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ORIGINAL RESEARCH

Ecosystem-scale biogeochemical fluxes from three bioenergy crop candidates: How energy sorghum compares to maize and miscanthus

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Abstract

Perennial crops have been the focus of bioenergy research and development for their sustainability benefits associated with high soil carbon (C) and reduced nitrogen (N) requirements. However, perennial crops mature over several years and their sustainability benefits can be negated through land reversion. A photoperiod-sensitive energy sorghum (*Sorghum bicolor*) may provide an annual crop alternative more ecologically sustainable than maize (*Zea mays*) that can more easily integrate into crop rotations than perennials, such as miscanthus (*Miscanthus × giganteus*). This study presents an ecosystem-scale comparison of C, N, water and energy fluxes from energy sorghum, maize and miscanthus during a typical growing season in the Midwest United States. Gross primary productivity (GPP) was highest for maize during the peak growing season at 21.83 g C m⁻² day⁻¹, followed by energy sorghum (17.04 g C m⁻² day⁻¹) and miscanthus (15.57 g C m⁻² day⁻¹). Maize also had the highest peak growing season evapotranspiration at 5.39 mm day⁻¹, with energy sorghum and miscanthus at 3.81 and 3.61 mm day⁻¹, respectively. Energy sorghum was the most efficient water user (WUE), while maize and miscanthus were comparatively similar (3.04, 1.75 and 1.89 g C mm⁻¹ H₂O, respectively). Maize albedo was lower than energy sorghum and miscanthus (0.19, 0.26 and 0.24, respectively), but energy sorghum had a Bowen ratio closer to maize than miscanthus (0.12, 0.13 and 0.21, respectively). Nitrous oxide (N₂O) flux was higher from maize and energy sorghum (8.86 and 12.04 kg N ha⁻¹, respectively) compared with miscanthus (0.51 kg N ha⁻¹), indicative of their different agronomic management. These results are an important first look at how energy sorghum compares to maize and miscanthus grown in the Midwest United States. This quantitative assessment is a critical component for calibrating biogeochemical and ecological models used to forecast bioenergy crop growth, productivity and sustainability.

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KEY WORDS

bioenergy cropping systems, carbon, eddy covariance, light use efficiency, nitrogen, water use efficiency

1 | INTRODUCTION

The long-term ecological sustainability of bioenergy cropping systems is largely dependent upon the carbon (C), nitrogen (N), water and energy fluxes within these ecosystems (German et al., 2017; Whitaker et al., 2018). Perennial crops offer the best trade-off for biomass production and C sequestration due to their low N requirements (Heaton et al., 2009; Smith et al., 2013) and their extensive belowground allocation that provides a long-term store of C (Anderson-Teixeira et al., 2013; Robertson et al., 2017). However, if this C and N becomes disturbed through land-use change, it can quickly leave the system and negate the sequestration benefits of the crops (Abraha et al., 2019; Gelfand et al., 2011; Moore et al., 2020; Zeri et al., 2011). Such consequences could make it difficult for land managers to rotate between food and fuel crops to keep pace with market demands while maximizing long-term C storage in these agro-ecosystems. Annual bioenergy crop varieties offer an alternative to perennials that could be more easily integrated into existing crop rotation cycles and still potentially supply the cellulosic fuel requirements mandated by the United States (US) Energy Independence and Security Act of 2007 (Mullet et al., 2014; Olson et al., 2012; Rahall, 2007). While studies continue to evaluate biogeochemical cycles within bioenergy cropping systems, much uncertainty remains regarding the long-term ecological sustainability of these agro-ecosystems (Whitaker et al., 2018).

Energy sorghum (*Sorghum bicolor*) is a promising bioenergy feedstock due to its annual life cycle, drought tolerance and high rate of biomass production when grown in regions with long day length (Mullet et al., 2014; Oikawa et al., 2015; Olson et al., 2012; Rooney et al., 2007). These qualities make it easier to rotate with other annual cropping systems (i.e. soybean and maize) while contributing high yields for bioenergy production. Energy sorghum differs from grain and forage sorghums in that it is photoperiod sensitive, so it will delay flowering when grown in regions where growing season day length is long (Mullet et al., 2014; Murphy et al., 2011; Rooney & Aydin, 1999). This results in cellulosic biomass accumulation in energy sorghum more akin to that of high-yielding sugarcane (*Saccharum officinarum*) and miscanthus (*Miscanthus × giganteus*; Mullet et al., 2014; Olson et al., 2012). There is also potential to make substantial improvements toward maximizing yield while reducing water use through genomic manipulation and breeding programs (Mullet et al., 2014; Rooney et al., 2007), utilizing sorghum's genetic diversity. The ability to grow energy sorghum in low

rainfall regions of the United States could also alleviate the pressure a growing biofuel industry could place on existing land used for food production (Gelfand et al., 2013; Oikawa et al., 2015).

Understanding ecophysiological differences between bioenergy crops is an important requirement for assessing their long-term ecological sustainability. Unlike maize and miscanthus that are harvested after crop senescence, energy sorghum is harvested while still green due to the photoperiod-sensitive crop remaining in an active growth phase without grain formation or senescence into the cooler fall months. This longer-growing season and difference in harvested tissue will likely alter the C and N balance of energy sorghum compared to maize and miscanthus. A larger portion of energy sorghum biomass is removed during harvest compared with maize grown for grain, where the stover is returned to the soil. While a limited number of studies have suggested that energy sorghum stover removal rates may have only a small effect on SOC stocks in the Southern US (Dou et al., 2014; Mitchell et al., 2016), there is still considerable uncertainty around the long-term consequences of bioenergy sorghum stover removal on SOC in the Midwest US. Additionally, large amounts of N are removed from maize during harvest due to high N allocation to grain, whereas low rates of N are removed from a miscanthus field owing to translocation of N to rhizomes before harvest (Masters et al., 2016; Smith et al., 2013), with neither process occurring appreciably in energy sorghum. Olson et al. (2013) found energy sorghum to have an N use efficiency similar to miscanthus and sugarcane, attributed to its long vegetative growth, high stem to leaf biomass ratio and efficient N mobilization during development. Required rates of energy sorghum N fertilization (Maughan et al., 2012; Olson et al., 2013), N loss throughout the growing season, N removed during harvest, and how these losses compare with maize and miscanthus all remain uncertain.

Energy partitioning between annual and perennial crops can also differ substantially during growing and non-growing seasons (Hickman et al., 2010; Miller et al., 2016). In addition to its direct effect on local climate (Georgescu et al., 2011), energy partitioning is fundamentally linked with the amount of light captured for growth (Miller et al., 2016), and water evapotranspired (VanLoocke et al., 2012; Zeri et al., 2013). Through their impact on soil temperature and moisture, these biophysical characteristics, in turn, can affect key soil biogeochemical pathways such as soil nitrous oxide (N₂O) and soil carbon dioxide (CO₂) fluxes (von Haden et al., 2019; Smith et al., 2013). Moreover, these biophysical parameters either directly or indirectly alter the way perennial

and annual crops are represented in biogeochemical models (Bagley et al., 2014; Berardi et al., 2020; Georgescu et al., 2011; Surendran Nair et al., 2012), highlighting their importance for long-term bioenergy sustainability assessment. Currently, it is unclear whether energy sorghum biophysical and biogeochemical characteristics are closer to those of maize or miscanthus, since there are ways in which it is more like maize (i.e. annual life cycle) and other ways in which it is similar to miscanthus (i.e. long vegetative growth, harvest index). Quantifying these differences will provide important information required for modeling these cropping systems for long-term sustainability assessments (Berardi et al., 2020).

Given the increased focus on energy sorghum as a potential annual cellulosic bioenergy crop, in this study we sought to compare aboveground and belowground fluxes of C, N, energy, and water in energy sorghum, maize and miscanthus during a single growing season. As an annual cropping system, energy sorghum is managed similarly to maize but its longer-growing season makes it more comparable to perennial systems like miscanthus (Olson et al., 2012, 2013). Considering this, we hypothesized that at the ecosystem-scale energy sorghum would fall between maize and miscanthus, with (1) N fluxes like that of the maize annual cropping system and (2) C, water and energy fluxes more similar to the miscanthus perennial cropping system.

2 | MATERIALS AND METHODS

2.1 | Site description

This experiment was conducted in 2018 at the University of Illinois Energy Research Farm in Urbana, Illinois, USA. The regional climate is humid continental, with hot summers and severe cold winters. Long-term (1981–2010) mean annual rainfall is 1009 mm and air temperature ranges from a mean monthly winter minimum of -6.7°C up to a mean monthly summer maximum of 28.6°C (Figure 1a, NOAA, 2019). The

2018 growing season showed only slight deviation from the long-term mean air temperature, and cumulative annual rainfall was slightly higher than average, which was in part due to 1–2 substantial rainfall events in late May and early June (Figure 1b). Across the growing season, neither cropping system experienced soil moisture below the typical crop wilting point of $0.14\text{ m}^3\text{ m}^{-3}$ for the Champaign region (Illinois State Water Survey, 2020). As such, the 2018 growing season months can be considered a near-average climatic year for comparing the three bioenergy cropping systems, reducing the impact of extreme climate events on crop performance. Soils at the site are Mollisols comprised primarily of Flanagan silt loams, Dana silt loams and Drummer silty clay loams (Soil Survey Staff, 2015).

To compare the crops, four replicated 1 ha plots of miscanthus and a maize–maize–soy rotation were established in 2008 (Anderson-Teixeira et al., 2013). In 2014, the 1 ha miscanthus plots were split in half (0.5 ha) to accommodate an N fertilization treatment. In 2018, the 1 ha maize plots were split in half (0.5 ha) and energy sorghum was planted on one half and the second year of maize in the other. These plots were used to collect spatially replicated survey measurements across the three crops. Complementing these smaller plots was a larger 4 ha plot for each crop, with miscanthus establishment completed in 2010, maize–maize–soy established in 2017 and energy sorghum established in 2018 (Table 1). Prior to 2018, the 4 ha energy sorghum field was in a maize–maize–soy rotation, with 2017 as the maize year. These 4 ha plots contained an eddy covariance flux tower in the center to record high-frequency (10 Hz) information on ecosystem C, water and energy flux. The establishment of the energy sorghum eddy covariance flux tower was completed in 2018 after planting of the field so crop comparisons of ecosystem C, water and energy fluxes were focused in July, typically the month of peak canopy development, optimum soil moisture availability and highest solar radiation. Despite inherent differences in management and duration of the growing season for each of the three crops, all three crops were operating

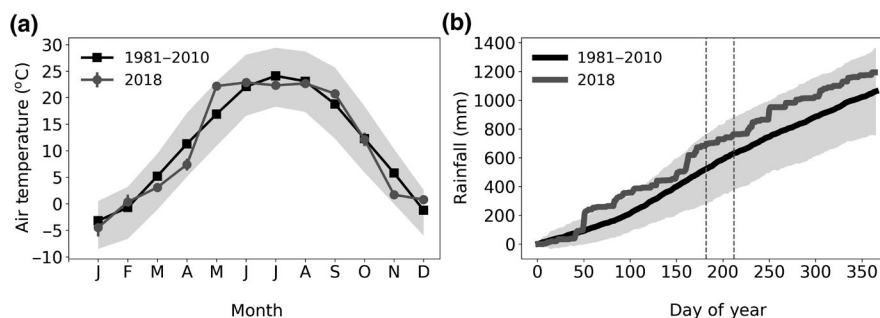


FIGURE 1 (a) Mean monthly air temperature (\pm SE) for 2018 against the long-term (1981–2010) monthly mean (\pm mean monthly max and min) and (b) cumulative annual rainfall for 2018 against the long-term (1981–2010) cumulative average (\pm 2 SD) for Champaign, IL, USA. (Long term rainfall = 1009 mm, 2018 rainfall = 1193 mm). The dotted vertical lines in (b) represent the peak growing season month of July. Long-term climate records were obtained from NOAA (2019)

TABLE 1 Agronomic management and yield metrics for *Zea mays* (Maize), *Miscanthus × giganteus* (Miscanthus) and energy *Sorghum bicolor* (Sorghum) for the 4 ha, and 0.5 ha plots at the University of Illinois Energy Research Farm during 2018. Yield values for maize are dry grain-only, miscanthus is senesced-dry biomass and sorghum is pre-senescence dry biomass

	Maize	Miscanthus	Sorghum
Fertilizer (N)	202 kg ha ⁻¹ 32% UAN, applied on 8th May	56 kg ha ⁻¹ granular urea N, applied on 18th May	112 kg ha ⁻¹ 32% UAN, applied on 8th May
Herbicide	Callisto, Infantry 4L & Verdict applied on 8th May HalexGT & Infantry 4L applied on 2nd June	N/A	Harness Xtra applied on 15th May at 4.2 kg ha ⁻¹
Tillage	Pre-plant using sunflower cultivator on May 8th Post-harvest using chisel plow on October 24th	N/A	Pre-plant using sunflower cultivator on May 8th Post-harvest using chisel plow on October 24th
Planting date	8th May	May 2008, reestablishment events in 2009 and 2010 to fill gaps	17th May
Planting density	83,980 seeds ha ⁻¹	~19 to 20,000 plants ha ⁻¹ (initial planting density)	185,250 seeds ha ⁻¹
Harvest date	9th October, 2018	March 7th, 2019	15th October, 2018
Peak biomass	19.87 ± 0.38 Mg ha ⁻¹	21.81 ± 0.48 Mg ha ⁻¹	23.00 ± 0.52 Mg ha ⁻¹
Yield	13.21 ± 0.32 Mg ha ⁻¹	12.86 ± 0.72 Mg ha ⁻¹	19.04 ± 0.95 Mg ha ⁻¹
Yield N-content	1.32 ± 0.13% N	0.28 ± 0.08% N	0.64 ± 0.05% N
N-removal	174.37 kg N ha ⁻¹	36.01 kg N ha ⁻¹	121.86 kg N ha ⁻¹

at, or close to, their maximum physiological range in July. All crops were managed according to best-known practice for the region, with major activities for each crop outlined in Table 1.

2.2 | Biomass and LAI

Leaf area index (LAI, m² m⁻²) was measured weekly for the three crops using a plant canopy analyzer (LI-2200; LICOR Biosciences). The peak in aboveground biomass production for each cropping system was assumed to be when weekly LAI measurements reached a plateau toward the end of the growing season. This was in early August for maize and in early September for miscanthus and energy sorghum, before inflorescence and translocation of nutrients in miscanthus (Masters et al., 2016). Biomass was collected biometrically from two locations, scaled and averaged in all 0.5 ha plots, and four locations in each 4 ha plot. A 75 × 75 cm quadrat was placed at random and all biomass was cut at approximately 10 cm from the ground, replicating combine/harvester activity. Biomass was separated by hand into major tissue fractions for maize (leaf, stem and seed/flower), then biomass for all three crops was oven dried at 60°C until dry, and weighed. Dried biomass fractions were ground using a Wiley Mill (Thomas Scientific), the maize fractions were mixed to homogenize and further sub-samples for all three crops were pulverized to a powder with a ball mill (Genogrinder

2010). The sub-samples were weighed into tin capsules and combusted in an Elemental Analyzer (Costech 4010) to determine percent C and N using apple leaves and acetanilide (National Institute of Science and Technology) as standards.

Maize yield was collected at plot scale in maize in October via combine (Case New Holland). Energy sorghum was harvested prior to senescence in October using a forage harvester (Case New Holland). All maize stover and the unharvested energy sorghum stubble were ploughed into the soil after harvest (Table 1). Miscanthus was harvested post-senescence the following spring using conventional forage harvesting chopping equipment, weighed and hauled away in forage wagons (Case New Holland). For harvest values, maize is reported as dry grain-only biomass, whereas miscanthus and energy sorghum are full-plant dry biomass (Table 1).

2.3 | Aboveground fluxes

The eddy covariance technique, as outlined in Moore et al. (2020), was used to characterize ecosystem-scale C, water (latent heat flux, LE) and energy (sensible heat flux, H) differences between maize, miscanthus and energy sorghum. Each flux tower supported an open path infrared gas analyzer (LI-7500RS; LICOR Biosciences) for atmospheric gas concentration and a 3D sonic anemometer (81000RE; RM Young) for wind speed and direction, all recorded at 10 Hz. Additional meteorological measurements included

air temperature and relative humidity (HMP-45C & 43347-IX; Campbell Scientific), incoming and outgoing short- and long-wave radiation (CNR1; Kipp & Zonen) and photosynthetically active radiation (LI-190; LICOR Biosciences), canopy temperature (SI-111; Apogee Instruments), soil heat flux at 10 cm (HFP01; Hukseflux), and soil temperature and moisture at 10, 20, 50 and 75 cm depths (Hydra Probe II; Stevens Water Monitoring Systems). Precipitation was obtained from the Illinois State Water Survey (Illinois State Water Survey, 2020). Meteorological measurements were recorded as 30-min averages.

All aboveground instruments were installed 2.5 m above the land surface, and height was increased as each crop canopy grew to ensure the instruments were ~1 m above the canopy at all times. The energy sorghum flux tower became operational on June 30, 2018 while the maize and miscanthus towers were operational since 2017. Given this, only growing season flux data for the three crops are presented, with maize ranging from planting date on May 8th to harvest on October 9th 2018, energy sorghum from June 30th to harvest on October 15th 2018 and miscanthus from emergence on May 8th to senescence on October 15th 2018 determined from phenocam imagery (Milliman et al., 2019).

The 10 Hz flux data were processed to 30-minute averages using EddyPro (v6.2.0; LICOR Biosciences). EddyPro settings included block averaging for flux de-trending, a double rotation to correct for instrument tilt, time lag correction using covariance maximization, Webb–Pearman–Leuning flux density correction (Webb et al., 1980), spike identification and removal from Vickers and Mahrt (1997), and a footprint calculation from Hsieh et al. (2000). The 30-minute flux and meteorological data were then quality assured and quality controlled (QA/QC) to remove spikes and apply a 50% footprint filter using the PyFluxPro tool as outlined in Isaac et al. (2017). PyFluxPro was also used to calculate a friction velocity (u^*) threshold for each site using the moving point test (Papale et al., 2006), which was 0.20 m s^{-1} for maize, 0.24 m s^{-1} for miscanthus and 0.17 m s^{-1} for energy sorghum.

Meteorological data were gap filled by PyFluxPro using external data sourced from a weather station at the University of Illinois Willard Airport (station ID: 725315–94870, 7.4 km away) and ERA5 data from the European Centre for Medium Range Forecasts. Next, the u^* filter was applied to each site to exclude flux data when conditions were not sufficient to support vertical turbulent transport, and then the C, water and energy fluxes were gap filled using a self-organizing linear output (SOLO) neural network model along with meteorological variables (Isaac et al., 2017). Evapotranspiration (ET, mm) was derived using gap filled LE (W m^{-2}) with the latent heat of vaporization of water. Lastly, net ecosystem exchange (NEE) was partitioned into ecosystem respiration (ER) and gross primary productivity (GPP) using the nighttime

temperature response function of Lloyd and Taylor (1994) and the SOLO model. All GPP, ER and NEE data reported are the average from these two models (\pm SE). Carbon flux abbreviations are applied based on Chapin et al. (2006).

2.4 | Belowground fluxes

Survey measurements of soil respiration were performed approximately weekly to determine growing season differences in autotrophic and heterotrophic respiration among the three crops. Shallow (installed 5–10 cm below the surface) and deep (installed 50 cm below the surface) polyvinyl chloride (PVC) collars were installed, and CO_2 flux was measured using a 20 cm diameter LI-8100-103 soil survey chamber and an LI-8100 portable gas analyzer (LICOR Biosciences). The shallow collars provided a measurement of total soil respiration (RS) and the deeper collars excluded most plant roots to provide an estimate of heterotrophic respiration (RH). The difference between RS and RH was the autotrophic respiration component (RA). Four collar pairs were installed in the 4 ha plots and two collar pairs were in each of the 0.5 ha plots to account for spatial variability. Measurements were made from June 1st to November 3rd 2018. Soil respiration fluxes that were more than five standard deviations outside of the mean for a cropping system within a given date, which accounted for only 0.25% of the total measurements, were taken to be non-representative and thus excluded from further analysis (Nelson et al., 2019). Soil flux abbreviations are based on those from Chapin et al. (2006).

Survey measurements of nitrous oxide flux (N_2O , $\text{mg N m}^{-2} \text{ day}^{-1}$) were also conducted from May 1st to August 31st 2018 to quantify N_2O losses to the atmosphere associated with each crop. Two-piece static flux chambers consisting of a PVC collar installed at 3–5 cm depth and a vented acrylonitrile–butadiene–styrene–plastic top were used. The collars were installed in the replicated plots and were left to settle for 30 min after installation to minimize the influence of N_2O loss from soil disturbance. The chamber head space was sampled at 10-minute intervals from 0 to 30 min after sealing each chamber. The gas samples were stored in evacuated glass vials and analyzed on a Shimadzu GC2014 gas chromatograph equipped with an electron capture detector. N_2O fluxes were calculated by fitting an exponential curve to the N_2O concentrations given by the GC as outlined in Matthias et al. (1978).

2.5 | Calculation of statistics and indices

Daily N_2O soil fluxes and soil respiration flux components (RS, RH and RA) were estimated using linear temporal interpolation between measured points, and cumulative growing

season fluxes were calculated for each crop using the daily estimates. Statistical differences of cumulative N_2O and soil respiration fluxes ($n = 5$) between the cropping systems were evaluated using a one-way ANOVA in R 3.6.3 (R Core Team, 2020). Normality and homogeneity of variance were verified using the Shapiro–Wilk test and Levene's test, respectively. Cropping system differences were assessed using the Tukey's HSD test for multiple comparisons ($p < 0.05$).

Descriptive statistics are reported for all flux tower derived values given the lack of spatial replication. Due to the difference in planting date, emergence and harvest/senescence for each crop, we calculated summary statistics for the month of July, as it is the month of peak growth and vegetative developmental stage for all three crops. The values presented are the mean (\pm SD) daily values for each crop during July.

Ecosystem physiological indices, in addition to the fluxes derived from the flux towers, were collected or calculated to provide a more in-depth comparison of the ecosystem-scale differences between the three crops. Daily water use efficiency (WUE) was defined by dividing net ecosystem productivity (NEP, g C m^{-2}) by ET (mm) to assess the amount of water used per gram of C uptake at the ecosystem scale. NEP was used instead of GPP to match the measurement scale of ET, as it is a combination of plant and soil processes at the ecosystem scale (Bernacchi & VanLoocke, 2015; Zeri et al.,

2013). Daily light use efficiency (LUE) was calculated by dividing GPP by mean daytime (i.e. 06:00–18:00 h, GMT-8) photosynthetically active radiation (PAR) to compare incident light energy (MJ) to C conversion efficiency for each crop. To determine differences in energy partitioning between the three crops, the Bowen ratio (β) was calculated as H/LE and albedo (α) was calculated as the ratio of outgoing-to-incoming short-wave radiation.

3 | RESULTS

3.1 | Carbon

During the 2018 growing season, ecosystem C fluxes from energy sorghum were more similar to those of miscanthus than maize (Figure 2), despite the annual life cycle of energy sorghum. During the peak growth month of July, energy sorghum had the highest mean daily NEE of $-11.87 \text{ g C m}^{-2}$ compared to maize with $-10.49 \text{ g C m}^{-2}$ and miscanthus with -7.44 g C m^{-2} (Table 2, includes \pm SD). This pattern was driven more by the relatively lower ER from energy sorghum (5.17, 8.13, 11.33 g C m^{-2} for energy sorghum, miscanthus and maize, respectively) than differences in GPP (Table 2; Figure 2b,c). In fact, mean daily July GPP for energy sorghum was 17.04 g C m^{-2} , which fell between

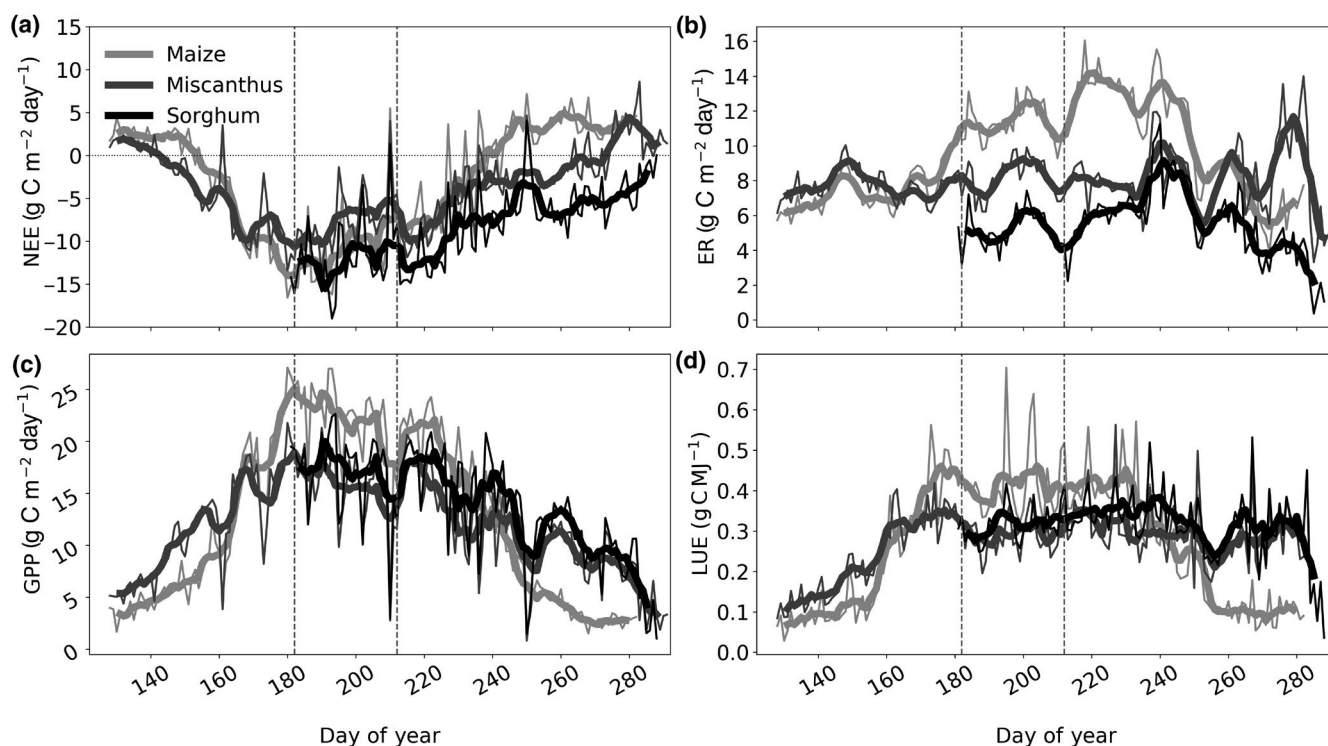


FIGURE 2 Daily (a) net ecosystem exchange (NEE), (b) ecosystem respiration (ER), (c) gross primary productivity (GPP) and (d) light use efficiency (LUE), all with a 7-day running mean (thick lines), observed during the 2018 growing season over energy *Sorghum bicolor* (sorghum), *Zea mays* (maize) and *Miscanthus × giganteus* (miscanthus) fields at the University of Illinois Energy Farm, Urbana, IL, USA. The dotted vertical lines in each subplot represent the peak growing season month of July

TABLE 2 Daily mean, SD, minimum and maximum values for fluxes and meteorological variables measured over *Zea mays* (maize), *Miscanthus × giganteus* (miscanthus), and energy *Sorghum bicolor* (sorghum) at the University of Illinois Energy Farm during July 2018. Variables include evapotranspiration (ET, mm day⁻¹), soil heat flux (Fg, W m⁻²), soil moisture at 10 cm (Sws, m³ m⁻³), soil temperature at 10 cm (T_s, °C), air temperature (T_a, °C), albedo (α), Bowen ratio (β), net ecosystem exchange (NEE, g C m⁻² day⁻¹), ecosystem respiration (ER, g C m⁻² day⁻¹), gross primary productivity (GPP, g C m⁻² day⁻¹), daytime mean photosynthetically active radiation (PAR, MJ m⁻²), ecosystem water use efficiency (WUE, g C mm⁻¹ H₂O⁻¹), ecosystem light use efficiency (LUE, g C MJ⁻¹), canopy temperature (T_c, °C) and leaf area index (LAI, m² m⁻²)

	Maize			Miscanthus			Sorghum		
	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max
ET	5.39 ± 1.44	0.96	7.35	3.61 ± 1.03	0.97	4.97	3.81 ± 1.08	0.67	5.37
Fg	-0.50 ± 5.46	-11.28	9.96	2.43 ± 3.69	-4.29	9.56	-0.35 ± 4.84	-9.88	9.20
Sws	0.30 ± 0.03	0.24	0.36	0.28 ± 0.03	0.23	0.33	0.38 ± 0.02	0.35	0.42
T _s	23.03 ± 1.90	19.26	26.35	21.92 ± 1.25	19.27	24.02	23.00 ± 1.85	19.64	26.10
T _a	22.32 ± 2.33	16.86	26.50	22.69 ± 2.37	17.06	26.97	23.31 ± 2.39	17.66	27.68
α	0.19 ± 0.05	0.13	0.30	0.26 ± 0.02	0.22	0.30	0.24 ± 0.02	0.19	0.28
β	0.13 ± 0.10	-0.04	0.33	0.21 ± 0.11	-0.07	0.43	0.12 ± 0.10	-0.10	0.36
NEE	-10.49 ± 4.40	5.51	-16.19	-7.44 ± 3.51	4.02	-13.82	-11.87 ± 4.12	1.35	-18.99
ER	11.33 ± 1.09	9.28	13.39	8.13 ± 1.08	6.22	9.91	5.17 ± 1.02	3.19	7.43
GPP	21.83 ± 4.48	3.78	27.01	15.57 ± 3.61	2.78	21.31	17.04 ± 4.02	2.97	22.65
PAR	54.65 ± 15.78	10.48	73.27	56.65 ± 16.12	10.53	77.29	54.74 ± 15.07	10.27	71.75
WUE	1.75 ± 1.46	-5.72	3.20	1.89 ± 1.24	-4.17	2.89	3.04 ± 1.19	-2.00	4.62
LUE	0.42 ± 0.09	0.32	0.70	0.29 ± 0.05	0.20	0.38	0.32 ± 0.04	0.25	0.42
T _c	23.61 ± 2.61	17.27	28.32	22.27 ± 2.41	16.62	26.64	21.98 ± 2.52	16.53	26.76
LAI	4.87 ± 0.69	4.30	5.87	5.53 ± 1.42	3.91	7.10	5.84 ± 0.59	5.16	6.59

miscanthus with 15.57 g C m⁻² and maize with 21.83 g C m⁻² (Table 2). Comparison of the three crops in terms of LUE during July revealed that maize was the most efficient at turning light into biomass with a mean daily LUE of 0.42 g C MJ⁻¹, miscanthus the least efficient at 0.29 g C MJ⁻¹ and energy sorghum falling between 0.32 g C MJ⁻¹ (Table 2; Figure 2d). At peak biomass, the cropping system with the highest biomass was energy sorghum at 23.00 Mg ha⁻¹, followed by miscanthus at 21.81 Mg ha⁻¹ and maize with 19.87 Mg ha⁻¹. The harvested dry biomass yields largely reflected this, with energy sorghum the highest due to its early harvest of 19.04 Mg ha⁻¹, and maize and miscanthus with less given the grain only harvest for maize at 13.21 Mg ha⁻¹ and late biomass harvest of 12.86 Mg ha⁻¹ for miscanthus (Table 1).

Soil CO₂ fluxes partially reflected differences seen in ER from the three crops. To correspond with measurements of eddy covariance, we only compared survey respiration measured between June 30th and October 9th of 2018 to ensure that there were overlapping daily estimates between the different methods. All three crops had similar total RS for this time period (486.70 g C m⁻², 473.30 g C m⁻² and 505.06 g C m⁻² for maize, miscanthus and energy sorghum, respectively, Figure 3). However, the RH contribution was significantly higher ($p < 0.05$, Figure 3) in maize (306.06 g C m⁻²) than in energy sorghum (212.20 g C m⁻²) and miscanthus

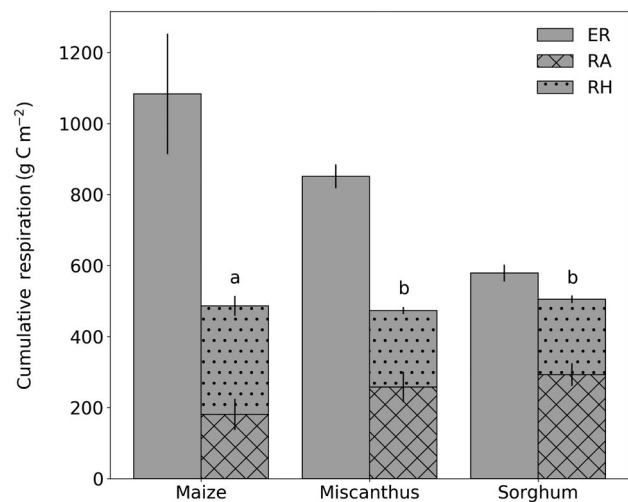


FIGURE 3 Total cumulative ecosystem respiration (ER) fluxes and the soil heterotrophic respiration (RH) and autotrophic respiration (RA) components for energy *Sorghum bicolor* (sorghum), *Zea mays* (maize) and *Miscanthus × giganteus* (miscanthus) from June 30th to October 9th of 2018 at the University of Illinois Energy Farm, Urbana, IL, USA. Total soil respiration (RS) represents the sum of RH and RA. Letters above bars represent significant differences between RH only

(215.22 g C m⁻²). This, in turn, resulted in energy sorghum and miscanthus having higher average RA than maize, but this was not statistically significant.

3.2 | Water

Comparison of ET showed maize had the highest flux, with a mean July rate of 5.39 mm day^{-1} , peaking at 7.35 mm day^{-1} on July 17th (Day of Year [DOY] 198, Table 2; Figure 4b). Energy sorghum showed ET rates very similar to miscanthus (Figure 4b), with a mean rate of 3.81 mm day^{-1} for energy sorghum and 3.61 mm day^{-1} for miscanthus during July (Table 2). Energy sorghum showed peak ET of 5.37 mm day^{-1} also on July 17th (DOY 198) but miscanthus ET peaked earlier in the growing season with 5.32 mm day^{-1} on June 3rd (Figure 4b). Interestingly, soil moisture was highest in the energy sorghum field for most of the season (Figure 5a) so it is unlikely that the high ET from maize was due only to soil moisture availability. Although maize had the highest ET, energy sorghum had the highest WUE in July (3.04 g C mm^{-1}), while miscanthus and maize were comparatively similar (1.89 and 1.75 g C mm^{-1} , respectively, Table 2). This WUE trend changed for maize in August when it began to senesce, resulting in its WUE noticeably deviating from miscanthus and energy sorghum (Figure 4c).

3.3 | Energy

Evaluation of the energy partitioning differences between the three crops during July revealed miscanthus to have the highest Bowen ratio (β) of 0.21 , while energy sorghum and maize were comparatively similar with 0.12 and 0.13 , respectively (Table 2; Figure 4a). The β was particularly high for the crops at the beginning of the growing season when LAI was low, indicating greater energy partitioning to sensible heat (H) when the plant canopy was still developing

(Figure 4a). Both miscanthus and energy sorghum showed very similar albedo (α , Figure 5c), with mean July values of 0.26 for miscanthus and 0.24 for energy sorghum. Interestingly, maize α was much lower than miscanthus and energy sorghum (Figure 5c), only reaching the range of the other crops briefly in July. Maize also saw a faster increase in its β due to earlier crop senescence. As such, maize had a mean July α of 0.19 , which likely contributed to the warmer canopy temperature of maize compared to energy sorghum and miscanthus through the growing season (Figure 5e).

3.4 | Nitrogen

Cumulative net soil-atmosphere N_2O fluxes over the 2018 growing season were similar between energy sorghum and maize, both of which were significantly higher than miscanthus (Figure 6). The highest N_2O fluxes for energy sorghum and maize occurred during two time points in June, which followed N fertilization (first increase) and coincided with increased air temperature and rainfall (second increase) during that month (DOY 150–180, Figure 1). After June, net N_2O fluxes for all three crops were low such that the cumulative N_2O fluxes stabilized. For the growing season months, total cumulative N_2O fluxes were $12.04 (\pm 2.00) \text{ kg N ha}^{-1}$ for energy sorghum, $8.86 (\pm 2.76) \text{ kg N ha}^{-1}$ for maize and $0.62 (\pm 0.10) \text{ kg N ha}^{-1}$ for miscanthus (Figure 6). Despite the high N_2O loss from energy sorghum, the amount of N removed during harvest was lower compared to maize, at 121.86 and $174.37 \text{ kg N ha}^{-1}$, respectively (Table 1). Miscanthus had the lowest N removal from harvested biomass at $36.01 \text{ kg N ha}^{-1}$ (Table 1).

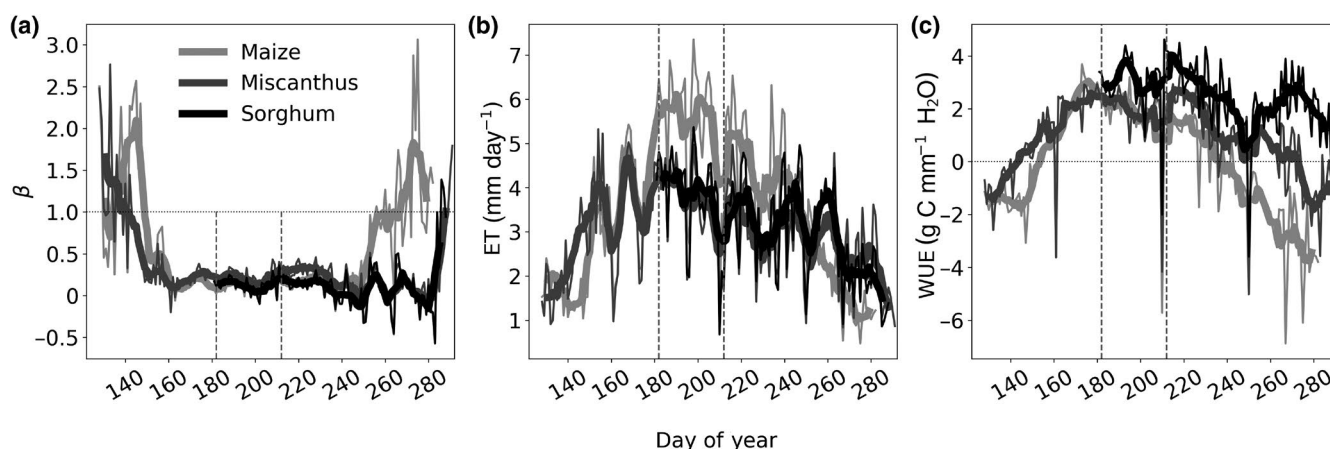


FIGURE 4 Differences in daily (a) Bowen ratio (β), (b) evapotranspiration (ET) and (c) water use efficiency (WUE), all with a 7-day running mean (thick lines), measured over energy *Sorghum bicolor* (sorghum), *Zea mays* (maize) and *Miscanthus × giganteus* (miscanthus) during the 2018 growing season at the University of Illinois Energy Farm, Urbana, IL, USA. The dotted vertical lines in each subplot represent the peak growing season month of July

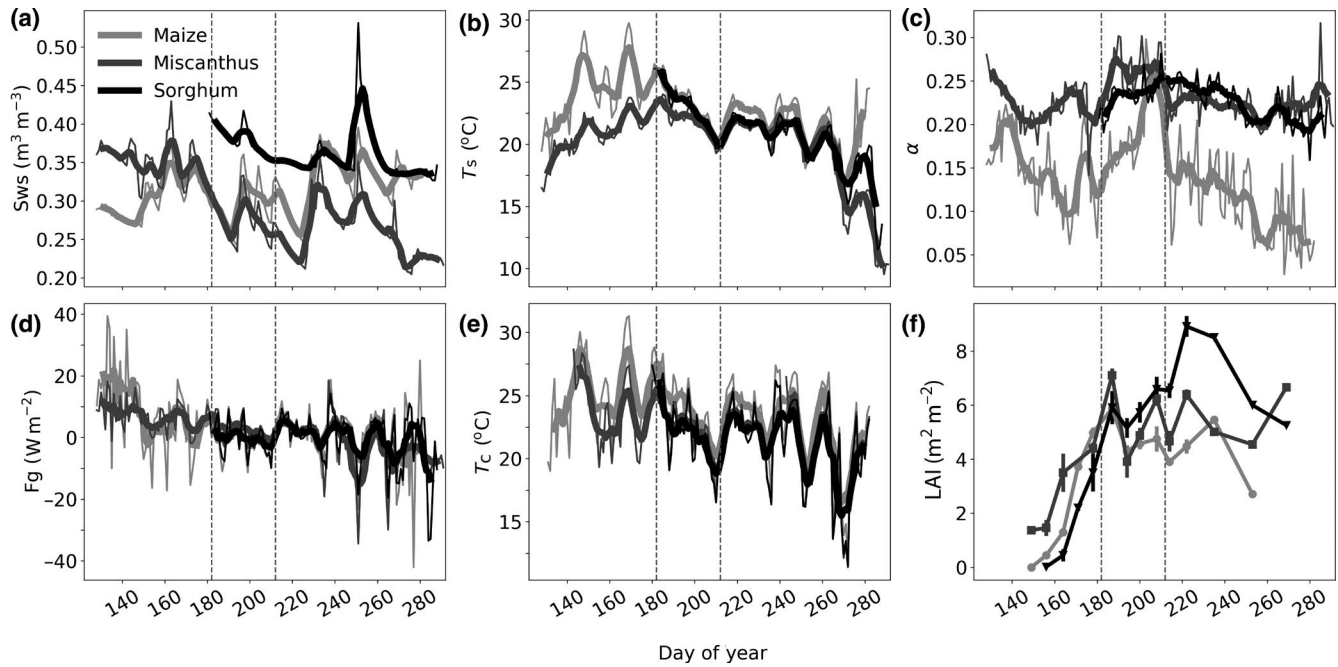


FIGURE 5 Comparison of (a) soil moisture at 10 cm (Sws), (b) soil temperature at 10 cm (T_s), (c) albedo (α), (d) soil heat flux at 10 cm (F_g), (e) canopy temperature (T_c) and (f) leaf area index (LAI) for energy *Sorghum bicolor* (sorghum), *Zea mays* (maize) and *Miscanthus × giganteus* (miscanthus) grown during the growing season of 2018 at the University of Illinois Energy Farm, Urbana, IL, USA. Figures (a)–(e) show daily data with a 7-day running mean (thick lines)

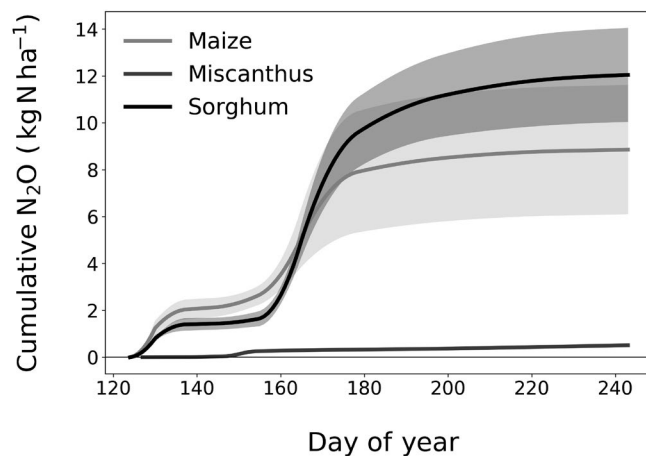


FIGURE 6 Cumulative soil nitrous oxide (N_2O) flux from energy *Sorghum bicolor* (sorghum), *Zea mays* (maize) and *Miscanthus × giganteus* (miscanthus) during the 2018 growing season at the University of Illinois Energy Farm, Urbana, IL, USA

4 | DISCUSSION

Increased interest in energy sorghum as a bioenergy feedstock in the United States necessitates an understanding of how this cropping system compares on an ecophysiological level to maize and miscanthus; two of the other bioenergy crop candidates. As hypothesized, energy sorghum falls between the two contrasting bioenergy cropping systems maize

and miscanthus in most of our measured ecophysiology parameters (Table 2). We showed during the peak growing season (i.e. July), when all three crops were at their maximum productive potential, that energy sorghum fell between maize and miscanthus for GPP (21.83, 17.04 and 15.57 $g C m^{-2} day^{-1}$ for maize, energy sorghum and miscanthus, respectively) and LUE (0.42, 0.32 and 0.29 $g C MJ^{-1}$ for maize, energy sorghum and miscanthus, respectively). Energy sorghum did have the highest July NEE, which was driven by comparatively lower ER than the other two crops (Table 2). However, assessment of cumulative RS components revealed that energy sorghum RA and RH were not significantly different from miscanthus over a longer-growing season period (June–October), whereas maize had significantly higher RH (Figure 3). For water use, energy sorghum had a July rate of 3.81 $mm day^{-1}$, falling between that of miscanthus on the low end with 3.61 $mm day^{-1}$ and maize the highest with 5.39 $mm day^{-1}$ (Table 2; Figure 4b). Yet, when ecosystem ET was scaled using net C uptake (NEP) by each ecosystem, the WUE of energy sorghum was the highest of the three crops (1.75, 1.89 and 3.04 $g C mm^{-1} H_2O$ for maize, miscanthus and energy sorghum, respectively). Energy sorghum was similar to maize in its N fluxes, with both cropping systems showing much higher soil N_2O loss than miscanthus (8.86, 12.04 and 0.51 $kg N ha^{-1}$ for energy sorghum, maize and miscanthus, respectively). However, the amount of N removed through harvest from energy sorghum was lower than maize, but not as low as miscanthus (121.86, 174.37 and

36.01 kg N ha⁻¹, respectively, Table 1). These findings indicate that while energy sorghum has an annual life cycle like a maize crop and has similar N₂O dynamics, it behaves more like a miscanthus crop during the growing season in the way that it captures light energy and uses water to produce biomass.

The longer growth period of energy sorghum, akin to that of the perennial miscanthus, makes it an ideal bioenergy feedstock candidate given the extra time it has to produce biomass (Mullet et al., 2014; Olson et al., 2012; Rooney et al., 2007). While maize GPP and ET exceeded that of energy sorghum and miscanthus during the peak (July) growing season, this was only short-lived. By mid-August, maize had transitioned into the senescence stage while both miscanthus and energy sorghum maintained high rates of GPP and ET through September (Figures 2c and 4b). The addition of lower peak growing season ET from energy sorghum compared to maize, despite the higher soil moisture in the energy sorghum plot that should promote higher ET, reflects the WUE and subsequent drought tolerance of energy sorghum (Mullet et al., 2014), which lends it to potential expansion across a wider climatic growing region than maize (Gelfand et al., 2013; Maw et al., 2017). While some studies have shown little difference in ET and WUE between maize and a hybrid energy sorghum–sudangrass variety (Roby et al., 2017), others have indicated energy sorghum's water demand is offset by its high productivity and thus WUE (Oikawa et al., 2015). Our WUE results suggest that energy sorghum does indeed produce a large amount of biomass per water volume used in the Midwest region (Table 2; Figure 4c), which highlights the climatic flexibility of energy sorghum as a bioenergy feedstock. The ability to grow non-irrigated energy sorghum in a wider climatic range to take advantage of its WUE will be important for mitigating competing interests between the food and fuel industry for land space. Extending this analysis to include an assessment of inter-annual WUE of the three cropping systems should be an important priority for further research.

The lower respiration fluxes observed from energy sorghum, particularly RH, also make it similar to miscanthus (Table 2; Figure 3). Although energy sorghum is an annual cropping system, it had a higher albedo than maize, resulting in cooler canopy and soil temperatures and less radiative loading to drive ET (Figure 5). The warmer temperatures likely contributed to higher ER in maize than energy sorghum, which was driven in part by higher RH from maize. Such a response is not so surprising given heterotrophic respiration rises with increasing temperatures (Lloyd & Taylor, 1994), and is reflective of the lower planting density and more open canopy of maize compared to energy sorghum and miscanthus (Figure 5). In addition to cooler soil temperature, the higher soil moisture in energy sorghum compared to maize may have also caused lower RH (von Haden et al., 2019; Moyano et al., 2013). The 4 ha energy sorghum plot,

which is adjacent to the maize plot but is slightly lower-lying, experienced substantial waterlogging following precipitation events in June; this likely contributed to lower RH and subsequent ER throughout July (Figure 3). The smaller replicated plots, where only the chamber-based measurements were made, were generally less prone to waterlogging, which may partially explain the unexpectedly small apparent difference between total soil respiration (chamber-based) and ER (eddy covariance-based) in energy sorghum. Even within the 4 ha plot, where both soil respiration and ER were measured, the temporally variable footprint of the eddy covariance ER measurements cannot be expected to exactly match the static footprint of the chamber-based soil respiration measurements. Despite the challenges of matching observations at different scales, our results provide a useful insight into differences in respiration processes occurring between the three bioenergy cropping systems and show that energy sorghum respiration fluxes are more similar, overall, to miscanthus than maize.

Maize was also the most efficient cropping system in terms of converting light energy into biomass, despite having lower LAI and higher ET. This result likely reflects the many years of genetic and agronomic development of maize to optimize productivity, which is supported by regional and global terrestrial primary productivity assessment studies that show maize is one of the most productive ecosystems during its peak growing season (Guan et al., 2016; Guanter et al., 2014). Both energy sorghum and miscanthus are yet to realize this level of agronomic optimization (Farrar et al., 2018; Mullet et al., 2014), so the opportunities to improve the LUE of both cropping systems remains promising. This agronomic optimization was also reflected in the higher albedo for energy sorghum and miscanthus, which was likely due to less refinement of leaf angle to increase light interception when compared to maize (Drewry et al., 2014), as well as leaf biophysical properties, such as higher epicuticular wax content seen in energy sorghum (Awika et al., 2017). Energy sorghum takes approximately 6 weeks to establish a closed canopy and reach its maximum daily GPP, but once it does so it remains green and productive until harvest due to its photoperiod sensitivity and long growth duration (Olson et al., 2012), as evidenced by its continued high GPP into August and September when maize is reduced (Figure 2c). Once harvested, the energy balance of energy sorghum may be more similar to maize than miscanthus through the winter months, given the greater ability of snow to influence albedo in annual compared to some perennial systems (Miller et al., 2016). This biophysical difference will be important for evaluating the seasonal energy contribution of energy sorghum to climate forcing through albedo feedbacks (Bagley et al., 2014; Georgescu et al., 2011), and should be a focused of continued research efforts of these three cropping systems.

Continued measurements will be critical for better resolving the time-integrated ecosystem C and N balances in these cropping systems. In the maize system, only the grain was harvested, which facilitates substantial C and N return to soil as residue. In contrast, most of the aboveground biomass were harvested in the energy sorghum system, and therefore aboveground C and N residue returns are minimal. Moreover, unlike maize and miscanthus, the energy sorghum system is harvested prior to senescence, which leads to higher N removal from energy sorghum biomass compared with miscanthus. While the maize and miscanthus cropping systems were established years prior to the study, the energy sorghum system was converted from a maize system at the onset of this study. As the energy sorghum system reaches steady state, the C and N fluxes are likely to shift drastically to reflect the perpetual reduction in biomass C and N inputs (Jin et al., 2014; Kent et al., 2020). Recent model-based work showed the potential for energy sorghum to increase soil organic C through root biomass input in regions of the United States where rainfall, temperature and moisture availability facilitate high growth rates (Gautam et al., 2020). However, this study was based on broad assumptions made regarding agronomic management and the energy sorghum variety used (Gautam et al., 2020), so further observational studies of long-term ecosystem C and N pools and fluxes are needed to fine-tune models that assess the long-term differences between these three bioenergy crop candidates.

Agronomic improvements of energy sorghum will require careful evaluation of its N requirements, given energy sorghum showed similar cumulative growing season N_2O fluxes as maize in this study (Figure 6), despite receiving half the fertilizer (Table 1). High N_2O effluxes in the early growing season for both maize and energy sorghum were likely derived from nitrification stimulated by high soil ammonium concentrations resulting from fertilizer N inputs (Edwards et al., 2018). Given the lower fertilizer application rate for energy sorghum, the early season cumulative N_2O flux was lower for energy sorghum compared to maize. In contrast, the high N_2O effluxes observed in the mid-growing season for both crops likely resulted from denitrification, an anaerobic process stimulated by wet soil conditions following rainfall events (Edwards et al., 2018). Energy sorghum plant establishment and root development was delayed when compared to maize due to the later sorghum planting date (May 17th vs. May 8th). During this time period, high N availability and soil moisture could contribute to higher N_2O efflux from sorghum than would be expected if N was applied closer to crop establishment. However, sorghum N_2O efflux also increased after the crops were well established (Figure 6). As a result, with higher soil moisture under energy sorghum, the mid-season peak in N_2O fluxes was higher for energy sorghum than maize, leading to comparable cumulative growing season N_2O fluxes for the two crops. Recent evidence also suggests

that optimum N fertilization rates for energy sorghum are approximately 56 kg N ha^{-1} (Maw et al., 2019; Schetter et al., 2020), which is closer to the rate applied to miscanthus in this study. It is therefore likely that our energy sorghum fertilization rate exceeded plant N requirements, and thus we would expect N_2O losses to be reduced with less N addition in future. Monitoring of N_2O fluxes and soil N cycling rates over multiple years with different precipitation patterns, as well as evaluation of energy sorghum N requirements will provide further insight into managing energy sorghum for more sustainable N cycling. Optimizing N fertilizer application for energy sorghum will not only reduce greenhouse gas emissions, but will help to reduce agricultural N runoff that could otherwise lead to hypoxic zones in marine systems (Hudiburg et al., 2016; VanLoocke et al., 2017).

This study showed that energy sorghum, despite having an annual life cycle, appeared to behave more like a perennial miscanthus ecosystem than a maize ecosystem in terms of its C, water and energy fluxes. However, it acted more like maize in terms of N fluxes. Continued observation of these fluxes over the three crops will be an important next step for comparing crop responses to extreme climate events (i.e. drought, floods and frost) and for assessing inter-annual biogeochemical differences. Perhaps most uncertain for energy sorghum are its long-term effects on soil organic C due to the high amount of biomass removed during harvest with little stover return (Dou et al., 2014; Gautam et al., 2020; Mitchell et al., 2016). A detailed understanding of the interaction between crop type, climate and management will be critical for forecasting the long-term sustainability of these key bioenergy crops that will play an important role in ensuring the United States meets its future cellulosic bioenergy requirements.

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AUTHOR CONTRIBUTION

All authors contributed to the experimental design. Manuscript preparation was led by Moore with input from all co-authors. Data contributions are as follows: Moore, Dracup, Gibson, Blakely and Bernacchi were responsible for measurement and analysis of the aboveground fluxes and LAI. von Haden, Burnham, Kantola, Masters, Yang and DeLucia were responsible for measurement and analysis of the belowground fluxes and biomass measurements.

DATA AVAILABILITY STATEMENT

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

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