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BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY

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Maize grown for bioenergy on peat emits twice as much carbon as when grown on mineral soil

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Abstract

The area of land dedicated to growing maize for bioenergy in the United Kingdom is rapidly expanding. To understand how maize production influences soil carbon (C) dynamics, and whether this is influenced by soil type, we measured net ecosystem exchange (NEE) using the eddy covariance technique over the 2021 growing season. We combined the NEE data with C imports and exports to calculate the net ecosystem productivity (NEP) of two maize crops grown for bioenergy in the United Kingdom, one site on mineral soil and the other on lowland agricultural peat. Maize was similarly productive at both sites—gross primary productivity was 1107 g C m^{-2} at the site with mineral soil and 1407 g C m^{-2} at the peat site. However, total ecosystem respiration was considerably higher from the peat site (1198 g C m^{-2}) compared with the mineral soil site (678 g C m^{-2}). After accounting for the removal of C in harvested biomass, both sites were net C sources, but C losses were over two times greater from the peat site (NEP = 290 g C m^{-2}) than the mineral site (NEP = 136 g C m^{-2}). While annual crops may be needed to produce bioenergy in the short term, growing maize for bioenergy in the United Kingdom does not appear to be a viable option for C sequestration over the long term, as it leads to high carbon losses from agroecosystems, especially those on organic soils. Instead, growing perennial bioenergy crops on mineral soils with a low organic C content is a more appropriate option.

KEYWORDS

carbon dioxide, eddy covariance, greenhouse gas, net ecosystem exchange, net ecosystem productivity

1 | INTRODUCTION

Bioenergy has received attention as a renewable resource and potential climate change mitigation measure, both as an alternative to fossil fuels and a method of carbon (C) sequestration when combined with C capture and storage (Calvin et al., 2021; de Freitas et al., 2021; Hanssen et al., 2020). In the United Kingdom, bioenergy is a significant source of renewable energy, generating around 11% of the country's total electricity supply in 2022 (DESNZ, 2024). Given the role of bioenergy in decarbonising the energy sector, and the UK's legally binding commitment to reach net zero greenhouse gas (GHG) emissions by 2050 or earlier, the demand for biomass is expected to increase significantly (DESNZ, 2023). There are a range of crops, both annual and perennial, that can be grown for bioenergy production (Pugesgaard et al., 2014). As of 2020, 121,000 ha of land, equivalent to 1.4% of the agricultural land area, were used to grow biomass for energy in the UK (Booth & Wentworth, 2023). Biogas is produced by anaerobic digestion (AD), where organic material is decomposed by microorganisms in an oxygen-limited environment, producing methane (CH_4) for use as energy (Gould, 2015; Vasco-Correa et al., 2018), and via biomass combustion, where organic material is combusted to produce heat (Skoufogianni et al., 2019). Although the C emitted via combustion during AD is balanced by the C fixed by plant photosynthesis, bioenergy cannot be described as completely C neutral because the carbon dioxide (CO_2) savings are likely to be offset by emissions of CO_2, CH_4 and nitrous oxide (N_2O) during crop growth, field management, biomass processing and transport (Crutzen et al., 2008; Don et al., 2011).

Much of the existing research has proposed that growing perennial crops for bioenergy, such as willow and *Miscanthus*, rather than annual crops like maize (*Zea mays L.*) and wheat, has fewer negative impacts on the environment as perennials have more permanent root systems and require less fertiliser input (Kantola et al., 2022; Karp & Richter, 2011; Pugesgaard et al., 2014). Globally, maize is one of the most grown bioenergy crops, as it is high yielding and has a high biogas output when anaerobically digested (Bright Maize, 2022; Herrmann, 2013). Maize is also grown extensively for bioethanol production, particularly in Brazil and the USA (Skoufogianni et al., 2019). To increase the scale and reliability of biogas production, the amount of arable land dedicated to the production of bioenergy crops, including maize, is growing (Hill, 2016; Souza et al., 2015). In 2021, 75,000 ha of land were used to grow maize for bioenergy production in the UK (DEFRA, 2021). In the UK, maize is usually harvested in October, meaning that the field is left bare over winter and is vulnerable to soil erosion, as there is insufficient time for a winter crop or cover crop to be sown and established (Naylor et al., 2022). In addition, whole-crop harvesting of maize for AD results in large-scale removal of crop residues that can deplete soil organic C (SOC; Ceschia et al., 2010; Raffa et al., 2015; Poyda et al., 2019; Wall et al., 2020). While most of the agricultural land in the United Kingdom is on mineral soil, around 1.1% (194,000 ha) is on drained lowland peat, representing approximately 7% of the UK's total peat area (Evans et al., 2017). Natural peatlands are a considerable C store; and so peat drainage, initiated at scale in the UK in the 1600s to facilitate agricultural expansion, increases soil aeration and thus decomposition, leading to soil C loss as CO_2 (Evans et al., 2016). Agricultural mineral soils are also sources of C following intensive management (Bhattacharyya et al., 2022; Franzluebbers, 2021; Ussiri & Lal, 2009), however to a lesser extent than drained lowland peatlands (Freeman et al., 2022).

Despite the likely continued increase in maize production for bioenergy in the United Kingdom, the existing research on GHG emissions from agricultural soils during the maize growing season, particularly on agricultural peat, is not comprehensive (Pohl et al., 2015). While there is an urgent need to move away from fossil fuels in the energy sector, it is important to improve our understanding of the C fluxes and potential environmental impacts associated with different components of the biomass supply chain. Given the predominance of growing maize for bioenergy, it is important to determine the impacts of growing maize for bioenergy on agricultural emissions and how this varies because of the environment in which it is grown (Lohila et al., 2003). The aim of this study was to determine the impact of soil type on the CO_2 sink or source strength of growing maize for bioenergy. This was achieved by carrying out the following objectives: (i) quantifying the CO_2 fluxes associated with growing maize for bioenergy at two commercial farms using an eddy covariance (EC) flux tower at each, one on mineral soil and the other on peat; and (ii) estimating the C sink or source strength of these systems by calculating net ecosystem productivity (NEP). It has been shown that GHG emissions are higher from crops grown on peat than on mineral soil (Evans et al., 2021; Oertel et al., 2016); thus, we hypothesise that the CO_2 balance will be more positive from the maize grown on peat than the maize grown on mineral soil.

2 | MATERIALS AND METHODS

2.1 | Study sites

The two sites used in this study are both commercial farms in eastern England. One is located in Yorkshire on a loamy calcareous brown earth from the Aberford series of Calcaric Endoleptic Cambisols (Cranfield University, 2018), (subsequently referred to as the mineral soil site [MS]) and the other is located 250 km south in East Anglia on drained lowland peat (subsequently referred to as the peat soil site [PS]). Both sites have a temperate oceanic climate characterised by mild winters and warm summers (Beck et al., 2018). Between 1992 and 2021, average annual temperature was higher at PS (10.7 ± 0.5°C, ranging from 9.5 to 11.7°C) than at MS (9.5 ± 1°C, ranging from 6 to 10.8°C; Met Office, 2019, 2023), whereas average annual precipitation was higher at MS (639 ± 142 mm, ranging from 289 to 916 mm) than at PS (561 ± 95 mm, ranging from 309 to 699 mm; Met Office, 2006, 2023). During the measurement period (2021 maize growing season), average daily temperature and total precipitation were 15.5°C and 230 mm at MS, and 15.6°C and 249 mm at PS, respectively (Figure 1); the similar air temperature and precipitation at the two study sites can be attributed to the north of England experiencing warmer and drier than average conditions through summer 2021, whereas the southeast was closer to average.

The field at MS (10.4 ha) has been under continuous arable rotation with conventional tillage since 1994 with a rotation of winter wheat, spring or winter barley, and oilseed rape and occasionally vining peas or potatoes. Prior to this, set aside and grass leys were included in the crop rotation. In September 2020, linseed was sown in the field, however, the crop failed due to frost conditions and so was terminated and planted with maize in June 2021. The PS is highly fertile and nutrient rich. From the 1600s onwards, lowland peatlands across the United Kingdom were widely drained for use in agricultural crop production (Rowell, 1986) but since the advent of electric pumps in the 20th century the process has become more efficient, leading to deeper drainage. The field at PS (41.7 ha) was drained during the 1940s and since then has been cultivated for agriculture with the water table controlled by electric pumps. During the measurement period the average daily water table depth was −139 cm, ranging from −160 cm to −110 cm. Soil properties of the maize fields are summarised in Table 1; notably, organic matter content, total C, total organic C and total N are higher at PS than at MS.

Detailed information on management practices at both sites during the study period are presented in Table 2. The planting density of maize was slightly higher at MS (110,000 seeds ha^{-1}) than at PS (95,000 seeds ha^{-1}), and nitrogen (N) fertilisation was similar at the two sites (76 kg N ha^{-1} at PS and 72.5 kg N ha^{-1} at MS). At MS, maize was planted on 02 June 2021 and harvested on 10 October 2021 (131 days) and at PS maize was planted on 27 April 2021 and harvested on 21 October 2021 (178 days). The farmer at MS opted for a high sowing density to maximise the potential for crop growth to compensate for the later planting date resulting from the failure of a previously sown autumn crop. Crop yield data for both sites were provided by the farmer; as quadrats were not used to measure yield, standard deviation of yield is therefore not reported.

2.2 | Measurement of CO_2 fluxes

Turbulent fluxes of CO_2 (μmol m^{-2} s^{-1}) and sensible and latent heat fluxes (H, LE; W m^{-2}) were measured with EC flux towers (Baldocchi, 2003; Moncrieff et al., 1997). At MS, CO_2 fluxes were measured using an LI-7200 RS enclosed infrared CO_2/H_2O gas analyzer (LI-COR Biosciences, n.d., USA); data were sampled at 10 Hz and combined with ancillary measurements by a CR1000X data logger (Campbell Scientific, n.d., USA) via a Smartflux 2 processing computer (LI-COR Biosciences, n.d., USA) and stored on a USB drive. At PS, CO_2 fluxes were measured with an LI7500A open path CO_2/H_2O gas analyzer (LI-COR Biosciences, n.d., USA); data were logged at 20 Hz using a CR3000 data logger (Campbell Scientific, n.d., USA). At both sites a Gill Windmaster three-dimensional sonic anemometer (Gill Instruments Ltd., n.d., UK) was used to measure atmospheric turbulence (u, v, w; m s^{-1}) and sonic temperature (*T*sonic;°C). Sensors were mounted on extendable masts, the height of which were increased over the maize growing season to ensure a minimum distance of 2 m between the EC sensors and crop canopy. At MS, the mean peak footprint distance was 40 m and had an average 90% contribution of 110 m (Figure S1; Kljun et al., 2015). At PS, the mean peak footprint distance was 35 m and an average 90% contribution of 97 m (Figure S2; Kljun et al., 2015). All measurements were taken during the 2021 maize growing season. The monitoring period at MS was 131 days (2 June 2021–10 October 2021) and at PS was 149 days (26 May 2021–21 October 2021); at PS, EC measurements are available from around 1 month after maize was planted due to instrument failure, and so this should be considered when interpreting results.

2.3 | Calculation of CO_2 fluxes

EddyPro® 7 V7.0.6 (LI-COR Biosciences, 2019) was used to compute 30-minute fluxes of H, LE and net ecosystem exchange (NEE) from raw EC data. NEE was calculated as the CO_2 flux plus the CO_2 storage term; as both towers had a height of below 10 m, the CO_2 storage term is likely to be negligible in comparison to the estimation of NEE (Nicolini et al., 2018). As Gill Windmaster sonic anemometers were used at both sites, the software applied the 'w-boost' bug correction (LI-COR Biosciences, 2024)

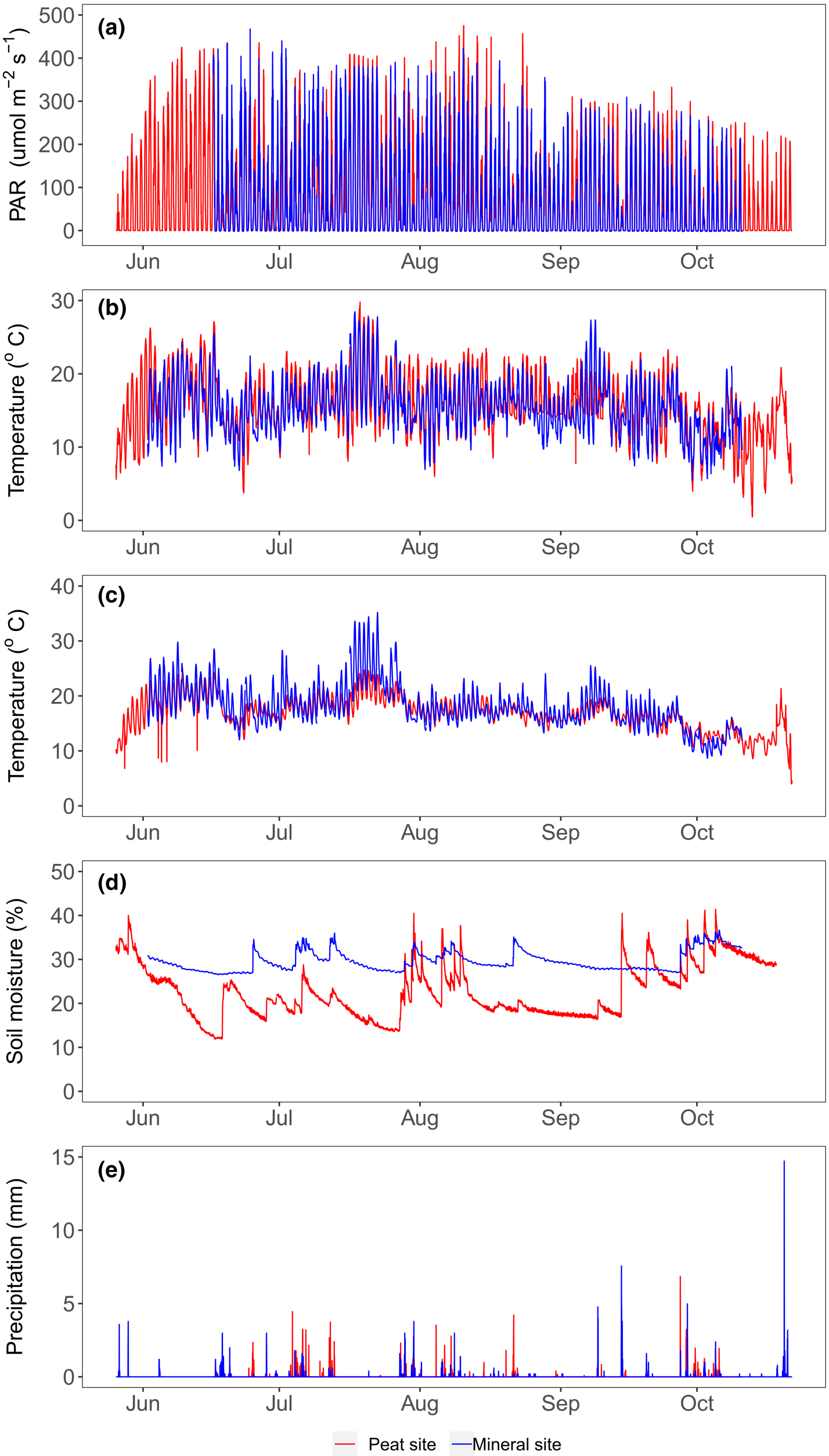

FIGURE 1 (a) photosynthetically active radiation (PAR), (b) air temperature, (c) soil temperature (5 cm), (d) soil moisture (5 cm) and (e) precipitation measured over the maize growing seasons at the study sites.

and applied a double coordinate rotation to correct for any tilt or misalignment of the anemometer (Wilczak et al., 2001). Cross-correlation was used to compensate for any time lags between the sonic anemometer and atmospheric scalars (Moncrieff et al., 1997, 2004), and fluxes were corrected for air density fluctuations using the Webb-Pearman-Leuning correction (Webb et al., 1980). The software removed statistical outliers and implausible values in the raw timeseries according to Mauder et al. (2013). Fluxes were also corrected for high and low frequency co-spectral attenuation according to Moncrieff et al. (1997, 2004). Random uncertainty estimation due to sampling error was estimated according to Finkelstein and Sims (2001).

Quality control was applied using The R Language and Environment for Statistical Computing V4.1.3 (R Core Team, 2022) to ensure only high-quality flux data were used, following the workflow by Morrison et al. (2019). Examples of when data were removed include: statistical outliers (Papale et al., 2006); data obtained when the signal strength of the LI-COR was higher than the baseline value (Ruppert et al., 2006); data identified as non-representative by the footprint model (i.e., when >20% of the data was recorded outside of the site boundaries; Kljun et al., 2004); data that was beyond realistic thresholds (i.e., when $H < -200$ or $> 450\,W\,m^{-2}$, when $LE < -50$ or $> 600\,W\,m^{-2}$, or when $NEE < -60$ or $> 30\,g\,m^{-2}$) and when friction velocity (u*; $m\ s^{-1}$) < 0.06 at MS and < 0.08 at PS. The REddyProc package (Reichstein et al., 2016) was used to gap fill and partition fluxes of NEE according to Reichstein et al. (2005). Periods of missing data (excluding the first month of the growing season at PS) were gap-filled using marginal distribution sampling and uncertainty was estimated as the standard deviation of the observations used to fill gaps (Reichstein et al., 2005, 2016). Gap-filled NEE accounted for 10% and 36% of the overall data set at MS and PS, respectively.

The micrometeorological sign convention is used for NEE, where a positive value indicates the ecosystem is losing C and a negative value indicates the ecosystem is accumulating C (Baldocchi, 2003). NEE of CO_2 is the difference between gross primary productivity (GPP) and total ecosystem respiration (TER) as shown in Equation (1) (Smith et al., 2010). Following gap filling, NEE was partitioned into GPP and TER (Reichstein et al., 2016).

$$NEE = TER - GPP \tag{1}$$

2.4 | Ancillary measurements

Additional micrometeorological measurements were recorded at both sites. Energy fluxes, including net radiation (Rnet), short-wave incoming radiation (SWin), short-wave outgoing radiation (SWout), long-wave incoming radiation (LWin) and long-wave outgoing radiation (LWout; $W\ m^{-2}$)

TABLE 1 Soil information for each site (mean ± SD, $N = 9$, for topsoil 0–30 cm).

	Mineral site (MS)	Peat site (PS)
Soil type[a]	Calcaric Endoleptic Cambisol	Histosol
Soil texture[b]	Clayey loam	Loamy peat over sand
Water table depth (m)	—	<1
Organic matter (%)	6.7 ± 0.6	59.2 ± 2.2
pH ($CaCl_2$)	6.9 ± 0.2	7.3 ± 0.1
Bulk density ($g\,cm^{-3}$)	1.3 ± 0.1	0.5 ± 0.1
Total carbon ($g\,kg^{-1}$)	39.5 ± 9	278.6 ± 37.6
Total organic carbon ($g\,kg^{-1}$)	22.9 ± 4.9	229.7 ± 9.1
Total nitrogen ($g\,kg^{-1}$)	2.3 ± 0.6	16.4 ± 2.2
C:N ratio	10:1	14:1
Plant available nitrogen ($g\,kg^{-1}$)	0.013 ± 0	0.085 ± 0.4

[a]Data obtained from World Reference Base for Soil Resources (IUSS, 2022).
[b]Data obtained from UK Soil Observatory (UK Research and Innovation, 2021).

TABLE 2 Management information for each site over the maize growing season.

Mineral site (MS)		Peat site (PS)	
Date	**Management**	**Date**	**Management**
Spring 2021	Fertiliser (N26 + 5SO3): 50 kg N ha^{-1}, 9.6 kg S ha^{-1}	27 April 2021	Planted maize (Pioneer variety) using precision drill: 95,000 seeds ha^{-1}
16 April 2021	Herbicide (Amega Duo): 2.1 L ha^{-1} (with 0.5 L ha^{-1} Phase II and 0.5 L ha^{-1} Spryte Aqua)	30 April 2021	Fertiliser (CHAFER N30.3 + 10.8SO3): 76 kg N ha^{-1}, 10.8 kg S ha^{-1}
06 June 2021	Herbicide (Pendimethalin): 3.3 L ha^{-1} Herbicide (Glyphosate): 2 L ha^{-1}	2 June 2021	Pesticide (Maya): 1 L ha^{-1}
18 May 2021 19 May 2021	Non-inversion tillage: 20–25 cm	10 June 2021 14 June 2021 29 June 2021	Fertilisers (Headland Copper 435, Headland Boron 150, Headland Zinc 150): 64 g copper ha^{-1}, 22.5 g boron ha^{-1}, 75 g zinc ha^{-1}
02 June 2021	Planted maize (Fieldstar variety) using precision drill: 110,000 seeds ha^{-1} Fertiliser (Di-ammonium phosphate): 22.5 kg N ha^{-1} and 57.5 kg P ha^{-1}	21 October 2021	Harvest: 11.3 t DM ha^{-1}
10 October 2021	Harvest: 12.3 t DM ha^{-1}		

were measured with an SN-500 net radiometer (Apogee Instruments, n.d., USA). Air temperature (Ta;°C) and relative humidity (RH; %) were measured with an HMP155 temperature and humidity probe (Vaisala BV, n.d., Finland). At MS, soil temperature (Tsoil;°C) and soil moisture (%) were measured using TEROS 11 temperature and moisture probes (METER Group Inc, n.d.) at a depth of 5 cm, soil heat flux (G; W m^{-2}) was measured using HFP01-SC heat flux plates (Hukesflux, 2023, Netherlands) at a depth of 5 cm, and precipitation (mm) was measured at a nearby COSMOS-UK weather station with an OTT Pluvio^2 rain gauge (OTT HydroMet, 2019, USA; Cooper et al., 2021). At PS, G was measured using HFP01-L heat flux plates (Hukesflux, Netherlands in Campbell Scientific, n.d., USA), Ta and Tsoil were measured using TDT soil water content sensors (Acclima, n.d., USA) at a depth of 5, 10, 15 and 25 cm, while water level (cm) was measured with a CS451 pressure transducer (Campbell Scientific, n.d., USA), and precipitation was measured with an SBS500 tipping bucket rain gauge (Environmental Measurements Ltd.).

2.5 | Energy balance

Energy balance closure (EBC) is a method used to assess the quality of EC data at a study site (Aubinet et al., 2001; Wilson et al., 2002). EBC assumes that the sum of fluxes measured by EC (LE + H) are equal to the available energy measured independently using other instruments (net radiation (Rnet)–G). The measured turbulent fluxes accounted for 76% and 72% of the available energy at MS and PS, respectively (Figure 2). The R^2 values (i.e., amount of variance) are within the typical range of reported EC measurements (0.7–0.9) (Foken, 2008; Wagle et al., 2018; Wilson et al., 2002).

2.6 | NEP and crop carbon use efficiency

Net ecosystem productivity is a measure of the C sink or source strength of an agroecosystem, and accounts for lateral fluxes of C, that is, C exported from the field via harvested biomass and C imported via seed or organic fertiliser (Equation 2—adapted from Evans et al., 2021), as well as NEE. The C content of harvested biomass (C_H) was calculated by analysing the C content of maize samples taken from the field on the day of harvest, and scaling this to the reported yield for the field. As this study assesses NEP at the field scale, it is assumed that all C within the exported biomass was converted back to atmospheric CO_2 during AD (Eichelmann et al., 2016;

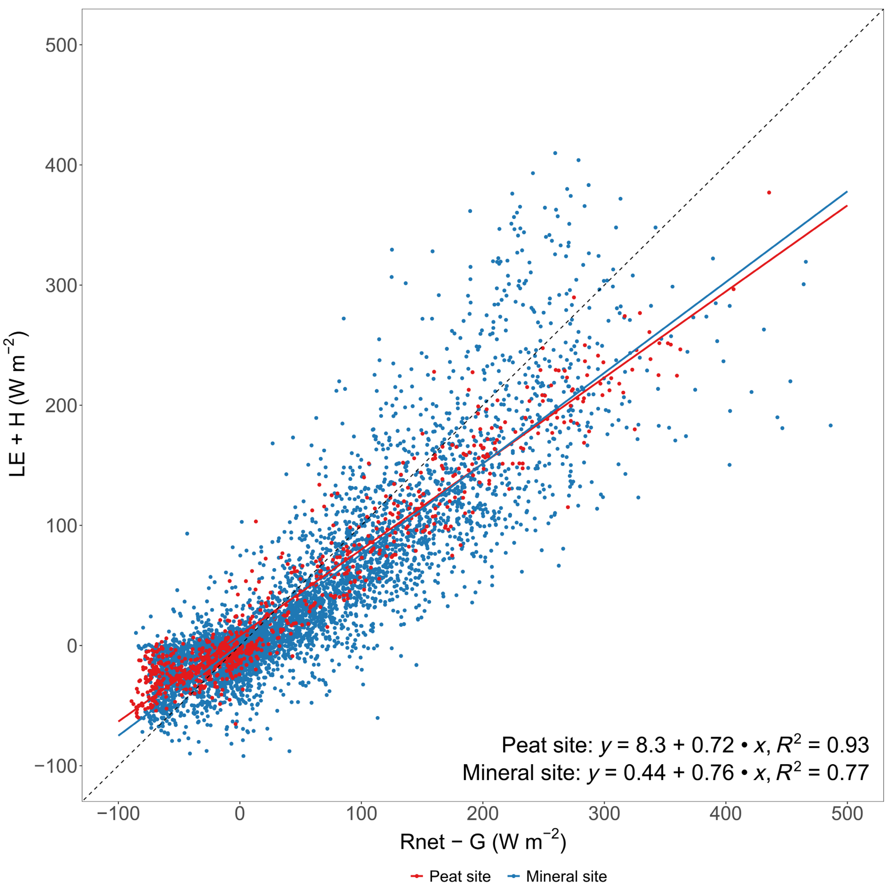

FIGURE 2 Energy balance at the study sites over the maize growing season where H is sensible heat flux, LE is latent heat flux, Rnet is net radiation and G is soil heat flux. Note that the EBC data for PS is from 04 August 2021 to 21 October 2021 due to missing data prior to this date.

Morrison et al., 2019). We note that this assumption requires further analysis; however, as the AD process involves storage and transformations of C across gaseous, liquid and solid phases, but a full life cycle analysis is beyond the scope of the present study. Carbon import (C_I) was in the form of seed only, as neither site was fertilised with organic amendments prior to maize planting or during the growing season. As in Evans et al. (2021), we use the micrometeorological sign convention for NEP where a positive value indicates the ecosystem is losing C and a negative value indicates the ecosystem is accumulating C.

$$NEP = NEE + C_H - C_I \quad (2)$$

The C use efficiency of harvested material (CUE_h) is a measure of how efficiently atmospheric C is converted into new plant material (Chen et al., 2018); CUE_h is calculated as C_H over GPP (Kim et al., 2022) as in Equation (3).

$$CUE_h = C_H / GPP \quad (3)$$

3 | RESULTS

3.1 | Carbon fluxes

Over the maize growing season, both sites exhibited in situ net CO_2 uptake as NEE, however the net CO_2 uptake at PS (-208 ± 49 g CO_2-C m^{-2}) was less than half of that at MS (-429 ± 57 g CO_2-C m^{-2}) (Figures 3 and 4; Table 3). Maximum CO_2 uptake was greatest at MS during August and at PS during September (Figure 4). Both sites were similarly productive, with GPP 1107 ± 113 g C m^{-2} at MS and 1407 ± 129 g C m^{-2} at PS, however TER was nearly twice as high at PS (1198 ± 100 g C m^{-2}) than at MS (678 ± 62 g C m^{-2}; Table 3). TER was notably higher during the night at PS than MS (Figure 4).

3.2 | Net ecosystem productivity

Cumulative NEP was positive at both sites, showing that C was being lost from both sites under maize cultivation,

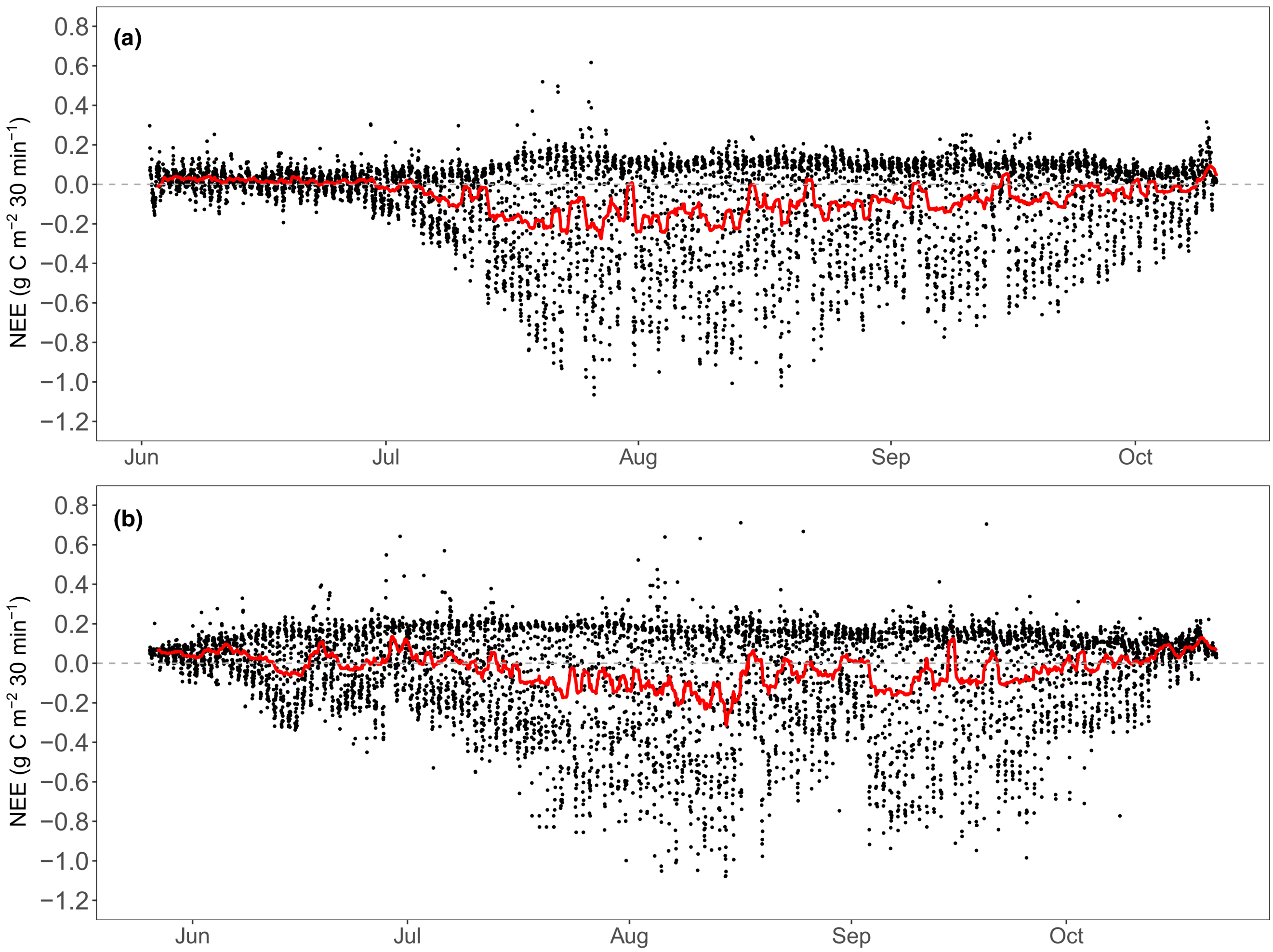

FIGURE 3 Thirty-minute fluxes of NEE at (a) the mineral site and (b) peat site over the maize growing seasons. The red line indicates the rolling daily mean.

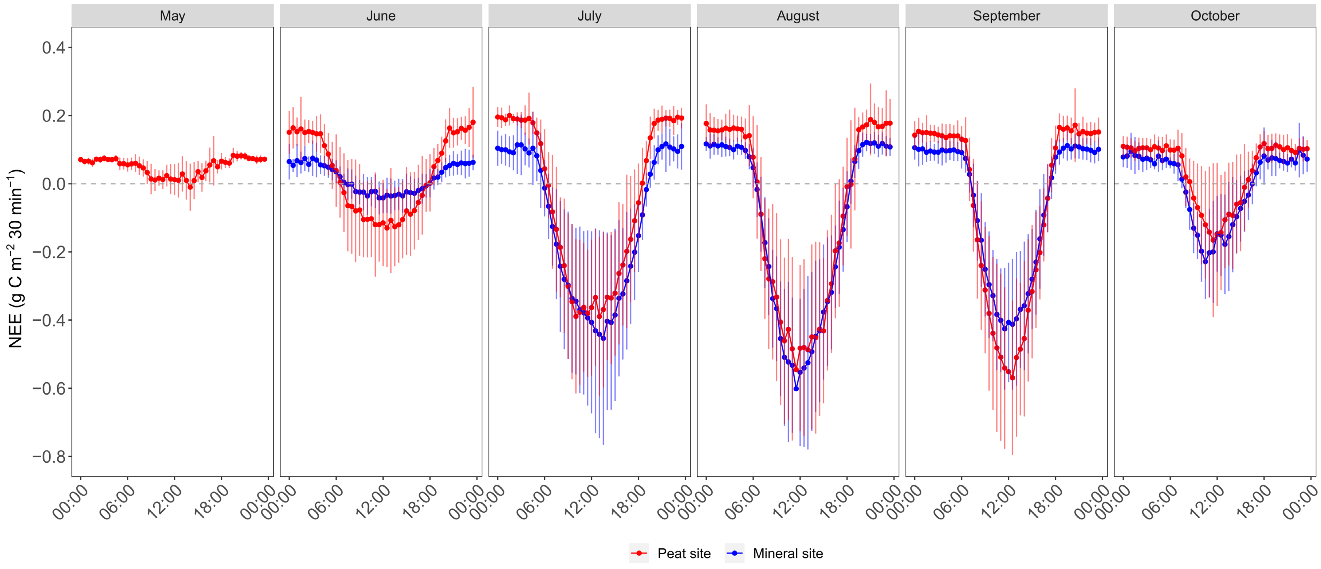

FIGURE 4 Mean diurnal NEE at the study sites over the maize growing seasons grouped by month. Error bars represent standard error of the mean.

TABLE 3 Carbon budget at the study sites ± root sum squared (aside from C_H where ± represents SD). The micrometeorological sign convention is used for NEE and NEP where positive values indicate C loss and negative values indicate C gain.

	Mineral site (MS)	Peat site (PS)
NEP (g C m^{-2})	136 ± 122	290 ± 99
NEP (t C ha^{-1})	1.4 ± 1.2	2.9 ± 1
NEE (g CO_2-C m^{-2})	−429 ± 57	−208 ± 49
GPP (g C m^{-2})	1107 ± 113	1407 ± 129
TER (g C m^{-2})	678 ± 62	1198 ± 100
Yield (t ha^{-1})	12.3	11.3
Maize C content (%)	46	44
CUE_h (g C g C^{-1})	0.51	0.35
C_H (g C m^{-2})	567 ± 65	499 ± 50
C_I (g C m^{-2})	2 ± 0	1 ± 0

although C losses from PS (290 ± 99 g C m^{-2} over growing season) were over twice those from MS (136 ± 122 g C m^{-2} over growing season; Table 3; Figure 5). The C_H at MS (567 ± 65 g C m^{-2}) was higher than that at PS (499 ± 50 g C m^{-2}), with yield also being slightly higher at MS, and C_I was minimal at both sites (2 ± 0 g C m^{-2} and MS and 1 ± 0 g C m^{-2} at PS), in the form of seed only (Table 3).

4 | DISCUSSION

4.1 | Carbon fluxes

While GPP was higher at PS, more CO_2 was lost to the atmosphere via soil respiration, and so this supports our hypothesis that the CO_2 balance will be more positive from the maize grown on peat than mineral soil. Given that GPP was similar at both sites, the difference in NEE between sites can be attributed to the fact that TER was nearly twice as high at PS than at MS. The large C store in peat is exposed and rapidly respired following peat drainage and the lowering of the water table due to increased oxygen diffusion, ultimately increasing decomposition of the peat and loss of CO_2 to the atmosphere (Evans et al., 2021; Lohila et al., 2003). Our results corroborate those of Purola and Lehtonen (2022) and Freeman et al. (2022) who found considerably higher rates of CO_2 emission from peatlands used for crop production compared to mineral soils.

This study is among the first to quantify growing season C fluxes of maize grown for bioenergy in the United Kingdom, particularly from bioenergy maize grown on peat. The growing season NEE measured at both study sites sit within the broad range reported throughout the literature (−880 g C m^{-2} from maize grown in the USA; Hollinger et al., 2005 to 64 g C m^{-2} from maize grown in Canada; Eichelmann et al., 2016; Table S1). When comparing the growing season NEE of MS in our study with that of other sites in temperate climates with mineral soil, our results are comparable and well within the reported range (Table S1). While there are no measurements from maize grown on peat to be compared with those from PS in our study, the growing season NEE from PS is less negative, that is, more of the GPP taken up by the crop was respired as TER, than most sites in temperate climates with mineral soil (Table S1).

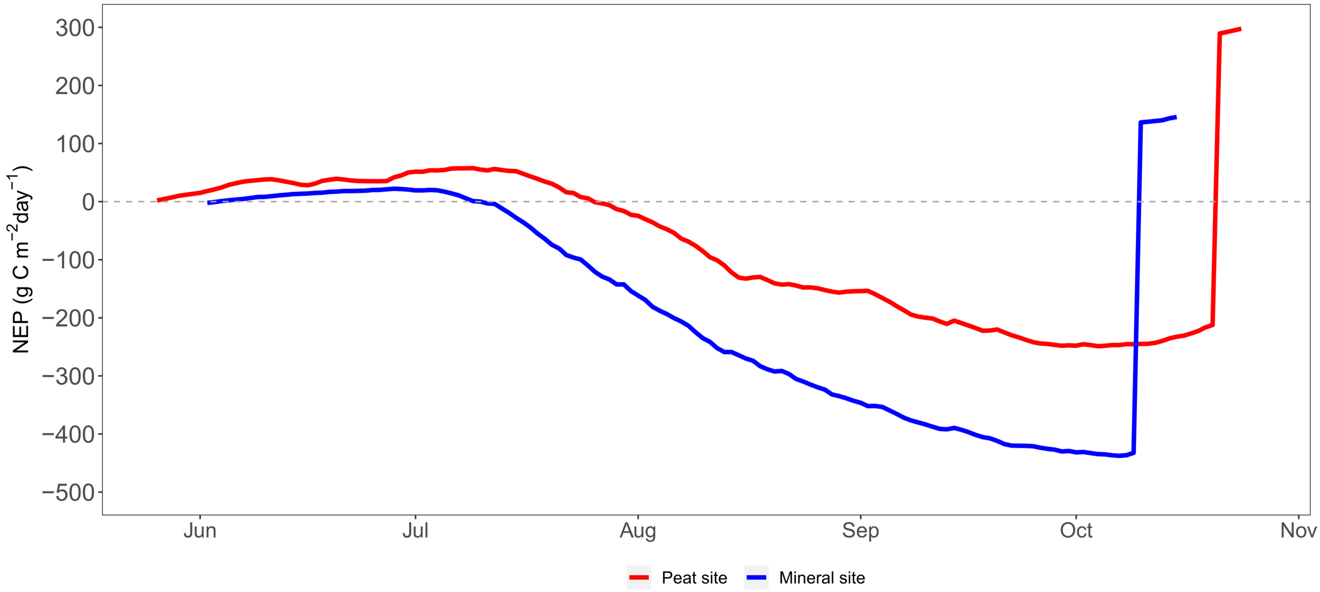

FIGURE 5 Cumulative daily NEP at the study sites over the maize growing season.

4.2 | Net ecosystem productivity

As C_H was greater than NEE, and C_I was minimal at both sites, growing season NEP was positive at both sites, although C losses from PS were over twice those from MS. The negligible contribution of C_I to NEP is observed throughout much of the literature (Table S1). The higher C_H at MS is attributed to the higher yield, maize C content and CUE_h at this site compared to PS. The yield at both sites fell within long-term UK averages for whole-crop maize of ~12 t DM ha^{-1} (Macmillan, 2023). The higher CUE_h of the maize grown at MS compared to PS indicates that atmospheric C was converted into new plant biomass more efficiently (Chen et al., 2018; Kim et al., 2022), meaning that less of the CO_2 taken up by the maize during photosynthesis was lost via respiration. Despite PS having lower C_H than MS, it also had a lower NEE, meaning that PS had a greater loss of C overall, that is, higher NEP.

The NEP of maize during the growing season reported across the literature is highly variable, although most studies report a positive NEP and thus an overall loss of C from the field (Table S1). As well as NEE, the magnitude of C_H is highly variable, ranging from 263 g C m^{-2} for maize grown in China (Liu et al., 2019) to 1083 g C m^{-2} for maize grown in New Zealand (Wall et al., 2020), and C_I is often zero or negligible in comparison (Table S1). Sites with a large C_I can still lose C overall, however, as C_H tends to be larger than NEE, as found by Loubet et al. (2011), Tallec et al. (2013) and Wall et al. (2020). Considering studies from temperate climates only, NEP is generally positive when the whole crop is harvested (i.e., C is lost), whereas NEP is more likely to be negative when only the grain is harvested (i.e., C is accumulated) (Table S1), as the C in leaves and stalks is left on the field as crop residue. The NEP of the maize grown at MS in our study (136 g C m^{-2}) is within the broad range reported from sites with mineral soil in temperate climate zones harvesting the whole crop (11 g C m^{-2}; Alberti et al., 2010) to 851 g C m^{-2} (Wall et al., 2020; Table S1), all of which behave as C sources, although to varying magnitudes. For a field to behave as a C sink or to be C neutral, the amount of C remaining in the field must be greater than, or equal to, all other losses of C via exported biomass or TER (Cates & Jackson, 2019). In bioenergy cropping systems, all of the biomass produced is removed for AD, and so very little crop residue is left on the soil surface after harvest. High rates of residue removal, combined with oxidation of the existing SOM (especially in peat soils) can therefore deplete the SOC pool.

4.3 | Implications for policy and research

Our results show that growing maize for bioenergy in the United Kingdom, especially on peat, is questionable as a climate change mitigation measure due to the ongoing loss of SOC under maize cultivation. Both agri-ecosystems we considered were net C sources once harvested biomass was considered, with emission from peat being two times greater than those of the mineral soil site. There is potential for these losses to exceed the avoided CO_2 emissions from subsequent bioenergy production (Brack & King, 2020). As stated in the UK Government's Biomass Strategy (DESNZ, 2023), the process of growing biomass for AD should not result in an overall loss of C from an agroecosystem and must reduce CO_2 emissions by at least 60% relative to fossil fuels once the full production life cycle is considered. Our data suggest that this may not be possible when growing maize for AD in the United Kingdom. There are multiple pathways by which the management practices used to grow maize for AD can cause SOC loss, such as ploughing (Bhattacharyya et al., 2022), residue removal (Naylor et al., 2022; Raffa et al., 2015) and the drainage of peat soils (Evans et al., 2016). Previous research has shown that growing maize is strongly associated with C loss from soil, often to a greater magnitude than other crops such as winter wheat (Ceschia et al., 2010; Poyda et al., 2019; Wall et al., 2020). Winter wheat has a longer growing season than maize, however, which is likely to be a primary factor controlling the differences in C uptake between the two crops. It is therefore important to consider entire crop rotations and the use of cover crops during fallow periods. It has also been argued that growing maize on productive agricultural land can contribute to food insecurity by reducing the availability of land for growing food crops (Kiesel et al., 2016; Qin et al., 2015) and could also lead to indirect CO_2 emissions because of the displacement of food crop production to other areas. If maize is to be grown for use as a bioenergy crop, our results show that it should be grown on mineral soils with a low C content. In addition, good practice would consider growing maize as part of a crop rotation, and with an input of organic materials via organic fertilisers, such as the digestate from the AD plant. Returning digestate from AD will likely be particularly important, as it is C-rich and has a considerable potential to offset C or GHG emissions from vehicles and the AD process itself (Moller, 2015), as well as contributing to a circular economy by reducing waste and enhancing resource efficiency (DESNZ, 2023). This C input would also offset some of the C removed as harvested biomass and contribute to enhancing the SOC stock (Sun et al., 2023; Yan et al., 2023). Alternatively, growing perennial, rather than annual, bioenergy crops would provide a greater input of C, as these crops often have a greater proportion of their residues left on the soil surface (Booth & Wentworth, 2023; Ferchaud et al., 2015). To avoid SOC loss and compromising food production, bioenergy crops should be grown in addition to, rather than instead of, existing food crops, on land that has a low existing SOC content, with a particular avoidance of peat. If peatlands are to be used for agricultural production they should be managed using methods which aim to minimise C loss, for example, by growing food or biomass crops that are tolerant of high water levels (Evans et al., 2021; Freeman et al., 2022).

Further research should consider the impacts of increasing C imports via organic amendments on the NEP of bioenergy maize, and the return of AD digestate on soil health and SOC, to evaluate whether substantially increasing C imports can equate to an overall reduction in SOC loss. As this study only presents data from one growing season, continuing to measure C fluxes from maize grown in the United Kingdom would provide a clearer indication of its average NEP and how this is influenced by annual variability in the climate, and over the full crop rotations that characterise agricultural practices in the United Kingdom and elsewhere. In addition, it would be beneficial to collect data from sites with varying levels of soil C. While growing maize on mineral soils with a low C content may be feasible in the future, the influence of SOM content on NEP is unknown. It is likely that crop N fertilisation will also have a strong impact on the GHG balance because of its impact on N_2O emissions. In addition, the low C:N ratio of the soil at both sites may also result in these sites being large sources of N_2O to the atmosphere (Klemedtsson et al., 2005). Thus, future research should measure N_2O emissions in addition to CO_2 fluxes to determine a complete GHG budget associated with growing maize for AD. Finally, it should be considered that our results represent NEP at the field scale during the maize growing season only, and, while beyond the scope of this study, a life cycle analysis considering the fate of the crop beyond the farm gate, and accounting for CO_2 emissions associated with the AD process and vehicles, is necessary to fully understand the CO_2 emissions associated with maize production for bioenergy.

AUTHOR CONTRIBUTIONS

I. L. Lloyd: Conceptualization; data curation; formal analysis; funding acquisition; investigation; visualization; writing – original draft; writing – review and editing. **R. Morrison:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; resources; software; supervision; writing – review and editing. **R. P. Grayson:** Conceptualization; data curation; investigation; resources; supervision; writing – review and editing. **A. M. J. Cumming:** Formal analysis; investigation; writing – review and editing. **B. D'Acunha:** Formal analysis; investigation; writing – review and editing. **M. V. Galdos:** Conceptualization; funding acquisition; supervision; writing – review and editing. **C. D. Evans:** Formal analysis; investigation; writing – review and editing. **P. J. Chapman:** Conceptualization; funding acquisition; project administration; supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are available at https://doi.org/10.5285/9b6c2393-b751-46b4-b139-71ca09321139.

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SUPPORTING INFORMATION

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