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Carbon dioxide fluxes at an intensively cultivated temperate lowland peatland in the East Anglian Fens, UK

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Abstract

This study reports the first recorded CO_2 flux measurements of a drained and intensively cultivated lowland peatland in the East Anglian Fens (UK) using the eddy covariance technique. Measurements were made over a complete lettuce crop rotation and a subsequent fallow period. Maximum average daytime CO_2 uptake and nocturnal loss rates were −10.39 and 7.63 µmol $CO_2\,m^{-2}\,s^{-1}$, respectively. Daily CO_2 budgets ranged from a net loss of 4.7 to a small net uptake of −1.23 g CO_2-C $m^{-2}\,d^{-1}$. Total vertical land/atmosphere CO_2 losses were estimated at 227.11 ± 46.5 g CO_2-C m^{-2} for a 120 day measurement period. Losses over a sixty day interval between field preparation and disking of the field at the end of the crop cycle were 74.22 ± 18.8 g CO_2-C m^{-2}. The site lost 152.89±30.6 g CO_2-C $m^{-2}\,d^{-1}$ during a sixty day fallow period. Net ecosystem production was estimated at 117.72 ± 18.8 g CO_2-C m^{-2} during the crop cycle and 270.61 ± 46.49 g CO_2-C m^{-2} for the entire measurement period when harvested crop exports were accounted for. These results represent the first micrometeorological measurements obtained over degraded lowland peatland in Britain, and illustrate the scale of CO_2 losses associated with agricultural production on temperate organic soils.

1 Introduction

Globally, peatlands cover less than three percent of the land surface, but store around one third of all terrestrial organic carbon (C) (Gorham, 1991; Turanen et al., 2002). Large areas of peatland have been drained and converted to productive land use (Joosten and Clarke, 2002; Byrne et al., 2004). Peatland drainage, however, destabilises peatland soil C stocks, resulting in large-scale transfers of historically accumulated soil C to the atmosphere in the form of carbon dioxide (CO_2). CO_2 emissions from drained and cultivated peatlands are amongst the highest from any type of land use, globally (Lohila et al., 2004; Couwenberg et al., 2011), and are recognised as a major

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anthropogenic flux within the global C cycle (Couwenberg et al., 2011; Leifeld et al., 2011).

The East Anglian Fens in the East of England contain the largest contiguous area of lowland fen peatland in the UK (Baird et al., 2009; Dawson et al., 2010). The majority of peat soils in the region were drained during the seventeenth century (Holden et al., 2004). Drained peat soils in the Fenland are amongst the most productive and profitable agricultural soils in the UK (Morris et al., 2000, 2010) but simultaneously represent one of the largest sources of greenhouse gas emissions (Thompson, 2008; Worrall et al., 2011). Drainage and intensive arable production has resulted in considerable and widespread peat wastage and land surface subsidence (Hutchinson, 1980).

At the current time, very limited data exist on CO_2 fluxes from cultivated temperate peatlands (IPCC, 2006; Couwenberg, 2011). Until now, estimates of CO_2 losses have been based on peat surface subsidence rates (e.g. Bradley, 1997; Leifeld et al., 2011). Although a valuable measure of overall C loss, subsidence-based estimates are limited by uncertainty in the fraction of surface lowering directly attributable to peat oxidation (Couwenberg et al., 2011; Leifeld et al., 2011; Page et al., 2011). Moreover, subsidence-based estimates do not provide information on short-term CO_2 exchange dynamics in response to agricultural management and/or weather conditions. More accurate quantification of CO_2 losses from cultivated peatlands is required for (i) improved land C accounting for the annual national communications to the United Nations Framework Convention on Climate Change (UNFCCC); (ii) making the C costs of food production visible to land managers, retailers and consumers; and (iii) identifying potential land management interventions that could reduce CO_2 losses.

In this study, we report eddy covariance (EC) measurements of CO_2 fluxes measured over a complete lettuce crop cycle and a subsequent fallow period at a drained and intensively cultivated peatland in East Anglia. CO_2 fluxes were captured over one of the wettest summer periods on record for this region. The objectives of the current research were to: (i) characterise temporal trends in CO_2 fluxes; (ii) estimate the magnitude of

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CO_2 losses at this intensively cultivated lowland fen; and (iii) compare our estimates with other published values from different types of peatlands.

2 Materials and methods

2.1 Site description

The study site (52°31.52′ N 0°28.16′ E) is a drained and intensively cultivated peatland located at the Methwold Fen area of the west Norfolk Fens. The climate of East Anglia is temperate, with a mean annual temperature of 10.4 °C (Climate data from the UK Met Office NIAB station in Cambridge). The region is characterised by mild winters and warm summers with a thermal growing season lasting from March to November. The Fenland region is one of the driest in the UK, receiving an average annual precipitation of 600 mm yr^{-1}, decreasing to 533 in lower-lying areas (Dawson et al., 2010). Monthly rainfall is well distributed throughout the year. Recent years, however, have experienced strong interannual variability in the timing and magnitude of precipitation events.

Land use is dominated by intensive arable production of cereals and horticultural salad crops. Peat soils are approximately 1 to 2 m in depth overlying fen clays, although localised peat depths of up to 5 m are present to limited extent (Burton and Hodgson, 1987). The study area was initially drained and converted to agriculture during the Second World War (M. Hammond, personal communication, 2012). Agricultural management is highly mechanised, and involves rotational production of vegetables (celery, lettuce, potatoes, onions, leeks and sugar beet) and wheat for commercial markets. To minimise aeolian losses of peat, crops are grown in small land parcels (average size of 6 ha) surrounded by shelterbelts (hedgerows) of varying height. Water levels are regulated using a system of field drains, ditches and control structures. A system of subsurface irrigation is used to regulate field water levels during the growing season (Dawson et al., 2010), with drainage depths depending on crop type. Average peat

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subsidence rates in the study area have been estimated at 1.48 cm yr^{-1} (Dawson et al., 2010). Surface elevation lies below mean sea level.

We installed a flux tower at a ditch boundary separating two land parcels. We aimed to sample fluxes originating from a land parcel to the south-west of the flux tower. The study site was instrumented on 21 June 2012. EC measurements commenced the day after the field was ploughed. An iceberg lettuce crop was planted between 25 and 27 June 2012 and harvested between 10 and 12 August 2012. This followed a fallow period at the site after a potato crop produced during the previous growing season. Peat depth was not measured across the field but was found to be > 1 m during works conducted when the EC system was installed at the site. Soil C content is approximately 36 % in the upper 1 m of the peat profile, with a C : N ratio of 17 (Taft et al., 2013). Peat pH is approximately 6. Crop management involved spraying with pesticides at around five day intervals. Only lettuce heads were removed during harvest and a large amount of leafy biomass was left growing in situ. The field was disked on 20 August 2012 and left to fallow over the autumn and winter period. The site was colonised by a cover of agricultural weeds in the weeks after disking. Notable colonists were nettle (*Urtica dioica*) and common chick weed (*Stellaria media*). Here, we report EC measurements obtained over a 60 day crop cycle from 22 June to 20 August 2012, and for a 60 day fallow period up to and including 19 October 2012.

2.2 Instrumentation

Fluxes of energy (momentum, latent and sensible heat) and net ecosystem CO_2 exchange (NEE) were measured using the EC technique (Baldocchi, 2003; Aubinet et al., 2012). The EC system comprises a CSAT3 sonic anemometer-thermometer (Campbell Scientific Ltd., Logan, Utah, USA) and a LI-COR Li7500 open-path CO_2/H_2O analyser (LI-COR Inc., Lincoln, Nebraska, US). The EC system was installed at a measurement height (z_m) of 1.5 m above the field surface and aligned with the prevailing south-westerly wind. The minimum available fetch was limited to approximately 130 m

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by a short (circa 2 m) hedgerow to the east of the flux tower, and extended to over 200 m along the prevailing wind direction. The low measurement height was selected to maximise the available fetch from the target land parcel.

A number of supporting environmental measurements were made at the site. Net radiation (R_{net}, W m^{-2}) was measured using an NR-Lite net radiometer (Kipp and Zonen, Delft, The Netherlands). Soil heat flux (G; W m^{-2}) was monitored using four HFP01-SC self-calibrating heat flux plates (Hukseflux, Delft, The Netherlands) installed at a depth of 0.08 m. Photosynthetically active radiation (PAR, µmol photons m^{-2} s^{-1}) was measured using an SKP01 Quantum sensor (Skye Instruments, Llandrindod Wells, UK). Air temperature (T_{air}, °C) and relative humidity (RH, %) were measured using an HMP45 (Vaisala, Helsinki, Finland). The temperature of the upper 0.06 m of the peat profile (T_{peat}, °C) was monitored using two TCAV averaging thermocouples (Campbell Scientific Ltd., Logan, Utah, USA). Volumetric peat moisture content (θ_{peat}, m^{-3} m^{-3}) was measured using two CS616 time domain reflectometers (Campbell Scientific Ltd., Logan, Utah, USA) installed horizontally at 0.05 m depth in the soil. Precipitation (P, mm) was measured using an ARG100 tipping-bucket rain gauge (Campbell Scientific Ltd., Logan, Utah, USA). All EC and environmental sensors (except the ARG100) were scanned at 20 Hz and logged using a CR3000 data logger (Campbell Campbell Scientific Ltd., Logan, Utah, USA).

2.3 Flux data processing

High frequency EC data were post-processed using the EdiRe Data Software Package (University of Edinburgh; version 1.5.0.32). Fluxes were computed as block averages over 30 min flux averaging intervals. Raw 20 Hz data were filtered for physically implausible values and despiked prior to flux calculations (Vickers and Mahrt, 1996). A two dimensional coordinate rotation procedure was applied to CSAT3 data for each averaging interval. High frequency temperature fluctuations were derived from the sonic temperature of the CSAT3 (Schotanus et al., 1983). Sensible (H) and latent heat (LE) coefficients were calculated for each 30 min averaging period (Mauder et al., 2008). Fluxes were corrected for limitations in the dynamic frequency response of the measurement system (Moore, 1986). CO_2 and LE fluxes were adjusted for atmospheric density fluctuations (Webb et al., 1980). Storage was assumed negligible at the low measurement height. NEE was considered equal to the turbulent exchange of CO_2. We adopt the micrometeorological sign convention, where fluxes from the surface to the atmosphere are positive.

2.4 Quality control

Quality control (QC) procedures included the removal of statistical outliers and tests that the theoretical assumptions of EC were not violated significantly. Large outliers were removed using the median absolute deviation method (Papale et al., 2006). Fluxes were also discarded: (i) during periods of non-stationarity and/or perturbed or insufficient turbulent mixing (Foken et al., 2004; Ruppert et al., 2006); (ii) when the momentum flux was positive; (iii) when the Li7500 AGC parameter was 10 % above its baseline value (Ruppert et al., 2006); (iv) when wind direction was outside ±90° from the southwest orientation of the sonic anemometer to restrict measurements to the land parcel of interest; and (v) when the Kormann and Meixner (2003) footprint model indicated 75 % flux recovery was beyond the target land parcel.

We did not identify a reduction in nocturnal NEE at low friction velocity (u^*) values at this site. No u^* threshold was applied except as a means of assessing uncertainty (see below). Results of integral turbulence and stationarity tests showed most of our accepted measurements were of high (76 %) quality according to the CarboEurope quality flag scheme (Mauder and Foken, 2011). This suggests flow distortions caused by shelterbelts were minimal. We acknowledge contributions from other peat fields with different crop types would have influenced our measurements under certain wind conditions (discussed below). The same QC procedures were applied to H and LE fluxes. Total data coverage after QC was 56 %, 54 %, and 48 % for H, LE and NEE, correspondingly.

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2.5 Data gap-filling and flux partitioning

Gaps in LE and NEE flux data records were filled using Marginal Distribution Sampling (Reichstein et al., 2005). Gap-filling was performed using an online implementation of the algorithm by Reichstein et al. (2005). The method is similar to the mean diurnal variation approach (Falge et al., 2001), modified to account for temporal autocorrelation and covariation of fluxes with meteorological variables, namely: global radiation (R_g), air temperature and vapour pressure deficit. R_g was not measured at the study site, and was estimated using a linear relationship (R_g = 0.51 PAR, r^2 = 0.99, n = 5280) derived from an SKP01 Quantum sensor (Skye Instruments, Llandrindod Wells, UK) and the R_g channel of a CNR1 net radiometer (Kipp and Zonen, Delft, The Netherlands) installed at a flux tower ca. 20 km south of the study site (Morrison et al., 2013). Partitioning of NEE into estimates of gross primary production (GPP) and ecosystem respiration (ER) was performed using the online version of Reichstein et al. (2005). Gap-filling and flux partitioning were performed separately for (i) the period between field preparation and harvest, and (ii) the fallow period. Separate periods were used due to rapid changes in ecosystem CO_2 fluxes associated with land management events.

2.6 Uncertainty assessment

There are numerous sources of uncertainty that will influence time-integrated sums of NEE (Richardson et al., 2012). Only the most important of these were considered in this study. A conservative ±20 % measurement error was applied to time-integrated estimates of NEE. In our study, we acknowledge measurements were likely influenced by crops growing in peat fields surrounding the target land parcel. To estimate the magnitude of this impact, we calculated the standard deviation (SD) of (gap-filled) NEE datasets generated for periods when 75 % flux recovery was within: (i) 135 m of the flux tower (minimum available fetch); (ii) 200 m (maximum available fetch); and (iii) 255 m (beyond the maximum available fetch). Although we did not identify a u^* threshold at this site, we explored the potential systematic underestimation of fluxes during periods

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of thermal stability as the SD of gap-filled datasets generated using u^* thresholds of 0, 0.05, 0.1 and 0.15 $m s^{-1}$. Random error associated with gap-filling was estimated using the uncertainty assessment provided by the online flux processing tool (Reichstein et al., 2005). Total uncertainty was estimated in quadrature using the error accumulation principle.

2.7 Energy balance closure

The plausibility of the flux dataset was assessed by reconstructing the surface energy balance. It was not possible to install the NR-lite over the crop canopy on a permanent basis due to regular farming (i.e. spraying) operations. Energy balance closure (EBC) was evaluated over two separate intervals. In the first case, the NR-Lite was installed over the lettuce crop canopy during the five day period between 20 to 25 July 2012. Following harvest, the NR-lite was installed permanently over a representative area. Closure was assessed during the fallow period between 20 August 2012 and the end of the measurement period. In both cases, the NR-Lite was installed at a height of 1.5 m. EBC was evaluated by linear regression of the sum of accepted turbulent energy fluxes (LE + H) against the independently measured available energy ($R_{net} - G$).

3 Results

3.1 Environmental conditions

Meteorological conditions were strongly atypical for the Fenland region (and southern UK more generally) prior to and during the flux measurement period (Fig. 1). The East of England experienced a state of extreme drought between early 2011 and April 2012 (Fig. 1b, c). During spring and summer 2012, persistent low pressure near or over the UK led to cloudier than normal conditions, and the second wettest summer since 1910 (Met Office, 2012). Total accumulated rainfall between June and September 2012 was

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135 % of the long-term average for the Fenland region (Fig. 1a). Monthly rainfall was within the normal range during August, drier than normal in September (Fig. 1a) with wetter than normal conditions returning in October. With the exception of August which was warmer than average, these wet conditions were associated with generally cooler than average air temperatures.

Figure 2 shows trends in key meteorological variables measured over the study period. PAR was generally low throughout the field campaign. Only a few bright periods were observed, notably during late June and July (Fig. 2a). Mean daily air and peat temperature were within a range of 6.3 to 23.8 °C, and 7.5 to 23.2 °C, respectively (Fig. 2b). Mean daily peat temperature was generally higher than air temperature during the study period (Fig. 2b). Increases in both temperature variables were associated with periods of increasing irradiance.

Rainfall was recorded on 71 days out of the 120-day measurement period (Fig. 2c). A number of days between July and September received rainfall totals approaching 50 % of long-term monthly averages for the respective months. Despite the high rainfall, land drainage ensured that field water levels were below −70 cm throughout the field campaign (manual recordings not shown). θ_{peat} ranged from 0.2 to 0.7 $m^{-3}\,m^{-3}$ and reflected the balance between rainfall and evapotranspiration (Fig. 2c–e). θ_{peat} was highest at the start of the measurement period and showed a strong decline over the crop growing period. The lowest soil moisture levels occurred during late summer and early autumn, and increased towards the end of the reported period with the shift to a positive meteorological water budget.

3.2 Energy balance closure

The slopes of linear regressions indicated EBC was 89 % and 81 % of the available energy during the crop growth and fallow periods, respectively (Fig. 3). For both periods, there was a tendency for the turbulent energy fluxes to be over- and underestimated at low and high levels of available energy, correspondingly. This pattern likely reflects well-documented problems of accurately measuring soil heat fluxes in peat soils (Harding

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and Lloyd, 2008; Laurila et al., 2012). The lower level of closure during the fallow period (Fig. 3b) may reflect greater heterogeneity in site conditions following harvest. Despite these limitations, EBC was within the 70 % to 90 % range typically attained at EC sites (Wilson et al., 2002).

3.3 Trends in NEE

A high temporal variation in NEE was observed over the measurement period (Fig. 4). At the start of the measurement period, the site was losing CO_2–C at a mean (±SD) rate of 3.95 ± 0.49 µmol CO_2 m^{-2} s^{-1}, with slightly higher rates of average efflux during warmer daytime periods. Rapid development of the photosynthetic capacity of the lettuce crop canopy resulted in an increase in mean net daytime uptake and nocturnal efflux rates and development of a clear diurnal cycle in response to the daily variation of PAR (Fig. 4).

Temperature and θ_{peat} were both important controls on CO_2 efflux rates at this agricultural peatland. At the thirty minute timescale, the responses of nocturnal NEE (i.e. ER) to temperature and θ_{peat} showed a high degree of scatter (not shown). As such, we used binned averages of nocturnal NEE to explore the sensitivity of ER to environmental drivers (Fig. 5). Nocturnal CO_2 losses increased with T_{air} (not shown) and T_{peat} (Fig. 5a), and were negatively correlated with variations along the observed θ_{peat} range (Fig. 5b). In both cases, a clear distinction was observed for crop and fallow periods. Binned averages of nocturnal NEE were higher during the crop period than for the fallow interval at similar values of T_{peat} and θ_{peat}. Higher CO_2 loss rates during the crop period at similar T_{peat} values are largely explained in terms of higher autotrophic contriutions during the period of vigourous crop growth. Similarly, differences in the (linear) response of noctrunal CO_2 losses to θ_{peat} are part-explained by reduced autotrophic contributions, as well as generally lower temperatures during the fallow period.

The amplitude of the average diurnal cycles increased as the crop canopy developed. The highest observed (mean ± SE) net uptake rates of -10.39 ± 0.07 µmol CO_2 m^{-2} s^{-1} were observed during the ten day period before harvest (Fig. 4). Average daytime

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uptake rates only showed a slight decline in the period after harvest as only the lettuce heads were removed and a large ammount of leaf material was left growing in the field. The highest average nocturnal CO_2 effluxes (mean of all noctural measurements) of $7.63 \pm 0.16\,\mu mol\,CO_2\,m^{-2}\,s^{-1}$ were observed during this period, most likely reflecting an increased availabilty of labile substrates deposited during harvesting operations, together with enhanced C mineralisation rates due to associated soil disturbance and generally higher temperatures (Figs. 4b and 5a).

A strong reducton in average net daytime CO_2 uptake and nocturnal efflux rates was observed after the peat field was disked on 20 August (Fig. 4a). The reduction in daytime uptake reflects the effects of disking on the photosynthesis of the remaining plant biomass, whereas strongly reduced rates of nocturnal CO_2 efflux are explained by a concurrent decline in autotrophic respiration rates.

A clear diurnal cycle was observed throughout the fallow period. Instantaneous net daytime flux rates were positive until October. Average nocturnal CO_2 efflux rates showed a clear declining trend over the fallow period, and were lower than the average nocturnal 30 min flux values at the start of the crop cycle (Fig. 4). Peak daytime flux rates became slightly negative towards the end of the measurement interval, explained by a reduction in peat mineralisation rates under cooler (Fig. 5a) and wetter conditions (Fig. 5b), as well as small amounts of photosynthesis as the secondary vegetation cover became established.

3.4 Carbon dioxide budgets

The arable fen showed strong temporal variation in daily CO_2 budgets over the measurement period (Fig. 6a). Daily CO_2 budgets ranged from a net loss of $4.7\,g\,CO_2$-$C\,m^{-2}\,d^{-1}$ to a small net uptake of $-1.23\,g\,CO_2$-$C\,m^{-2}\,d^{-1}$. Daily estimates of GPP and ER ranged from 0 to $-8.91\,g\,C\,m^{-2}\,day^{-1}$ and from 2.05 to $8.56\,g\,C\,m^{-2}\,day^{-1}$, correspondingly (Fig. 6a). Net CO_2 losses were highest during the days between initial field preparation and planting when ER was high and a CO_2 fixing surface was absent.

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Daily CO_2 budgets showed a progressive decline as GPP increased as the crop canopy became established (Fig. 6a). Net uptake of CO_2 occurred on sixteen days between mid-July and harvest in early August as heterotrophic CO_2 losses were outweighed by the photosynthesis of the lettuce crop. A large release of CO_2 occurred on 31 July when photosynthetic activity was reduced during strongly overcast conditions (Fig. 6a).

The site became a net daily source for atmospheric CO_2 after the crop was harvested (Fig. 6a). The increase in net CO_2 loss following crop removal reflected a reduction in GPP and an increase in daily ER. A strong increase in daily CO_2 efflux rates was observed after the field was disked in mid-August and GPP was strongly reduced relative to ER. Daily CO_2 losses showed a declining trend throughout September and early October, reflecting the combination of decreasing ER under falling autumn temperatures (Fig. 5a) and increasing volumetric peat moisture content (Fig. 5b), as well as small amounts of late season photosynthesis as the site was colonised by arable weeds (Fig. 6a).

Accumulated CO_2 losses from the arable fen were estimated at 227.11 ± 46.49 g CO_2-C m^{-2} over the total 120 day measurement period (Fig. 6b). Total GPP and ER were estimated at 327.38 and 554.48 g C m^{-2} period^{-1}, respectively. CO_2 budgets calculated using different u^* thresholds for this period resulted in CO_2 balances of 227.4, 226.84, and 227.12 g CO_2–C m^{-2} period^{-1} for u^* values of 0.05, 0.1 and 0.15 m s^{-1}, respectively. Similarly, CO_2 budgets estimated using less conservative footprint criteria of 200 and 255 m yielded estimates of 226.02, and 226.21 g CO_2–C m^{-2} period^{-1}, correspondingly. These results show that our estimate of NEE was insensitive to these QC criteria. In the latter case, this most likely reflects the similarity of crops growing in peat fields to the south of the study site. Uncertainties associated with measurement error and data gap-filling were larger at 45.42 and 9.90 g CO_2–C, respectively. On the basis of the same uncertainty calculations, total CO_2 losses for the crop period between field preparation and disking were estimated at 74.22 ± 18.83 g CO_2-C m^{-2}. GPP for the crop period was estimated at 264.87 g CO_2-C m^{-2} with ER estimated 339.08 g C m^{-2} period^{-1} (Fig. 7). Estimates of accumulated GPP and ER for the fallow interval were both lower than during the crop period at 62.51and 215.40 g CO_2 – C m^{-2} $period^{-1}$, respectively (Fig. 7). The relative reduction in GPP was larger than the reduction in ER. The net CO_2 loss during the fallow period was higher than for the crop period at 152.89 ± 30.64 g CO_2 – C m^{-2} $period^{-1}$.

NEE estimated using the EC technique only includes the vertical land/atmosphere exchange of CO_2 and does not include lateral C exports during harvest. According to farm records, lettuce yields on organic soils in The Fenland are approximately 29 Mg ha^{-1} (M. Hammond, personal communication, 2012). Assuming a (measured) mean water content of 97 % (SD = 0.2 %, $n = 3$), and a C content of 50 %, this equates to an additional C loss of approximately 43.5 g C m^{-2}. We note this is a slight overestimate, since lettuce plants were planted as plugs (i.e. representing a small net import of C); however, this import term is small relative to harvested exports and was neglected here. Including harvested exports of C results in a net ecosystem production (NEP) of 117.72 ± 18.83 g CO_2-C m^{-2} for the sixty-day lettuce crop cycle (Fig. 7). NEP was estimated at 270.61 ± 46.49 g CO_2-C m^{-2} for the complete 120 day measurement period.

4 Discussion

This study has presented the first micrometeorological flux measurements of land/atmosphere CO_2 exchange from a drained and cultivated peatland in the East Anglian Fens. To the best of our knowledge, our study is the first to quantify CO_2 fluxes at an intensively cultivated temperate lowland fen (Couwenberg, 2011). Footprint calculations indicated the majority of the measured fluxes originated from the agricultural field of interest. Our analysis suggests, however, that the estimate of time-integrated NEE was relatively insensitive to footprint criteria, possibly reflecting the similarity of crops in fields to the south of the study site. Within these constraints, EC data availability was within the typical range of coverage attained at EC sites (Falge et al., 2001)

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and EBC was towards the higher end of the 70 to 90 % range reported from a range of EC measurement sites, globally (Wilson et al., 2002).

To the best of our knowledge, no EC measurements are currently available for similar crops on peat soils in the temperate region and beyond. At our site, maximum net CO_2 uptake rates (ca. −10.39 µmol CO_2 m^{-2} s^{-1}) were lower than values reported for other crops on organic soils, whereas maximum nocturnal CO_2 efflux rates (7.63 ± 1.55 µmol CO_2 m^{-2} s^{-1}) were similar or slightly higher. Lohila et al. (2004) for example, reported maximum daytime uptake rates (units converted) of −23 µmol CO_2 m^{-2} s^{-1} and −17 µmol CO_2 m^{-2} s^{-1} for barley and ley grass at a boreal agricultural fen, respectively, with maximum nocturnal losses estimated at 8 µmol CO_2 m^{-2} s^{-1} for both crop types. Maximum net CO_2 uptake rates of −18 µmol CO_2 m^{-2} s^{-1} and nocturnal losses of 7.2 µmol CO_2 m^{-2} s^{-1} were reported for a reed canary grass plantation on degraded organic soil in Finland (Shurpali et al., 2009). Peak season uptake and loss rates of −17.2 µmol CO_2 m^{-2} s^{-1} and 8 µmol CO_2 m^{-2} s^{-1} were measured at a temperate pasture on organic soil in New Zealand (Nieveen et al., 2005).

The highest net daily losses of CO_2 were observed following ploughing and field preparation at the start of the measurement period. This clearly reflects the influence of extreme soil disturbance associated with tillage, particularly the increased aeration of the near-surface peat layer and the lack of a CO_2 fixing vegetation cover. Maximum daily CO_2 losses at our site (4.7 g CO_2-C m^{-2} d^{-1}) were higher than daily values reported for cultivated boreal peatlands. For example, maximum losses of 2.72 g CO_2−C m^{-2} day^{-1} to 4.36 g CO_2−C m^{-2} day^{-1} were reported in the study of Lohila et al. (2004). Higher net daily CO_2 losses of 8 g CO_2−C m^{-2} day^{-1} have been reported for a grazed and degrading peatland in California, but under warm rather than cool temperate climatic conditions (Hatala et al., 2012).

A significant reduction in daily CO_2 losses was observed as the crop canopy developed. Net CO_2 uptake only occurred on sixteen days during the crop period at our temperate site. Although we only report on part of the growing season, this contrasts strongly with growing season net sink periods of 40 to 84 days, and 66 to 96 days reported by Lohila et al. (2004) and Shurpali et al. (2009), respectively.

Maximum daily net uptake values ($-1.23\,g\,CO_2-C\,m^{-2}\,day^{-1}$) were significantly less negative than values reported at other cultivated peatlands. In the study of Lohila et al. (2004) maximum uptake rates of -4.1 and $-5.45\,g\,CO_2-C\,m^{-2}\,day^{-1}$ were observed for grass and barley, correspondingly. Shurpali et al. (2009) reported maximum daily uptake of -4.5 to $-9.6\,g\,CO_2-C\,m^{-2}\,day^{-1}$ over a four-year study period. These differences are explained by the longer crop periods and higher productivity of cereal and other graminoid crops relative to lettuce, as well as generally higher rates of peat mineralisation at our site's more southerly temperate location. For example, maximum estimates of daily GPP ($-8.91\,g\,CO_2-C\,m^{-2}\,day^{-1}$) and ER ($8.56\,g\,CO_2-C\,m^{-2}\,day^{-1}$) at our site contrast with maximum GPP and ER values of -15.8 and $7.6\,g\,CO_2-C\,m^{-2}\,day^{-1}$ respectively, reported by Shurpali et al. (2009).

A large amount of CO_2 was lost over the 60-day fallow period. Total vertical CO_2 losses over this period ($152.89\,g\,CO_2-C\,m^{-2}\,period^{-1}$) were larger than our estimate of NEP for the crop period ($117.72\,g\,CO_2-C\,m^{-2}\,period^{-1}$). The site switched to a daily CO_2 source after the crop was harvested and became a strong net source after disking. This large increase in daily CO_2 efflux rates is attributed primarily to the reduction in crop assimilation as plant roots were severed. Peat mineralisation rates were also likely enhanced due to an increased availability of labile crop residues and oxygen in the upper peat profile following disturbance of the peat surface, although to a lesser degree than the extreme soil disturbance associated with ploughing and field preparation.

The reduction in net CO_2 losses towards the end of the reported period was in part due to colonisation by a secondary vegetation cover and increasing soil moisture content. These results imply that adoption of less intensive management practices (i.e. no-till, cessation of disking) and/or maintenance of a CO_2 fixing vegetation cover following harvest, together with efforts to maintain higher soil moisture content following crop removal could reduce net in situ CO_2 losses from cultivated fens in this region. Any

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such CO_2 emissions reduction would need to be weighed against potential changes in nitrous oxide (N_2O) and methane (CH_4) emissions (Elder and Lal, 2008).

Although we have not provided an annual CO_2 budget, net CO_2 losses can be expected throughout the year at this intensively managed site. Our partial annual estimate of NEE exceeds annual losses of 79 ± 25 to $210 \pm 28\,g\,CO_2{-}C\,m^{-2}\,yr^{-1}$ (290 ± 91 to $771 \pm 104\,g\,CO_2{-}C\,m^{-2}\,yr^{-1}$) reported for cultivated boreal fens (Lohila et al., 2004) although our partial annual estimate of NEP remains lower than the 336 to $452\,g\,CO_2{-}C\,m^{-2}\,yr^{-1}$ reported by these authors. Further, total CO_2 losses (both in terms of NEE and NEP) over the 120 day measurement period are already within the 250 to $500\,g\,CO_2{-}C\,m^{-2}\,yr^{-1}$ (734 to $1835\,g\ CO_2\,m^{-2}\,yr^{-1}$) range estimated for cultivated temperate fens on the basis of long-term subsidence rates (Leifeld et al., 2011). Our estimate is more than double the annual emissions estimate of $109\,g\,CO_2{-}C\,m^{-2}\,yr^{-1}$ ($400\,g\,CO_2\,m^{-2}\,yr^{-1}$) currently reported for shallower ($< 1\,m$) drained and cultivated peats in the UK National GHG Inventory Report (Choudrie et al., 2008), but less than a quarter of the $1280\,g\,CO_2{-}C\,m^{-2}\,yr^{-1}$ ($4698\,g\,CO_2\,m^{-2}\,yr^{-1}$) used to represent emissions from deeper ($> 1\,m$) peats.

The large CO_2 loss at our site over just part of the annual cycle highlights the scale of ongoing CO_2 losses from drained and cultivated fens in East Anglia and temperate fens more generally. Although the magnitude of annual CO_2 losses will in part depend on the type of crops grown and associated management intensity during the rest of the year, annual CO_2 losses can be expected to be at least double our current estimate of NEP.

The flux measurements reported here were obtained during some of the wettest summer conditions on record for the Fenland and the UK more generally. Moreover, extremely wet conditions were accompanied by a generally cooler than average growing season (with the exception of August). At the present time, and on the basis of this short measurement interval, it is not possible to quantify the impacts of these atypical meteorological conditions on the CO_2 balance of cultivated peatlands in this region. Previous studies at peatland environments show that CO_2 losses tend to become more

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positive during warmer and drier conditions (e.g. Shurpali et al., 1996; Bubier et al., 2003; Cai et al., 2010). Increasing nocturnal CO_2 efflux rates in response to increasing temperature and declining soil moisture levels implies a similar response is likely at this agriculturally used site. This highlights the need for longer-term measurements to characterise the temporal variability in CO_2 dynamics under a wider spectrum of environmental conditions and agricultural management practices.

This study only considered CO_2 fluxes at a single location. Full C and GHG accounting requires quantification of all climatically relevant C and GHG exchanges. In agricultural peatlands this includes emissions/removals of methane (CH_4), emissions of nitrous oxide (N_2O), and vertical and lateral movements of particulate and dissolved organic C (Warburton, 2003; Dawson and Smith, 2007; Teh et al., 2011). An annual estimate of GHG emissions using chamber flux measurements at our field site for the period 10 May 2011 to 9 May 2012 indicates that as a proportion of total annual emission (CO_2-e) from three land parcels at this site, CH_4 emission was negligible, and N_2O emission (estimated at between 4.88 and 7.83 t CO_2-e ha^{-1} y^{-1} on bare soils, and between 3.99 and 7.07 t CO_2-e ha^{-1} y^{-1} on cropped soils) was small compared to soil respiration (estimated at between 19.75 and 33.05 t CO_2-e ha^{-1} y^{-1} on bare soils, and between 23.37 and 36.03 t CO_2-e ha^{-1} y^{-1} on cropped soils) (Taft et al., 2013). Measurements of lateral C transfers via the aeolian pathway using methods similar to Warburton (2003) and of fluvial C fluxes are both underway. EC measurements of CO_2 exchange are ongoing at this site and will aim to capture CO_2 dynamics over a greater number of different crop cycles and meteorological conditions.

EC measurements obtained at a single location do not provide information on the spatial variability in land/atmosphere CO_2 exchange. Dawson et al. (2010) for example, reported that subsidence rates (and presumably net CO_2 losses) were higher for less degraded peats in the same study area. Moreover, net CO_2 losses will be higher for crops requiring more intensive agricultural management than lettuce (i.e. tillage practices, fertilisation, liming). Future research will compare EC and chamber flux measurements. We are currently exploring methods to upscale measurements from field to

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landscape scale, and the fusion of continuous and longer-term EC measurements with very-high resolution spatial datasets, in particular.

5 Conclusions

This study has reported the first direct micrometeorological measurements of net ecosystem CO_2 exchange at an intensively cultivated peatland in the East Anglian region. Measurements were obtained over one complete lettuce crop rotation and a fallow period. To the best of knowledge, our measurements represent the first direct flux measurements to be obtained at an intensively cultivated lowland fen in East Anglia, and one of the first to quantify CO_2 losses from a temperate cropland on organic soil. Measurements were obtained during one of the wettest summer periods on record. The cultivated fen was a net source of $117.72 \pm 18.83\,\mathrm{g\,CO_2\text{-}C\,m^{-2}}$ over a sixty day lettuce crop cycle. $152.89 \pm 30.64\,\mathrm{g\,CO_2{-}C}$ was lost during a sixty day fallow period. The site was a net source of $270.61 \pm 46.49\,\mathrm{g\,CO_2\text{-}C\,m^{-2}}$ over the 120 day measurement period when harvested crop exports were included. These results highlight the scale of ongoing CO_2 emissions resulting from food production on temperate organic soils.

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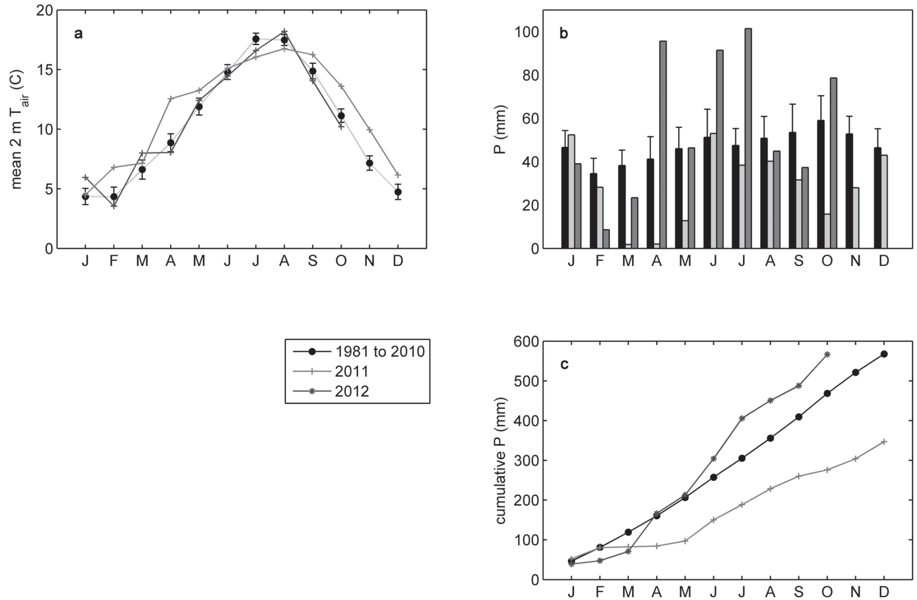

Fig. 1. Monthly average air temperature **(a)** precipitation sums **(b)** and cumulative monthly precipitation **(c)**. Long-term monthly averages were calculated using a 1981 to 2010 climatic baseline. Data are from the UK Met Office NIAB Station in Cambridge (54.35° E 26.06° N, 26 m a.m.s.l.). Data supplied by the Met Office.

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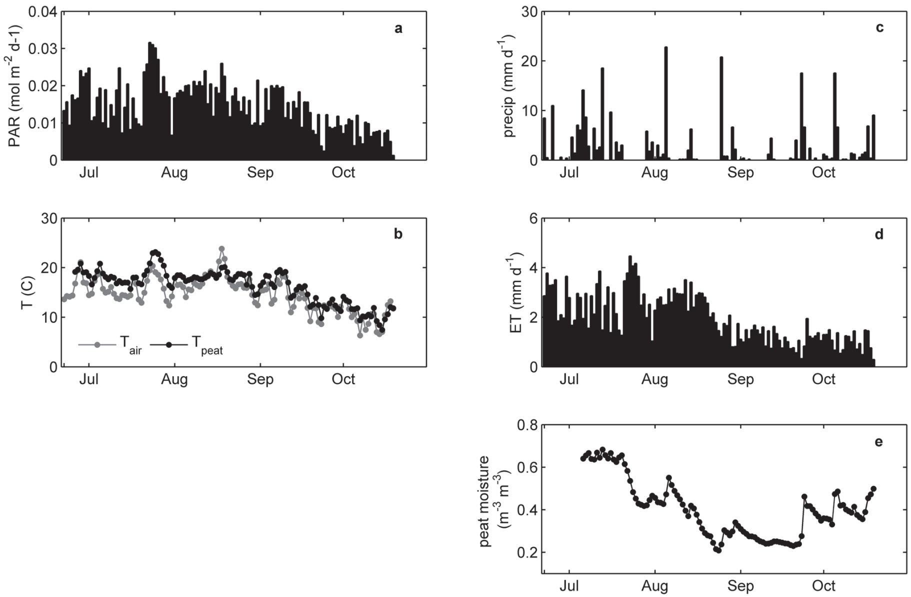

Fig. 2. Variation in daily environmental variables over the measurement period. Plots show: **(a)** total PAR (mol photons day^{-1}); **(b)** mean air and peat temperature (°C): **(c)** rainfall totals (mm day^{-1}); **(d)** total daily evapotranspiration (ET) measured by EC (mm day^{-1}); and **(e)** mean volumetric peat moisture content (m^{-3} m^{-3}).

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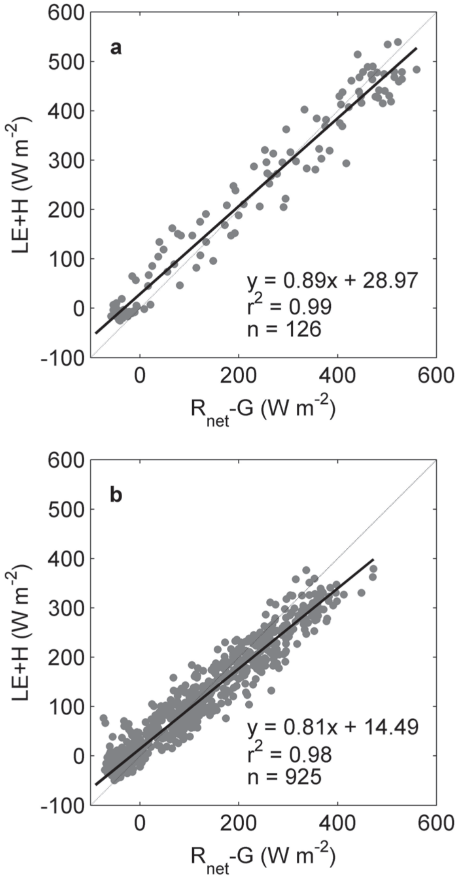

Fig. 3. Energy balance closure for **(a)** crop and **(b)** fallow periods.

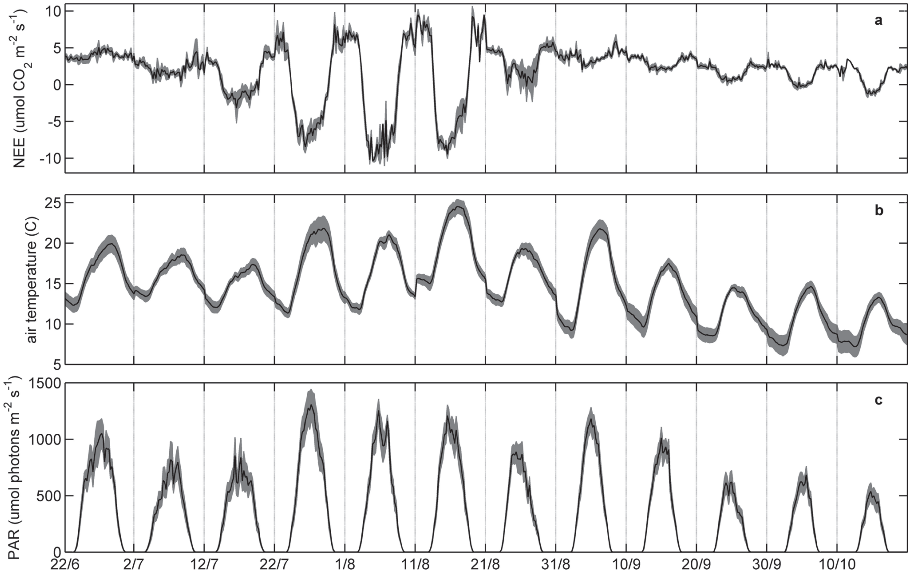

Fig. 4. Mean diurnal cycles of **(a)** net ecosystem CO_2 exchange (µmol CO_2 m^{-2} s^{-1}); **(b)** air temperature (°C); and **(c)** photosynthetically active radiation (µmol photons m^{-2} s^{-1}). Positive NEE values denote CO_2 losses to the atmosphere. The diurnal cycles shown represent averages over ten day periods commencing on the dates given on the x-axis. NEE values are measured and not gap-filled data. Shaded areas show standard errors.

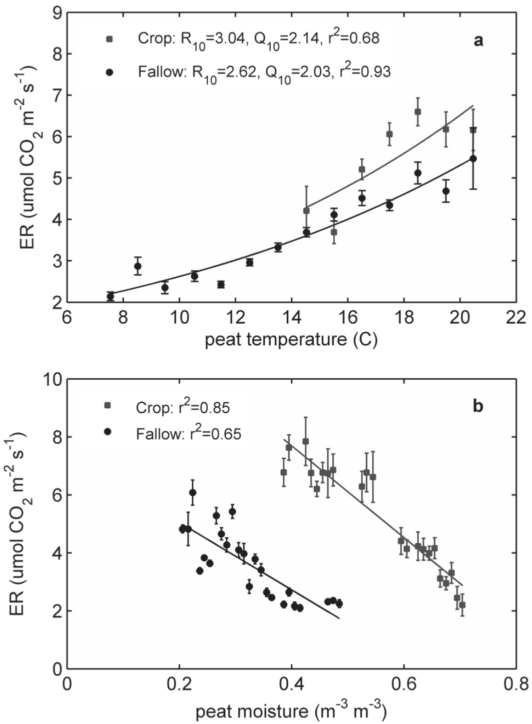

Fig. 5. Partial response of nocturnal NEE (ER) to **(a)** air temperature and **(b)** soil moisture for crop and fallow periods. In plot **(a)** data are bin averages for 1 °C peat temperature classes. Temperature responses are illustrated using non-linear fits of an exponental respiration model of the form: $R_{10} \cdot Q_{10}^{(T_{\text{peat}}-10\,^{\circ}\text{C})/10}$, where R_{10} (μmol $CO_2\,m^{-2}\,s^{-1}$) and Q_{10} are parameters describing basal ecosystem respiration normalised to 10 °C, and the sensitivity of ER to a 10 °C temperature increase, respectively. The equations of the fitted curves and determination coefficeints are provided on the plot. In plot **(b)** data are bin averages for 0.01 $m^{-3}\,m^{-3}$ soil moisture classes. Lines show linear fits. Error bars show standard errors.

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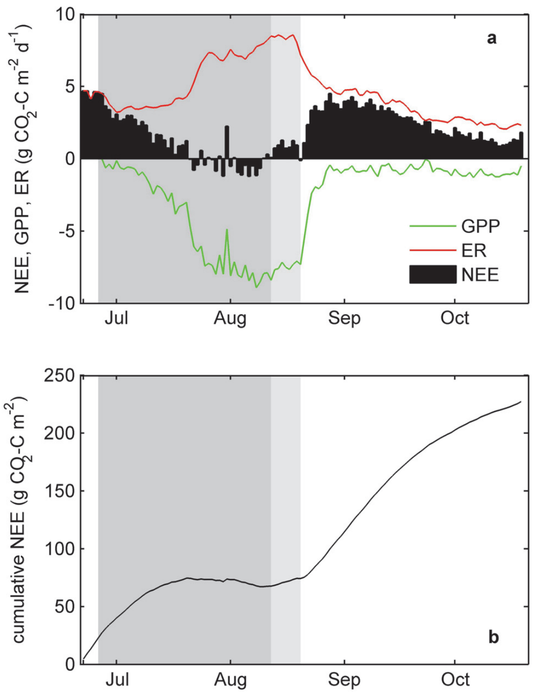

Fig. 6. Daily CO_2 budgets **(a)** and accumulated daily CO_2 fluxes **(b)**. Light and darker shaded areas represent the period between crop planting and harvest, and the period between harvest and disking.

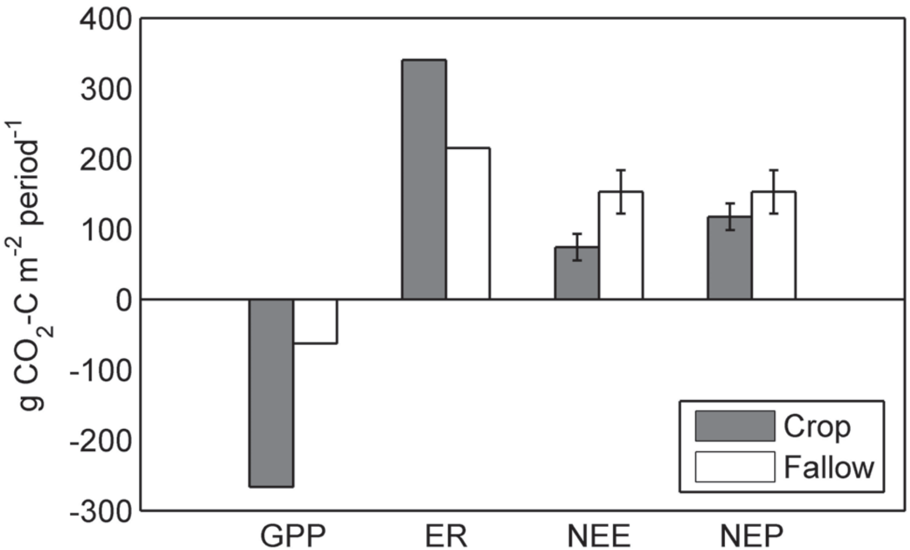

Fig. 7. Comparison of CO_2 flux components during the sixty day crop and fallow periods. Error bars indicate the uncertainty range for estimates of NEE and NEP. Note that NEE and NEP are the same for the fallow period.

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