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ORIGINAL RESEARCH

A minimally managed switchgrass ecosystem in a humid subtropical climate is a source of carbon to the atmosphere

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Abstract

Bioenergy has been identified as a key component of climate change mitigation. Therefore, quantifying the net carbon balance of bioenergy feedstocks is crucial for accurate projections of climate mitigation benefits. Switchgrass (*Panicum virgatum*) has many characteristics of an ideal bioenergy crop with high yields, low maintenance, and deep roots with potential for belowground carbon sequestration. However, the assessments of net annual carbon exchange between switchgrass fields and the atmosphere are rare. Here we present observations of net carbon fluxes in a minimally managed switchgrass field in Virginia (Ameriflux site US-SB2) over 5 years (3–7 years since establishment). Average annual net ecosystem exchange (NEE) of carbon was near zero (60 g C m^{-2} $year^{-1}$) but the net ecosystem carbon balance that includes harvested carbon (HC) was a net source of carbon to the atmosphere (313 g C m^{-2} $year^{-1}$). The field alternated between a large and small source of carbon annually, with the interannual variability most strongly correlated with the day of the last frost and the interaction of temperature and precipitation. Overall, the consistent source of carbon to the atmosphere at US-SB2 differs substantially from other eddy covariance studies that report switchgrass fields to be either neutral or a sink of carbon when accounting for both NEE and HC. This study illustrates that predictions of net carbon climate benefits from bioenergy crops cannot assume that the ecosystem will be a net sink of carbon from the atmosphere. Background climate, management, and land-use history may determine whether widespread deployment of switchgrass as a bioenergy feedstock results in realized climate change mitigation.

KEYWORDS
bioenergy, biomass, carbon, climate, eddy covariance, net ecosystem exchange, switchgrass

1 | INTRODUCTION

Carbon dioxide (CO_2) concentrations continue to rise in the atmosphere, primarily due to fossil fuel combustion (Christensen et al., 2013; Friedlingstein et al., 2020). One possible method of reducing CO_2 emissions is to replace fossil fuels with bioenergy (Pacala, 2004; Ragauskas et al., 2006). Bioenergy crops absorb atmospheric CO_2 to create biomass, with some portion that is harvested and used as fuel. In perennial bioenergy crops, the aboveground biomass is harvested and processed into fuel, while the belowground components remain on site. Therefore, perennial biofuel crops have the potential double benefit of offsetting CO_2 emissions by preventing fossil fuel combustion and sequestering carbon belowground. (Adler et al., 2007; Anderson-Teixeira et al., 2013; Wullschleger et al., 2010).

Switchgrass (*Panicum virgatum*) has emerged as a promising bioenergy feedstock for the United States (McLaughlin & Adams Kszos, 2005; Wright, 2007). Switchgrass is a fast-growing, perennial, grass species that is native to North America. It can have high yields (aboveground biomass) and is well-suited to various climate conditions (Parrish & Fike, 2005; Wright, 2007). Furthermore, switchgrass can have high belowground biomass, enhancing the potential to sequester carbon from the atmosphere into belowground pools (Parrish & Fike, 2005; USDA-Natural Resources Conservation Service, 2011). It has been shown to have low fertilizer and pesticide requirements and is compatible with conventional farming equipment (Wright, 2007). Sustained high yields of switchgrass biomass can require less than 50 kg N ha^{-1} $year^{-1}$, and some studies have shown sustained yields with little to no nitrogen additions (Bransby et al., 1998; Owens et al., 2013; Parrish & Fike, 2005).

While high yield production with few management inputs is important for a bioenergy crop, yields alone do not fully represent the climate mitigation potential of the crop because they do not represent the full carbon balance of the bioenergy ecosystem (O'Halloran & Bright, 2017). In addition to yields, the net ecosystem carbon balance (NECB) of a bioenergy feedstock includes the nongrowing season carbon fluxes and the carbon stored belowground. Therefore, field scale, year-round observations of CO_2 exchange with the atmosphere are required for a full accounting of the carbon balance of the bioenergy ecosystem.

Eddy covariance (EC) is a widely used method for measuring the net ecosystem exchange (NEE) of CO_2 between terrestrial ecosystems and the atmosphere at the field scale (Baldocchi, 2014). However, only a small number of studies have used EC to study the carbon balance of bioenergy switchgrass systems. Skinner and Adler (2010) studied a switchgrass field in Pennsylvania for 4 years, finding a net sink the first 3 years and a source the fourth year. Zeri et al. (2011) examined multiple bioenergy crops, including switchgrass, in central Illinois for 2.5 years and found switchgrass to be sink over the whole observation period. Wagle and Kakani (2014) used EC to study 2 and 3-year-old switchgrass stands in Oklahoma and found switchgrass to be either a small sink or small source depending on the climate conditions. However, their measurements were limited to the growing season, excluding any potential respiration fluxes during the dormant season (Wagle & Kakani, 2014). Eichelmann et al. (2016) used EC to study a mature switchgrass (sixth and seventh year) field in Ontario, Canada for 2 years and found that switchgrass can alternate between sink and source depending on the climate conditions. Di Virgilio et al. (2018) studied switchgrass using EC during the first 4 years of establishment in the Po River Valley in Northern Italy and found switchgrass to be a strong sink each year, even including harvested carbon (HC). Finally, Abraha et al. (2018) used EC to study two switchgrass fields for 8 years following establishment in Michigan and found that the switchgrass field's carbon balance depended on the previous land use. In particular, switchgrass planted on former agricultural land was a carbon sink, while switchgrass planted on former conservation grassland was a minor source.

Based on evidence to date, switchgrass fields are usually a net sink of carbon, with potential influences of age and the legacy effects from the previous land use on the sink strength (Abraha et al., 2018). However, with the existing small sample size, it is difficult to generalize to other regions and management regimes. In particular, the EC studies to date have not included warm and wet climatic conditions typical of the subtropical Southeastern United States, a region where switchgrass is currently being deployed as a bioenergy feedstock. Furthermore, the EC studies have also included regular nutrient fertilization as part of switchgrass management (Table 1) despite other non-EC studies showing that repeated nutrient fertilization is not necessarily required for sustained yields (Owens et al., 2013; Parrish & Fike, 2005).

To address this limitation we present 5 years of NEE observations, baled yields, and the NECB at a newly established EC site in central Virginia, USA. The site complements prior studies that were in cooler and less humid environments and were more intensively managed through nutrient fertilization. Furthermore, the site is an operational switchgrass field where the timing of harvest activities varies from year to year based on logistical and weather constraints. Therefore, this study includes the influences of weather and the timing of management events on annual carbon fluxes. Our study covers the years 3–7 since switchgrass establishment following conversion from a perennial grass field used for hay production.

TABLE 1 Annual carbon balance, climate, and fertilization rate from published eddy covariance switchgrass studies and this study

Age		GPP	RE	NEE	HC	NECB	Precipitation	Temperature	N Rate
Years	Year	g C m^{-2}	g C m^{-2}	g C m^{-2}	g C m^{-2}	g C m^{-2}	mm	C	kg N ha^{-1}
Virginia, USA									This study
3	2016–17	−2422	2635	213	127	340	1041	14.9	0
4	2017–18	−2335	2189	−146	297	150	972	13.2	0
5	2018–19	−2327	2486	160	258	418	1637	14.3	0
6	2019–20	−2930	2655	−276	508	232	1105	13.2	0
7	2020–21	−2326	2673	347	82	429	1626	14.7	0
Ontario, CA									Eichelmann et al. (2016)
7	2012	−1354	833	−380	486	106	533	9.4	78
8	2013	−1430	869	−430	371	−59	868	7.2	101
Pennsylvania, USA									Skinner and Adler (2010)
1	2004–05	−941	911	−31	0	−31	868	10.0	0
2	2005–06	−916	798	−118	38	−80	995	9.7	56
3	2006–07	−926	678	−248	154	−94	1071	9.9	56
4	2007–08	−915	726	−189	239	50	1059	9.8	56
Oklahoma, USA									Wagle and Kakani (2014)[a]
2	2011	−1192	884	−308	160	−148	525	16.7	75
3	2012	−2015	1526	−490	560	70	673	17.2	76
Illinois, USA									Zeri et al. (2011)
2	2009			−453	200	−253	1302	10.6	0
3	2010			−485	350	−135	931	11.7	56
Bolgna, Italy									Di Virgilio et al. (2018)
1	2012–13	−1191	786	−402	280	−122	575	14.4	0
2	2013–14	−1666	937	−726	520	−206	802	13.9	50
3	2014–15	−1755	5	−780	420	−360	829	15.0	50
4	2015–16	−1544	870	−675	490	−185	679	14.4	50
Michigan, USA (AGR)									Abraha et al. (2018)
1	2010			170	0	170	936	10.0	0
2	2011			−217	201	−16	975	9.0	56
3	2012			−177	201	24	796	11.3	56
4	2013			−289	453	164	1139	9.1	56
5	2014			−535	441	−94	971	7.5	0
6	2015			−355	430	75	1173	8.4	56
7	2016			−555	345	−210	948	10.7	56
Michigan, USA (CRP)									Abraha et al. (2018)
1	2010			−82	0	−82	936	10.0	0
2	2011			−235	138	−97	975	9.0	56
3	2012			−237	171	−67	796	11.3	56
4	2013			−382	376	−6	1139	9.1	56
5	2014			−346	244	−102	971	7.5	0
6	2015			−357	342	−15	1173	8.4	56
7	2016			−442	259	−183	948	10.7	56

[a]Cumulative sums from the growing season only.

2 | METHODS AND MATERIALS

2.1 | Site characteristics

We deployed an EC system in March 2016 over an 8.4-ha switchgrass field located on Sweet Briar College's campus in central Virginia (37.5605 N, −79.0884 W, elevation 240 m) as part of the Sweet Briar College Land Atmosphere Research Station (Figure S2). The site is registered on the Ameriflux Network as US-SB2. The field was previously used for hay production for at least several years and probably decades and was dominated by fescue species with some Johnsongrass (*Sorghum halepense*). The field was converted to switchgrass with multiple herbicide applications, including two applications of glyphosate in spring 2014 and spot treatments of sulfosulfuron for Johnsongrass in summer 2014. An upland cultivar of switchgrass (Blackwell) and 10% big bluestem (*Andropogon gerardii*) was sown in June 2014. The seed mixture included a micronutrient blend, but no further fertilization was applied in subsequent years. Mowing, bailing, and harvest removal occurred in the late summer to autumn of each year (Table 2).

The regional climate is humid subtropical (Köppen climate classification Cfa), with warm-humid summers and cool-mild winters. Temperatures over the period of observation were approximately equal to the 30-year average (Table 3). Precipitation varied substantially across the five study years, with approximately normal precipitation in 2016–17, 2017–18, and 2019–20 (ca. 1000 mm), and record-high precipitation in 2018–19 (1637 mm) and 2020–21 (1626 mm; Table 3). The soil is Clifford clay loam and Wintergreen clay loam, both severely eroded soils with very small organic horizons.

2.2 | Flux measurements

Flux measurements began on April 1, 2016, using the EC method. Here we use data covering the first 5 years of observation ending March 31, 2021. The EC instruments were mounted at 4 m above the ground level and included a sonic anemometer (Gill Windmaster Pro, Gill Scientific) and a closed path infrared-gas analyzer for measuring CO_2 and H_2O gas concentrations (Licor 7200; Licor Environmental). Data were collected continuously at 10 Hz and analyzed at 30-min time intervals using EddyPro version 7.0.6 (LI-COR & Inc., 2019). We implemented widely used EC processing algorithms in EddyPro, including double coordinate rotation, block average detrending, and density fluctuation compensation. Raw data were screened for spikes, amplitude resolution, drop-outs, absolute limits, skewness, and kurtosis according to Vickers and Mahrt (1997). Footprint estimation was performed according to Kljun et al. (2004). Because this footprint model depends on canopy height, we supplied a dynamic height file to the EddyPro software that specified daily switchgrass height. Height was determined by visually inspecting PhenoCam images (Seyednasrollah et al., 2019), using a vertical PVC pipe in the field, marked every 10 cm from the ground up to 2 m. We did not include an angle of attack correction, as the available correction includes artificial inflation of the vertical wind measurement (LI-COR & Inc., 2019). We used the meteorological sign convention where negative fluxes indicate flux downward toward the ground (i.e., negative NEE indicates carbon sink into the ecosystem).

2.3 | Biometeorology instruments

The tower was equipped with a four-way net radiometer (CNR4; Kipp & Zonen) to measure the incoming and outgoing shortwave and longwave radiation, 4 m above the ground and extended southward away from the tower base to avoid nonvegetation in the view shed of the instrument. Rainfall was measured by tipping bucket rain gauge (TR-525M; Texas Electronics). Air temperature and humidity were measured at two heights (2 and 4 m) using a thermistor/hygrsitor (HUMICAP HMP155; Vaisala) housed in a custom-aspirated radiation shield. Soil heat flux was measured using three replicate soil heat flux plates (HFP01; Hukseflux) installed 10 cm below the surface. Biometeorology observations were logged at 1-min intervals and subsequently averaged or summed to 30-min values to match EC observations. Air temperature, relative humidity, and incoming solar radiation were used to gap-fill missing carbon flux data, as described below.

2.4 | Filtering, gap-filling, and partitioning

We applied a two-part spatial filter to the half-hourly fluxes to limit the influence of observations that may not represent the switchgrass field. First, we used the flux footprint model (Kljun et al., 2004) estimates to identify the distance and direction where the cumulative normalized contribution to the flux footprint equaled 70%. Second, we removed any observations where the distance and direction of the 70% footprint fell outside of the switchgrass field. Finally, we removed all fluxes originating from the north quadrant (above 315° and below 45°) due to potential contamination from a brush pile at a range of 145 m.

To remove data with inadequate turbulence, we applied a friction velocity (u^*) filtering routine. This method removes observations where u^* falls below a calculated threshold, indicating that fluxes cannot be calculated using the EC method. We determined the u^* threshold by examining the relationship between u^* and NEE fluxes as in the study by Papale et al. (2006) using the REddyProc R package (version 1.2; Wutzler et al., 2018). The u^* threshold was determined for each calendar year individually such that the thresholds were 0.101, 0.093, 0.124, 0.094, and 0.113 for years 1–5, respectively. The final data coverage after all of the filters were applied was 47%. Data coverage for each observational year was 49%, 49%, 37%, 52%, and 49%, respectively, and missing data were distributed randomly throughout the year (Figure S1). While the data coverage was moderately low, this amount of filtering was required to ensure that the reported results represent the switchgrass in this small field.

To obtain annual and seasonal totals of NEE, we filled the gaps resulting from measurement interruptions or filtering with modeled values using the REddyProc R package (version 1.2) marginal distribution sampling algorithm (R Core Team, 2021; Reichstein et al., 2005; Wutzler et al., 2018), a widely used approach. This method utilizes the covariation of fluxes with meteorological variables and the temporal autocorrelation with the time of day. Gaps are filled by applying averages derived for a specific time of day, time of year, and meteorology.

To partition observations of NEE into gross primary production (GPP) and ecosystem respiration (RE) fluxes, we applied the REddyProc R package (version 1.2) implementation of the Reichstein partitioning method (Reichstein et al., 2005; Wutzler et al., 2018). The method uses nighttime data, when fluxes from photosynthesis are not present, to estimate the relationship between measured fluxes and air temperature. This relationship was then used to calculate daytime respiration fluxes using daytime air temperature observations. GPP was calculated as the difference between observed NEE and modeled RE. For more detail on this algorithm, see the study by Wutzler et al. (2018).

To analyze the ecosystem carbon fluxes that are most relevant for climate mitigation, we also calculated the NECB (Chapin III et al., 2011). We calculate NECB as NECB = NEE + HC, where HC is the harvested carbon. Therefore, NECB followed the same sign convention at NEE where negative numbers are net sinks of carbon from the atmosphere. HC was determined by using biomass weights reported by the harvesting company on a per field basis. We used the harvesting company standards of 15% moisture content and a carbon content of 44% (Eichelmann et al., 2016). Finally, we assumed contributions from other ecosystem carbon fluxes, including leaching, emission of volatile organic C, methane, and carbon monoxide were minimal.

2.5 | Uncertainty estimation

We estimated the gap-filling and observational uncertainty of each observation and its effect on annual cumulative sums of NEE. We assessed these sources of uncertainty by making 1000 random draws for each half-hour observation from a representative distribution. For half-hours that were gap-filled, this was based on a normal distribution centered on the estimated flux, with the standard deviation based on the variation resulting from different sized windowing within the REddyProc gap-filling algorithm (Wutzler et al., 2018). For non-gap-filled observations, the Laplace distribution was used based on the study by Hollinger and Richardson (2005), where the distribution is centered on the observed flux, and the scale increases with the flux magnitude. This resulted in 1000 randomly distributed flux estimates for each half-hour that were then averaged to the daily time step and summed over the whole time series and within observation year.

2.6 | Energy balance closure

We used energy balance closure (EBC) to evaluate the quality of our EC measurements. EBC was calculated by comparing the sum of the turbulent heat fluxes (sensible and latent heat) to the net radiation (longwave, shortwave, and ground heat flux). Our 30-min average EBC for the full observation period was 71%. The EBC of the individual observations years were 73%, 68%, 68%, 72%, and 74%, respectively. This EBC is not ideal but close to the typical range EC of studies globally, approximately 80% (Foken, 2008; Twine et al., 2000; Wilson et al., 2002). Lack of EBC at the half-hourly scale could result from multiple sources, including not resolving mesoscale eddies, errors in radiation measurements, and heat storage in biomass (Butterworth et al., 2020). Since the EC community has not widely adopted corrections for carbon fluxes due to lack of EBC, we report our results here solely for transparency.

2.7 | PhenoCam and phenology determination

To track the development of the switchgrass independently of the flux measurements, we installed a web camera connected to the PhenoCam network (Seyednasrollah et al., 2019) under the site name "sweetbriargrass." This webcam captures standard RGB images and uploads them to the PhenoCam server every 30 min. Per standard PhenoCam network methods (Seyednasrollah et al., 2019), we calculated a green chromatic coordinate (GCC) for the switchgrass pixels in the image by dividing the green layer by the total of all three layers such that GCC = Green/Green + Red + Blue.

Key phenological phases were determined using this GCC product and the NEE data from the EC system. Emergence was defined as the first day that GCC exceeded

0.36 within that year. This value is site specific and approximates the inflection point of the GCC time series. Determining the inflection points using standard methods proved problematic due to multiple peaks and valleys in the grass phenology (Figure 1). The beginning of the senescent period was determined by the sharp increase in daily NEE values apparent in the NEE time series. We determined the last frost date by examining the daily minimum air temperature and selecting the last day in each calendar year, before June 1, that the daily minimum was less than 0°C.

To examine the potential drivers of interannual variability in the net carbon balance, we examined the relationship between phenological, physiological, and management-related variables and annual NECB. Specifically, we focused on mean annual temperature (MAT), mean annual precipitation (MAP), the interaction of MAT and MAP (MAT × MAP), the date of switchgrass emergence, the date of the last frost, the date the field was mowed, the length of time between mowing and removal, and the NECB of the previous year. We demonstrate the strength of the pairwise relationships using the Pearson's correlation coefficient, and tested for significance using the corrplot R package (Wei & Simko, 2021). Other statistical tests, such as multiple linear regression, were not appropriate due to strong covariances among the predictor variables.

3 | RESULTS

3.1 | Phenology and Seasonal NEE

The temporal dynamics of NEE strongly reflect the seasonal phenology of a perennial grass crop. In the 2016–17 measurement year, emergence occurred on April 19, 2016 (Figure 1, Table 2). Daily NEE was negative for the first time on May 14, 2016, following a brief period of CO_2 release to the atmosphere that was potentially due to mowing that occurred immediately before the EC system installation (Figure 2). NEE decreased until June 18, after which NEE increased rapidly (Figure 2). The switchgrass field was mowed and raked into rows on September 11, 2016. However, due to rain and logistical delays, baling and removal occurred 26 days later on October 7, 2016. NEE decreased following harvest, and stabilized near zero in early November.

In the 2017–18 measurement year, emergence occurred on March 6, 2017, following winter temperatures 2.7°C above the 30-year normal (Table 3). NEE decreased until July 3, after which NEE increased rapidly (Figure 2). The maximum daily carbon uptake was stronger in 2017 than in 2016, reaching -9.5 g C m^{-2} day^{-1} on June 20, 2017 (Figure 2). The switchgrass field was mowed on August 20, 2017, immediately followed by bailing and removal on August 23, 2017 (Figure 1; Table 2). This relatively early and quick harvest and removal was followed by a steep increase in GCC, indicating a regrowth of switchgrass after removal of the bailed grass (Figure 1). Daily NEE totals remained positive during this period of regrowth, but the magnitude of CO_2 release was reduced.

In the 2018–19 measurement year, emergence occurred on April 23, 2018. NEE decreased until June 26, after which NEE increased rapidly (Figure 2). Mowing did not occur until October 7, 2018, with bailing and removal 17 days later, on October 24, 2018 (Table 2). There was no regrowth in 2018, with only a small change in GCC after harvest.

In the 2019–20 measurement year, switchgrass emerged on March 30, 2019, prior to the start of the observation year (observation year starts April 1). NEE decreased until June 24, 2019, after which NEE increased rapidly. The field was mowed on August 10, 2019 with the cut grass bailed and removed after 2 days on August 12, 2019. This early bailing and removal again allowed for the substantial regrowth of switchgrass, as shown in the increase in GCC (Figure 1). While the large secondary regrowth was similar to 2017–18, unlike in 2017–18, the field was a net sink of carbon shortly after the harvested grass was removed. During this regrowth period, daily NEE values were similar to the NEE during the growing season (Figure 2).

In the 2020–21 measurement year, emergence did not occur until May 1, 2020, the latest of all 5 years. This followed a very warm winter with temperature 3.1°C above

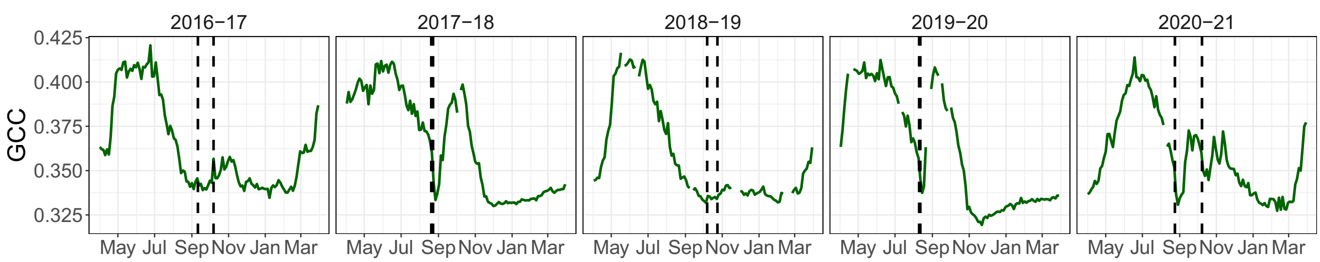

FIGURE 1 Green chromatic coordinate (GCC) for 2016–2021 from the Phenocam located at the field. Dashed vertical lines indicate when the field was mowed (first line within an observation year) and when the harvest was removed (second line within a calendar year)

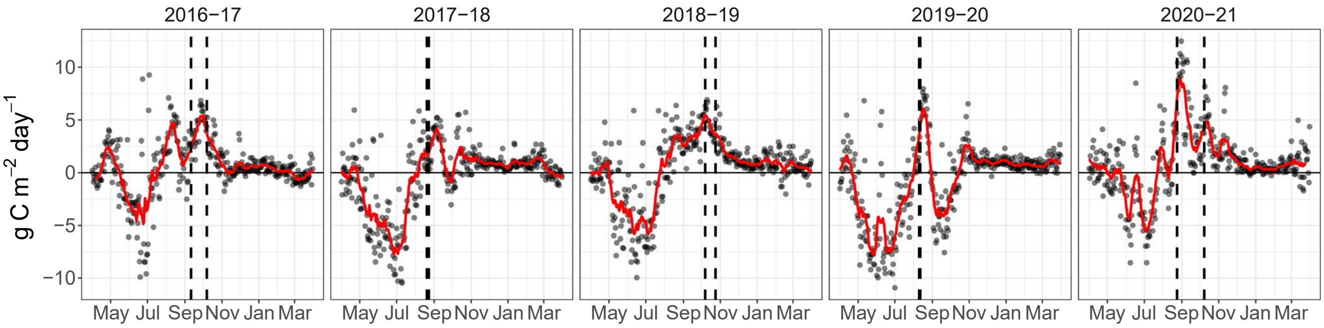

FIGURE 2 Daily sum of the net ecosystem exchange for 2016–2021 at US-SB2. The red trend line is a 14-day moving average. Dashed vertical lines indicate when the field was mowed (first line within a calendar year) and when the bales were removed (second line within a calendar year). Negative values indicate carbon being absorbed from the atmosphere

TABLE 2 Timing of major switchgrass phenology and management events for the field in central Virginia

Event	2016	2017	2018	2019	2020
Emergence	April 19	March 6	April 23	March 30	May 1
Senescent	June 18	July 3	June 26	June 24	July 6
Cutting	September 11	August 20	October 7	August 10	August 24
Removal	October 7	August 23	October 24	August 12	October 8

the 30-year normal. During the growing season, the daily NEE was negative on average, but, unlike the other years, included a period where NEE was near zero (Figure 2). NEE increased rapidly after July 6, 2020. The field was mowed on August 24, but bailing and removal did not occur until October 8, 2020. This was the only year that showed steep increase in GCC between mowing and bailing, indicating regrowth while cut grass was laying in the field (Figure 1).

3.2 | Cumulative sums

Over the five observation years, the switchgrass field was a net carbon source to the atmosphere, releasing a total of 300 g C m^{-2} (221–374; 95% confidence interval) or 60 g C m^{-2} $year^{-1}$ on average. The field alternated between a small source and small sink annually (Table 4). Mean annual RE was 2528 g C m^{-2} $year^{-1}$, and mean annual gross primary production (GPP) was 2486 g C m^{-2} $year^{-1}$ (Table 4).

The mean annual HC, calculated from yields reported by the operating company, was 254 g C m^{-2} $year^{-1}$ (Table 4). The 2 years with the lowest yields, 2016–17 and 2020–21, coincided with the longest time between mowing and removal (Table 2), indicating degradation of the laying grass. The yields in 2019–20 were double the average yield at 508 g C m^{-2}, coinciding with the earliest harvest observed.

The NECB is defined as the sum of all incoming and outgoing carbon fluxes at the plot or field level (Chapin III et al., 2011). Similar to NEE, we used the convention that a negative NECB is a net storage of carbon in the ecosystem. The NECB revealed that all years were net losses of carbon from the ecosystem, releasing 314 g C m^{-2} $year^{-1}$ to the atmosphere on average (assuming the HC was completely incinerated. The annual NECB alternated between larger and smaller sources (Table 4). Overall, NECB had lower interannual variability than NEE (NECB sd: 121 g C m^{-2} $year^{-1}$; NEE sd: 260 g C m^{-2} $year^{-1}$) because productive years with more negative NEE were associated with an increase in carbon removed through biomass harvest.

To examine the potential influence of meteorology, phenology, and management events on interannual variation in NECB, we calculated the correlation between the NECB and seven possible explanatory variables. We found that NECB was most strongly correlated with the emergence date ($r = 0.97$), the day of the last frost ($r = 0.93$), and the interaction of precipitation and temperature ($r = 0.92$; Figure 3). However, these variables were strongly correlated with each other, therefore the role of each factor alone or in combination as drivers of interannual variability cannot be evaluated.

4 | DISCUSSION

We found that a switchgrass field in central Virginia, actively used for bioenergy feedstock production but not fertilized, was a net carbon source to the atmosphere. This

TABLE 3 Monthly temperature and precipitation for 2016–2021 and the 30-year monthly averages from the nearest weather station to US-SB2 (Lynchburg, VA)

Month	Normal	2016–17	2017–18	2018–19	2019–20	2020–21
Temperature (°C)						
April	13.0	16.2	11.8	15.2	13.3	14.1
May	17.3	17.1	18.0	21.5	20.8	17.1
June	22.0	22.4	21.9	23.6	22.2	23.3
July	24.1	25.3	25.0	24.7	25.8	27.3
August	23.4	25.1	23.2	24.2	24.7	25.2
September	19.4	22.7	19.9	22.4	23.7	20.0
October	13.4	15.9	15.6	15.2	16.2	16.0
November	8.2	9.7	7.8	6.3		11.8
December	3.1	3.8	3.0	4.2	6.1	4.5
January	1.7	4.4	0.2	2.1	5.1	3.1
February	3.4	8.1	6.8	5.7	6.4	3.6
March	7.7	8.6	5.3	6.8	12.3	10.0
Average	13.1	14.9	13.2	14.3	13.2	14.7
Precipitation (mm)						
April	84	106	122	102	192	69
May	95	175	200	211	53	93
June	92	159	53	124	97	125
July	111	153	84	147	82	95
August	83	30	57	113	82	278
September	99	86	49	172	4	165
October	79	44	65	121	171	163
November	87	30	26	180	43	216
December	82	79	18	182	72	136
January	80	96	75	72	101	97
February	74	15	146	123	136	108
March	91	68	78	90	71	81
Sum	1056	1041	972	1637	1105	1626

TABLE 4 Carbon budget of the US-SB2 switchgrass field (g C m^{-2})

	NEE			NECB			
Year	Median	(95% CI)	HC	Median	(95% CI)	GPP	RE
2016–17	213	(178, 245)	127	340	(305, 367)	2422	2635
2017–18	−146	(−175, −116)	297	150	(122, 181)	2335	2189
2018–19	160	(125, 192)	258	418	(383, 450)	2327	2486
2019–20	−275	(−311, −238)	508	232	(197, 270)	2930	2655
2020–21	349	(308, 384)	82	429	(390, 466)	2326	2673
Average	60	(44, 74)	254	314	(298, 328)	2468	2528

Abbreviations: GPP, gross primary production; HC, harvested carbon; NECB, net ecosystem carbon balance; NEE, net ecosystem exchange; RE, respiration of ecosystem.

differs from other switchgrass EC studies, where most sites were net sinks of carbon from the atmosphere over their observation periods (Figure 4). Our site differs from the sites in these studies in multiple ways, including the combination of climate conditions, management activities, and land-use history.

Previous EC switchgrass studies included annual nutrient fertilization after establishment, while our site had no

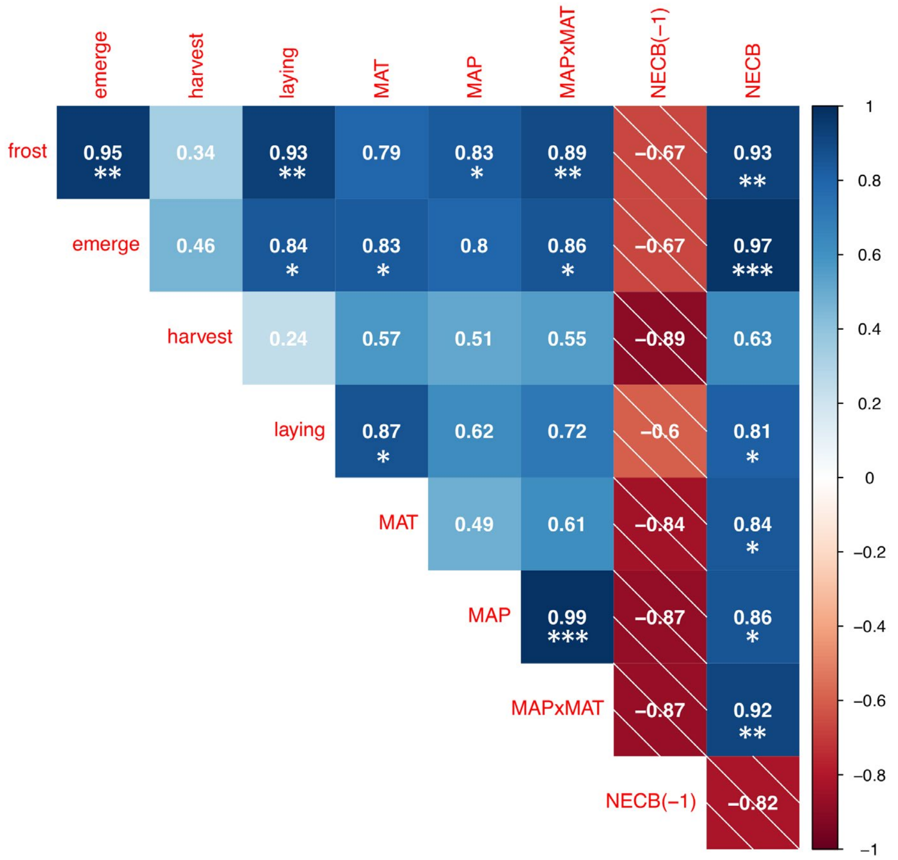

FIGURE 3 Correlation matrix of annual ecosystem carbon balance (NECB) and potential drivers of interannual variability. Stars demonstrate statistical significance, one star ($p < 0.1$), two stars ($p < 0.05$), and three stars ($p < 0.01$). Blue coloration with no hatches indicates positive correlation, and red coloration with hatches indicates negative correlation. Variables include the day of year (DOY) of the last spring frost (frost), the DOY of switchgrass emergence (emerge), the harvest DOY (harvest), the time between mowing and removal (laying), the mean annual temperature (MAT), the mean annual precipitation (MAP), the interaction of MAT and MAP (MAP × MAT), and the previous year's carbon balance (NECB(−1))

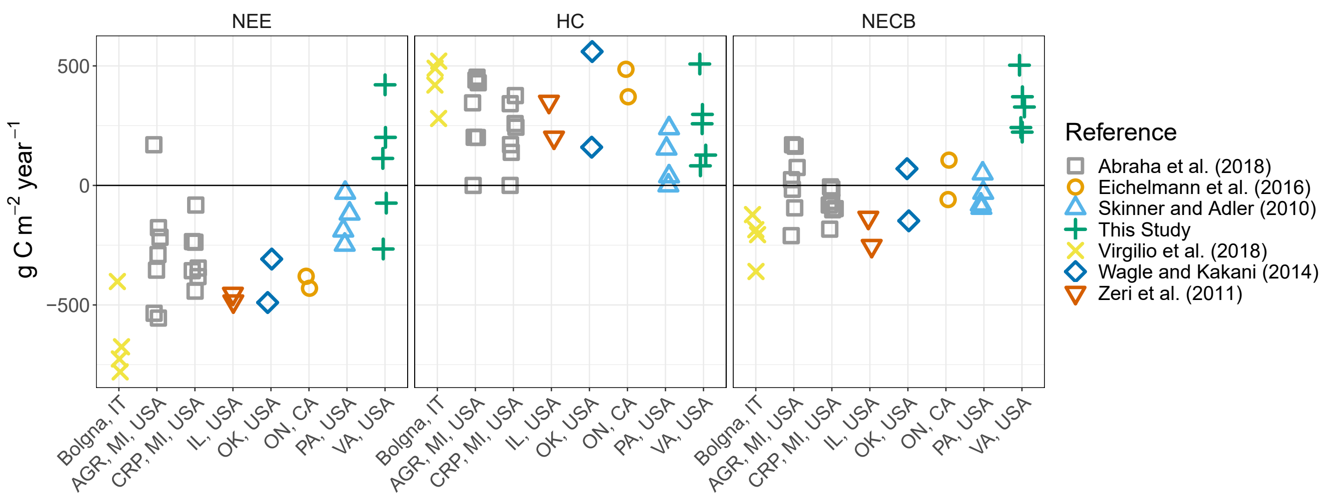

FIGURE 4 Overview of annual carbon balance, with and without accounting for harvested carbon, for published eddy covariance switchgrass studies and this study (Abraha et al., 2018; Di Virgilio et al., 2018; Eichelmann et al., 2016; Skinner & Adler, 2010; Wagle & Kakani, 2014; Zeri et al., 2011). Width of bars for each site depends on the number of site years

nutrient fertilization application after planting. The effect of fertilization on the net source or sink status of a switchgrass field is uncertain. While nitrogen additions have been shown to increase aboveground biomass, they can also reduce allocation to belowground biomass and increase root litter and soil decomposition (Stewart et al., 2016). This would suggest that our unfertilized field should have decreased decomposition and therefore belowground respiration. However, the lack of nitrogen additions increases the likelihood that this field was nitrogen limited. Grass species have been shown to prime soil decomposition through root exudation, presumably in search of nutrients

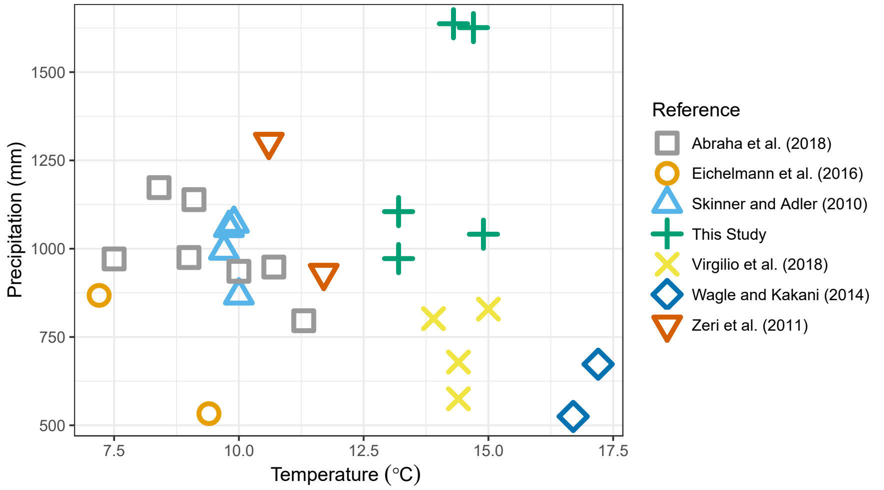

FIGURE 5 Climatic conditions (mean annual precipitation vs. mean annual temperature) from published switchgrass eddy covariance studies

(Kuzyakov et al., 2000; Shahzad et al., 2015). Given that the field had comparable yields to other EC studies (Figure 4), it is possible that the lack of nutrient fertilization resulted in an increase in priming-associated respiratory losses that were necessary to have similar yields. However, we lack any direct observations of this mechanism and future work should examine the role of priming in ecosystem carbon balance of switchgrass fields.

In addition to differences in nutrient fertilization, our site had the highest annual mean precipitation of other EC switchgrass studies, including two record years with rainfall that was 300 mm more than the next closest site. Our site was also among the warmest. Overall, this humid subtropical climate was unique among switchgrass EC studies (Figure 5). This warm-wet climate may alter the annual carbon balance through changes in the timing of key phases of NEE dynamics. First, spring NEE is not substantially different among EC studies in that daily NEE is first negative during the year in May across all EC studies that report daily time series and our study (Eichelmann et al., 2016; Skinner & Adler, 2010; Wagle & Kakani, 2014). However, growing season NEE dynamics appears to be accelerated. Other EC studies show that daily NEE remains negative until September, after which average NEE is near zero. Our study has positive NEE fluxes as early as July 18, leading to substantial losses of carbon as high as 10.3 g C m^{-2} day^{-1}, offsetting the carbon absorbed earlier in the year (Figure 2). The earlier timing of zero to positive NEE did not result in lower yields; carbon removed during harvesting (HC) at our site is very similar to other sites (Figure 4). The switchgrass field at our site may be completing the phenological cycle earlier in the year in concert with higher background respiration rates, resulting in the early positive NEE. Years with earlier harvest and regrowth of switchgrass were associated with a return to zero or negative daily NEE, suggesting that the climate may be able to support an earlier harvesting schedule that could be used to maintain negative daily NEE fluxes longer through the year by encouraging regrowth. The earlier harvest could allow for multiple harvest within a year but that was not directly explored in our study.

For our switchgrass field to be a carbon source to the atmosphere 3–7 years since establishment, the field must be releasing carbon that accumulated in the ecosystem during the prior land use or the first 2 years of switchgrass growth. Before conversion to switchgrass, the field was a perennial C_3 grassland used for hay production. Other studies examining postconversion carbon balance have found carbon losses when the previous land use was natural grassland with large soil carbon stocks (Abraha et al., 2018). Our site continues to respire carbon that had accumulated under a prior land use even 7 years after the conversion.

While the cumulative sum of NEE over the 5 years was positive, NEE showed interannual variability with 2 years exhibiting negative NEE. However, this interannual variability was lower when considering NECB variability because it combined NEE and HC (Table 4) and NEE was negatively correlated with baled yields. The timing of spring, as measured through emergence of switchgrass or date of last frost, was positively correlated with annual NECB (i.e., earlier spring is associated with more carbon storage in the ecosystem), suggesting that earlier springs from climate change (Hibbard et al., 2017) could reduce NECB, thus increasing carbon mitigation potential of the ecosystem. However, this conclusion should be made with caution because the years with earlier springs (as defined by the date of last frost) were highly correlated with the management outcome of the cut grass laying longer before baling and removing and with warm-wet annual weather conditions (Figure 3). These effects cannot be disentangled without a longer time series or more controlled experimental environment.

This work has implications for national bioenergy policy. Previous work has suggested that biofuel crops benefit climate by offsetting CO_2 and increasing belowground carbon storage (Adler et al., 2007; Anderson-Teixeira et al., 2013). However, there can be large differences in carbon sequestration rates based on species, region, age, and land-use history (Abraha et al., 2018; Di Virgilio et al., 2018; Eichelmann et al., 2016; Follett et al., 2012; Zeri et al., 2011). At this relatively warm and wet switchgrass site that was converted from a pasture, we found no net carbon sequestration 3–7 years after switchgrass establishment. This differs from previous work that has shown switchgrass fields to be a carbon sink or only a small carbon source even when HC is added to the annual sums. Overall, our study illustrates that predictions of net carbon climate benefits from bioenergy crops cannot assume that the ecosystem will be a net sink of carbon from the atmosphere. Climate, management, and land-use history may determine whether the widespread deployment of switchgrass as a bioenergy feedstock results in realized climate change mitigation. Future analyses need to consider this variation when assessing the climate benefits of switchgrass and other bioenergy crops.

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CONFLICT OF INTEREST

All 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 STATEMENT

The data that support the findings of this study are openly available at Zenodi at 10.5281/zenodo.5550340. Data will also be archived on the Ameriflux database under site ID US-SB2.

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