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# Quantifying the impact of climate smart agricultural practices on soil carbon storage relative to conventional management

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ABSTRACT

Climate smart agricultural practices have received considerable attention recently for their potential for climate change mitigation through sequestering atmospheric carbon. Despite the enthusiasm for climate smart practices, there is limited evidence they are more effective at removing carbon from the atmosphere and storing it in the soil than current practices. We hypothesized that a field with aspirational (ASP) practices (i.e., no-till corn-soybean-wheat-hay rotation with cover crops) would accumulate more soil organic carbon (SOC) versus a business-as-usual (BAU) field (i.e., conventional-tillage, corn-soybean-soybean rotation). We used deep soil cores (1 m) to assess changes in soil organic carbon (ΔSOC) between 2016 and 2022 for the two fields and compare with estimates based on eddy covariance calculation of ΔSOC. We found that the ASP field had ΔSOC that was positive, and larger than the BAU field. Both the soil sample method ($\Delta SOC_{SS}$) and the eddy covariance method ($\Delta SOC_{EC}$) agreed on this point, but the magnitude of ΔSOC was much larger when estimated with soil samples ($\Delta SOC_{SS}$ was $1.9 \pm 1.7$ % $yr^{-1}$ and $-0.7 \pm 1.3$ % $yr^{-1}$ at ASP and BAU, respectively) than with eddy covariance ($\Delta SOC_{EC}$ was $0.80 \pm 0.09$ % $yr^{-1}$ and $0.12 \pm 0.06$ % $yr^{-1}$ at ASP and BAU, respectively). Finally, we used the continuous measurements of carbon fluxes from the eddy covariance towers to examine how conservation practices (cover crops, no-till, or expanded crop rotation) led to increased carbon storage. We found that unharvested cover crops add carbon to the soil that offsets net carbon losses that otherwise reduce soil carbon storage when the field is fallow. No-till and expanded crop rotations also affect the carbon budget of the agroecosystems. Results from this study illustrate the value of conservation practices in a changing climate and the value of eddy covariance measurements for assessing climate smart practices.

## 1. Introduction

Climate smart practices that can sequester atmospheric carbon in agricultural soils are generating substantial interest for enhancing soil health and mitigating climate change (Lipper et al., 2014; Poeplau and Don, 2015). Agricultural regions cover large areas of land, so even small changes in soil carbon storage could have large impacts on the global atmosphere when those changes are propagated across millions of acres (Bernacchi et al., 2005). In the U.S. Midwest region, agricultural production is dominated by maize-soybean (*Zea mays-Glycine* max) rotations that have been shown to be the most productive ecosystem in the world during the growing season (Guanter et al., 2014). This, combined with the observation that soil carbon has been heavily depleted across the U.S. Midwest, has led to optimism that these agroecosystems can be used to help mitigate climate change (Lal, 2004b, 2004a). Recent efforts, however, show the effectiveness of climate smart agricultural practices to sequester carbon is mixed and there is ongoing debate regarding their efficacy (Amundson and Biardeau, 2018; Blanco-Canqui, 2022; Rumpel et al., 2020). Some agricultural practices now being used as climate smart practices have been studied for much longer having been motivated by desires to decrease soil erosion, particularly reduced and no-tillage.

The mechanisms via which several individual conservation practices affect soil carbon have been widely assessed. For example, conservation tillage—practices that maintain at least 30 % plant residue cover on the soil surface after harvest—was proposed as an approach to increase soil carbon storage by reducing soil respiration (Al-Kaisi and Yin, 2005; Baker and Griffis, 2005; Chi et al., 2016). Other studies have found

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conservation tillage to increase soil respiration (Chen et al., 2021) and the practice has not been useful for increasing soil carbon stocks on its own (Baker et al., 2007; Blanco-Canqui and Lal, 2008; Christopher et al., 2009). Similarly, cover crops have been seen as a promising conservation practice to increase soil carbon stocks (Jian et al., 2020; McClelland et al., 2021; Poeplau and Don, 2015). However, cover crops do not universally increase soil carbon content over the long term (Blanco-Canqui, 2022). Additionally, there is a lack of data demonstrating that the increased soil carbon in fields under cover crops was caused by enhanced removal from the atmosphere. Cover crops are known to reduce soil erosion (Baffaut et al., 2020), so increased soil carbon observed here could simply be due to cover crops preventing carbon losses in runoff (Baffaut et al., 2020).

The inconsistency in the reported success of climate smart agricultural practices is in part due to variable environmental conditions and in part due to the challenge in obtaining repeatable, robust measurements of carbon sequestration by agricultural soils. Traditionally, soil core samples are the most common approach to measure soil organic carbon (SOC). To detect statistically significant differences in SOC, samples must be obtained several years apart, making long-term experiments necessary, and samples must capture the spatial variability in SOC stocks (Gamble et al., 2017; Knops and Tilman, 2000; Lal et al., 1998). Additionally, conservation practices, such as no-till agriculture, modify the distribution of SOC throughout the soil profile (Christopher et al., 2009). This makes deep soil cores necessary to assess net changes in SOC across no-till and tilled systems (Christopher et al., 2009). Soil cores, however, do not measure carbon uptake from the atmosphere. To directly measure net ecosystem carbon uptake from the atmosphere, the eddy covariance method is the most common approach. This approach has been applied to study the carbon flux in maize-soybean cropping systems across the Midwestern U.S. (Baker and Griffis, 2005; Chen et al., 2018; Dold et al., 2017, 2021; Menefee et al., 2022). Eddy covariance data can be used to calculate a carbon balance for a field. It does not, however, measure the amount of carbon that stays in soils, rather the exchange between the atmosphere and land surface. Therefore, a more holistic understanding of carbon storage by agricultural soils can be attained by combining data from eddy covariance and soil sampling; yet this is uncommon due to the expense and expertise required to perform both (Dold et al., 2021; Gamble et al., 2021).

In this study, we used a combination of eddy covariance measurements and deep soil cores to examine the impact of several conservation practices on soil carbon. The Long-Term Agroecosystem Research (LTAR) network was developed by the USDA Agricultural Research Service to assess the effectiveness of various conservation practices aimed at improving agricultural sustainability (Wallbridge and Shafer, 2011). The combination of several conservation practices represents an aspirational (ASP) systems approach to cropland management. We evaluated the benefits of this ASP approach by comparing it with a conventional, “business-as-usual” (BAU) approach using two fields in the Central Mississippi River Basin (CMRB). The CMRB represents a large region of the U.S. Midwest with a relatively shallow topsoil layer caused by a restrictive claypan layer that makes large portions of the land marginal for farming and boosts the cost effectiveness of conservation practices (Conway et al., 2020). We evaluated a combination of conservation practices, including no-till, cover crops, and a diversified crop rotation by testing two hypotheses: (1) the ASP field accumulates more SOC compared to the BAU field, and (2) eddy covariance measurements can capture changes in soil carbon observed from soil analysis.

The ASP treatment in this study contains several conservation practices which may affect soil carbon through various mechanisms. The first potential mechanism is that no-till reduces soil respiration, which would lead to more C storage in soils, as long as gross primary productivity (*GPP*) remains unchanged (Al-Kaisi and Yin, 2005; Baker and Griffis, 2005; Chi et al., 2016). The second potential mechanism is that the expanded crop rotation creates higher net carbon uptake at the ASP site as the carbon budget is known to vary widely for different crops, especially if diversified rotations cause temporal intensification of crop growth (Menefee et al., 2022). One of the crops in the ASP rotation is hay that includes species meant to mimic tallgrass prairie and there is evidence that tallgrass prairie increases soil carbon relative to agricultural fields (Huggins et al., 1998). The third proposed mechanism is that the cover crops that are not harvested, create additional biomass by increasing *GPP* when a conventional field would be fallow (Jian et al., 2020; McClelland et al., 2021; Poeplau and Don, 2015).

## 2. Methods

### 2.1. Study sites

This study was conducted at the CMRB LTAR site located in central Missouri, USA (Kleinman et al., 2018; Sadler et al., 2015a). The LTAR experiment at this site was established in 2015 with the primary goal of comparing the ASP management system to the BAU system. Although the LTAR network is designed for region-specific ASP treatments at each site, there are some common aspirational practices for row crops, including cover crops and no-till. The CMRB site is located within the U. S. Midwest where maize and soybean are the most common crops. While LTAR network research was initiated in 2015 at this location, various aspects of the ASP and BAU treatments have been in place since 1991 (Sadler et al., 2015).

The ASP treatment consists of an expanded crop rotation of maize-soybean-wheat-hay, no-till, precision variable-rate nitrogen management, and cover crops implemented to continuously maintain cover on the field (Yost et al., 2017). The hay crop is a grass/legume mix and includes Timothy Grass (*Phleum pratense*) and Medium Red Clover (*Trifolium pratense*). The cover crops are not harvested with residues left on the field. The BAU field is managed by a local farmer with conventional tillage and a maize-soybean-soybean rotation without cover crops. Details on planting and harvest dates can be found in Table 1. Tillage is performed with a Turbo Till vertical tillage tool with one pass to 10 cm depth. The two study sites are approximately 2.5 km apart and share similar climate and soils (Fig. 1). Soils at both the ASP and BAU sites are Adco silt loam (fine, smectitic, mesic Vertic Albaqualfs) in summit positions with 0–1 % slopes, and Mexico silt loam (fine, smectitic, mesic Vertic Epiaqualfs) in backslope (1–3 % slope) and footslope (1–2 % slope) positions (Veum et al., 2015). Although slopes and topographic relief at both fields are minimal, runoff potential is high due to the claypan layer that greatly restricts infiltration (Baffaut et al., 2020).

### 2.2. Instrumentation and eddy covariance data

The EC towers were installed in the ASP and BAU fields to measure the net ecosystem fluxes of $CO_2$ and water vapor (Fig. 1). The monitoring efforts in the watershed have been ongoing since 1971 and have been described previously (Sadler et al. (2015a), and Sadler et al. (2015b)). This brief description of the instrumentation focuses on the process to obtain the data necessary to analyze carbon fluxes and stocks in the soils. Eddy covariance data collection began on October 1, 2015 at the ASP site and June 1, 2016 at the BAU site using an integrated sonic anemometer and gas analyzer (IRGASON, Campbell Scientific Inc., Logan, UT). The IRGASON sensors are rotated when we perform calibrations to eliminate the potential for biased measurements between the two sites. The height of the EC instruments was varied between 1.8 and 3.6 m to maintain a consistent height above vegetation, which preserves a consistent measurement footprint that does not intersect the edge of the field. The ASP and BAU fields are approximately 26 and 18 ha, respectively.

The EC systems measure wind velocities, (sonic) air temperature, and $CO_2$ and $H_2O$ densities at 10 Hz resolution, from which covariances between wind and gasses were computed at 30 min time steps using

**Table 1**

Crop type with planting and harvest dates for the ASP and BAU fields. Note that hay is harvested three times throughout the year. The carbon balance components Yield C, change in soil organic carbon ($\Delta SOC_{EC}$), gross primary productivity (GPP), ecosystem respiration ($R_{eco}$), and net ecosystem productivity (NEP) are presented for each crop growing season.

| Site | Cash Crop Year | Crop | Crop Planting (mm/dd/yyyy) | Crop Harvest (mm/dd/yyyy) | Tillage | Yield C [g/m$^2$] | $\Delta SOC_{EC}$ | GPP | $R_{eco}$ | NEP |
|---|---|---|---|---|---|---|---|---|---|---|
| ASP | 2016 | Maize | 4/15/2016 | 9/30/2016 | | 412 | −32 | 1236 | 852 | 385 |
| | 2017 | Cereal Rye (Cover Crop) | 10/3/2016 | 5/10/2017† | | – | 69 | 499 | 428 | 71 |
| | 2017 | Soybean | 5/17/2017 | 10/19/2017 | | 162 | 48 | 1083 | 862 | 221 |
| | 2018 | Wheat | 10/19/2017 | 7/2/2018 | | 179 | 65 | 839 | 591 | 247 |
| | 2019 | Summer Cover Crop‡ | 8/9/2018 | 6/3/2019 | | – | −76 | 874 | 927 | −53 |
| | 2019 | Soybean | 6/11/2019 | 10/23/2019 | | 185 | 76 | 774 | 500 | 274 |
| | 2020 | Wheat | 10/23/2019 | 7/8/2020 | | 153 | 129 | 968 | 682 | 286 |
| | 2021 | Hay | 3/6/2020 | 9/14–18/2020, 6/9–14/2021, 7/29–8/6/2021 | | 480 | 2 | 2732 | 2231 | 501 |
| BAU | 2016 | Soybean | 5/22/2016 | 10/25/2016 | 3/21/2016 | 182 | 115 | 1256 | 950 | 306 |
| | 2017 | Maize | 4/19/2017 | 10/13/2017 | 4/19/2017, 11/6/2017 | 467 | 68 | 1135 | 589 | 546 |
| | 2018 | Soybean | 5/12/2018 | 10/30/2018 | 4/27/2018 | 217 | 154 | 985 | 596 | 389 |
| | 2019 | Soybean | 6/4/2019 | 10/18/2019 | | 209 | 64 | 1081 | 805 | 276 |
| | 2020 | Maize | 5/10/2020 | 10/31/2020 | 5/10/2020 | 441 | 102 | 1110 | 559 | 551 |
| | 2021 | Soybean | 5/19/2021 | 11/10/2021 | | 121 | 24 | 812 | 667 | 144 |

† Cereal Rye is not harvested but rather terminated in the spring, prior to planting, with a herbicide application. The species within the Summer Cover Crop would have either winterkilled or been terminated similarly in the spring.

‡ Summer Cover Crop is a mixture of: Sunn Hemp, Cowpeas, Balansa Clover, Crimson Clover, Spring Oat, Winter Barley, Cereal Rye, Diakon Radish, Sunflower, Buckwheat, Phacelia Angelia, and Sorghum Sudangrass.

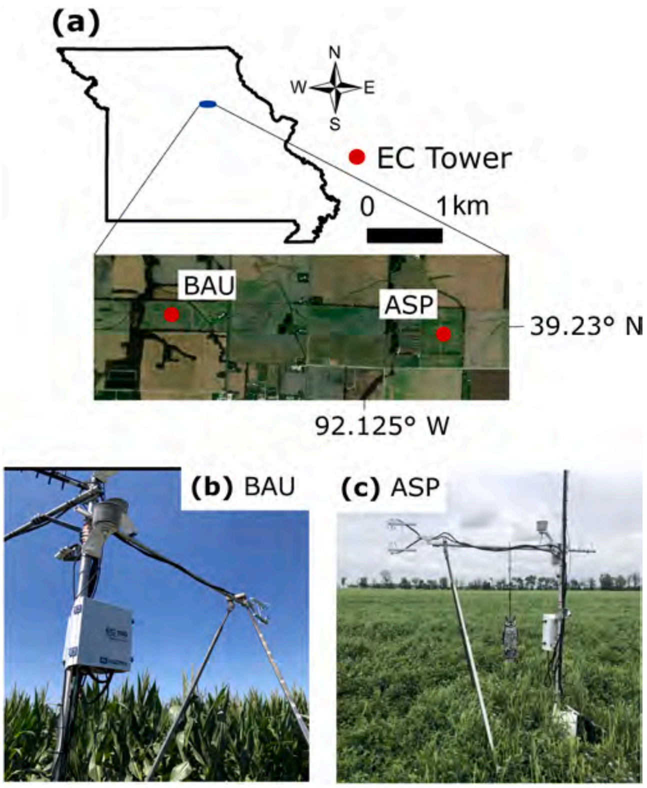

**Fig. 1.** The (a) two study fields located within central Missouri, USA are instrumented with eddy covariance systems at the (b) business-as-usual (BAU) field (July 24, 2020) and (c) spirational (ASP) field (May 25, 2021).

block averaging. Fluxes were rotated (2-d) into the natural wind coordinate system (Tanner and Thurtell, 1969). The effects of air density fluctuations on gas fluxes were accounted for by applying the so-called "WPL terms" for sensible and latent heat fluxes (Webb et al., 1980).

Half hourly data were screened to retain high quality data. To account for fog or water on the gas analyzer, spikes in measurements were filtered at the 30 min time step when the signal strength of the gas analyzer measurement was less than 80 %. Additional spikes when net ecosystem $CO_2$ exchange (*NEP*) values were $NEP > 90$ or $< -60$ μmol m$^{-2}$ s$^{-1}$, and latent heat (*LE*) or sensible heat (*H*) values were *LE* or $H < -200$ W m$^{-2}$ or $>800$ W m$^{-2}$ were removed. Micrometeorological conditions when the EC assumptions are not valid were identified using an objective friction velocity ($u_*$) filtering method (Papale et al., 2006). We determined a different $u_*$ threshold for each season with the moving point method (Papale et al., 2006; Wutzler et al., 2018). The percent of missing carbon flux data due to gaps from all sources is 37 % and 27 % at ASP and BAU, respectively. Gaps in the turbulent fluxes were filled using the marginal distribution sampling (MDS) method with default parameters (Wutzler et al., 2018). The partitioning of *NEP* into *GPP* and ecosystem respiration ($R_{eco}$) was accomplished using the nighttime partitioning method (Reichstein et al., 2005). We used REddyProc software to perform u* filtering, gap filling, and carbon flux partitioning using the nighttime method (Wutzler et al., 2018). Random measurement uncertainty was estimated using the daily differencing approach (Hollinger and Richardson, 2005).

We followed the approach of Baker and Griffis (2005) to infer changes in SOC from eddy covariance estimates of net CO2 exchange. The carbon budget of an agricultural field between time t1 and t2 can be written as (Baker and Griffis 2005):

$$\int_{t_1}^{t_2}(NEP)dt-\int_{t_1}^{t_2}\frac{d(SOC_{EC})}{dt}dt-\int_{t_1}^{t_2}Y\left[C_f\right]dt+\int_{t_1}^{t_2}(C_d-C_e)dt+\int_{t_1}^{t_2}P([PIC])dt-\int_{t_1}^{t_2}R([DIC]+[DOC])dt-\int_{t_1}^{t_2}J([DIC]+[DOC])dt=0 \tag{1}$$

where *NEP* is the net ecosystem productivity, *SOC* is the soil and detrital organic C on a mass per unit area basis, *Y* is the harvested mass per unit area with a fractional carbon content $C_f$, $C_d$ and $C_e$ are rates of carbon deposition and removal in particulate transport, *P* is precipitation rate, *R* is runoff rate, and *J* is drainage rate, with mean concentrations of dissolved organic carbon, *DOC*, and dissolved inorganic carbon, *DIC*. It is often assumed that carbon in precipitation and carbon loss from drainage and runoff are negligible and neglected. (Baker and Griffis, 2005; Gamble et al., 2021). Under these assumptions, Eq. (1) can be rearranged as:

$$\int_{t_1}^{t_2} \frac{d(SOC_{EC})}{dt} dt = \int_{t_1}^{t_2} (NEP) dt - \int_{t_1}^{t_2} Y\left[C_f\right] dt \tag{2}$$

The *NEP* is calculated over each time period using the EC measurements, *NEP* is equal, but opposite sign to *NEE*. Grain crop mass yield was measured with a combine-mounted yield monitor at both sites. Mass yield of the baled hay crop was obtained by summing the mass obtained of each bale upon removal from the field. Prior to harvest, manual samples were also collected for nutrient content analysis from five georeferenced monitoring locations which aligned with a subset of the soil sampling locations within each site. Carbon concentration was measured from the grain or plant material using high temperature combustion followed by infrared gas analysis. The average C content of grain yield (or plant biomass for the hay crop) at standard moisture basis was used to calculate the mass of C removed from each field during harvest. The uncertainty in grain yield measurements was established as 5 % of the observed value, based on previous research quantifying yield monitor uncertainty (Burks et al., 2004; McNaull and Darr, 2020). The change in SOC measured with the eddy covariance system ($\Delta SOC_{EC}$) is the NEP with the C in yield subtracted. In order to include the yield carbon in the equation, we calculate the $\Delta SOC_{EC}$ for each cropping period, i.e., from seeding to harvest/termination. Positive values indicate increased soil carbon storage and negative values indicate carbon losses from the soil.

### 2.3. Soil carbon measurements

Change in soil carbon at each field was assessed using deep soil cores. Soil cores were extracted from each field to a depth of ~1 m using a Giddings probe (3.45 cm inner diameter). Soil sampling locations were selected pseudo-randomly to provide representative spatial coverage of each field (Fig. 2). The first set of samples was collected on March 23 and 25, 2016 at ASP and BAU, respectively. A second set of soil samples was collected on April 28 and May 13, 2022, at ASP and BAU, respectively. Soil cores were split by diagnostic pedogenic horizon, air-dried, ground using a mortar and pestle, and passed through a sieve (<2 mm). Soil bulk density was determined using the known soil volume and measured dry soil mass. For soil samples where the calculation of bulk density was not possible, the field average bulk density for that soil horizon was used. Total soil organic carbon (SOC) was measured by combustion on a Leco Trumac CN Analyzer (Leco Corp., St. Joseph, MI). The change in SOC in the top 1 m of soil ($\Delta SOC_{SS}$) between 2022 and 2016 was calculated for each core:

$$\Delta SOC_{SS} = \sum \left(\rho_{B,i} \times \Delta SOC_i \times T_i\right) \tag{3}$$

where $\rho_{B,i}$ is the bulk density of soil layer i [g m$^{-3}$], SOC is the fraction of soil mass composed of organic C, and $T_i$ is the thickness of the soil layer [m]. Positive and negative values of $\Delta SOC_{SS}$ represent increases and decreases in SOC, respectively. The uncertainty was assessed as the standard deviation of the $\Delta SOC_{SS}$ between cores at each field.

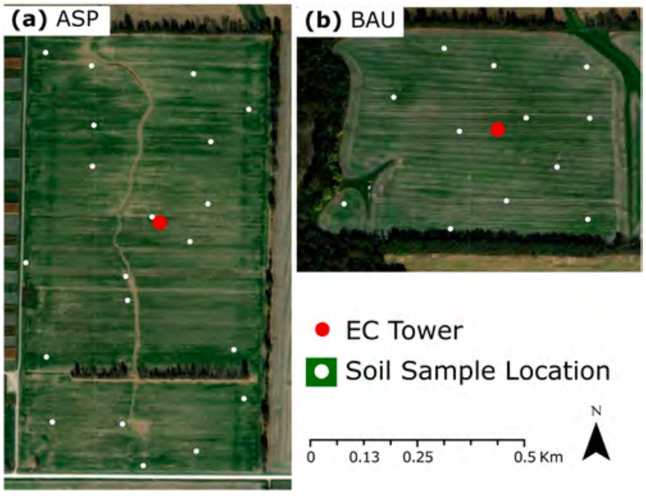

**Fig. 2.** Images of the CMRB LTAR ASP (a) and BAU (b) fields with the locations of the eddy covariance (EC) tower as well as the locations where soil core samples were extracted.

### 2.4. Analysis techniques

To test our hypotheses, that the ASP treatment led to greater uptake of C by soils than the BAU treatment and that eddy covariance measurements can capture any observed changes, we analyzed both the EC data and soil cores. A two-tailed *t*-test was used to test for significant differences between the $\Delta SOC_{SS}$ for the ASP and BAU fields, and to test for significant differences from 0 using $\alpha = 0.05$. Differences between $\Delta SOC_{EC}$ and $\Delta SOC_{SS}$ are assessed by comparing the values. Our hypothesis 1 is substantiated if the values for $\Delta SOC_{EC}$ are within the uncertainty range of the values of $\Delta SOC_{SS}$. Each soil core was separated by soil horizon; across each field there is variability in which soil horizons are present, and the depth at which they are found. To present a standardized comparison of where the largest changes in SOC occurred throughout the soil profile, cores with varied depth intervals were depth weighted to standardized 1 cm intervals using the "dice" function in the {aqp} r package (Beaudette et al., 2022, 2013) specifically with the slice and slab functions. The slice function allows a user to define the length of a unit used to divide a profile. Here we used 1 cm. The 1 cm slice will have the same ΔSOC values as the horizon it originated from. The standard deviation of the depth weighted averages is presented as the uncertainty in the $\Delta SOC_{SS}$ by depth interval.

The EC measurements provide an areal average value for each field. We considered the $\Delta SOC_{EC}$ at the ASP and BAU fields to be significant if the measurement uncertainty does not overlap 0. Measurement error was calculated as the quadrature sum of random flux error, including random error from gap-filled timesteps, plus the uncertainty in carbon removed as yield. If both soil and EC methods agree, we interpret that to be strong evidence of a change.

To evaluate how the three conservation practices may contribute to increased carbon storage at the ASP site, we further analyzed the eddy covariance data. We evaluate how soil respiration responds to the conservation practices by analyzing $R_{eco}$ at both ASP and BAU sites from the EC data. We calculated the sum of $R_{eco}$ over the 6-year period at both sites. Respiration is likely to be reduced by no-till and increased by the addition of cover crops (and the additional *GPP*). Therefore, we compute the ratio of $R_{eco}/GPP$ for the ASP and BAU fields. If the ratios are equivalent, this suggests that ΔSOC is not caused by reduced $R_{eco}$ from no-till in the ASP system. The value of $R_{eco}$ obtained from EC measurements contains above and belowground autotrophic respiration as well as soil heterotrophic respiration, so it is possible that a higher value of $R_{eco}$ at the ASP field does not represent a change in microbial carbon cycling.

We evaluated how the carbon balance responded to the expanded crop rotation by computing the mean growing season ΔSOC for each crop. We note that differences in ΔSOC by crop are specific to this rotation because crop residue from the previous crop, including aboveground and belowground biomass, is left on the field to decompose. This contributes to $R_{eco}$ during the growing season that lowers the *NEP* for that season. We do not have measurements of both aboveground and belowground biomass for all crops to estimate the contribution of decomposition of previous season crops to the observed fluxes. In particular, we focus on cover crops by comparing the *GPP*, $R_{eco}$, and *NEP* from the periods with cover crops to the periods with fallow ground. The impacts of the expanded crop rotation and cover crops to the carbon budget are primarily to change the *GPP* and the amount of carbon in plant material and root exudates input to the soil. An increased *GPP* at the ASP site would reflect the importance of increasing photosynthetic carbon gain of a system to promote soil carbon storage.

## 3. Results

### 3.1. Aspirational practices lead to increased soil carbon storage

Over 6 years, we found that $\Delta SOC_{EC}$ was positive for both fields, indicating carbon uptake from the atmosphere, while $\Delta SOC_{SS}$ was negative for the BAU field, indicating carbon loss (Fig. 3). According to the EC method, $\Delta SOC_{EC}$ at the ASP site was 440 ± 48 g C $m^{-2}$ over the 6-year period (73.3 g C $m^{-2}$ $yr^{-1}$), and 71 ± 38 g C $m^{-2}$ over the 6-year period (11.8 g C $m^{-2}$ $yr^{-1}$) at the BAU site. The EC method, therefore, suggests that both are accumulating SOC, but increases are smaller at the BAU site, where the uncertainty is large compared to the observed change.

Estimates from the soil method suggest larger ΔSOC than the EC method, but with higher uncertainties. Over 6 years, $\Delta SOC_{ss}$ at the ASP field was 1042 ± 948 g C $m^{-2}$ (174 g C $m^{-2}$ $yr^{-1}$), and significantly different from zero according to a one-sample *t*-test ($p = 0.0002$). In contrast, $\Delta SOC_{ss}$ at the BAU field was -403 ± 820 g C $m^{-2}$ (−67 g C $m^{-2}$ $yr^{-1}$) and not different than 0 ($p = 0.12$). The initial SOC content in 2016 was similar between the two sites, but slightly higher at the BAU site, 9118 g C $m^{-2}$ and 10,166 g C $m^{-2}$ at ASP and BAU, respectively. The ASP site has a larger ΔSOC than the BAU site according to a two-sample equal variance *t*-test applied to $\Delta SOC_{ss}$ ($p = 0.029$). As a result, we can conclude that hypothesis 1 is accepted; the ASP site has greater ΔSOC than the BAU site, and this ΔSOC is greater than 0. Additionally, the $\Delta SOC_{EC}$ within the range of uncertainty of the $\Delta SOC_{SS}$, providing evidence that eddy covariance techniques are capable of estimating ΔSOC at this location.

By depth weighting $\Delta SOC_{SS}$ at each location and taking the average, we build the average profile of $\Delta SOC_{SS}$ with soil depth (Fig. 4). At the ASP site, $\Delta SOC_{SS}$ is low for the top 30 cm and even negative at 25 cm depth. Between 30 and 75 cm depths, however, $\Delta SOC_{SS}$ is positive with values that approach 20 g C $m^{-2}$ per cm of soil depth. The $\Delta SOC_{SS}$ returns to near 0 by 1 m depth. At the BAU site a different pattern emerges. The $\Delta SOC_{SS}$ in the top 50 cm of soil is negative with larger losses in SOC near the ground surface. Beneath this, the $\Delta SOC_{SS}$ is relatively unaffected.

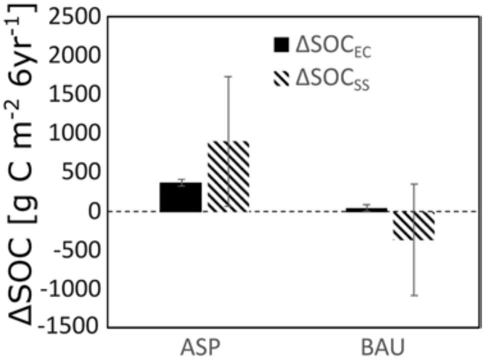

**Fig. 3.** Change in soil carbon storage (ΔSOC) at CMRB LTAR field sites from 2016 to 2022 estimated by eddy covariance (EC) and deep soil core samples. Error bars represent the uncertainty of the measurement. For EC they represent the random error uncertainty plus the uncertainty in carbon removed as yield (grain and hay biomass) and for the soil method they represent the standard deviation of change in carbon storage.

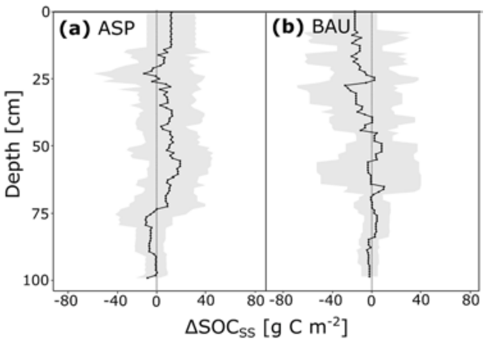

**Fig. 4.** Change in soil organic carbon measured with soil sampling ($\Delta SOC_{SS}$) with depth at the (a) ASP and (b) BAU fields. Data from soil cores was depth weighted in 1 cm intervals and the average value across all cores is presented as a solid black line with the standard deviation shown in the shaded region.

### 3.2. Mechanisms causing ASP to have higher carbon sequestration than BAU

The ASP treatment incorporates three conservation practices relative to the BAU treatment. We evaluate the degree to which the three practices contributed to increased ΔSOC at the ASP versus BAU site. To understand the value of each conservation practice within our ASP system, we examine the following three lines of evidence.

#### 3.2.1. Soil respiration response to conservation practices

The first potential mechanism we explore is whether no-till reduced soil respiration at the ASP site, which would allow carbon to accumulate. The ASP site had significantly higher *GPP* and $R_{eco}$ than the BAU site (Fig. 5). Over the 6-year period, *GPP* was 9680 ± 32 g C $m^{-2}$ and 7354 ± 26 g C $m^{-2}$ at the ASP and BAU sites, respectively. Similarly, $R_{eco}$ was 7576 ± 38 g C $m^{-2}$ and 5589 ± 36 g C $m^{-2}$ over the 6-year period at the ASP and BAU sites, respectively. The higher respiration at the ASP site is not simply due to higher *GPP*, the $R_{eco}/GPP$ fraction is 0.78 at the ASP site and 0.76 at the BAU site. This indicates that no-till is not reducing respiration and we can reject this mechanism as a primary cause of greater ΔSOC at the ASP site.

#### 3.2.2. Conservation practice impact on carbon production

The second potential mechanism we explore is whether the wheat and hay crops included in the ASP rotation are better able to increase carbon storage than a simple maize-soybean rotation. To examine the importance of this mechanism, we compared the $\Delta SOC_{EC}$ for each of the crops at the ASP and BAU sites. We are treating the crops as rotation specific, which means two things. First, crops can be compared even if

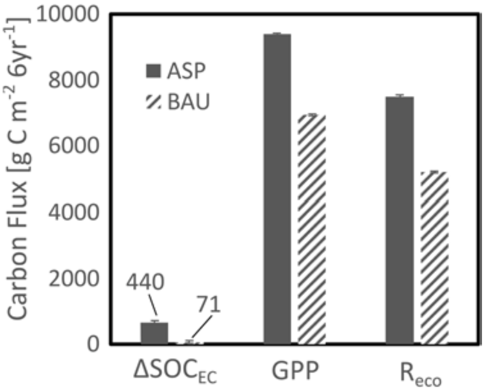

**Fig. 5.** Carbon flux measured with the eddy covariance towers at the ASP and BAU sites. Error bars represent the random measurement uncertainty from the eddy covariance technique.

their growing season is not the same length or at the same time. For example, wheat is grown over the winter and harvested in the early summer, so it is subject to different growing conditions than maize or soybean which grow over the summer. But if a wheat crop is grown in a particular year, a maize or soybean crop is not grown, so if a farmer replaces maize or soybean with wheat, the total crop carbon flux is the value of interest, regardless of different weather conditions over the winter. Second, the $\Delta SOC_{EC}$ for each crop is influenced by the crop or cover that preceded it. The preceding crop leaves residue which continues to decompose when a crop is planted and creates $R_{eco}$, which subsequently affects the carbon balance for a crop.

During the study period, the total GPP from cash crops (i.e., excluding cover crop periods) at the ASP site was 7632 g m$^{-2}$ while at the BAU site it was 6379 g m$^{-2}$ (Table 1). The mean $\Delta SOC_{EC}$ for each crop grown on the ASP and BAU fields is shown in Fig. 6. At the BAU site, both maize and soybean crops have relatively high $\Delta SOC_{EC}$ of 89 ± 32 and 85 ± 13 g C m$^{-2}$, respectively. This increase in carbon storage during the crop growing season is, however, offset by an average $\Delta SOC_{EC}$ of -100 ± 3 g C m$^{-2}$ (i.e., C emission) during the fallow periods. In the ASP rotation, the maize and hay are approximately carbon neutral, with $\Delta SOC_{EC}$ not different from 0, while the soybean crop has a $\Delta SOC_{EC}$ of 62 ± 21 g C m$^{-2}$ per cropping period. This is in part because when harvesting the hay most of the aboveground biomass is removed from the system, rather than just the grain yield. The wheat crop at the ASP site has a relatively larger impact on the carbon budget. The $\Delta SOC_{EC}$ of the wheat crop was 97 ± 13 g C m$^{-2}$ per growing season. Because of the limited time period of the study (6 years total), we do not have multiple cycles of the crop rotation at the ASP site, which makes comparison of carbon fluxes from different crops difficult. The fact that the average $\Delta SOC_{EC}$ from maize and soybean is different between the ASP and BAU sites, suggests that the legacy effects from the previous cover in the crop rotation are significant. Additionally, the wheat crop at the ASP site did not have higher $\Delta SOC_{EC}$ than either maize or soybean at the BAU site.

The final potential mechanism that may have increased ΔSOC at the ASP site is the cover crops increase biomass production that becomes available to develop SOC. The carbon fluxes (*NEP, GPP*, and $R_{eco}$) for the ASP and BAU sites for the periods when cash crops are not grown are shown in Fig. 7. For the ASP site, this is the period when cover crops are present and for the BAU site this is the fallow period. Because the expanded crop rotation at the ASP site includes wheat and hay, which are grown during the winter and have long growing seasons, the number of days with cover crops at ASP is less than the number of days of fallow at BAU (857 vs 1295 days, respectively). This also means that cover crops at the ASP site are sometimes growing during the summer, they are simply on the field when a cash crop is not being grown. At the ASP site, the cover crop period is associated with modest $\Delta SOC_{EC}$, the *NEP* is 160 ± 26 g C m$^{-2}$, but the *GPP* and $R_{eco}$ are both higher than the BAU site. At the BAU site, the *NEP* is -466 ± 19 g C m$^{-2}$ during the period that the field is fallow. This is because $R_{eco}$ is 1424 ± 9 g C m$^{-2}$ while the *GPP* is only 976 ± 12 g C m$^{-2}$. The $R_{eco}$ is higher than the *GPP* because crop residue from the preceding growing season is left on the field to decompose. The *GPP* during the fallow period at BAU is caused by weeds. At the ASP site *GPP* of 2053 g C m$^{-2}$ compensates for the decomposition of crop residue from the preceding crop. Taken together, the presence of carbon neutral cover crops, prevents the system from being a large $CO_2$ source, as would be the case if the field were fallow.

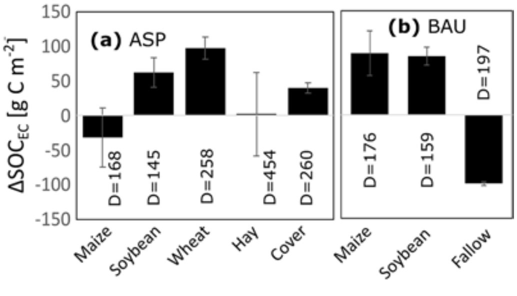

**Fig. 6.** Mean $\Delta SOC_{EC}$ (NEP – carbon in yield) from each of the crop types at the CMRB LTAR ASP (a) and BAU (b) fields. The sum of the entire growing season for each crop is used, the growing season lengths are not consistent. The average number of days in each crop growing season (D) is presented. Error bars represent the annual sum of random measurement uncertainty and uncertainty in yield C propagated in quadrature for each crop with multiple growing seasons.

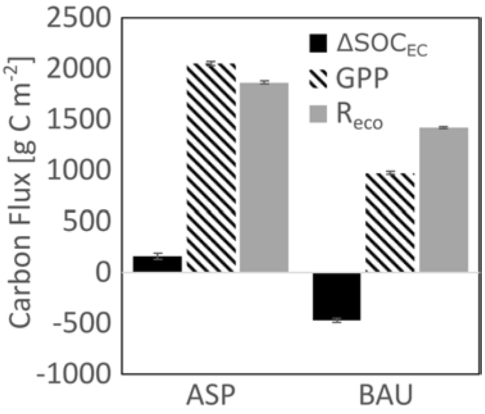

**Fig. 7.** $\Delta SOC_{EC}$, GPP, and $R_{eco}$ estimated with the eddy covariance towers at the CMRB LTAR ASP and BAU sites during cover crop (ASP) and fallow (BAU) periods. The sum of all cover crop (ASP) and fallow (BAU) periods is used. Due to management and different crop rotations, these periods do not match. The cover crop period at ASP is 857 days while the fallow period at BAU is 1295 days. The error bars represent the random measurement uncertainty from the eddy covariance technique.

## 4. Discussion

### 4.1. Evaluating contributions of conservation practices to increased carbon storage

We evaluated three conservation practices that could cause the ASP field to accumulate carbon: (1) no-till reduces $R_{eco}$ and allows carbon to accumulate, (2) the addition of wheat and hay to the crop rotation stimulates carbon uptake, and (3) the inclusion of cover crops creates additional biomass input to the soils, facilitating increased carbon storage. Our analyses indicate that ΔSOC in the ASP system is not caused by reduced $R_{eco}$. Both the $R_{eco}$ and the ratio of $R_{eco}/GPP$ are higher at the ASP site than the BAU site. This suggests that carbon is returned to the atmosphere at a slightly higher rate at the ASP field than the BAU field and that no-till is not suppressing $R_{eco}$ within the ASP cropping system.

While the amount of carbon returned to the atmosphere is similar between the two sites, the carbon removed from the atmosphere as plant growth is not. Attribution of increases in soil carbon storage to particular crops is difficult in this study because an unknown amount of crop residue (including aboveground and belowground biomass) is left on the field after harvest or termination of the cover crops. During the subsequent growing season, this biomass residue serves as a substrate for heterotrophic respiration, which amplifies $R_{eco}$. This is illustrated by the difference in ΔSOC from maize and soybean at the ASP and BAU fields. The total yield and *GPP* for the two treatments is similar. Therefore, the large differences in ΔSOC during the growing season of maize and soybean are more likely related to decomposition of cover crop residue. At the ASP field, cover crop residue is decomposing during the maize or soybean growing season, which lowers the measured *NEP*. At the BAU field there is relatively little residue following the fallow period, so the *NEP* is higher. A key point underscored by analyses is the context dependence needed when interpreting EC results for individual crops because there is strong short-term memory of management in the prior cropping cycle. In other words, extrapolating our results to make claims that certain crops have more carbon sequestration potential than others is inappropriate because the ΔSOC for each crop depends on the antecedent conditions.

The inclusion of cover crops, which produces biomass that is retained in the ASP field, is the conservation practice best supported by our evidence. The cover crops in the ASP field are present when cash crops are absent and provide small, positive ΔSOC during these times in contrast to the large carbon losses experienced during fallow periods at BAU. The total amount of carbon removed from the ASP field as harvested biomass was 1571 ± 8 g C $m^{-2}$ compared to 1636 ± 7 g C $m^{-2}$ at the BAU field. While the carbon removed in wheat yield is low, the hay crop harvest removes most of the aboveground biomass, resulting in large amounts of carbon removed during the hay crop. The similar amount of carbon in yield, combined with the higher $R_{eco}$ at the ASP site means that in order to increase soil carbon storage the ASP site needs much higher *GPP* than the BAU site. The cover crops at the ASP site produce 885 g C $m^{-2}$ more *GPP* over the study period than the fallow period at the BAU site. Importantly, the portion of this *GPP* stored in plant material is added to the soil carbon budget because it is not harvested.

A potential mechanism that we have not explicitly tested in this experiment is if differences in microbial communities – potentially caused by different crop rotations or nitrogen management – between the fields affect the soil carbon cycling. There is evidence that N fertilization can stimulate the microbial community and lead to increases in SOC (Alvarez and Alvarez, 2005; Lu et al., 2009), though the greenhouse gas emissions from the fertilizer make this approach unsuccessful for mitigating climate change (Schlesinger, 2010). The fertilizer applications at the ASP site are controlled to minimize excess fertilizer input, which may suppress microbial activity and reduce $R_{eco}$ (Kitchen et al., 2015). We argue that this does not explain the differences in SOC between the ASP and BAU sites, primarily because the $R_{eco}$ at the ASP site is not lower than at the BAU site. This could be simply because the ASP site produces more biomass (i.e., more food for microbes), but the $R_{eco}/GPP$ ratio is higher at the ASP site than the BAU site (0.78 vs 0.76, respectively). Therefore, we believe there is not a big enough difference in nitrogen rates to elicit differences in the microbial communities.

### 4.2. Significance for design of climate smart agricultural practices

It has been proposed in the “4 per mil” initiative that anthropogenic emissions of $CO_2$ can be ameliorated by increasing carbon sequestration in soils at a global rate of 0.4 % (Chabbi et al., 2017). This proposal has been found to be technically feasible, though highly unlikely due to socioeconomic constraints (Soussana et al., 2019). At the ASP site, the rate of carbon accumulation in the soil is consistent with meeting the goal of 0.4 % $yr^{-1}$. The $\Delta SOC_{SS}$ corresponded to 1.7 % $yr^{-1}$, relative to the 2016 carbon stock, while the $\Delta SOC_{EC}$ rate was 0.80 % $yr^{-1}$. In contrast, the BAU site did not accumulate carbon at a rate consistent with the 4 per mil goal. The $\Delta SOC_{SS}$ rate was −0.7 % $yr^{-1}$ and the $\Delta SOC_{EC}$ rate was 0.12 % $yr^{-1}$. While it is unlikely that the high rate of carbon increase will continue indefinitely, due to soil carbon saturation, conservation practices can cause changes in soil carbon at a rate above the 0.4 % $yr^{-1}$ threshold. This is important because the 4 per mil initiative aims to have 0.4 % $yr^{-1}$ increases in global soil carbon stock, primarily by increasing carbon in agricultural and degraded lands (Chabbi et al., 2017; Minasny et al., 2017). It may be worth noting, however, that our soil measurements are for the top 1 m of soil and the eddy flux measurements measure the flux at the surface represent an unknown depth into the soil. While there are some discrepancies regarding which depth to measure changes in soil carbon, most studies examine the change in soil carbon over the top 30 or 40 cm of soil (Poulton et al., 2018). If we restrict our analysis to the top 30 cm of soil, the $\Delta SOC_{SS}$ at BAU is similar to the value using the deep cores, but the observed change at ASP misses $\Delta SOC_{SS}$ at deeper levels. Over the 6-year period, the $\Delta SOC_{SS}$ in the top 30 cm was −247 g C $m^{-2}$ at ASP while the total $\Delta SOC_{SS}$ was 1042 g C $m^{-2}$. This highlights the importance of deep soil cores when assessing soil carbon storage.

Previous studies have demonstrated that local climate influences the efficacy of climate smart practices, in particular finding they are more effective in warmer climates (Bai et al., 2019). Therefore, these results from the southern edge of the U.S. Corn Belt could provide insight into how Corn Belt agroecosystems to the north may respond to future warming trends (Bai et al., 2019). The relatively warm winters in Missouri, compared to the rest of the Corn Belt, allow cover crops to produce more biomass and therefore more carbon storage, during the winter season. Overall, this is likely a key factor controlling carbon storage changes at this site.

### 4.3. Suitability of eddy covariance and soil sampling to assess changes in soil carbon storage

Evidence regarding the effectiveness of climate smart agricultural practices has been mixed (Alvarez and Alvarez, 2005; Blanco-Canqui, 2022; McClelland et al., 2021; Rumpel et al., 2020). This is in part due to the challenge in accurately measuring changes in SOC in heterogeneous landscapes (Stanley et al., 2023). In this study, we demonstrate how eddy covariance data may be used to assess the impact of a collection of various climate smart practices. Spatial variability of soil carbon is high, which means many soil cores are required to assess field level changes (Gamble et al., 2017). Even with many soil cores, this variability results in high levels of uncertainty meaning that the change must be large enough to observe, which typically takes multiple years. Previous authors have suggested that EC measurements are useful for evaluating natural climate solutions because they measure the flux between an ecosystem and the atmosphere regardless of which pool the carbon ends up in (Hemes et al., 2021). In addition to this advantage, in our study, the EC method has lower uncertainty than the soil samples. It should be noted, however, that we have not performed an exhaustive analysis of the uncertainty from the EC approach.

Surprisingly, the eddy covariance system estimated lower values of ΔSOC than the soil samples at both the ASP and BAU fields. We expected this to be reversed as it is most likely that some carbon is washed away in runoff, which would not be detected by the EC because it did not return to the atmosphere within the flux footprint. In this study we only measure soil organic carbon and fluxes of carbon dioxide, so we are potentially missing carbon pathways such as $CH_4$ fluxes that affect the carbon balance. The uncertainty in both measurements, however, is high and the error bars overlap. Therefore, we cannot say that the EC method and the soil method give different results. Since both the EC method and the soil core method show that the ASP site had an increase in SOC over the 6-year period and no increase in SOC at the BAU site, we interpret this as strong evidence that the conservation practices were successful in building SOC derived from atmospheric $CO_2$.

## 5. Conclusions

In this study, we synthesized deep soil core data and eddy covariance measurements to assess the impact of climate smart agricultural practices on soil organic carbon in two fields in the Central Mississippi River Basin within the U.S. Corn Belt. We found the soil samples and eddy covariance methods agreed that the ASP site saw significant increases in SOC relative to the BAU site. This was only the case, however, when we used 1 m deep soil samples. When we restricted our analysis to the top 30 cm of soil, as is commonly done, the ASP site had almost 5x less change in SOC than when the 1 m soil samples were used. This highlights the importance of deep soil cores when analyzing changes in carbon stocks. We also examined how three conservation practices (no-till, cover crop, and expanded crop rotation) contribute to increased SOC. We used the continuous measurements of carbon flux from the eddy covariance towers to perform this analysis. We found that the combination of no-till, cover crops, and the expanded crop rotation were effective practices to offset soil carbon losses observed in the business-as-usual approach. The cover crops, which were not harvested, produced additional biomass relative to the fallow conditions at the BAU field. During the fallow period, losses of SOC occurred at the BAU field that were not observed at the ASP field. This was the primary time period that the ASP field had larger increases in carbon storage than the BAU field, reflecting the importance of the additional *GPP* from cover crops. These results highlight the importance of including cover crops, when they are not harvested and provide the field with continuous cover, as a key component of a climate smart agricultural system in the southern U.S. Corn Belt.

## CRediT authorship contribution statement

**Adam P. Schreiner-McGraw:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Curtis J. Ransom:** Methodology, Data curation, Writing – review & editing. **Kristen S. Veum:** Data curation, Writing – review & editing. **Jeffrey D. Wood:** Methodology, Writing – review & editing. **Kenneth A. Sudduth:** Data curation, Writing – review & editing. **Lori J. Abendroth:** Data curation, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data is publicly available from the AmeriFlux website.

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