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GREENHOUSE GAS FLUX HETEROGENEITY ACROSS A TEMPERATE LOWLAND FEN UNDER RESTORATION MANAGEMENT

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SUMMARY

Natural peatlands function as a carbon (C) sink and long term C store. However, past management has led to substantial net losses of stored C across the UK, other areas of northern Europe and more recently in tropical peatlands. Degraded peatlands are being targeted for restoration to reduce current emissions and restore their original C sink potential. This study investigates GHG flux heterogeneity across a partially degraded lowland fen on the west coast of the UK, where a tall fen, short fen and former improved pasture were subjected to management interventions, including burning, hand-cutting and excavation. The upscaling of chamber measurements to annual budgets found the tall fen acted as a net sink of C throughout the study period, whilst the short fen acted as a net source of C following intervention. The opposing response in GHG fluxes from the tall and short fen following intervention has implications for the management of degraded fens and highlights the importance of taking into consideration initial conditions in restoration decisions.

Keywords: *peatland, restoration, greenhouse gas flux*

INTRODUCTION

Natural peatlands act a net sink of atmospheric carbon and long term C store due to the imbalance of ecosystem respiration (R_{ECO}) and gross primary productivity (GPP). Globally, peatlands contain a third of the terrestrial C store, whilst covering only 3% of the Earth‘s surface (Gorham, 1991). Past management of peatlands, predominately involving drainage for agriculture and extraction, has led to substantial net losses of stored C. The drainage of peatlands affects the hydrological function of the soil, increasing aeration and thus favouring higher ecosystem respiration rates which (provided they are not accompanied by a larger increase in gross primary productivity) lead to net CO_2 emissions. In contrast, drained peatlands are associated with lower CH_4 emissions due to the increased opportunity for methane oxidation within the aerobic layer of the soil. In order to reduce emissions, degraded peatlands are increasingly being targeted for restoration, with the aim of restoring their original C sink potential as well as achieving favourable nature conservation status (Lunt *et al.,* 2010). The restoration of peatlands can also provide other benefits such as increased biodiversity, as well as emission reductions being included in national GHG reporting to meet targets to the UN Framework Convention on climate change (IPCC, 2013). Within the UK, studies of restoration effects on GHG fluxes have predominately focused on upland blanket bogs, with little focus on lowland fen peatlands. The aim of this study is to investigate the effects of restoration interventions, namely burning, hand-cutting and excavation, on the CO_2 and CH_4 fluxes across a UK lowland fen.

METHODS

The study area is located within the Anglesey Fens Special Area of Conservation, on the west coast of the UK (53°31‘ N, 4°29‘ W) and experiences a temperate maritime climate. The study site, Cors Erddreiniog is a partially degraded lowland fen covering an area of 289 ha, and comprises of a tall fen, a short fen and an excavated area of former improved pasture, hereafter referred to as ‗restored pasture‘. The site underwent a series of restoration interventions as part of the Anglesey and Llyn Fens LIFE project (LIFE07 NAT/UK/000948) in 2012 which aimed to restore favourable or recovering conditions through burning, hand-cutting and excavation. A total of 12 measurement plots were established across Cors Erddreiniog encompassing the tall and short fen, restored pasture and the different interventions applied (Table 1): at both the tall and short fen, some areas underwent burning and hand-cutting, whilst some areas remained as unmanaged controls. At the restored pasture where the nutrient enriched topsoil associated with the former pasture land was removed in 2012, bare soil and recolonising plots were identified, together with a grassland control plot which did not undergo excavation.

Table 1. Site description

Measurement plot	Dominant vegetation (no. collars)	pH	Electrical conductivity ($\mu S\ cm^{-1}$)	Organic matter (%)	Mean water table depth (mm)
Tall fen - control	*Cladium mariscus* (3) *Phragmites australis* (3)	5.94 5.73	81 83	69.9 70.6	-80 -60
Tall fen – burnt	*Phragmites* (4)	5.65	92	84.6	64
Tall fen – hand cut	Grassland (4)	5.92	118	83.0	-39
Short fen – control	*Sphagnum* hummock (3) Brown moss hollow (3) *Juncus* species (3)	6.67 6.77 6.75	73 142 142	89.7 84.1 90.5	-102 10 -47
Short fen – burnt	*Phragmites australis* (4)	6.76	218	75.6	-83
Short fen – hand cut	Grassland (4)	6.70	126	74.0	-61
Restored pasture – grassland	Grassland (3)	7.45	148	35.6	-97
Restored pasture – recolonising	Short sedges e.g. Black-bog rush (3)	7.36	184	64.5	1
Restored pasture – bare soil	Bare soil (3)	7.30	318	31.5	-115

CO_2 and CH_4 flux measurements were carried out approximately every 4 weeks from March 2014 – March 2015 using a static chamber approach and portable field gas analyser (Los Gatos UPGGA). In addition to GHG flux measurements, environmental variables were measured simultaneously including soil temperature, photosynthetically active radiation (PAR), water table depth (WTD) and air pressure. GHG fluxes were calculated based on the change in gas concentration in the chamber headspace over time. Here, the atmospheric sign convention is followed: the uptake of C from the atmosphere to the ecosystem is defined as negative fluxes, whilst fluxes of C from the ecosystem to the atmosphere are defined as positive fluxes.

Annual flux estimates of R_{ECO}, GPP and CH_4 were initially calculated for each collar using the entire 12 month dataset, however this gave a high sensitivity to outliers and consequently data was pooled by vegetation group to produce more robust models. GPP was modelled using a Michaelis-Menten relationship with PAR, with the addition of 10cm soil temperature as an explanatory variable which improved the model fit. R_{ECO} was modelled using the Arrhenius type model by Lloyd and Taylor (1994) using 10cm soil temperature as the single explanatory variable. Annual methane fluxes were modelled using multiple linear regression using 10cm soil temperature, PAR and WTD. Annual flux estimates were converted to CO_2-equivalents using the 100 year global warming potential (GWP) of 25 for methane, according to Forster *et al.* (2007).

The differences between measured CO_2 and CH_4 fluxes from measurement plots were identified using the Kruskal-Wallis test, whilst the correlations between C fluxes and environmental variables were determined using Kendall Tau statistic. All data processing and analysis was carried out using the statistical programme R (R Development Core Team, 2009).

RESULTS

CO_2 fluxes

CO_2 fluxes were significantly correlated with temperature at all measurement plots, with a greater net sink of CO_2 observed at higher temperatures. Lower water table levels were correlated with a greater net sink of CO_2 at all plots within the short and tall fen ($p < 0.05$), however only the intervention plots at the restored pasture demonstrated this relationship. An increase in PAR was associated with a greater net sink of CO_2 at all plots, except for tall fen-burnt intervention plot ($p < 0.05$). R_{ECO} and GPP showed a clear seasonal pattern during the study period, with the greatest fluxes occurring between May and September.

Within the tall fen, the control and intervention plots all acted as net sinks of CO_2 throughout the study period, with the *Cladium* dominated collars (tall fen-control) acting as the greatest net sink (figure 1). The short fen-control plot acted as a net sink of CO_2, however the short fen-intervention plots both acted as a net CO_2 source. Within the tall and short fen, no significant differences were observed in measured NEE fluxes between the control and intervention plots as a whole. At the vegetation level, the *Cladium* dominated collars (tall fen-control) acted as a greater net sink of CO_2 compared to tall fen-hand cut plot ($p < 0.05$). Ecosystem respiration was higher in the short fen-hand cut plot compared to the short fen-control plot ($p < 0.05$), with further investigation at the vegetation level showing differences arose between the *Juncus* collars ($p < 0.05$) and brown moss collars ($p < 0.01$) with the hand-cut plot.

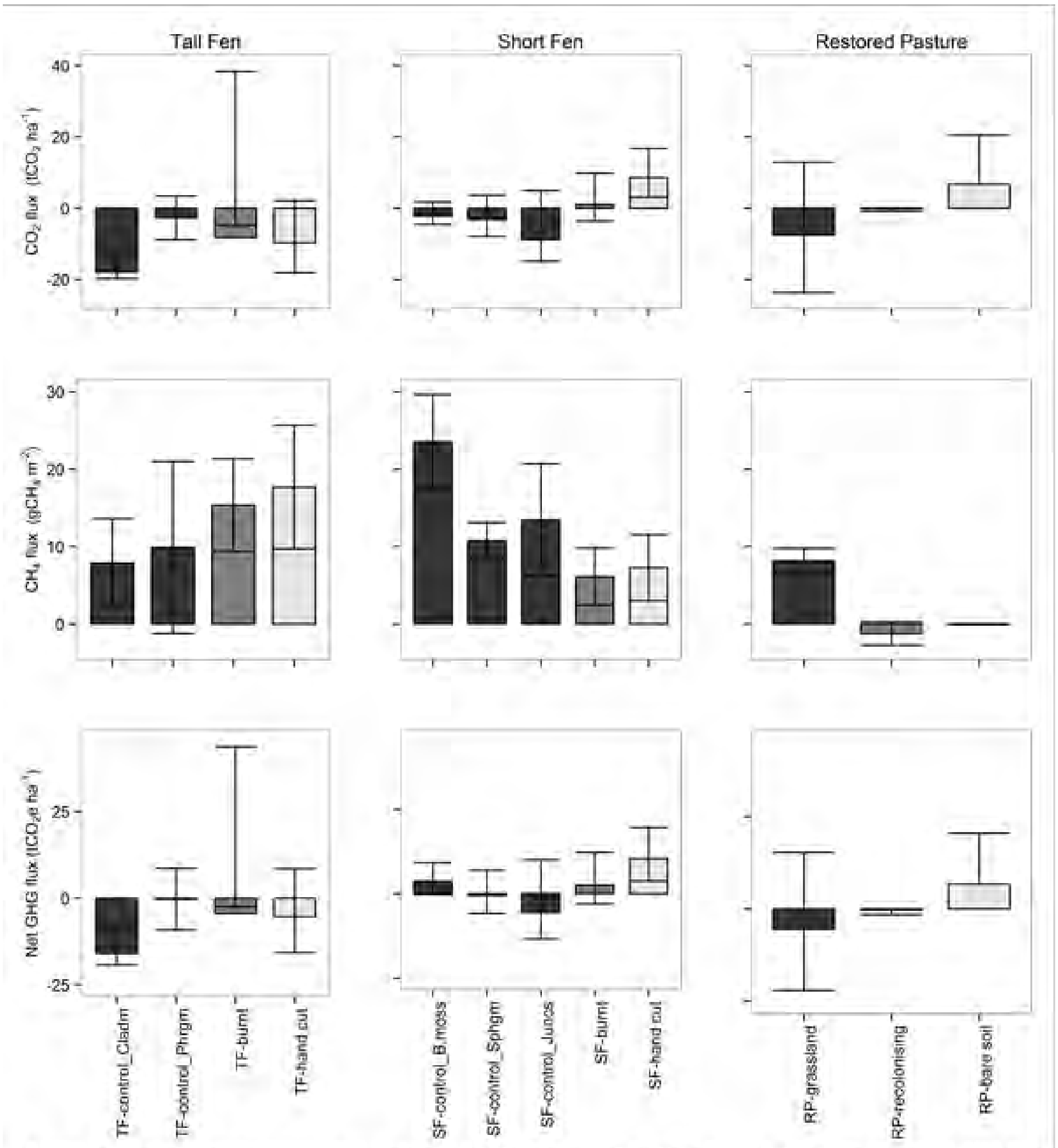

Figure 1. Top row: Annual net ecosystem exchange; Middle row: annual methane fluxes; Bottom row: annual net GHG flux (in CO_2-equivalents), for the vegetation groups at measurement plots.

Within the restored pasture, the bare soil plot acted as a net source of CO_2, whereas the control and recolonising plots were CO_2 sinks, though the latter was negligible. The restored pasture-control plot acted as a significantly greater CO_2 sink compared to the restored pasture intervention plots ($p < 0.01$).

CH_4 fluxes

At all measurement plots higher methane fluxes were observed at higher temperatures ($p < 0.05$), as found with CO_2 fluxes. Methane emissions were only significantly correlated with water table depth at the short fen plots, and within the tall fen control plot, where higher CH_4 emissions were associated with a water table closer to the surface. Methane fluxes had a similar but less pronounced seasonal pattern to CO_2 fluxes, with the greatest CH_4 fluxes from April to September.

All plots acted as a net source of CH_4 throughout the study period, with the highest fluxes originating from the short fen control and tall fen intervention plots (figure 1). Within the tall fen and the short fen, no significant differences were observed between the control and intervention plots, however when considered at the vegetation level tall fen-burnt had higher CH_4 fluxes compared to *Cladium* collars at tall fen-control ($p < 0.01$).

Methane fluxes were higher from the restored pasture control plot compared to the restored pasture intervention plots ($p < 0.01$), with no difference observed between the bare soil and the recolonising plots.

Net GHG flux (in CO_2-equivalents)

The tall fen control and intervention plots both had a negative net GHG flux (i.e. a net cooling effect). Overall, the short fen-control plot also had a negative GHG flux, however the brown moss collars had a positive GHG flux (i.e. net warming effect) driven by high CH_4 emissions, along with both short fen intervention plots. The restored pasture control plot had a net cooling effect, with the restored pasture recolonising having a negligible GHG flux and the restored pasture bare soil having a net warming effect.

DISCUSSION

Model Performance

Model performance was rated using the thresholds outlined by Hoffman *et al.* (2015) including; mean absolute error, coefficient of determination (r^2), percent BIAS and Nash-Sutcliffs model efficiency, with all models achieving at least a satisfactory fit of modelled v. measured fluxes. The only threshold to not meet this satisfactory criteria was the RSR (RMSE-observations standard deviation ratio) for modelling R_{ECO} at the restored pasture bare soil, however no other model provided an improved fit so the Lloyd and Taylor model was used. A common limitation of modelling annual fluxes from chamber measurements is the bias towards daytime measurements, which leads to not measuring at the full temperature and PAR range. In this study, all flux measurements were carried out between 10:00 – 16:00 and consequently modelling could have benefitted from diurnal campaigns to capture conditions outside of these hours, or using partial shading of chambers to create a range of PAR conditions (e.g. Elsgaard *et al.,* 2012). However, the logistical demands of measuring GHG fluxes using chamber based approaches meant it was not possible to intensify measurements.

GHG fluxes

The lack of studies on GHG fluxes from semi-natural lowland peatlands means there are few values in the literature to compare this study to. Studies on GHG fluxes from permanent grassland on peat soils in Europe predominantly show a net loss of C, with extensively managed grasslands having an annual NEE of -0.9 (0.70) tC ha^{-1} (Renou-Wilson *et al.,* 2014) to 6 (3.8) tC ha^{-1} (Görres *et al.,* 2014), a range also found by Elsgaard *et al.* (2012) across permanent grasslands in Denmark (-1.5 tC ha^{-1} a^{-1} to 10.9 tC ha^{-1} a^{-1}). In terms of vegetation at Cors Erddreiniog, the hand cut intervention plots are most similar to the extensively managed grasslands from the literature, with short fen-hand cut NEE values falling within the range above, and the tall fen-hand cut plot acting as a marginally greater CO_2 sink (-2.67 tC ha^{-1} a^{-1}). CO_2 and CH_4 fluxes have been measured at a rewetted fen in NE Germany for *Phragmites* dominated stands, with NEE values ranging from -2.25 to 1.64 tC ha^{-1} a^{-1} and CH_4 fluxes of 1 to 23 gCH_4 m^{-2} a^{-1} over the two years of the study (Günther *et al.,* 2013 and Günther *et al.,* 2015). The annual NEE and CH_4 fluxes from *Phragmites* dominated collars in this study fall within the ranges reported by Günther *et al.* (2013; 2015), except for the NEE from the tall fen-burnt plot which acts as a marginally greater CO_2 sink (-3.05 tC ha^{-1} a^{-1}). Generally the difference in GHG fluxes between the tall and the short fen appear to be linked to productivity, with the tall fen accumulating more biomass over the year, and therefore acting as a stronger C sink compared to the short fen.

Intervention effect

The net radiative effect across the restored pasture varies from a net cooling effect from the control plot, to neutral (recolonising plot) to a net warming effect from the bare soil. Following topsoil removal, the bare soil acts as a net source of C as no photosynthesis can occur, however as vegetation establishes and primary productivity begins to dominate, net sequestration occurs. The vegetation in the recolonising plots has been developing for approximately 2 years before measurements commenced and this study suggests the net source of C following excavation may be short lived if the bare soil is able to recolonise, either naturally or from an imported seed bank. Further research would be required to account for inter-annual variability of fluxes and to assess the magnitude of fluxes once the vegetation is fully established. Measurements before, during and after excavation would also be desirable to identify when the recolonising plots switched from a net source to net sink, and into the future to quantify long term effects on GHG fluxes. Further to this, quantification of the topsoil removed would enable the exported C to be accounted for and a net ecosystem carbon balance to be produced.

The differences in net radiative effect between the tall fen and short fen control plots are predominately vegetation driven, with the *Cladium* collars in the tall fen-control having significantly greater ecosystem respiration and productivity compared to the brown mosses and *Juncus* collars of the short fen-control ($p < 0.01$). Within the tall fen and short fen, the same pattern emerges with the net GHG emissions (in CO_2 equivalents) becoming increasingly positive from control to burnt to hand-cut plots, although the range in net GHG emissions at the site level within the tall fen is small (-8.13, -7.36, -5.34 t CO_2e ha^{-1} respectively). At the short fen, the increase in net GHG emissions observed could be explained by the difference in ecosystem respiration, with the short fen-hand cut plot having significantly greater R_{ECO} compared to the brown moss and *Juncus* collars of short fen-control ($p < 0.05$) and the short fen-burnt plot having greater R_{ECO} compared to the brown moss collars ($p < 0.05$).

CONCLUSION

This study produces annual CO_2 and CH_4 flux estimates for a partially degraded UK lowland peatland which has undergone a range of interventions including hand-cutting, burning and excavation. This study suggests that following restoration through topsoil removal, the C sink function can return to peatlands within a few years, provided there is the opportunity for recolonization, however further research is required to determine the magnitude of this C sink, effects of inter-annual variability and therefore long-term success. Although the differences observed in GHG fluxes between measurement plots here are predominately vegetation driven, soil conditions also play a key role in determining whether there is a net sink or release of C. This has important implications for restoration management decisions as the response of GHG fluxes following intervention can differ depending on initial conditions.

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