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Substantial carbon loss respired from a corn–soybean agroecosystem highlights the importance of careful management as we adapt to changing climate

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Substantial carbon loss respired from a corn–soybean agroecosystem highlights the importance of careful management as we adapt to changing climate





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Abstract

Understanding agroecosystem carbon (C) cycle response to climate change and management is vital for maintaining their long-term C storage. We demonstrate this importance through an in-depth examination of a ten-year eddy covariance dataset from a corn–corn–soybean crop rotation grown in the Midwest United States. Ten-year average annual net ecosystem exchange (NEE) showed a net C sink of $-0.39 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. However, NEE in 2014 and 2015 from the corn ecosystem was 3.58 and $2.56 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$, respectively. Most C loss occurred during the growing season, when photosynthesis should dominate and C fluxes should reflect a net ecosystem gain. Partitioning NEE into gross primary productivity (GPP) and ecosystem respiration (ER) showed this C 'burp' was driven by higher ER, with a 51% (2014) and 57% (2015) increase from the ten-year average ($15.84 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$). GPP was also higher than average ($16.24 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$) by 25% (2014) and 37% (2015), but this was not enough to offset the C emitted from ER. This increased ER was likely driven by enhanced soil microbial respiration associated with ideal growing season climate, substrate availability, nutrient additions, and a potential legacy effect from drought.

1. Introduction

As climate variability increases and extreme weather events become more frequent, it is critical that we understand how agroecosystems respond, and what management approaches affect agroecosystem resilience. *Zea mays* L. (corn) is one of the most important food and fuel crops in the United States (US), with annual production accounting for $\sim 33\%$ of

global yield, and the crop production value worth US\$ 61 billion to the economy in 2020 (USDA NASS 2021). Yet corn is particularly susceptible to drought, as demonstrated in the Midwest US during 2012, where drought reduced corn yield by 13% on average (Lobell *et al* 2014). In addition to yield losses, climate variability and land management practices can drive additional loss of soil organic carbon (SOC) from cropping systems—an important determinant

of soil health and overall crop ecological sustainability (Sanderman *et al* 2017). A key driver of SOC loss from agroecosystems is associated with tillage practices (Bernacchi *et al* 2005, Blanco-Canqui and Ruis 2018, Ogle *et al* 2019), yet carbon (C) turnover in soil is also enhanced by higher soil temperature and optimal moisture conditions that promote activity from soil microbial communities (Castellano *et al* 2011, Black *et al* 2016, von Haden *et al* 2019). While the former can be mitigated with no-till practices, managing the soil microclimate, and potential shifts in microbial communities as the climate changes is a more difficult task (Bond-Lamberty *et al* 2018), and the development of potential microbiome-specific mitigation strategies is still ongoing (Jansson and Hofmockel 2020).

Capturing the inter-annual variability in the response of agroecosystems, including ecosystem C inputs and outputs, to different climate and land management approaches requires a focus on long-term data collection (i.e. five or more years), ideally including above- and below-ground measurements over replicated field trials across multiple years of measurement. Such measurements are time consuming and can be cost prohibitive. In addition, long-term research visions can often be precluded by short-term funding cycles. Fortunately, research groups are prevailing in spite of these challenges, with long-term consecutive year ecosystem monitoring datasets becoming increasingly available from eddy covariance flux tower networks (Beringer *et al* 2016, Novick *et al* 2018, Pastorello *et al* 2020), which measure the net exchange of carbon dioxide (CO₂), methane (CH₄), water, and energy between plants and the atmosphere over time (Baldocchi *et al* 2001). Each year these networks grow and contribute more data to freely available data archives. These data are vital for capturing changes in ecosystem C exchange due to anomalous climate events, yet agroecosystems remain underrepresented in availability of long-term data (Baldocchi *et al* 2018).

Using a long-term (ten-year) eddy covariance dataset (Ameriflux site: US-UiC, Bernacchi *et al* 2022), we demonstrate the importance of long-term monitoring of agroecosystems for capturing inter-annual variability in net C fluxes from a corn–corn–soybean crop rotation. Beginning mid-2008, this dataset encompasses the 2012 drought that impacted the Midwest region (Lobell *et al* 2014, Joo *et al* 2016), as well as average and above average rainfall years up to the end of 2018 (table 1). Our objective in this manuscript was to scrutinize two years (2014 and 2015) of anomalously high respiration fluxes from the corn agroecosystem relative to the whole ten-year dataset. We discuss the likely mechanisms driving these high respiration fluxes and the implications for agroecosystem management in the face of increased climate variability (Zhou *et al* 2021).

2. Eddy covariance data processing method

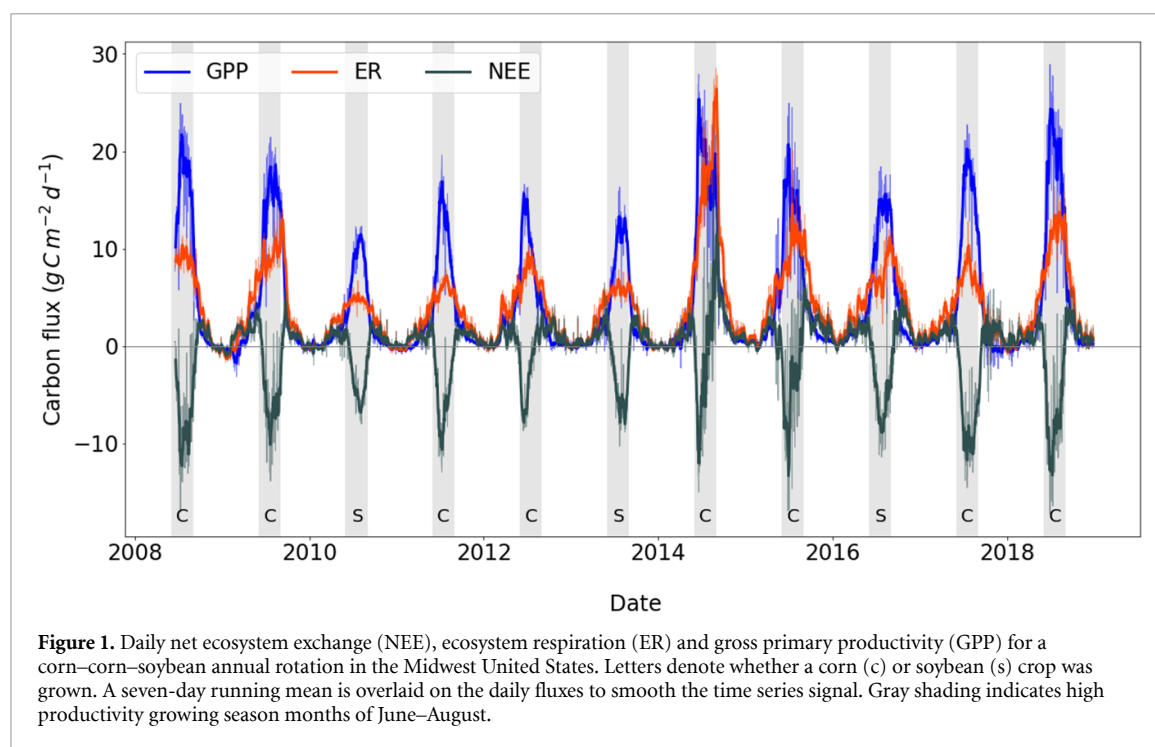
Eddy covariance data require rigorous processing to obtain complete and reliable time series of ecosystem fluxes. The data used in this letter were processed as per Moore *et al* (2020), where detailed information can be found. In brief, the high resolution flux tower measurements (10 Hz) were processed to 30 min averages using EddyPro v 3.2.0 (LICOR Biosciences, Lincoln, NE, USA). Next, the data underwent quality assurance and quality checking (QA/QC) to remove erroneous data spikes before the missing data were gap filled to provide complete time series of gas flux and meteorological variables (table S1 available online at stacks.iop.org/ERL/17/054029/mmedia). Carbon flux data (net ecosystem exchange, NEE) occurring below a turbulence threshold (u^*) were removed (table S1 and figure S1), then the NEE data were gap filled and partitioned into gross primary productivity (GPP) and ecosystem respiration (ER) using a nocturnal temperature response function that describes changes to ER (Lloyd and Taylor 1994). Once ER was calculated from NEE, the difference between ER and NEE provided an estimate of GPP (Siebers *et al* 2021). Partitioning NEE in this way enables a more detailed investigation of the climatic, physiological and ecological processes that govern photosynthesis (i.e. GPP) and respiration (plant and microbial) at the ecosystem scale over time. All post-processing of 30 min flux and meteorological data was performed using PyFluxPro (Isaac *et al* 2017).

3. Evidence of substantial ecosystem C loss during two growing seasons

There was a substantial release of C during the growing season of 2014 and 2015, causing this ecosystem to switch to an annual C source (table 1 and figure 1). Across the ten-year measurement period, average annual NEE showed this corn–corn–soybean ecosystem has a C sink strength of $-0.39 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ (table 1). In contrast, annual NEE was $3.58 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ in 2014 and $2.56 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ in 2015, indicating substantial C loss from the ecosystem. Partitioning of NEE into GPP and ER revealed this increased C loss was driven by markedly higher ER in 2014 ($23.95 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$) and 2015 ($24.84 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$), representing a 51% and 57% respective increase from the ten-year average ($15.84 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$, table 1). GPP was also higher than its ten-year average of $16.24 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ by 25% in 2014 and 37% in 2015, and this increased productivity was supported by high annual yields from the field (table 2). Despite the increase in plant productivity, it was not enough to offset the C emitted

Table 1. Annual totals of net ecosystem exchange (NEE) including random and model uncertainty, ecosystem respiration (ER) and gross primary productivity (GPP) provided in $\text{Mg C ha}^{-1} \text{ yr}^{-1}$ for a corn (C) and soybean (S) crop rotation grown at the University of Illinois Energy Farm in Urbana, IL, USA. Annual and growing season (G_S , June–August) total precipitation (precip, mm) and mean air temperature (T_a , $^{\circ}\text{C}$) are also provided. Long-term carbon (C) flux averages (Avg) and G_S averages are calculated using the ten-year dataset, while annual precip and T_a averages are given using long-term climate records obtained from the Illinois Water Survey (Illinois State Water Survey 2020). Negative NEE fluxes denote C uptake while positive NEE fluxes represent C lost from the agroecosystem. The two years of particular interest (2014/2015) are highlighted in gray.

Year/crop	NEE	ER	GPP	Precip	P_{G_S}	T_a	$T_{a_{G_S}}$
2008-C	N/A	N/A	N/A	1335	149	10.3	22.8
2009-C	-2.10 (0.48)	13.39	15.49	1252	342	11.4	22.8
2010-S	-0.09 (0.13)	10.88	10.97	888	324	13.0	25.7
2011-C	-1.34 (0.10)	11.85	13.20	1074	159	13.0	25.7
2012-C	0.51 (0.09)	12.88	12.37	902	191	13.8	25.5
2013-S	0.42 (0.16)	11.31	10.88	956	262	10.4	21.9
2014-C	3.58 (1.69)	23.95	20.37	1167	430	9.7	21.7
2015-C	2.56 (0.16)	24.84	22.29	1305	309	11.3	22.0
2016-S	-1.74 (0.45)	18.04	19.78	1039	389	12.4	23.9
2017-C	-3.19 (0.31)	13.45	16.64	910	156	12.3	22.7
2018-C	-2.55 (0.66)	17.84	20.39	1245	378	11.4	23.1
Avg	-0.39 (0.42)	15.84	16.24	1064	281	11.2	23.5



from ER (table 1). Interestingly, the majority of this C loss occurred during the growing season, when photosynthesis should dominate and C fluxes should reflect a net gain by the ecosystem (figure 1).

Several data processing tools now exist that facilitate streamlined flux data processing (Isaac *et al* 2017, Wutzler *et al* 2018, Pastorello *et al* 2020). However, these tools still require a fundamental understanding from the user of how the climate, biota, and parent material may drive fluxes at their site to make informed decisions on data inclusion/exclusion—the ‘*know thy site*’ philosophy (van Gorsel *et al* 2018). Using this philosophy we opted to allow more data to pass QA/QC checks, providing these data followed diurnal patterns and did not appear as clear spikes

in the dataset (Moore *et al* 2020, 2021). While this approach is perhaps subject to some user bias, it also avoids removing data that fall outside the perceived ‘norm’ for ecosystem processes, which has particular relevance for detecting ecosystem responses to outlier climate or management conditions.

Our first hypothesis on seeing the 2014/2015 ER spikes was to check the data for signs of instrument malfunction, which may have been missed during the QA/QC checks. However, careful inspection of the data revealed no evidence for poorly behaving instrumentation, with a co-spectral analysis showing the frequency distribution of eddies (Kaimal and Finnigan 1994) measured by the tower in 2014–2015 decaying at the same rate as those in 2017–2018

Table 2. Agronomic management, yearly harvest information and meteorological information for a corn–corn–soybean field located at the University of Illinois Energy Farm in the Midwest United States. A moldboard plow was used to prepare the field for tower installation in 2008, then a sunflower cultivator was used for pre-planting tillage and a chisel plow was used for post-harvest tillage. The ecosystem harvest index (EHI) was calculated as per Hollinger et al (2005).

Year	Crop and planting date	Tillage dates	Yield (Mg ha ⁻¹) and harvest date	Ecosystem harvest index (EHI)	Fertilizer rate and date				Herbicide rate (1 ha ⁻¹) and date
					N 28% liquid (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)	Lime (Mg ha ⁻¹)	
2008	Corn 6 May	28 April 6 May 29 October	15.19 28 October	N/A	168, 6 May	—	—	—	Lumax 0.7, 7 May Roundup 0.3, 2 July
2009	Corn 12 May	12 May 12 November	9.60 3 November	0.24	202, 12 May	—	—	—	Lumax 1.1, 12–13 May
2010	Soybean 25 May	25 May	3.50 12 October	0.10	N/A	—	—	—	Prowl 0.7, 24 May Glycophosphate, 0.4, 28 June
2011	Corn 12 May	12 May 11 October	8.83 6 October	0.17	179, 11 May	—	—	—	Lumax 1.1, 11 May
2012	Corn 18 April	18 April 4 October	4.82 20 September	0.25	168, 18 April	—	—	0.3, 28 September	Lumax 0.7, 18 April Roundup 0.3, 5 June
2013	Soybean 14 May	14 May	3.24 28 October	0.14	N/A	—	—	—	Prefix 0.7, 14 May
2014	Corn 6 May	6 May 25 November	14.49 6 November	0.46	168, 6 May	224, 12 April 196, 21 November	224, 12 April 224, 21 November	—	Lexar 7.0, 6 May
2015	Corn 20 April	28 April 15 November	11.02 15 November	0.89	202, 28 April	—	—	—	Harness Xtra 1.0, 28 April
2016	Soybean 27 May	18 April 25 May	4.88 1 November	0.13	N/A	—	—	—	Authority Assist 0.4, 25 May
2017	Corn 16 May	10 May 8 November 14	12.94 8 November	0.16	202, 10 May	—	—	—	FlexstarGT 0.7, 29 June
2018	Corn 8 May	8 May 24 October	11.40 9 October	0.18	202, 8 May	—	—	—	Harness Xtra 1.0, 10 May

(figure S2), no drift evident in the CO₂ or water vapor measured by the gas analyzer (figure S3), and no substantial deviation in energy balance closure (table S1). In addition, if it were only the CO₂ fluxes affected by a faulty gas analyzer, we would expect to see evidence of drift in the CO₂ fluxes measured, yet the fluxes hovered around zero before the growing season and returned to this level after the crop was harvested (figure S3).

The partitioned NEE data from US-UiC also indicates the flux tower instruments were operating as they should during 2014/2015. While the NEE values initially seemed amiss, the GPP and ER time series showed that GPP dominated early on in the growing season (i.e. June) when the corn canopy was establishing, then in early July, ER started to overtake GPP, despite GPP maintaining rates typical of other growing seasons (figure 1). This high GPP from corn in 2014 and 2015 is supported by the correspondingly high yield removed during harvest for each year (table 2). However, it is the ER response in 2014 and 2015 that differs substantially from other years, indicating that respiration processes were driving the shift of this corn ecosystem from a net sink to a net source of C during the peak of the growing season (figure 1, table 1).

4. Soil microbial activity as the likely causes of increased respiration

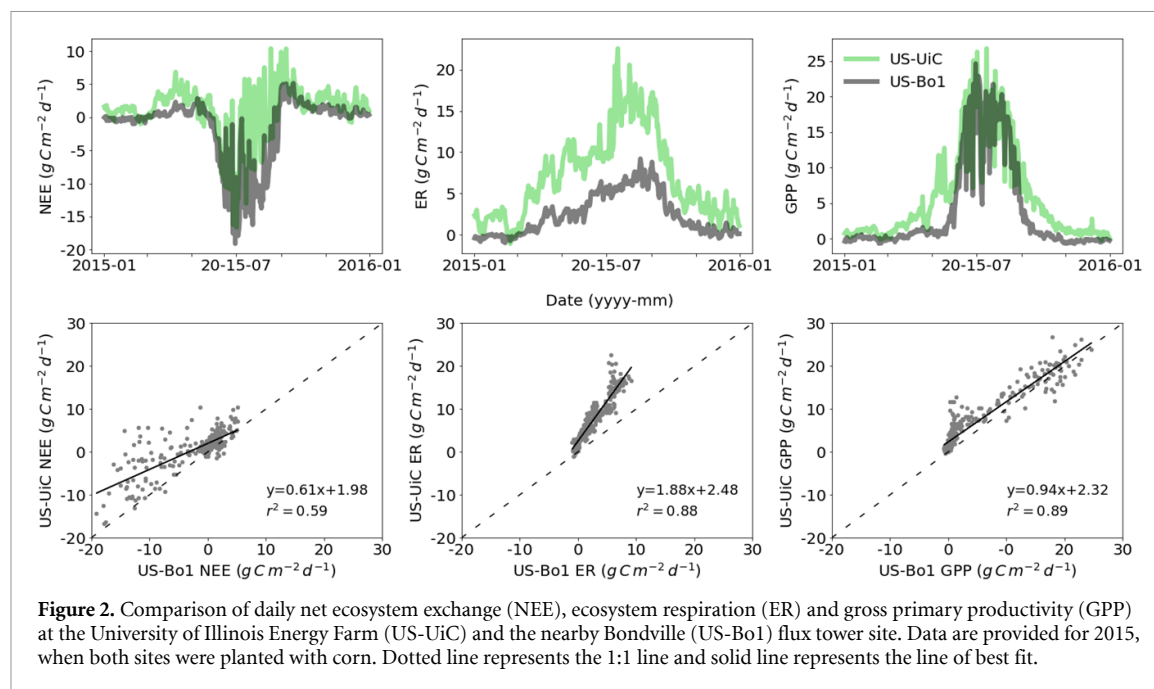
We hypothesize the higher NEE fluxes in 2014 and 2015, which caused a burp of C from the ecosystem during these two years, were driven by increased soil microbial respiration. Unfortunately, we cannot directly test this hypothesis, as no complementary measurements were collected as in previous years, such as soil respiration chambers to partition soil fluxes into autotrophic and heterotrophic contributions, or soil cores to identify labile C and nutrient availability (Anderson-Teixeira *et al* 2013). However, our micrometeorological measurements help to characterize the climate conditions for each growing season measured (table 1 and figure S4), and detailed agronomic information describes how the land was managed each year (table 2). These data show the 2014 and 2015 growing seasons were wetter than usual (table 1 and figure S4), which correlates with increased NEE, particularly at night (figure S4). Partitioned NEE also show increased GPP and ER in 2014 and 2015, relative to other years (table 1). An increase in GPP would cause a corresponding rise in autotrophic respiration, but given the high yields in 2014/2015, autotrophic respiration did not outpace primary productivity. What this higher productivity would have led to is greater root production (Amos and Walters 2006), which was demonstrated in a recent long-term assessment showing 2014 with the highest peak belowground biomass measurements (Kantola *et al* 2022). This increase in belowground

biomass would have provided a larger pool of labile C to support increased rates of soil microbial respiration (Kuzyakov *et al* 2000, Fang *et al* 2018).

Anomalous spikes in ER are not unheard of and have been detected in eddy covariance datasets before. For example, over a three-year period, Xu *et al* (2004) showed how rainfall pulses enhanced ER from an annual grassland and an oak/grass savanna, which was driven by increased soil microbial respiration. The amount of C lost from each site was positively correlated with biomass production and SOC content (Xu *et al* 2004), indicating the more productive the ecosystem was, the more labile C there was to fuel microbial respiration processes. Also using eddy covariance, Gomez-Casanovas *et al* (2012) showed how GPP fueled soil microbial respiration at longer timescales than root respiration in a native prairie ecosystem, including the importance of soil moisture in regulating this response. It is likely this same response was captured by our eddy covariance system, whereby the wetter 2014 and 2015 growing season supported higher crop productivity (table 2 and figure 1), which would have supported higher microbial respiration.

In combination with favorable climate conditions were additional agronomic approaches in 2014. The annual fertilizer regime for this agroecosystem includes nitrogen (N) application (table 2). However, prior to planting and after harvest in 2014, potassium and phosphorus were added alongside the regular application of N to the field each year (table 2). At the end of the 2013 growing season, lime was also applied to the field to neutralize pH (table 2). The interaction of moist soil conditions (Ahmed *et al* 2018), more nutrients than previous years (Chen *et al* 2014), and pH increases (Aye *et al* 2018), likely created ideal conditions for an increase in soil microbial biomass, microbial community shifts, and an increase in the decomposition of SOC under a corn field that is conventionally tilled each year (Fang *et al* 2018, Jansson and Hofmockel 2020).

In addition to the optimal conditions for soil microbial activity, increased C inputs from above- and belowground sources may have caused SOC priming. SOC priming is a change in the rate of decomposition of existing SOC in response to the addition of a new substrate (Kuzyakov *et al* 2000). The incorporation of stover into topsoil and the theorized increase in rhizodeposition as a result of increased root biomass from higher corn productivity (Amos and Walters 2006) may have induced a positive priming effect (increase in SOC decomposition) in this ecosystem during 2014 and 2015 (Fang *et al* 2018). There may have also been a legacy effect occurring in response to the 2012 drought, and sustained dry conditions into 2013 (table 1) that enhanced this priming effect. Moisture deficits often lead to an alteration in survival strategy by microbes, whereby microbes may become dormant or resort to more resource expensive adaptive measures, such as cell wall-thickening, in



response to osmotic pressure (Evans and Wallenstein 2014). Lack of moisture, lower N availability, along with decreased availability of labile substrates during the 2012 drought may have shifted microbial community makeup in this agroecosystem, potentially favoring slower growing k-strategists who are able to use more recalcitrant forms of SOC (De Vries and Shade 2013, Schimel 2018).

The resultant C fluxes for 2012 reflect a potential decrease in microbial activity due to community shifts and decreased moisture, followed by another potential shift in microbial community make-up and response in 2014 as moisture and nutrient availability increased (table 2 and figure S4). Re-wetting, nutrient additions, increased rhizodeposition and new substrate additions have all been implicated in the reactivation and accelerated growth of faster growing microbes (r-strategists), and consequently, an increase in the decomposition of SOC in previously dry soil in both field and laboratory experiments (Kumar *et al* 2016, Huo *et al* 2017, Gibson *et al* 2018, Najera *et al* 2020). While re-wetting, coupled with the availability of labile substrates, may have reactivated dormant microbial communities, the addition of lime, N, and other nutrients, as well as a hypothesized increase in corn rhizodeposition, likely sustained the enhanced microbial respiration until the microbiome stabilized during the next corn rotation in 2017 (figure 1).

5. The interacting complexities of climate and land management

With this dataset, we have shown the importance of maintaining long-term monitoring sites for understanding the complex interactions of climate/

soil legacies, management, and contemporary conditions. To explore this climate/management interaction in more detail, we compared our US-UiC site to the nearby independently operated Ameriflux Bondville site (US-Bo1) described by Meyers and Hollinger (2004). Using data from 2015, the contrast in growing season NEE between these two sites showed US-Bo1 did not experience the same shift in NEE as seen at US-UiC (figures 2 and S5). We gap filled and partitioned US-Bo1 NEE into GPP and ER using the same processing routines as for US-UiC (Moore *et al* 2020), and found GPP was very similar between the two sites. It was in their ER that the two sites differed markedly, with US-UiC almost double that of US-Bo1 (figure 2).

The US-Bo1 site is approximately 8 km from the US-UiC site, so the two sites experience a very similar climate. However, US-Bo1 is managed as a no-till corn–soybean rotation, while US-UiC is a conventionally tilled system in a corn–corn–soybean rotation. Given this rotation difference, we could not compare all years of data between sites (i.e. 2008–2018). However, in 2015 the two sites were both planted with corn, so our comparison between the two sites focused on this year. In 2015, US-Bo1 received $230 \text{ kg ha}^{-1} \text{ N}$, $177 \text{ kg ha}^{-1} \text{ K}$, and $98 \text{ kg ha}^{-1} \text{ P}$, while US-UiC received $224 \text{ kg ha}^{-1} \text{ K}$ and $196 \text{ kg ha}^{-1} \text{ P}$ after harvest in 2014 and $202 \text{ kg ha}^{-1} \text{ N}$ before planting in 2015 (table 2). While receiving slightly less N per ha, the US-UiC site received more P and K per ha, which combined with the conventional tillage and lime addition (table 2), would have enhanced soil nutrient mixing. This management practice coinciding with a wetter than average year climatically, likely provided the perfect environmental conditions to promote increased soil microbial activity at the US-UiC site (Shi *et al* 2013).

6. Implications for agroecosystem management and monitoring

The large ER pulse captured in two years of a ten-year corn–soybean monitoring dataset demonstrates the important interaction between climate and land management when assessing the C balance of an agroecosystem. Increased ER from corn during two high yield years, to the point where ER overtook GPP, indicates turnover of SOC, which has implications for the long-term ecological sustainability of cropping systems. While our ability to definitively determine a mechanism is limited by a lack of ancillary measurements to support the ecosystem fluxes measured, we discuss the climate and land management mechanisms which, when combined, likely led to an ideal combination to promote soil microbial activity that resulted in high turnover of SOC. Long-term monitoring, coupled with a core set of critical ecosystem measurements, is key for capturing pulse events like this from corn and other cropping systems, including the need for further work comparing lime and nutrient additions to quantify priming interactions. Addressing these outstanding questions is important for constraining biogeochemical and life cycle assessment models that project the future sustainability of food and fuel cropping systems.

Data availability statement

The data that support the findings of this study are available from the Ameriflux data portal or from the corresponding author upon reasonable request.

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