Research Centre. Soil volumetric water content was measured using a moisture meter (Delta-T Devices Ltd, Cambridge, UK).

2.3. Flux measurements and calculations

During the growing period of cover crops, daytime ecosystem respiration (R_{eco}), net ecosystem exchange (NEE), soil N_2O and CH_4 fluxes were measured fortnightly. On each measurement occasion, gas samplings were conducted during 9:00-11:00 am, while the measuring order of the treatments were randomized. R_{eco} was measured with opaque chambers and NEE with transparent chambers, which were connected to a PP-Systems EGM-5 infrared gas analyser (PP Systems Inc., Amesbury, MA, USA). The NEE chamber is modified from clear plastic cloche, which is made of amorphous polyethylene terephthalate.

The chamber is dome shaped (16 cm diameter, 22 cm height), which allows for maximum light penetration and minimum reflection. The CO_2 concentration within the chambers was manually recorded every 30 seconds, with each measurement lasting for three minutes. We excluded the first data point and calculated the fluxes based on the linear increase in concentrations during the last 4-5 samplings. The linearity of increase in CO_2 concentrations with the duration of chamber closure ($R^2 \geq 0.98$) was checked for each measurement, and in the very few cases where a non-linear response was observed, we excluded the last data point and calculated the fluxes based on the linear increase in concentrations during 3 samplings. The air temperature and photosynthetically active radiation were also recorded with each measurement. For NEE, positive values indicate release of CO_2 into the atmosphere while the negative values represent uptake of CO_2. Gross primary productivity (GPP) was estimated as the sum of R_{eco} and NEE. Fluxes of N_2O and CH_4 were measured using static chambers (16 cm diameter, 11 cm height), which were made of polyethylene with a gas sampling port. We removed gas samples of 20 mL each at 1, 21, and 41 min following chamber closure using a syringe. Gas samples were stored into pre-evacuated 20-mL vials with rubber septa. Sample analysis was conducted within two weeks of collection using a Clarus 580 gas chromatograph with a Turbomatrix (HS-40) auto sampler (PerkinElmer Inc., Waltham, USA). N_2O was measured with an electron capture detector, and CH_4 with a flame ionisation detector. The instrument detection limits were 43 ppb N_2O and 0.19 ppm CH_4. The change in gas concentration was used to estimate gaseous fluxes after taking into account the temperature and the ratio between headspace volume and soil area. The vast majority of the measurements showed a linear change in GHG concentrations with the duration of chamber closure ($R^2 \geq 0.90$).

2.4. Soil air concentration measurements

On each measurement occasion, soil air samples were also taken from two depths (-15 cm and -40 cm) within the mesocosm cores. Soil air samples were taken from water-tight, gas permeable silicone samplers, which were inserted horizontally into the mesocosms at depths of -15 cm and -40 cm below the soil surface. The sampler, consisted of a silicone tube (length 12 cm, inner diameter 10 mm, wall thickness 2.5 mm), which was sealed at one end with a silicone stopper (length 1 cm). The other end of the sampler was connected to a gas impermeable tubing (consisting of a 4 cm or 30 cm tube with an inner diameter of 6.4 mm, depending on the sampling depth) fitted with a three-way stopcock, as described in Pausch and Kuzyakov (2012). The gas samplers were installed two weeks before the first sampling in order to reduce disturbance, and were left permanently in soil. We took 5-mL gas samples using a plastic syringe, and placed the samples into pre-evacuated 20-mL vials equipped with rubber septa. After taking the samples back to the lab, another 15 mL of pure N_2 gas was added to them to dilute the soil air to meet the measuring range of the gas chromatograph.

2.5. Soil solution measurements

On each measurement occasion, soil solution samples were also taken from two depths (-15 cm and -40 cm) within the mesocosm cores. Soil solution samples were taken using 5 cm long Rhizon soil solution samplers (Rhizosphere Research Products, Wageningen, the Netherlands), which were inserted horizontally into the mesocosms at depths of 15 cm and 40 cm below the soil surface. Dissolved organic C (DOC) was measured using a Multi N/C 2100/2100 analyser (AnalytikJena AG, Jena, Germany). Ammonium (NH_4^+) and NO_3^- were measured by spectrophotometry on a PowerWave-XS microplate reader using the colorimetric methods described in Mulvaney (1996) and Miranda et al. (2001).

2.6. Statistical analyses

Each parameter was first tested for normal distribution using Shapiro-Wilk's test, and for equality of variance using Levene's test. Parameters with non-normal distributions or unequal variances were either logarithmically transformed or square-root transformed. Soil properties of three soil layers were assessed using one-way analysis of variance (ANOVA) with Tukey's test. For aboveground biomass, differences among treatments were analyzed using two-way ANOVA and LSD tests. For time-series data (e.g. R_{eco}, NEE, N_2O and CH_4 flux, soil air concentrations, and soil solutions), we used linear mixed effects (LME) models, which included water table depth (-30 cm and -50 cm) and cover crops (vetch, rye, no plant) as fixed effect with sampling date and replicates as random effects. Fixed effects were considered significant based on the analysis of variance at $P \leq 0.05$. Spearman's rank correlation analyses were used to explore relationships of GHG fluxes with possible explanatory soil factors across the entire measurement period. All statistical analyses were conducted using R 2.15.3 (R Development Core Team, 2013).

3. Results

3.1. Soil properties

No difference was detected among the three soil layers in pH and EC ($P > 0.05$; Table 1). The deep layer (30-50 cm depth) had a lower bulk density than the upper layers ($P = 0.011$), while the WFPS of the deep layer was higher compared to other layers ($P = 0.038$). Moreover, the deep layer had a higher soil C content and lower N content than the upper layers ($P = 0.005$), and possessed a greater C:N ratio ($P = 0.001$).

3.2. GHG fluxes

Rates of daytime ecosystem respiration (R_{eco}) were comparatively low during the initial stages of the experiment, but increased strongly as cover crop biomass increased over time (Fig. 2a). Across the whole measurement period, R_{eco} was higher from soils under the low water table than the high water table (P = 0.008). Cover crop type also had an additional impact on R_{eco} ($P < 0.001$), with the highest emission observed in the vetch mesocosms and the lowest in the bare mesocosms. However, the interaction between water table depth and cover crops was not found to be statistically significant (P = 0.098). The planted mesocosms consistently took up CO_2 during the daytime throughout the measurement period, shown by the negative results in NEE, and displayed a clear pattern with plant growth (Fig. 2b). However, no difference of daytime NEE was detected either between water table levels (P = 0.899) or among cover crops (P = 0.133). Similarly, no significant difference was found in GPP between treatments (all $P > 0.1$).

Average soil N_2O fluxes decreased from 53.5 ± 17.3 μg N m^{-2} h^{-1} (mean ± standard errors, n = 4) in November to 0.39 ± 2.9 μg N m^{-2} h^{-1} in January, with a levelling off of emissions observed during the winter (Fig. 3a). Generally, the bare mesocosms showed a similar pattern of soil N_2O flux to the planted mesocosms, except for an emission pulse that occurred at the end of April. No overall difference in N_2O emissions was detected either between water table levels (P = 0.128) or between cover crops (P = 0.172).

Soil CH_4 fluxes ranged from -22.2 to 41.7 μg C m^{-2} h^{-1} during the measurement period (Fig. 3b). The average CH_4 flux rates were generally close to zero, regardless of water table level. No significant difference in CH_4 emissions was found between water table (P = 0.884) or cover crop treatments (P = 0.768). Likewise, the interaction between water table depth and cover crop was not significant (P = 0.572).

3.3. Soil air concentrations

In general, soil GHG concentrations at -40 cm depth were markedly higher than at -15 cm depth. Soil-air CO_2 concentrations at both depths displayed considerable spatial and temporal variability (Fig. 4a, b), as shown by the large standard errors of the means. Throughout the entire measurement period, no difference in soil-air CO_2 concentration was found either between water table levels or among cover crops in the -15 cm and -40 cm soil layers (all $P > 0.1$). We observed a higher soil-air N_2O concentration under high water table conditions (Fig. 4c, d), although a statistical difference was only detected at -40 cm depth ($P < 0.01$). Soil-air N_2O concentrations did not differ among cover crops either in the -15 cm ($P = 0.933$) or -40 cm soil layers ($P = 0.926$). Although a high water table level had no effect on soil-air CH_4 concentrations at -15 cm depth ($P > 0.1$, Fig. 4e), it raised CH_4 concentration at the -40 cm depth ($P < 0.001$, Fig. 4f). Additionally, soil-air CH_4 concentrations were influenced by cover crop type ($P = 0.026$), being higher in the vetch and bare soil mesocosms in comparison to those planted with rye.

3.4. Soil solution concentrations

Soil DOC concentration at -15 cm depth was not changed by either water table levels ($P = 0.250$) or cover crops ($P = 0.317$), and kept relatively stable during the entire period (Fig. 5a). At the -40 cm layer, however, maintaining a high water table decreased DOC concentration, although DOC concentrations increased slowly over time irrespective of water table depth (Fig. 5b). The presence of cover crops also decreased DOC concentration at -40 cm depth in comparison to bare mesocosms ($P = 0.049$).

Soil NO_3^- concentrations at -15 cm depth decreased sharply in November 2017 and levelled off thereafter (Fig. 5c), while concentrations at -40 cm depth decreased gradually during the experimental period (Fig. 5d). Differences between treatments were detected at the -15 cm depth, with significantly higher NO_3^- concentration in the bare mesocosms compared to the planted mesocosms ($P < 0.001$). Soil NH_4^+ concentrations were relatively low in both layers (Fig. 5e, f). In the -40 cm layer, high water table conditions significantly increased soil NH_4^+ ($P < 0.001$), whereas no difference was found between the cover crops ($P = 0.147$).

3.5. Aboveground dry biomass

Dry biomass of cover crop was significantly affected by water table levels ($P = 0.017$) and cover crop species ($P < 0.001$), while no interactive effect was observed ($P = 0.101$). Raising water table level decreased aboveground dry biomass by 29% and 22% for vetch and rye, respectively (Table 2). Biomass C and C:N ratio were significantly affected by water table levels ($P < 0.001$), and the interactive effect was also observed in biomass C:N ratio ($P = 0.007$).

3.6. Relationships of GHG fluxes and concentrations with environmental variables

R_{eco} were positively correlated with soil CO_2 concentrations, while soil N_2O fluxes were also positively correlated with soil N_2O concentrations (Supplementary Table S2). However, no correlation was detected between soil CH_4 fluxes and CH_4 concentrations. For N_2O and CH_4, soil air concentrations at -15 cm depth were positively correlated with the concentrations at -40 cm depth. R_{eco} and soil-air CO_2 concentrations were positively correlated with DOC, while soil N_2O fluxes and soil-air N_2O concentrations were positively correlated with NH_4^+ and NO_3^- concentrations at different depths. Although no significant correlation was found between CH_4 flux and environmental variables, we did find that soil-air CH_4 concentrations were positively related to DOC and water table depth.

4. Discussion

4.1 Effect of water table on GHG fluxes and cover crops

The lower daytime R_{eco} with high water table highlight the potential to physically alter the peatland hydrological regime to reduce CO_2 losses. This is in agreement with our previous incubation experiment in which heterotrophic respiration rates in this peat soil decreased by 73% under fully saturated conditions compared to drained conditions (Wen et al., 2019). Similarly, other studies have also reported a decrease in CO_2 emissions following the raising of the water table (Dinsmore et al., 2009; Musarika et al., 2017). This is attributable to the decreased depth of the oxic layer, resulting in a smaller volume of peat exposed to rapid aerobic decomposition (Dinsmore et al., 2009). Based on previous field observations, the CO_2 losses are typically more or less proportional to the total depth of exposed peat (Couwenberg et al., 2011; Evans et al., 2017). In our study, raising water table decreased the average daytime R_{eco} by two-third from bare mesocosms (i.e. heterotrophic respiration), suggesting that more than half of the CO_2 emitted under deep-drained conditions may originate from the subsoil (30-50 cm). This is also supported by the positive correlation observed between R_{eco} and soil-air CO_2 concentrations, reflecting the upward diffusive flux of CO_2 from lower parts of the mesocosm to the soil surface and then the atmosphere.

Unlike R_{eco}, soil N_2O emissions were not significantly affected by water table level, although it is generally assumed that a reduction in aerobic conditions under high water table may decrease N mineralization and subsequent N_2O emission (Regina et al., 2015). In contrast to our expectation, higher N_2O concentrations occurred with a higher water table level, pointing to denitrification as the dominant process regulating N_2O fluxes. The denitrification pathway is prevalent once NO_3^- is formed and anaerobic condition is imposed with microbial reduction of the N oxides (Butterbach-Bahl et al., 2013). Soil physical (e.g. water or oxygen content, temperature, porosity) and biochemical factors (e.g. NO_3^- and organic C, which are the electron donors and acceptors of denitrification) concurrently influence soil N_2O production in soil, and consequently the net N_2O flux to the atmosphere

(Wen et al., 2016). Additionally, the positive correlation between N_2O concentration and NO_3^- further indicate that denitrification is the dominant N_2O production process as NO_3^- is the substrate of denitrification (Butterbach-Bahl et al., 2013). Although a significant correlation was observed between soil N_2O concentration at lower/upper depths and N_2O fluxes, the pattern of belowground N_2O concentrations (i.e. high water table > low water table) was not mirrored in surface fluxes. This is possibly because large amounts of N_2O were reduced to N_2 by the terminal step of denitrification before being emitted to the atmosphere (Wen et al., 2016).

Increasing the water table from -50 to -30 cm significantly reduced the loss of CO_2 from soil (as inferred from daytime R_{eco} in bare mesocosms), thus representing a potential mitigation strategy for GHG emissions. However, some concerns have been expressed that reducing CO_2 emissions from re-wetted peatlands could lead to a counterbalancing increase in CH_4 emissions (Tuittila et al., 2000; Wilson et al., 2009; Cooper et al., 2014). Indeed, we found that water table level had a significant influence on soil-air CH_4 concentrations, particularly in the deeper peat layers under a high water table level. This is likely due to the higher production in these lower anoxic soil layers combined with the lower CH_4 consumption (Munir and Strack, 2014). Importantly, however, the pattern of belowground CH_4 concentrations (i.e. high water table > low water table) was not observed in surface emissions (i.e. no difference between treatments). This suggests that either methanotrophy during diffusive transport of CH_4 to the surface, or the presence of a physical barrier (e.g. compaction layer) decreased CH_4 emissions from the soil surface to the atmosphere (Dinsmore et al., 2009). Consistent with our results, some previous studies have also reported that a 20 cm water table raise would not significantly affect soil CH_4 fluxes (e.g. Couwenberg and Fritz, 2012; Turetsky et al., 2014). The extremely high variability in soil CH_4 concentrations together with the lack of correlation between soil air concentration and soil flux as well as between soil air concentrations at -15 cm and -40 cm indicate large spatial heterogeneity in rates of CH_4 production and oxidation within the peat soil profile.

The effect of water table on plant growth is dependent on plant species and the waterlogging tolerance of their rooting systems (e.g. potential to form aerenchyma) (Berglund and Berglund, 2011; Musarika et al., 2017). This can be highly cultivar specific (Tase, 2002), and at present cover crops are rarely selected for this trait in comparison to their selection for either productivity or cold hardiness. Water table rise suppressed the above-ground biomass of vetch and rye, which is in agreement with the observed reduction in plant productivity under increased water tables (e.g. Renger et al., 2002; Kahlown et al., 2005), as excess water in the plant rooting zone and the associated anoxic soil conditions can negatively influence root growth and crop yield (Wang et al., 2004). However, limited effect was observed on biomass-N, indicating that raising the water table did not significantly influence the reduction of N loss in the cover crop treatments. To better evaluate the response of cover crops to a raised water table, root growth and architecture should be included in future studies.

4.2 Effect of cover crops on GHG fluxes

A dramatic increase in daytime R_{eco} and a gradual decrease in daytime NEE with the development of plant growth demonstrated the importance of cover crops for CO_2 production and consumption. To investigate how cover crops and water table levels influence R_{eco} in peat soils, there is a need to distinguish between soil organic matter-derived (heterotrophic) and plant-derived CO_2 (autotrophic) emissions (Kuzyakov, 2006), which can be affected independently by water table levels (Olefeldt et al., 2017). In this study, due to the similar soil temperature in bare and planted mesocosms (P > 0.05), we estimated autotrophic respiration by subtracting the respiration rate of the bare mesocosm from the planted mesocosm (Koerber et al., 2010). Using this approach, we found higher autotrophic respiration from the vetch mesocosms in comparison to those planted with rye. We ascribe this to the higher productivity of vetch, as shown by the higher aboveground biomass. Additionally, higher rhizodeposition could have been expected from the vetch cover crop compared to the rye, resulting in a higher microbial activity and GHG emissions with vetch. Across the entire measurement period, daytime autotrophic respiration represented on average 54-56% and 81-86% of daytime R_{eco} under low and high water table, respectively. Similar results were reported by Olefeldt et al. (2017), who found that autotrophic respiration accounted for 41-63% and 70% of R_{eco} during dry and wet conditions, respectively. Although the contribution of autotrophic respiration was altered by water table depth, the emission rates were identical (323 vs. 329 mg C m^{-2} h^{-1} in vetch mesocosms; 165 vs. 142 mg C m^{-2} h^{-1} in rye mesocosms). Therefore, we concluded that water table had no overall effect on autotrophic respiration within the vetch and rye mesocosms, but it did affect heterotrophic respiration rate and consequently the contributions of autotrophic and heterotrophic respiration to R_{eco}. Considering the contrasting patterns of C and N rhizodeposition from legumes and cereals (Zang et al., 2018), rhizosphere priming may be different between vetch and rye cultivation. Estimation of the relative magnitude of the priming effect and SOM decomposition in response to cover crop cultivation will be a vital next step in improving our understanding of the source and age of C losses as well as mitigation options for cultivated peatland (Kuzyakov, 2010; Zang et al., 2017).

Uptake of available N by winter cover crops significantly reduced NO_3^- in soil solution, thereby lowering the potential for leaching and both direct N_2O emission (Baggs et al., 2000) and indirect N_2O emission associated with NO_3^- leaching. Additionally, transpiration and water utilisation by cover crops would have reduced the downward movement of water through the soil profile, further reducing N loss (Jackson et al., 1993). In the last measurement campaign, a pulse of N_2O flux occurred in bare soil under low water table level, which was similar to the pattern of NO_3^- concentration at -15 cm depth. This was possibly due to a lack of competition for N between plants and microbes (Repo et al., 2009), combined with the biological response to increased temperature as well as the production of easily available N for microorganisms from enhanced mineralization (Regina et al., 2004). Although high water table decreased aboveground biomass of cover crops, it did not significantly influence N uptake, and thus might have limited influence on the reduction of N loss in comparison to a low water table level.

Although plants are thought to be an important factor controlling CH_4 production and transportation (Pangala et al., 2014), no difference in CH_4 flux was observed between the planted and bare mesocosms. Nevertheless, a significant influence of plants was observed in soil-air CH_4 concentrations, showing higher CH_4 concentrations in the vetch and bare mesocosm than in the rye mesocosms. This is possibly because vetch had a significantly higher biomass than rye, and thus may input more labile C and N via root exudates and litter decomposition, which could fuel methanogenesis leading to higher CH_4 concentrations in the mesocosms (Agethen et al., 2018). Meanwhile, rye may attenuate CH_4 production by transferring oxygen into the rhizosphere leading to lower CH_4 concentration compared to the bare unplanted mesocosm.

As the agricultural region studied here does not have a tradition of planting cover crops, our study represents an initial exploration into their potential to improve the sustainability of the cropping system. Further usage of cover crops (single/multi species cultivation, harvest or incorporation) as well as the interaction with the growth of succeeding cash crops and fertilization should be investigated. Moreover, the effect of cover crops on peat soil erosion during winter period should also be considered to obtain a complete evaluation of cover cropping on drained agricultural peat soils. Additionally, subsequently drainage for cash cropping planting (water table level at -50 cm) need to be evaluated as wetting-drying cycles may lead to significant alteration in soil physico-chemical processes and thus substantial GHG emissions, particularly in N_2O emissions (Dinsmore et al., 2009). High-temporal resolution measurements will also be needed to capture the pulse of emissions and upscale the individual measurements to the cumulative amount. To achieve a comprehensive evaluation of these mitigation strategies, further integrated investigations of water table raising and cover cropping under field conditions and across season/years are required.

5. Conclusions

The lower daytime loss of CO_2 by ecosystem respiration observed under high water table level suggests that raising water table levels during the non-cropping period has the potential to decrease CO_2 loss from cultivated peat soils. We also show that cover crops uptake available N, thus lowering the potential for NO_3^- leaching and N_2O emission during the non-cropping period. Our study suggests that there is great potential to raise water table levels and introduce cover crops to reduce greenhouse gas emissions if the conflicts with other environmental protection strategies/farm management practices (trafficability) can be resolved. Further studies are required to achieve a complete evaluation of these strategies outside of growing season, which may provide a significant mitigation benefit in the C-rich cultivated peatland.

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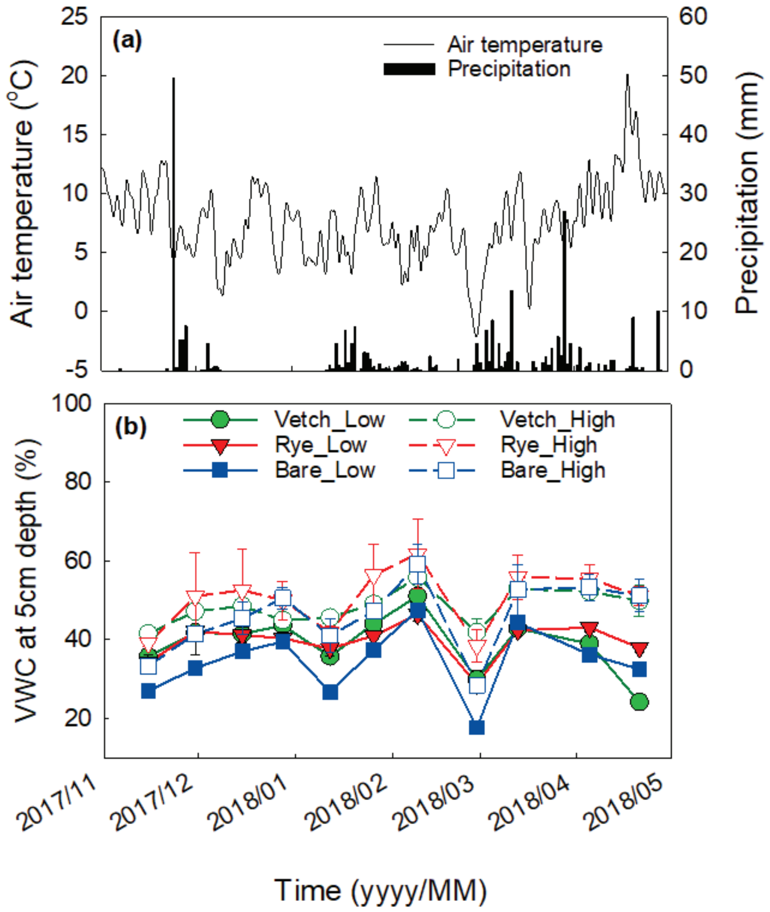

Fig. 1 Air temperature, precipitation (a) and soil volumetric water content (VWC) at 5 cm depth from the peat mesocosms (b; means ± standard errors, n = 4). Low indicates water table level at -50 cm depth; High indicates water table level at -30 cm depth. Vetch and Rye indicate the cover crop species that were planted in the mesocosms, and Bare means no plants in the mesocosm during the whole measurement period (November 2017 - May 2018).

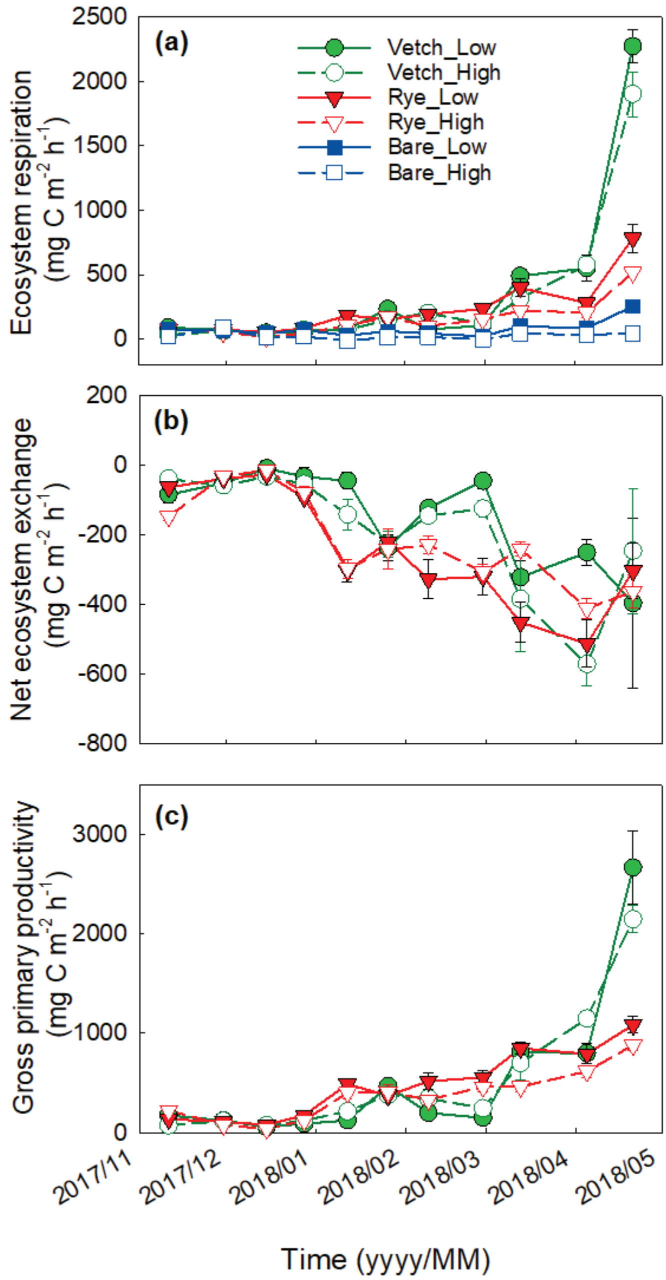

Fig. 2 Temporal variation of daytime ecosystem respiration (a), net ecosystem exchange (b), and gross primary productivity (c) from the peat mesocosms (means ± standard errors, n = 4). Low indicates water table level at -50 cm depth; High indicates water table level at -30 cm depth. Vetch and Rye indicate the cover crop species that were planted in the mesocosms, and Bare means no plants in the mesocosm during the whole measurement period (November 2017 - May 2018). Note that net ecosystem exchange was not measured in the bare mesocosms, as it equals ecosystem respiration.

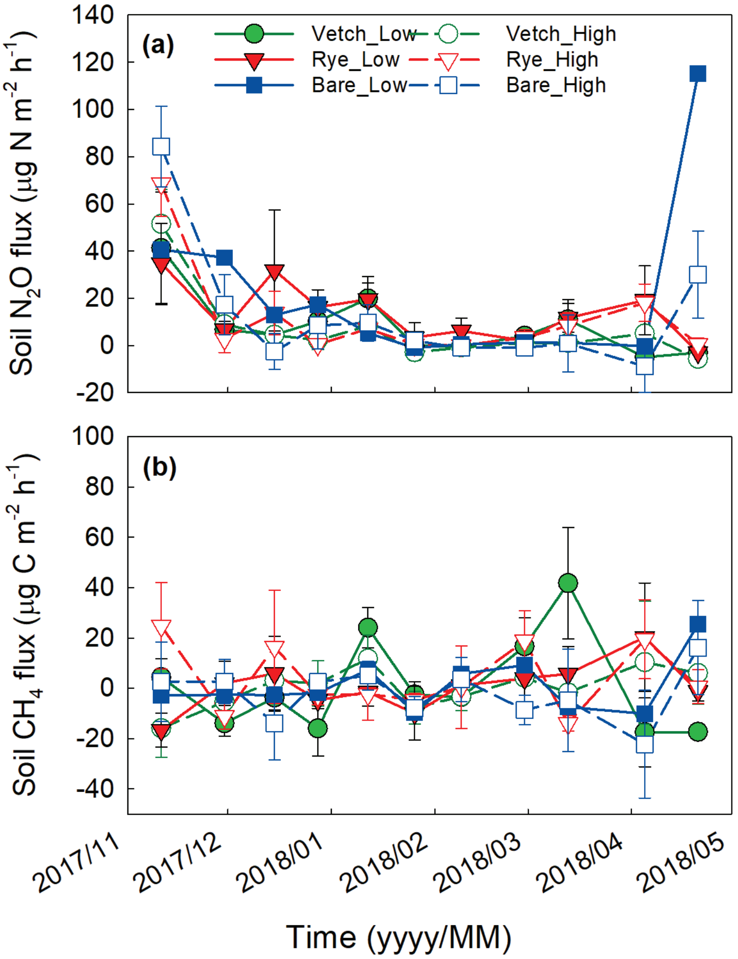

Fig. 3 Temporal variation of soil N_2O flux (a) and soil CH_4 flux (b) from the peat mesocosms (means ± standard errors, *n* = 4). Low indicates water table level at -50 cm depth; High indicates water table level at -30 cm depth. Vetch and Rye indicate the cover crop species that were planted in the mesocosms, and Bare means no plants in the mesocosm during the whole measurement period (November 2017 - May 2018).

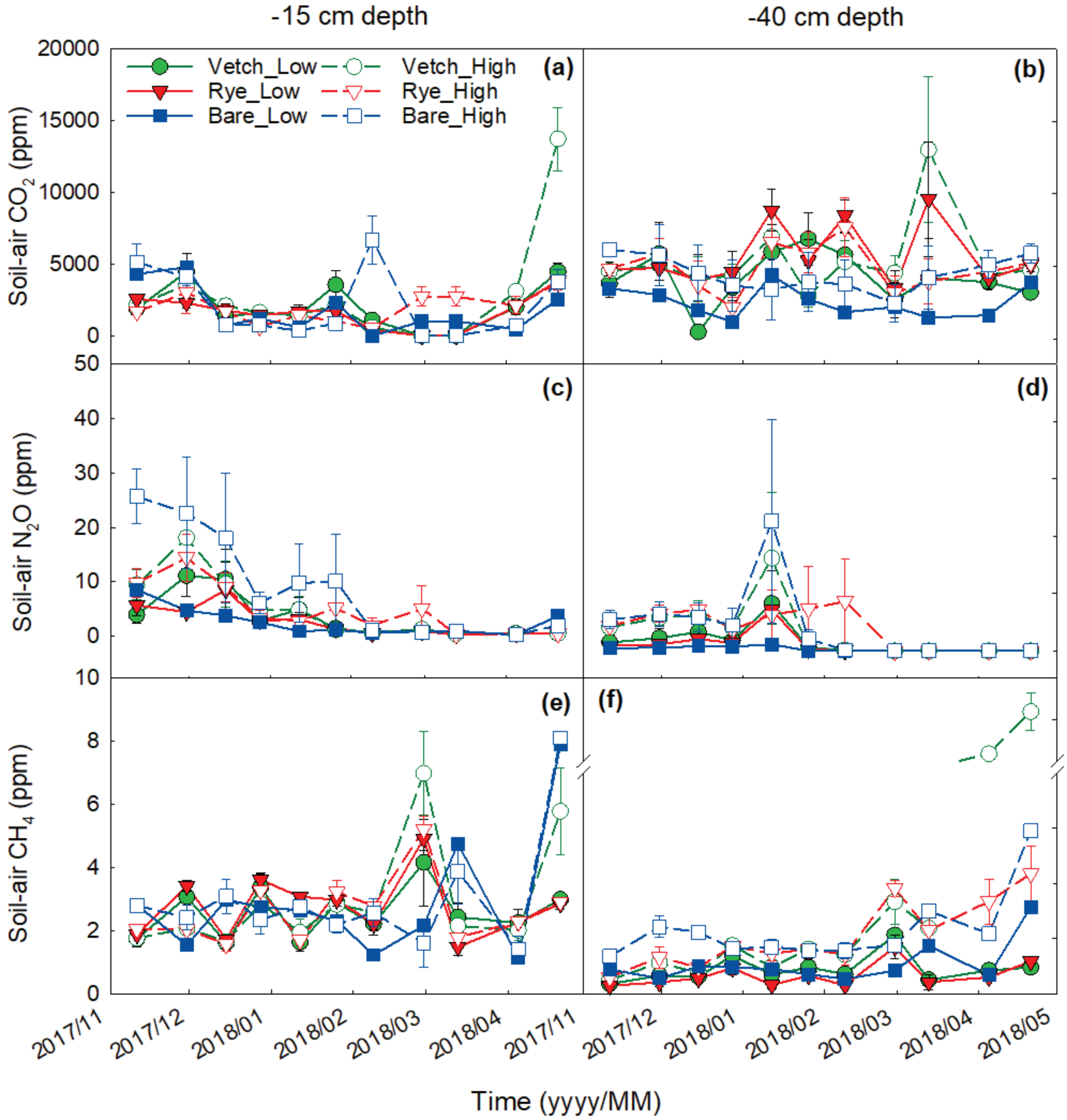

Fig. 4 Temporal variation of soil-air CO_2 (a, b), N_2O (c, d), CH_4 (e, f) from -15 cm and -40 cm depths within the peat mesocosms (means ± standard errors, n = 4). Low indicates water table level at -50 cm depth; High indicates water table level at -30 cm depth. Vetch and Rye indicate the cover crop species that were planted in the mesocosms, and Bare means no plants present in the mesocosms during the whole measurement period (November 2017 - May 2018). Note that y-axes with different scales.

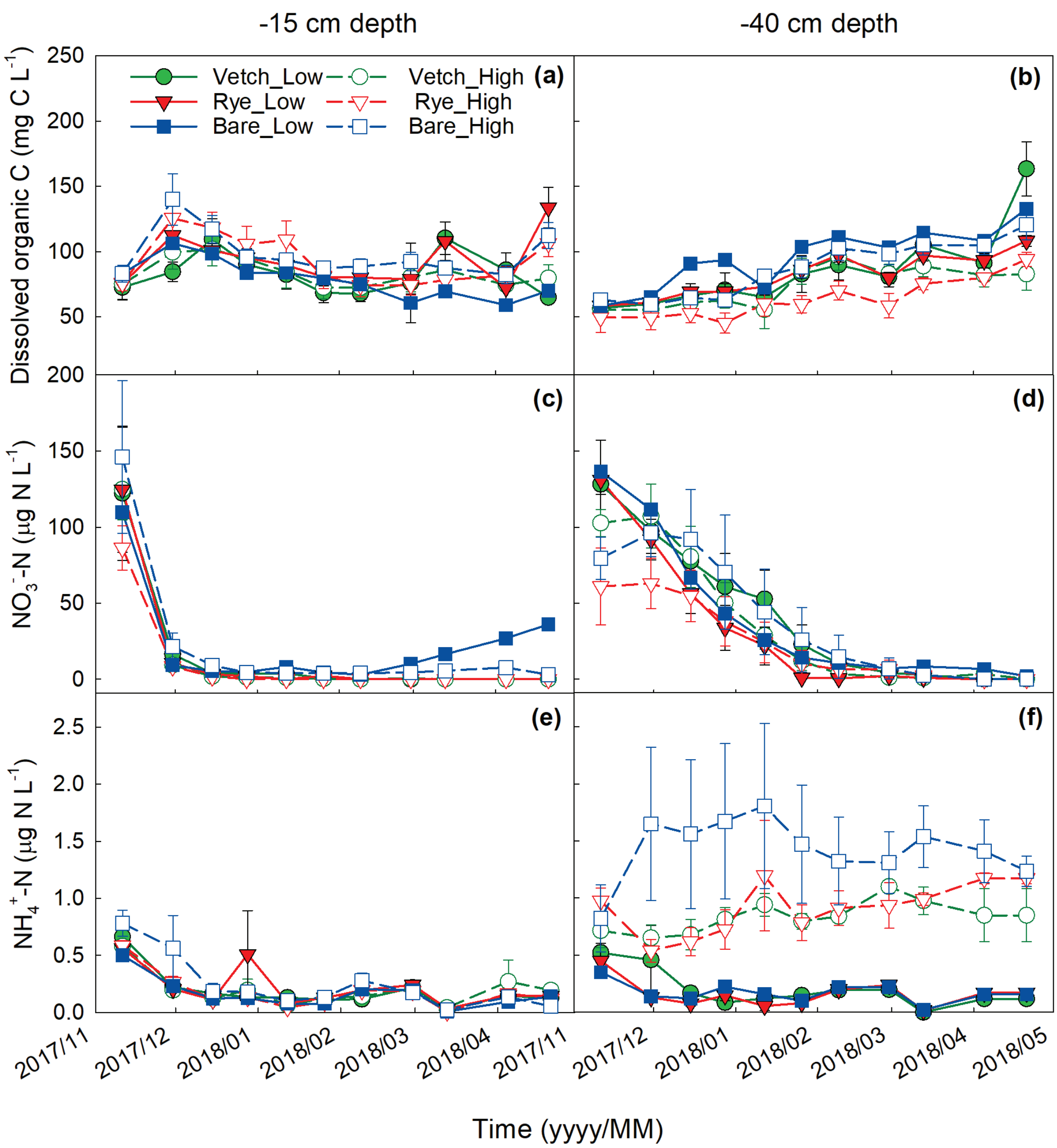

Fig. 5 Temporal variation of dissolved organic C (a, b), NO_3^--N (c, d), NH_4^+-N (e, f) from -15 cm and -40 cm depths within the peat mesocosms (means ± standard errors, *n* = 4). Low indicates water table level at -50 cm depth; High indicates water table level at -30 cm depth. Vetch and Rye indicate the cover crop species that were planted in the mesocosms, and Bare means no plants were present in the mesocosms during the whole measurement period (November 2017 - May 2018).

Table 1 Soil properties measured at the beginning of the study (Nov. 2017).

Soil sampling depth	pH	Bulk density (g cm^{-3})	WFPS (%)	Total C (g C kg^{-1})	Total N (g N kg^{-1})	C:N	EC (μS cm^{-1})
0-10 cm	6.45 ± 0.10	0.32 ± 0.03 a	65.6 ± 5.2 ab	507 ± 4 b	27.1 ± 0.4 a	18.7 ± 0.2 b	394 ± 120
10-30 cm	6.29 ± 0.08	0.31 ± 0.01 a	64.0 ± 2.9 b	505 ± 3 b	27.1 ± 0.3 a	18.6 ± 0.1 b	558 ± 119
30-50 cm	6.09 ± 0.11	0.22 ± 0.02 b	78.8 ± 2.5 a	548 ± 7 a	24.5 ± 0.7 b	22.4 ± 0.9 a	377 ± 30

WFPS, water filled pore space. EC, electrical conductivity. Values represent means ± standard errors (*n* = 4). Different letters within a column indicate significant differences between depths.

Table 2 Dry mass, biomass C:N ratio, biomass-C, and biomass-N from two winter cover crops (vetch and rye) under either a low (-50 cm) or high (-30 cm) water table depth (means ± standard errors, $n = 4$).

	Vetch_Low	Vetch_High	Rye_Low	Rye_High
Dry mass (g m^{-2})	1898 ± 115 a	1347 ± 198 b	554 ± 60 c	433 ± 43 c
Biomass C:N ratio	13 ± 0 c	14 ± 1 c	45 ± 4 b	59 ± 1 a
Biomass-C (g C m^{-2})	817 ± 44 c	590 ± 89 c	241 ± 26 a	186 ± 19 b
Biomass-N (g N m^{-2})	63 ± 4 a	45 ± 10 b	5 ± 1 c	3 ± 0 c

Different letters within a row indicate significant differences between treatments.