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Evaluation of miscanthus productivity and water use efficiency in southeastern United States☆

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HIGHLIGHTS

- Dryland *Miscanthus* × *gigantus* yield was 12–15 Mg ha^{-1} in the southeastern USA.
- Carbon budgets indicated that both miscanthus and maize fields lost carbon.
- Miscanthus water use efficiency was comparable to maize when not under drought stress.

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ABSTRACT

Second generation biofuels, such as perennial grasses, have potential to provide biofuel feedstock while growing on degraded land with minimal inputs. Perennial grasses have been reported to sequester large amounts of soil organic carbon (SOC) in the Midwestern United States (USA). However, there has been little work on biofuel and carbon sequestration potential of perennial grasses in the Southeastern US. Biofuel productivity for dryland *Miscanthus* × *gigantus* and irrigated maize in Georgia, USA were quantified using eddy covariance observations of evapotranspiration (ET) and net ecosystem exchange (NEE) of carbon. Miscanthus biomass yield was 15.54 Mg ha^{-1} in 2015 and 11.80 Mg ha^{-1} in 2016, while maize produced 30.20 Mg ha^{-1} of biomass in 2016. Carbon budgets indicated that both miscanthus and maize fields lost carbon over the experiment. The miscanthus field lost 5 Mg C ha^{-1} in both 2015 and 2016 while the maize field lost 1.37 Mg C ha^{-1} for the single year of study. Eddy covariance measurement indicated that for 2016 the miscanthus crop evapotranspired 598 mm and harvest water use efficiencies ranged from 6.95 to 13.84 kg C ha^{-1} mm^{-1}. Maize evapotranspired 659 mm with a harvest water use efficiency of 19.12 kg C ha^{-1} mm^{-1}. While biomass yields and gross primary production were relatively high, high ecosystem respiration rates resulted in a loss of ecosystem carbon. Relatively low biomass production, low water use efficiency and high respiration for *Miscanthus* × *gigantus* in this experiment suggest that this strain of miscanthus may not be well-suited for dryland production under the environmental conditions found in South Georgia USA.

Abbreviations: DM, dry matter; EC, Eddy covariance; ET, evapotranspiration; EWUE, ecosystem water use efficiency; G, ground heat flux; GPP, gross primary production, estimated from NEE (GPP > 0 denotes photosynthetic carbon uptake); H, sensible heat; HWUE, harvest water use efficiency; IRGA, infrared gas analyzer; IRGASON, integrated infrared gas analyzer and sonic anemometer; LE, latent heat; NECB, net ecosystem carbon balance (NECB<0 denotes net ecosystem carbon uptake); NEE, net ecosystem exchange, measured by the EC system (NEE < 0 denotes ecosystem carbon uptake); NPK, nitrogen (N), phosphorus (P) and potassium (K) fertilizer; Qm, energy stored in plant metabolic process; Reco, ecological respiration, estimated from NEE (Reco > 0 denotes carbon losses from respiration); Rnet, total radiation; Rs, shortwave radiation; SOC, soil organic carbon; u*, shear velocity; WUE, water use efficiency.

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1. Introduction

Second-generation biofuels are among the several types of advanced biofuels that include sources of fuel other than ethanol derived from corn starch and have lifecycle greenhouse gas emissions that are at least 50% less than baseline greenhouse gas emissions (Energy Independence Security Act [EISA], 2007). The use of second-generation biofuels is mandated in EISA to increase from 3 to 16 billion gallons between 2015 and 2022. The southeastern region of the USA is projected to contribute approximately half of the feedstocks required to meet the EISA goal (USDA, 2010). This region is highly suited to feedstock production (Bouton, 2002; Lowrance et al., 2010) where warm-season perennial grasses, including giant miscanthus, have shown potential for high yields (Behrman et al., 2014; Coffin et al., 2016; Na et al., 2015). Lignocellulosic feedstocks have the potential to reduce some of the negatives of current biofuel sources by way of requiring less intensive agriculture practices with reduced inputs while maintaining beneficial ecosystem services (Coffin et al., 2016; Heaton et al., 2008; Zhuang et al., 2013).

Miscanthus is a perennial, C4 photosynthetic pathway plant that has the potential for greater photosynthetic efficiency, water use efficiency, and nitrogen use efficiency than other crops. In European systems, miscanthus has been reported to yield 23–38 Mg dry biomass ha^{-1}· year^{-1} under ideal conditions and 14–15 Mg ha^{-1} year^{-1} under poor conditions (Lewandowski et al., 2000), making it a promising candidate for production on marginal land with reduced inputs. *Miscanthus* × *gigantus* is a sterile hybrid used as a biofuel feedstock in Europe (Jones and Walsh, 2001) that has performed well in Europe and in the US Midwest (Heaton et al., 2010) indicating potential biomass productivity greater than maize or switchgrass (Zhuang et al., 2013). When produced under rainfed conditions in the Midwestern USA, miscanthus was reported to have greater water use efficiency per unit of produced biomass than maize (VanLoocke et al., 2012; Zeri et al., 2013) and to store organic carbon in soil as a net carbon sink (Zeri et al., 2011).

Although some studies conducted in the southeastern USA have shown low yields (Burner et al., 2015; Fedenko et al., 2013), measurements were only taken during the first few years following establishment and may have underestimated yield potentials (Lewandowski et al., 2000, 2016). In addition, early reproductive conversion (Clifton-Brown and Lewandowski, 2000; Ings et al., 2013; Nunn et al., 2017) and sensitivity to drought and heat stress (Clifton-Brown et al., 2001; Lewandowski et al., 2000, 2016) are factors that may decrease biomass productivity in the region.

The objectives of this study are to evaluate changes in biomass productivity, carbon exchange, and soil organic carbon (SOC) change and water use efficiency in fields under miscanthus production in South Georgia and compare to traditionally cropped maize. Unique features of this study include measurements in a mature (3–5 yr.) miscanthus stand that was harvested twice a year to overcome issues of reproductive conversion early in the growing season. The non-destructive and non-invasive eddy covariance (EC) technique, which has been widely used to assess environmental controls on biofuel production (Anderson et al., 2015; Wagle et al., 2015; Wagle and Kakani, 2014a, 2014b; Zeri et al., 2011, 2013), was used in combination with soil and plant sampling to estimate net above ground primary plant productivity, water use efficiency, carbon respiration and change in SOC.

2. Materials and methods

2.1. Experimental site and management

Two EC towers were established in farm fields near Tifton, Georgia, USA (Fig. 1). One site at (31°26′22.24″ N, 83°35′29.24″ W, elevation = 101 m) (Fig. 1a) was managed to produce miscanthus (*Miscanthus* × *giganteus* IL Clone). The site was planted in May 2012 under minimal management practices and a rainfed water regime. The growing season for miscanthus on this location is from March through October. Yield measurements were taken 3 years after establishment in 2015 and 2016. Prior to 2012, the field was used for a mixture of vegetable and row crop production. The EC system was established in the field July 2015, with data collected through 2016.

The second site (31°30′39.19″ N, 83°37′04.61″ W, elevation = 96 m), was managed for row-crop production by a local farmer and monitored by Southeast Watershed Research Laboratory (Fig. 1b). The EC system was established in this field August 2015. Cotton (*Gossypium hirsutum*) was produced in 2015 and maize (*Zea mays*) in 2016. The data presented here are for the 2016 maize crop. The maize farm is irrigated via center-pivot.

Average annual precipitation for the area is 1200 mm, and maximum and minimum mean monthly temperatures are 33 °C and 2.6 °C (1981–2010 Climate Normal from NCDC). The study area is located within the Tifton Upland portion of the Southeastern Plains ecoregion of Georgia, USA. Soils in the area are well drained acidic loamy sands in which the sandy topsoil extends about 40 cm and is underlain by a clay sublayer. Soils are predominantly a Tifton loamy sand (6.5% clay, 84.1% sand, 9.4% silt, 0.73% SOC) with smaller areas comprised of a Stilson loamy sand, a Carnegie sandy loam and an Alapaha loamy sand (from Web Soil Survey online: https://websoilsurvey.sc.egov.usda.gov/; accessed 03/30/2018). The soil at the miscanthus site is well drained and does not retain water, most of the planted maize site is similar except for a portion of the north part of the field near the irrigation pond which remains saturated much of the year (Fig. 1b).

Fields (13.9 ha) were prepared for miscanthus planting by harrowing and laying of beds on 90 cm spacing. Miscanthus rhizomes were planted in three rows per bed at 30 cm spacing with a target population of 35,800 rhizomes ha^{-1}. After initial establishment irrigation and pesticides were not used and crops were maintained under minimal management, without irrigation. Fertilizers were applied based on spring soil sampling and University of Georgia Extension Service recommendations for hybrid millets (Table 1). From 2015 through 2016 miscanthus was harvested twice a year after reaching reproductive senescence, once in early June after approximately 50% of the miscanthus had produced seed heads, and again in September or October. All biomass was baled and removed from the fields (Table 1). Weed competition was observed in 2016 with substantial stand loss in some portions of fields in 2017.

The maize (*Zea mays*) field was prepared early march with no-till and the application of chicken litter (4.5 mg ha^{-1}) and nitrogen fertilizer (22 kg ha^{-1}). Maize was planted March 14, 2016 in double rows at 1 plant per 25 cm with 25 cm spacing between rows (Table 2). Space between double rows alternated with 50 and 81 cm spacing, for a plant population of 88,889 ha^{-1}. Irrigation of 292 mm was applied through center-pivot during the growing season March–July 2016. Nitrogen was applied through irrigation at 56 kg ha^{-1} four times April – May 2016 (Table 2) for a total of 247 kg ha^{-1} of nitrogen applied to the crop. The maize crop was harvested August 8, 2016.

2.2. Biophysical measurements

Miscanthus biomass measurements were taken from twenty-one sample points determined to fall near the EC tower footprint (see Fig. 1a and c). At each harvest interval, the research farm was mowed using a mower (Wintersteiger - Cibus TRM Silage Plot Harvester, Salt Lake City, UT, USA)[1] except for a circular area having a 9.1 m radius

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[1] Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

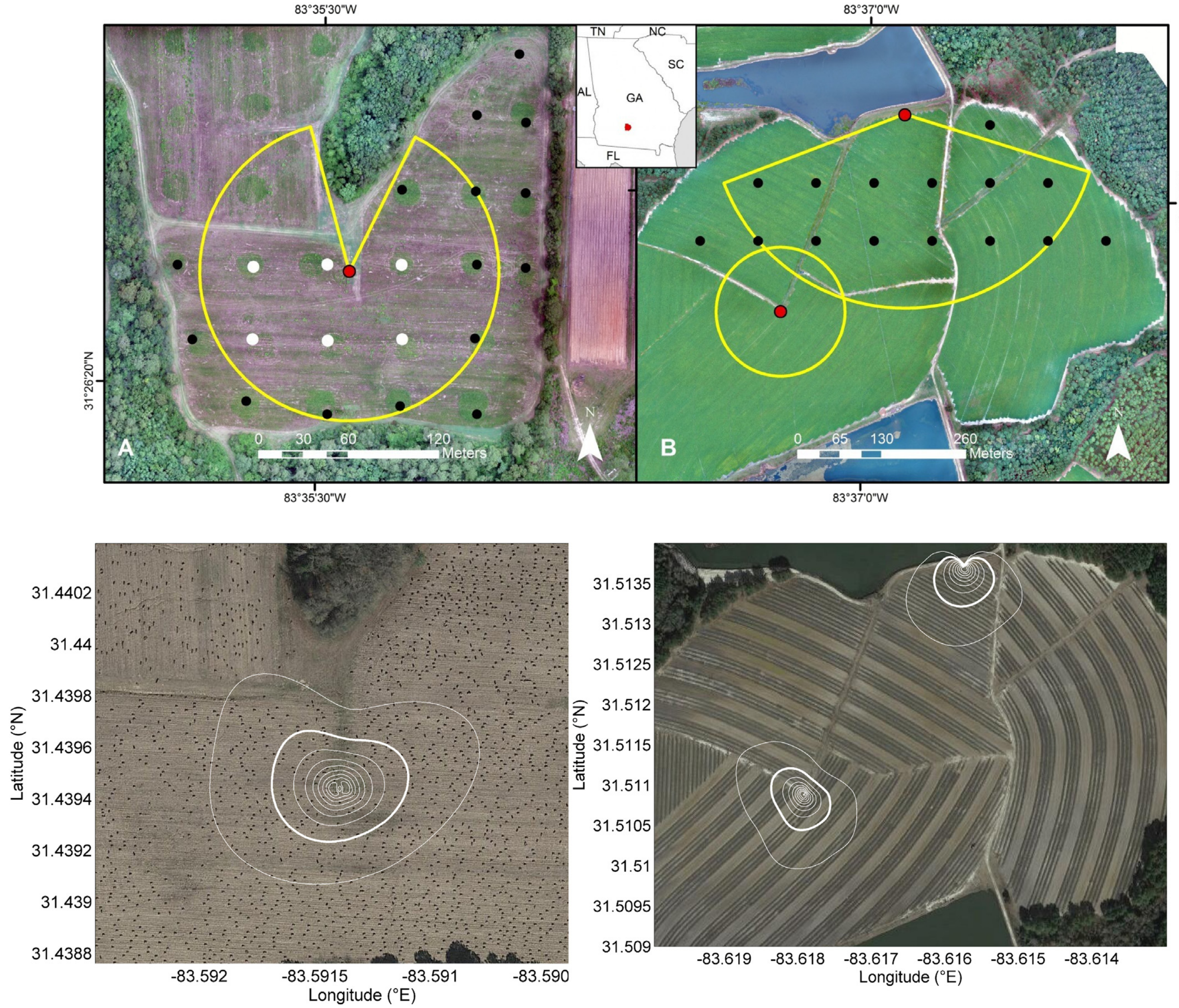

Fig. 1. Eddy Covariance sensor filter boundary and footprints. Sensors were located in Tift County, Georgia, USA (red point on inset map). Sensor filter boundary at (A) miscanthus site of 100 m radius with area behind tower of 350°–20° (azimuthal values with north = 0°) removed (sensor placed facing 190°). Sensor filter boundary at (B) maize site. Boundary for center field location is at 100 m and radius and at the edge of field 300 m. A section of 250°–100° is filtered from the sensor data (sensor placed facing 170°). Average wind direction was 190°. Points indicate sample locations for biomass and soils; white points were additionally sampled for root mass. Sensor footprint models (C) and (D) were generated by the Kljun model (Kljun et al., 2015). Footprint contour lines representing mean contributions to the cumulative flux distribution are shown in steps of 10% from 10 to 90% (80% bold). The basemaps for (A) and (B) are from aerial imagery captured on 14 June 2017 (A), and 2 October 2017 (B) using an unmanned aerial vehicle. The basemaps for (C) and (D) are from google maps (image date 11 December 2014) (projection: UTM17N, NAD83). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

around each sampling point. A 2.4 m swath was cut through the standing biomass at each sample point and weighed. Five grab samples of biomass were then collected for moisture and nutrient analyses. Maize biomass was estimated from fifteen sample points determined to fall near the EC tower footprint where the plant material from 1.5 m of double planted row was gathered up (Fig. 1b and d). All plant material from both sites was weighed and then dried at 60° C until reaching a constant weight to determine moisture content. Maize kernels were separated from the cob, weighed and processed separately. Dried material was then ground to pass a 1 mm screen (Wiley Mill Model 4; Thomas Scientific, Swedesboro, New Jersey, USA) prior to analysis for total carbon and nitrogen content by combustion (Vario EL III; Elementar Americas Inc., Mt. Laurel, NJ, USA).

Soil carbon was measured at the miscanthus site in May 2012, December 2016 and May 2017 and from the maize site in May 2017 at the same points used for biomass sampling. Soil cores were taken using a tractor mounted Giddings probe fitted with a clear plastic sleeve inside the sampling tube (Giddings Machine Company, Windsor, Colorado; 5.8 cm diameter core). Each core was plugged with paper towels to minimize disturbance of the soil surface layer, capped, transported to the lab, and stored at 4 °C until processed. Cores were sub-sampled by depth increment (0–15 cm, 15–30 cm, 30–45 cm, 45–60 cm) for analysis. Depth increment samples were air-dried 48 h followed by the disruption of clods with a wooden rolling pin. Roots were removed by hand, and the remaining sample was sieved (#10; <2 mm). Sieved material was dried 24 h at 105 °C and the mass remaining above the sieve recorded as stones. Three sub-samples (~10 g) of material passing the sieve were taken to determine an average soil oven dry mass (105 °C) and water content. Soil samples were dried, pulverized in a roller mill and analyzed for carbon and nitrogen content (Vario EL III Elementar Americas Inc., Mt. Laurel, New Jersey, USA).

Table 1
Management of miscanthus fields.

Date	Management activity
5/15/2012	Miscanthus planted
11/2012	Roundup herbicide applied by roller to kill grasses
01/30/2013	Miscanthus harvested, remainder mowed and left in field
3/15/2013	NPK applied 112-56-56 kg ha^{-1}
1/15/2014	Miscanthus mowed and material baled and removed from field
10/7/2014	Miscanthus mowed and material baled and removed from field
3/4/2015	Lime applied at 4.5 Mg ha^{-1}
3/23/2015	NPK applied 84-10-21 kg ha^{-1}
6/5/2015	Miscanthus mowed and material baled and removed from field
6/22/2015	NPK applied 84-10-21 kg ha^{-1}
9/11/2015	Miscanthus mowed and material baled and removed from field
3/22/2016	NPK applied 22-22-22 kg ha^{-1}
3/23/2016	Gypsum applied at 4.5 Mg ha^{-1}
6/7/2016	Miscanthus mowed and material baled and removed from field
6/22/2016	NPK with Agrotain™ applied 149-64-149 kg ha^{-1}
6/24/2016	Spread Lime at 2.5 Mg ha^{-1}
10/3/2016	Miscanthus mowed and material baled and removed from field

Root samples were collected December 2016 at the miscanthus site at six locations near the EC tower in the same manner as the soil cores. Samples were stored overnight in 5% sodium hexametaphosphate solution to loosen the soil. Samples were then washed through a 1 mm sieve and rhizomes and roots separated visually by hand. Roots were dried at 60 °C. Dry root and rhizome samples were weighed on a microbalance and carbon and nitrogen content measured on the Vario EL III as above. Root samples were grouped into the mass collected from 0 to 30 cm and that from 30 to 90 cm.

2.3. Eddy covariance flux measurements

The EC system was installed at the miscanthus site on July 10, 2015 and at the maize site on August 13, 2015. Continuous measurements were collected with some interruptions during harvest and for instrument maintenance. The two EC sites were equipped identically. Flux measurements were taken with an integrated, three-dimensional, sonic anemometer and open path infrared gas analyzer (IRGA) (IRGASON; Campbell Scientific Inc., Logan, Utah, USA). Shortwave and longwave radiation was measured with a four-component net radiometer (NR01; Hukseflux Thermal Sensors B.V., Delft, The Netherlands). Air temperature and relative humidity (Rh) were measured with an integrated probe (HygroClip2; Rotronic Instrument Corp., Hauppauge, New York, USA). Canopy temperature was measured via infrared sensor (SI-111; Apogee Instruments, Inc., Logan, Utah, USA). Near surface soil heat flux (G) was measured by a pair of heat flux plates (HFP-01; Hukseflux Thermal Sensors B.V., Delft, The Netherlands) buried at 8 cm along with soil temperature probes (TCAV; Campbell Scientific, Logan, Utah, USA) at 2 and 6 cm. Near surface soil moisture was measured at 3 cm with a water content reflectometer (CS650; Campbell Scientific, Logan, Utah, USA). Soil temperature and radiation variables were measured at 1 min intervals and averaged to 30 min intervals. The IRGA and sonic anemometer were sampled at 10 Hz, and covariance flux was computed at 30 min intervals. The equipment was mounted on site on two towers, the IRGASON along with the controller, barometer and temperature probe were mounted on one tower and the radiometer and infrared sensor on the second. The EC sensor at the miscanthus site was mounted at 2 m in the middle of the field and adjusted up to a height of 4 m to maintain a sensor clearance at least twice the crop height. The footprint was filtered to remain within 100 m fetch (see data processing procedures and Fig. 1a). The EC sensor at the maize field was initially located in the middle of the field and constrained to a height of 2 m due to the necessity of clearing the irrigation rig (1/1/2016–5/19/2016); because of this constraint, when the maize crop growth exceeded 1 m the system was relocated to the edge of the field and placed at a height of 4.2 m (5/19/2016–12/30/2016) (Fig. 1b). There were two large gaps in the EC data collected at the maize field during which the EC device was removed for maintenance (3/3/2016–3/30/2016, and 8/5/2016–10/18/2016). These gaps were outside the growing season and filled using nearby meteorological data applied to the gap filling method described in Section 2.4.

Table 2
Management of maize field.

Date	Management activity
2/1/2016	Monoammonium Phosphate applied N 22 P 120 kg ha^{-1}
3/10/2016	Chicken litter applied 4.5 Mg ha^{-1}
3/10/2016	Nitrogen applied 22 kg ha^{-1}
3/14/2016	Maize planted
4/6/2016	Nitrogen applied 56 kg ha^{-1}
4/11/2016	Roundup applied 1.4 kg ha^{-1}
4/11/2016	Atrazine 2.3 L ha^{-1}
4/19/2016	Nitrogen applied 56 kg ha^{-1}
5/3/2016	Nitrogen applied 56 kg ha^{-1}
5/19/2016	Nitrogen applied 56 kg ha^{-1}
8/8/2016	Maize harvest

2.4. Data processing procedures

EC data were collected at 10 Hz and processed to 30-min time steps using EddyPro software (version 6.1.0) (LI-COR Inc., Lincoln, NE, USA) (Fratini and Mauder, 2014). Default settings and statistical tests data screening were used for the software. The following standard corrections were all applied in EddyPro: Raw data was screened using statistical tests and spike removal (Vickers and Mahrt, 1997). Anemometer coordinates were aligned using the double rotation method for tilt correction (Wilczak et al., 2001). Linear trends were removed from each 30 min set of data using block averaging and linear detrending (Gash and Culf, 1996). Density fluctuations were accounted for by applying the Webb-Pearman-Leuning terms (Webb et al., 1980). The resulting 30 min fluxes were used to calculate variance and covariance for sensible heat (H), CO_2, and H_2O. Turbulence quality check was done using the Mauder and Foken 0-1-2 rating system for stability and turbulence (Foken et al., 2004). Data flagged with a rating of 2 using the Mauder and Foken system (indicating instability or low turbulence) were discarded in analysis. Random flux uncertainty due to sampling error was calculated according to integral turbulence time-scale (Finkelstein and Sims, 2001). Footprint estimation was based on crosswind-integrated flux footprint model (Kljun et al., 2004, 2015) (Fig. 1c and d). Data were filtered by 30 min average wind direction and footprint so that at least 90% of the cumulated flux came from within the target area (Kljun et al., 2004).

The REddyProc package (Reichstein et al., 2005) in R (CRAN; https://CRAN.R-project.org/) was used for determining a range of u* scenarios, gap filling fluxes and partitioning NEE into ecological respiration (Reco) and gross primary production (GPP). Random error, gap filling error, and 5–95 percentiles of the data distribution were calculated with the REddyProc software according to the methods in Wutzler et al. (2018). U* scenarios were calculated in REddyProc using the relation of nighttime NEE verses u* according to the method of Papale et al. (2006). Flux partition was done with the REddyProc software using the nighttime flux partitioning method of Reichstein et al. (2005).

For the EC instrument at the maize field there were 17,568 observations with 28% of the data marked missing and 8% removed in footprint filter. U* scenario ranges were between 0.03 and 0.12. After u* filtering between 51 and 57% of the total measurements were gap filled. For the EC instrument at the miscanthus site 3% of the data were marked missing and 8% of the data was removed by the footprint filter. U* scenario range was between 0.07 and 0.13. After u* filtering 53–58% of the total data was marked as gaps to be filled. All fluxes were corrected for energy closure, balancing daily total radiation (Rnet) by the daily summed values of H, latent heat (LE) soil heat flux (G) and plant metabolic

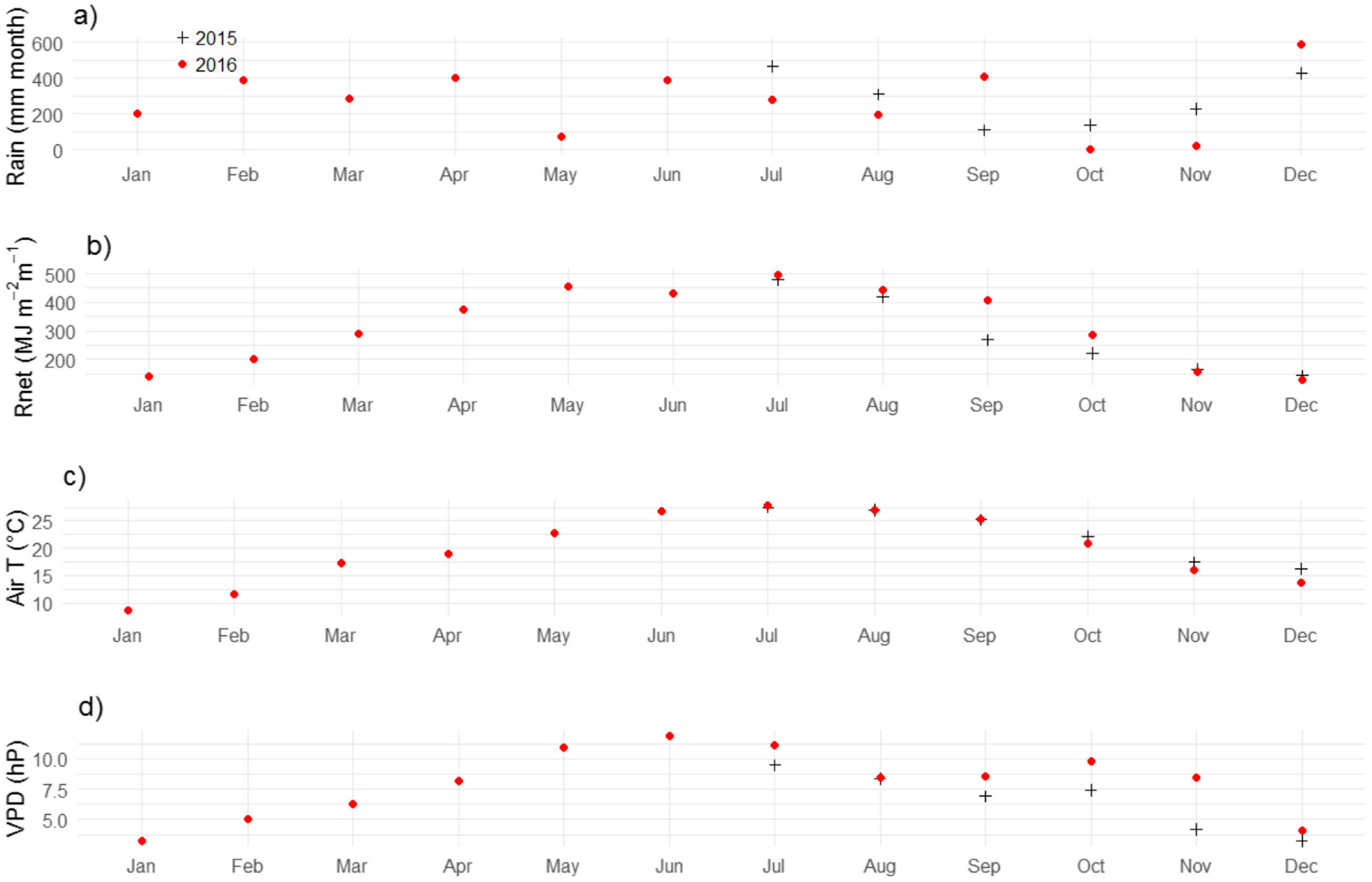

Fig. 2. Daily meteorological data for study site (a) total monthly precipitation, (b) total daily net radiation (Rnet), (c) monthly mean of mean daily air temperature (air T), (d) monthly mean of mean daily vapor pressure deficit (VPD). Total monthly precipitation and mean daily temperature for study site. Data from station at miscanthus field.

process (Qm). Qm was determined from observations of net carbon flux (Meyers and Hollinger, 2004). H and LE were then adjusted to close the energy balance and the gas flux was corrected (Anderson and Wang, 2014; Leuning et al., 2012).

2.5. Crop and biome net carbon

Carbon exchange and water use were calculated on both a harvest and annual basis. The purpose was to quantify the contribution based

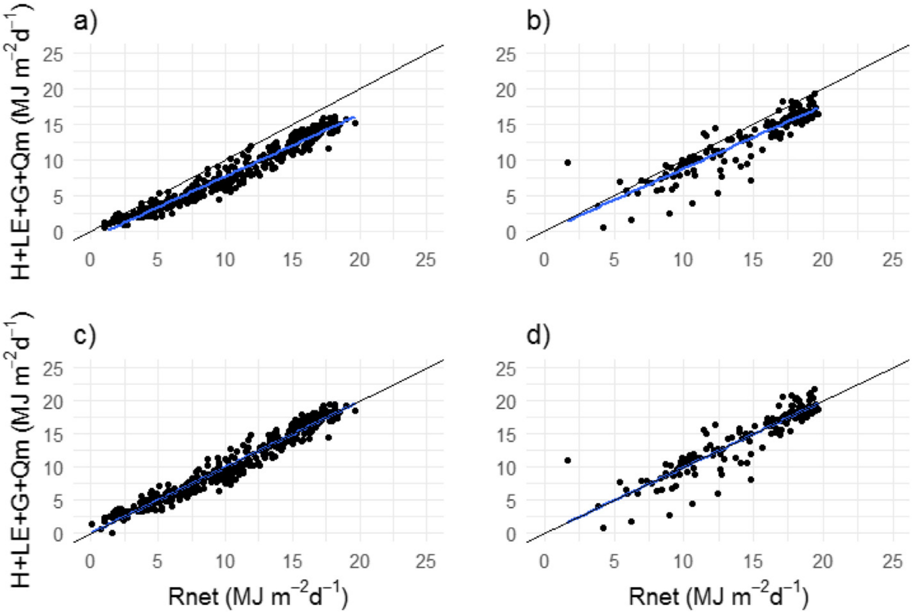

Fig. 3. Energy balance closure for 2016 growing season at miscanthus site for net radiation (Rnet) vs. sensible heat (H), latent energy (LE), ground heat flux (G), and plant metabolic energy (Qm) (a) before and (c) after energy balance adjustment. 2016 growing season at maize site (b) before and (d) after energy balance adjustment. Lines indicate 1:1 relationship and the linear regression fit.

Table 3
Dry weight silage biomass and carbon content for miscanthus and maize.

	Date	Silage (Mg ha^{-1})	Seed (Mg ha^{-1})	Total carbon (Mg ha^{-1})	Carbon removed at harvest[a] (Mg ha^{-1})
Miscanthus 1st	4/5/2015–6/09/2015	5.93	–	2.59	2.08
Miscanthus 2nd	7/10/2015–9/22/2015	9.61	–	4.25	3.40
Miscanthus Annual	2015 (total)	15.54	–	6.84	5.48
Miscanthus 1st	4/5/2016–6/09/2016	3.65	–	1.60	1.28
Miscanthus 2nd	7/1/2016–10/3/2016	8.15	–	3.64	2.91
Miscanthus Annual	2016 (total)	11.80	–	5.23	4.19
Maize	3/14/2016–8/12/2016	13.54	16.66	12.61	6.83

Mean of 21 samples for miscanthus and 15 samples for maize.

[a] Estimated as silage harvested multiplied by baling efficiency (80%).

on the crop growth versus dormant (miscanthus) and fallow (maize) seasons (Kutsch et al., 2010; Zeri et al., 2013). Carbon exported from the field was calculated by multiplying the harvested biomass by the measured carbon fraction. Net ecosystem exchange (NEE) of CO_2 was measured by the EC technique. Net ecosystem carbon balance (NECB) was calculated by taking the difference between the measured NEE and the carbon exported during harvest; these values are integrated over the total period of measurement.

2.6. Water use efficiency calculations

Evapotranspiration (ET) was measured by the EC system as latent heat flux and converted to mass units. Water use efficiency (WUE) was calculated as the amount of carbon fixed by the crop/ecosystem for a given amount of ET. Parallel to crop and ecosystem net carbon determined above, the crop harvest water use efficiency (HWUE) was calculated as the harvest weight (estimated by sampling) (kg C) per mm ET per ha and ecosystem water use efficiency (EWUE) as the NEE (kg C) per mm ET per ha.

3. Results and discussion

3.1. Meteorological measurements

Annual precipitation at the miscanthus field was 1200 mm for 2015 and 1250 mm for 2016. Annual precipitation at the maize field was 1309 mm in 2016 with an additional 292 mm added via center pivot irrigation. The monthly precipitation pattern at both sites differed between years with 2015 being wetter in July, August, October and November while 2016 was wetter in September and December (Fig. 2). Winds were predominantly from the south and west with the average wind direction being 190°. Average annual air temperatures were similar between years, 19.4 °C in 2015 and 19.5 °C in 2016 (Fig. 2).

3.2. Energy balance

A calculation of the daily energy balance indicated that 16% of the net energy was unaccounted for at the maize site and 18% at the miscanthus site. These imbalances are within the range reported across EC tower networks (Leuning et al., 2012; Wilson et al., 2002). The daily gas flux and heat flux were adjusted at both sites by these amounts (Fig. 3).

3.3. Carbon inventory measurements

Miscanthus was harvested twice per year in 2015 and 2016 with the first harvest in June and the second in September–October (Table 1). The second harvest for each year was almost twice as large as the June harvest (Table 3). Annual harvested miscanthus biomass was 15.54 Mg ha^{-1} in 2015 and 11.80 Mg ha^{-1} in 2016 (Table 3). This is similar to other reported dryland miscanthus harvests in various locations of the Southeast USA (Burner et al., 2015; Fedenko et al., 2013) however it is much lower than the yields of 22–44 Mg ha^{-1} that have been reported in the Midwestern USA (Dohleman et al., 2012; Dohleman and Long, 2009). This high variability in miscanthus biomass has been reported as being due in large part to the sensitivity of miscanthus biomass production to climate, water and nitrogen supply (Arundale et al., 2014; Heaton, 2004; Ings et al., 2013; Joo et al., 2016; Song et al., 2015). The miscanthus biomass harvest was lower in 2016 than 2015 (Table 3), possibly due to heavy weed competition and low rainfall in July and August of 2016 (Fig. 2).

The maize harvest was substantially higher than the regional average; the expected average seed yield for irrigated corn in Georgia is about 12.6 Mg ha^{-1} (Lee, 2016), while this harvest was 16.66 Mg ha^{-1}. Total biomass harvest for the maize, silage and seed, was 30.20 Mg ha^{-1}. This indicates the maize was grown under a management regime with relatively high water and nitrogen inputs for maximized yield.

Soil carbon in the top 15 cm of soil of the miscanthus field increased between May 2012 and May 2017 but tended to decline in depths from 15 to 60 cm (Table 4). Overall mean values decreased over the five-year study, but due to the high variation in measured samples mean values were not significantly different across years for the miscanthus experiment (one-way ANOVA $\alpha = 0.05$).

As a perennial crop, a significant amount of miscanthus biomass is stored below the ground. About half of the biomass is below ground with 65–89% of the below ground mass in rhizomes (Kahle et al., 2001). The total root and rhizome carbon content measured in December 2016 was 24.6 Mg ha^{-1} (Table 5). Although root samples were collected at a subset of only six sites proximate to the EC tower and had a large variation, the observed below ground dry matter of 59.7 Mg ha^{-1} is substantially higher than the 14.1–27.1 Mg ha^{-1} reported by Dohleman et al. (2012; Table 2) for five study locations north of 40° latitude. The ratio of harvested biomass to end of season root biomass has been reported at about 1:1 (Dohleman et al., 2012; Kahle et al., 2001) in our case we find root to shoot ratio of 6.1:1 for biomass and 5.6:1 for carbon (ratio of December root biomass to annual silage harvested for 2016 at six sample points). The low harvest relative to the high below ground matter is an unusual observation but may be

Table 4
Soil % carbon measured at EC tower location.

Depth (cm)	Miscanthus						Maize	
	May 2012		Dec. 2016		May 2017		May 2016	
	Mean % C	SEM	Mean % C	SEM	Mean % C	SEM	Mean % C	SEM
0–15	0.73	0.03	0.51	0.06	0.78	0.04	0.50[a]	0.03
15–30	0.65	0.04	0.45	0.06	0.55	0.03		
30–45	0.52	0.07	0.39	0.05	0.43	0.04		
45–60	0.36	0.05	0.39	0.05	0.28	0.03		

The data represent mean and standard error of the mean (SEM) (n = 21).

[a] Samples taken from 0 to 30 cm.

Table 5
Root mass and carbon content at the miscanthus field in December 2016.

	Dry matter ($Mg\ ha^{-1}$)	SEM	C content ($Mg\ ha^{-1}$)	SEM
Rhizome	51.5	11.1	21.5	4.8
Roots 0–30 cm	6.4	1.0	2.5	0.5
Roots 30–90 cm	1.9	0.9	0.6	0.3
Total	59.7	12.1	24.6	5.2

The data represent mean and standard error of the mean ($n = 6$).

related to miscanthus responding to the double harvest or the heat and drought stress with carbon partitioning favoring below ground accumulation.

3.4. Annual and seasonal flux measurements

Seasonal fluxes differed across years and crops. The hourly carbon exchange flux for the entire year is illustrated in Fig. 4. Negative numbers indicate carbon entering the study area during daily photosynthesis. Nighttime hours are characterized by positive numbers as carbon is released through plant and soil respiration.

The second growth miscanthus had a greater NEE in 2015 than in 2016 (Fig. 4a–b and Table 6). Observed NEE differences were particularly dramatic in July but continued through the second growing season (Fig. 4a–b). Gross productivity and silage harvested is similar between seasons, but respiration is two times higher in 2016 than in 2015 (Table 3 and Table 6). The reduction in soil carbon between 2012 and 2017 measurements suggests a loss of carbon over the span of 5 years (Table 4) and supports the EC measurements of high respiration compared to productivity (Table 6). The observation that root biomass in the top 90 cm of soil was 5.6 times greater than the miscanthus harvested in 2016 from the six sites nearest the EC tower suggests that roots may account for substantial ecosystem respiration in addition to the net soil C loss. In 2016 low rainfall in June likely led to drought stress and lower productivity, a wet September in 2016 led to higher productivity in that month but also disproportionally higher respiration.

Miscanthus has a longer growing season (April–September) (Fig. 4) than maize (April–August) and hence a potential for greater productivity, but maize had higher productivity in its growing season than the miscanthus as measured by vegetative biomass at harvest (Table 3). A significant factor in this difference was the greater water available to the maize supporting higher evapotranspiration of the maize crop (659 mm over 3/14/2016–8/12/2016) than for the miscanthus (598 mm over 4/5/2016–10/3/2016) (Table 6). Although harvested biomass was greater for maize than miscanthus, miscanthus had higher productivity as measured by GPP for 2016 (Table 6). The high GPP for miscanthus was offset by higher respiration resulting in a net loss of carbon for 2016 as measured by NEE of 0.8 Mg C ha^{-1}.

Maize had a greater absolute measured annual carbon uptake (NEE) compared to miscanthus (Fig. 5 a–b), indicating greater carbon fixation in maize relative to miscanthus. While the 2016 total annual GPP for miscanthus was greater than maize (30.73 Mg ha^{-1} vs. 26.43 Mg ha^{-1}) the respiration for miscanthus was much greater than for maize (31.54 Mg ha^{-1} vs. 20.96 Mg ha^{-1}) leaving a very small cumulative NEE for miscanthus (Table 6 and Fig. 5). Miscanthus showed positive cumulative NEE trends, indicating respiration higher than GPP, over the period October–April with sharp increases after mowing particularly after the June 2016 harvest (Fig. 5a). The respiratory requirements of new shoot development, the exposed soil and the plant matter left in the field, and increased solar radiation at the soil surface following mowing may have contributed to the high respiration and the net loss of carbon at this time.

3.5. Net ecosystem carbon balance

Total NEE was negative for both crops over most of the study periods, except for the miscanthus field for 2016, indicating a gain of ecosystem carbon for the growing season (Table 6). However, once biomass removed with harvests is accounted for (NECB), both fields show a net loss of carbon (Table 6). Carbon lost from the miscanthus field was particularly large, with NCEB of 5 Mg ha^{-1} in both 2015 and 2016. Carbon lost from the maize field was 1.37 Mg ha^{-1} in 2016 (Table 6). Prior

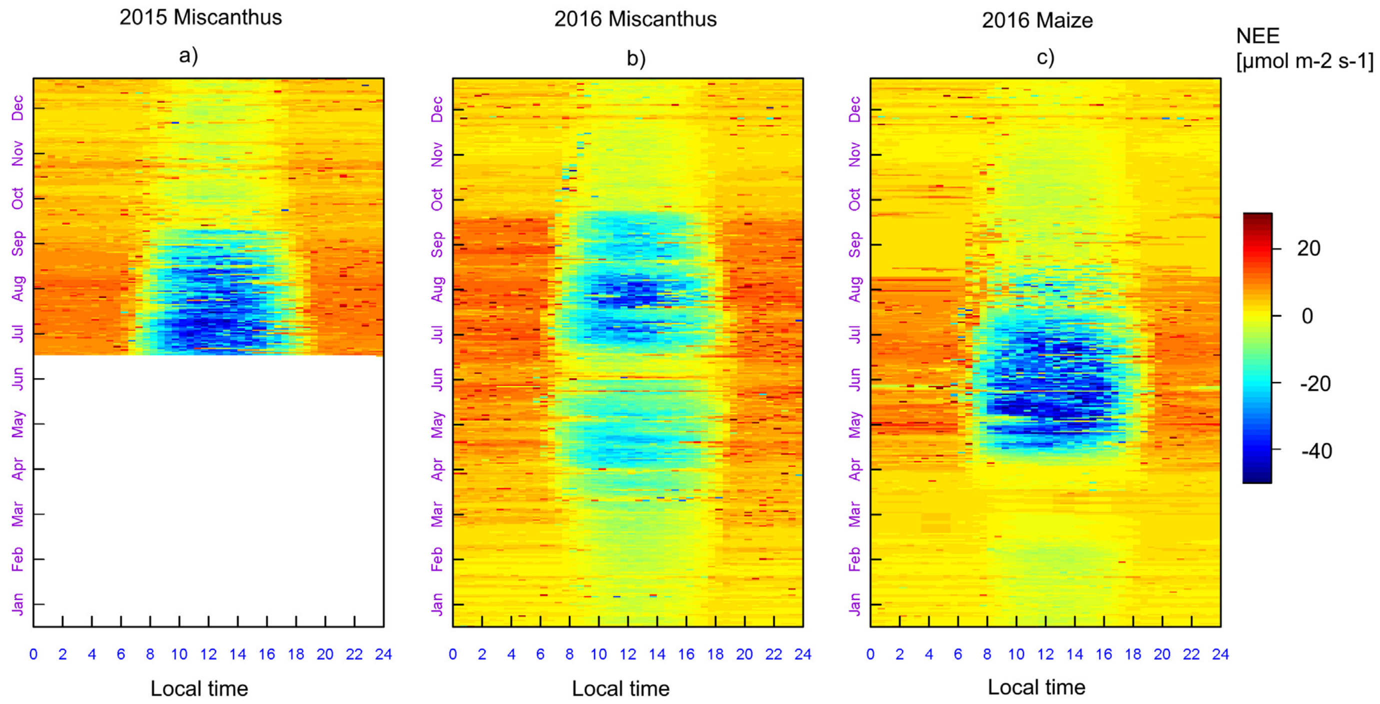

Fig. 4. Fingerprint plots of 30-minute NEE fluxes for (a) miscanthus 2015, (b) miscanthus 2016 and (c) maize 2016.

Table 6
Seasonal and annual fluxes measured by EC.

	Date	NEE (Mg ha^{-1})[a]		GPP (Mg ha^{-1})[a]		Reco (Mg ha^{-1})[a]		ET (cm)[a]		carbon removed at harvest (Mg ha^{-1})	NECB (Mg ha^{-1})	
		value	range	value	range	value	range	value	range			
Miscanthus 1st	4/5/2015–6/09/2015	NA	–	NA	–	NA	–	NA	–	2.08	–	
Miscanthus 2nd	7/10/2015–9/22/2015	−3.20	0.03	13.59	0.03	10.39	0.05	30.70	0.06	3.40	0.20	0.03
Miscanthus annual	2015	−0.45	0.11	16.55	0.0	16.10	0.11	39.73	0.10	5.48	5.03	0.11
Miscanthus 1st	4/5/2016–6/09/2016	−0.97	0.06	8.08	0.03	7.11	0.03	22.99	0.04	1.28	0.31	0.06
Miscanthus 2nd	7/1/2016–10/3/2016	−1.19	0.26	15.08	0.38	13.89	0.63	36.80	0.09	2.91	1.72	0.26
Miscanthus annual	2016	0.81	0.34	30.73	0.36	31.54	0.70	88.62	0.21	4.19	5.00	0.34
Maize	3/14/2016–8/12/2016	−6.49	0.18	20.58	0.02	14.09	0.19	65.94	0.15	6.83	0.34	0.18
Maize annual	2016	−5.47	0.29	26.43	1.41	20.96	1.70	94.76	0.28	6.83	1.37	0.29

Negative numbers indicate carbon entering the field.
Calculations of carbon removed assume 80% bailing efficiency.

[a] EC data is followed by the range of the data between the 5% and 95% of the distribution obtained by varying the u* cut off.

studies in Europe and northeastern United States have indicated miscanthus would store carbon in the soil (Clifton-Brown and Lewandowski, 2000; Clifton-brown et al., 2007; Dohleman et al., 2012; Heaton et al., 2010; Zatta et al., 2014). The failure of miscanthus in our study to store carbon may be due to a combination of factors. Lewandowski et al. (2016) show that clones of miscanthus can have variable response to abiotic stress; this Illinois clone may not be not well adapted to the climate or soils of the southeast. The southeast United States experiences a moist subtropical climate; even with relatively plentiful rainfall, relatively high daytime temperatures and solar radiation lead to drought stress in plants and high plant respiration. At this study site well-drained soils above a clay hardpan limit the water available to the plants. Well aerated and sandy soils of the study area can support high rates of biotic respiration.

3.6. Water use efficiency for miscanthus and maize

The water use efficiency as measured by the EWUE was always lower than the HWUE, because in all seasons and years the fields lost carbon (Table 7). Annual EWUE was always lower than growing season EWUE, because the annual EWUE includes late fall and winter precipitation when the vegetation is dormant. Comparing the fall 2015 and 2016 miscanthus harvests the EWUE and HWUE were lower in 2016 (3.23 and 9.88 kg C ha^{-1} mm^{-1}) than in 2015 (10.42 and 13.84 kg C

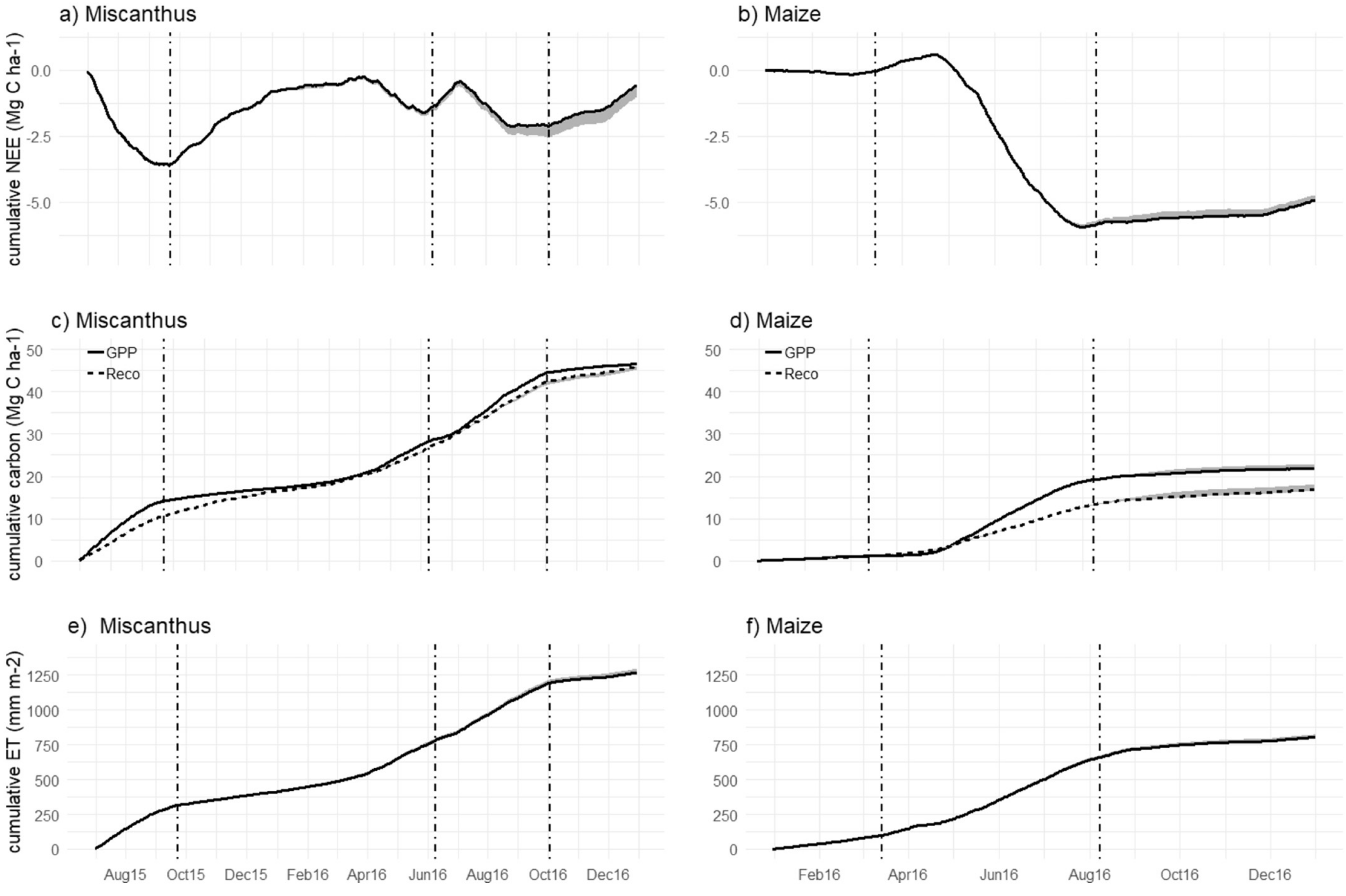

Fig. 5. Cumulative CO2 flux from (a) miscanthus and (b) maize. Cumulative GPP and Reco from (c) miscanthus and (d) maize. Cumulative ET from (e) miscanthus and (f) maize. Lines indicate the 50th percentile of the data distribution while gray area indicates the 5th and 95th percentiles. Vertical lines indicate miscanthus harvest dates and maize planting date and harvest date. Miscanthus data is from July 2015 to December 2016 and maize data is from January–December 2016.

Table 7
Water use efficiency.

	Date	EWUE (kg C ha^{-1} mm^{-1})	HWUE (kg C ha^{-1} mm^{-1})
Miscanthus 1st	4/5/2015–6/09/2015	NA	NA
Miscanthus 2nd	7/10/2015–9/22/2015	10.42	13.84
Miscanthus annual	2015	1.13	NA
Miscanthus 1st	4/5/2016–6/09/2016	4.22	6.95
Miscanthus 2nd	7/1/2016–10/3/2016	3.23	9.88
Miscanthus annual	2016	0.91	5.91
Maize	3/14/2016–8/12/2016	9.84	19.12
Maize annual	2016	5.77	13.30

ha^{-1} mm^{-1}) and can likely be attributed to low rainfall in July and August of 2016 (Fig. 2). Irrigated maize achieved a higher EWUE and HWUE (9.84 and 19.12 kg C ha^{-1} mm^{-1}) compared to the miscanthus in 2016 but was similar to the second crop of miscanthus in 2015. During the fall of 2015 rainfall was adequate leading to less of a benefit due to supplemental irrigation. In 2016 a greater difference between the irrigated and non-irrigated crops was observed due to lower rainfall during the growing season (July and August) (Fig. 2).

3.7. Comparisons between miscanthus in southeast and Midwest

Comparisons were made to miscanthus grown in Georgia and in the Midwestern US (Table 8). Locally grown Miscanthus had similar yield but higher respiration and lower water use efficiency than miscanthus grown in the Midwest as reported by Zeri et al. (2013). Miscanthus in Tifton had GPP nearly twice as high as miscanthus in Urbana, Illinois, US; however, respiration was almost three times higher, leading to an annual positive NEE at Tifton (environmental carbon loss) and an annual negative NEE balance at Urbana (environmental carbon gain) (Table 8).

4. Conclusion

Biomass production, carbon balance and water use efficiency were examined for dryland miscanthus (2015–2016) and irrigated maize (2016) in South Georgia USA. The observed miscanthus yields where on the low end of what have typically been found in the Midwestern USA and Europe. We believe that high temperatures, periods of water stress, early reproductive conversion, weed pressure and harvest before senescence all played a part in reducing the productivity of the miscanthus stand, but the incorporation of a second harvest mitigated yield reduction resulting from early reproductive conversion. In addition, although we sampled below ground biomass at only six sites in 2016, it is possible that the high root:shoot ratios we observed (6.1:1 for biomass and 5.6:1 for carbon) are a physiological resource allocation response to stress from drought, heat, double harvests or some combination thereof. Inclusion of root:shoot measurements in future studies may provide valuable insight into management and breeding strategies to improve yield.

This study found a loss of carbon over the 17-month period for the dryland miscanthus counter to what has been observed in the Midwest. This carbon loss may be due to several factors including well drained sandy soil, the effect of high temperatures and associated diurnal drought stress experienced by the more temperate-adapted Illinois miscanthus clone, exposed soil and decomposition of residue following the June harvest, and physiological shifts driving substantial increases in plant respiration as resources were shifted to the production of new shoot biomass. However, periods of positive NEE were observed outside the growing season September – March and particularly large positive fluxes in June 2016 after mowing indicating that exposed soils after mowing and dormant fields were contributors to the loss of soil carbon. Weed pressure in miscanthus likely also contributed to yield reductions, more robust research designs are needed to evaluate the complex interactions among these system components.

Table 8
Miscanthus in Midwest[a] vs. Southeast.

	Harvest (Mg C ha^{-1})	NEE (Mg C ha^{-1})	Reco (Mg C ha^{-1})	GPP (Mg C ha^{-1})	ET (cm)
Urbana, IL 2011	4.76	−7.48	10.90	18.46	56
Tifton, Ga 2016	5.23	0.81	31.54	30.73	88.62

[a] Midwest harvest example and data from (Joo et al., 2016; Zeri et al., 2013) used for comparison purposes.

The combination of relatively low biomass production and net ecosystem C losses suggests that this strain of miscanthus may not be well-suited for dryland production under the environmental conditions found in South Georgia USA. However, improved management practices and breeding programs targeted to better adapting miscanthus to the Southern USA may greatly increase productivity. We measured carbon balance of both crops using standard eddy covariance carbon budget methods, and we did not account for carbon sequestered in the root mass, which would presumably be quite different for maize and miscanthus. While this provides a correct balance for carbon flux in both crops, it does not account for carbon sequestered beyond the period of measurement in miscanthus rhizomes, nor does it touch upon the added potential ecosystem services of a rhizomatous root mat. A suggested practice of managing miscanthus along riparian buffers and grass waterways may prove ideal for this crop (Coffin et al., 2016).

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References

Anderson, R.G., Wang, D., 2014. Energy budget closure observed in paired Eddy Covariance towers with increased and continuous daily turbulence. Agric. For. Meteorol. 184, 204–209. https://doi.org/10.1016/j.agrformet.2013.09.012.

Anderson, R.G., Tirado-Corbalá, R., Wang, D., Ayars, J.E., 2015. Long-rotation sugarcane in Hawaii sustains high carbon accumulation and radiation use efficiency in 2nd year of growth. Agric. Ecosyst. Environ. 199, 216–224. https://doi.org/10.1016/j.agee.2014.09.012.

Arundale, R.A., Dohleman, F.G., Heaton, E.A., Mcgrath, J.M., Voigt, T.B., Long, S.P., 2014. Yields of Miscanthus × giganteus and Panicum virgatum decline with stand age in the Midwestern USA. GCB Bioenergy 6, 1–13. https://doi.org/10.1111/gcbb.12077.

Behrman, K.D., Keitt, T.H., Kiniry, J.R., 2014. Modeling differential growth in switchgrass cultivars across the central and southern Great Plains. BioEnergy Res 7, 1165–1173. https://doi.org/10.1007/s12155-014-9450-8.

Bouton, J.H.H., 2002. Bioenergy Crop Breeding and Production Research in the Southeast, Final Report for 1996 to 2001, ORNL/SUB-02-19XSV810C/01. Oak Ridge, TN. https://doi.org/10.2172/814494.

Burner, D.M., Hale, A.L., Carver, P., Pote, D.H., Fritschi, F.B., 2015. Biomass yield comparisons of giant miscanthus, giant reed, and miscane grown under irrigated and rainfed conditions. Ind. Crop. Prod. 76, 1025–1032. https://doi.org/10.1016/j.indcrop.2015.07.071.

Clifton-Brown, J., Lewandowski, I., 2000. Water use efficiency and biomass partitioning of three different miscanthus genotypes with limited and unlimited water supply. Ann. Bot. 86, 191–200. https://doi.org/10.1006/anbo.2000.1183.

Clifton-Brown, J.C., Lewandowski, I., Andersson, B., Basch, G., Christian, D.G., Kjeldsen, J.B., Jørgensen, U., Mortensen, J.V., Riche, A.B., Schwarz, K.-U., Tayebi, K., Teixeira, F., 2001. Performance of 15 genotypes at five sites in Europe. Agron. J. 93, 1013. https://doi.org/10.2134/agronj2001.9351013x.

Clifton-brown, J.C., Breuer, J., Jones, M.B., 2007. Carbon mitigation by the energy crop, Miscanthus. Glob. Chang. Biol. 13, 2296–2307. https://doi.org/10.1111/j.1365-2486.2007.01438.x.

Coffin, A.W., Strickland, T.C., Anderson, W.F., Lamb, M.C., Lowrance, R.R., Smith, C.M., 2016. Potential for production of perennial biofuel feedstocks in conservation buffers on the coastal plain of Georgia, USA. Bioenergy Res 9, 587–600. https://doi.org/10.1007/s12155-015-9700-4.

Dohleman, F.G., Long, S.P., 2009. More productive than maize in the Midwest: how does Miscanthus do it? Plant Physiol. 150, 2104–2115. https://doi.org/10.1104/pp.109.139162.

Dohleman, F.G., Heaton, E.A., Arundale, R.A., Long, S.P., 2012. Seasonal dynamics of above- and below-ground biomass and nitrogen partitioning in Miscanthus ?? giganteus and Panicum virgatum across three growing seasons. GCB Bioenergy 4, 534–544. https://doi.org/10.1111/j.1757-1707.2011.01153.x.

Fedenko, J.R., Erickson, J.E., Woodard, K.R., Sollenberger, L.E., Vendramini, J.M.B., Gilbert, R.A., Helsel, Z.R., Peter, G.F., 2013. Biomass production and composition of perennial grasses grown for bioenergy in a subtropical climate across Florida, USA. Bioenergy Res 6, 1082–1093. https://doi.org/10.1007/s12155-013-9342-3.

Finkelstein, P.L., Sims, P.F., 2001. Sampling error in eddy correlation flux measurements. J. Geophys. Res. Atmos. 106, 3503–3509. https://doi.org/10.1029/2000JD900731.

Foken, T., Göockede, M., Mauder, M., Mahrt, L., Amiro, B., Munger, W., 2004. Post-field data quality control. Handbook of Micrometeorology. Kluwer Academic Publishers, Dordrecht, pp. 181–208 https://doi.org/10.1007/1-4020-2265-4_9.

Fratini, G., Mauder, M., 2014. Towards a consistent eddy-covariance processing: an intercomparison of EddyPro and TK3. Atmos. Meas. Tech. 7, 2273–2281. https://doi.org/10.5194/amt-7-2273-2014.

Gash, J.H.C., Culf, A.D., 1996. Applying a linear detrend to eddy correlation data in realtime. Boundary-Layer Meteorol 79, 301–306. https://doi.org/10.1007/BF00119443.

Heaton, E., 2004. A quantitative review comparing the yields of two candidate C4 perennial biomass crops in relation to nitrogen, temperature and water. Biomass Bioenergy 27, 21–30. https://doi.org/10.1016/j.biombioe.2003.10.005.

Heaton, E.A., Dohleman, F.G., Long, S.P., 2008. Meeting US biofuel goals with less land: the potential of Miscanthus. Glob. Chang. Biol. 14, 2000–2014. https://doi.org/10.1111/j.1365-2486.2008.01662.x.

Heaton, E.A., Dohleman, F.G., Miguez, A.F., Juvik, J.A., Lozovaya, V., Widholm, J., Zabotina, O.A., McIsaac, G.F., David, M.B., Voigt, T.B., Boersma, N.N., Long, S.P., 2010. Miscanthus. A promising biomass crop. Adv. Bot. Res. 56, 76–137. https://doi.org/10.1016/B978-0-12-381518-7.00003-0.

Ings, J., Mur, L.A.J., Robson, P.R.H., Bosch, M., 2013. Physiological and growth responses to water deficit in the bioenergy crop Miscanthus × giganteus. Front. Plant Sci. 4, 468. https://doi.org/10.3389/fpls.2013.00468.

Jones, M.B., Walsh, M., 2001. Miscanthus for Energy and Fibre. Routledge, London, UK.

Joo, E., Hussain, M.Z., Zeri, M., Masters, M.D., Miller, J.N., Gomez-Casanovas, N., Delucia, E.H., Bernacchi, C.J., 2016. The influence of drought and heat stress on long term carbon fluxes of bioenergy crops grown in the Midwestern US. Plant Cell Env., 1928–1940 https://doi.org/10.1111/pce.12751.

Kahle, P., Beuch, S., Boelcke, B., Leinweber, P., Schulten, H.-R., 2001. Cropping of Miscanthus in Central Europe: biomass production and influence on nutrients and soil organic matter. Eur. J. Agron. 15, 171–184. https://doi.org/10.1016/S1161-0301(01)00102-2.

Kljun, N., Calanca, P., Rotach, M.W., Schmid, H.P., 2004. A simple parameterisation for flux footprint predictions. Boundary-Layer Meteorol 112, 503–523. https://doi.org/10.1023/B:BOUN.0000030653.71031.96.

Kljun, N., Calanca, P., Rotach, M.W., Schmid, H.P., 2015. A simple two-dimensional parameterisation for Flux Footprint Prediction (FFP). Geosci. Model Dev. 8, 3695–3713. https://doi.org/10.5194/gmd-8-3695-2015.

Kutsch, W.L., Aubinet, M., Buchmann, N., Smith, P., Osborne, B., Eugster, W., Wattenbach, M., Schrumpf, M., Schulze, E.D., Tomelleri, E., Ceschia, E., Bernhofer, C., B??ziat, P., Carrara, A., Di Tommasi, P., Grunwald, T., Jones, M., Magliulo, V., Marloie, O., Moureaux, C., Olioso, A., Sanz, M.J., Saunders, M., Søgaard, H., Ziegler, W., 2010. The net biome production of full crop rotations in Europe. Agric. Ecosyst. Environ. 139, 336–345. https://doi.org/10.1016/j.agee.2010.07.016.

Lee, D., 2016. A guide to corn production in Georgia 2016. http://grains.caes.uga.edu/, Accessed date: 20 May 2017.

Leuning, R., van Gorsel, E., Massman, W.J., Isaac, P.R., 2012. Reflections on the surface energy imbalance problem. Agric. For. Meteorol. 156, 65–74. https://doi.org/10.1016/j.agrformet.2011.12.002.

Lewandowski, I., Clifton-Brown, J.C., Scurlock, J.M.O., Huisman, W., 2000. Miscanthus: European experience with a novel energy crop. Biomass Bioenergy 19, 209–227. https://doi.org/10.1016/S0961-9534(00)00032-5.

Lewandowski, I., Clifton-Brown, J., Trindade, L.M., van der Linden, G.C., Schwarz, K.-U., Müller-Sämann, K., Anisimov, A., Chen, C.-L., Dolstra, O., Donnison, I.S., Farrar, K., Fonteyne, S., Harding, G., Hastings, A., Huxley, L.M., Iqbal, Y., Khokhlov, N., Kiesel, A., Lootens, P., Meyer, H., Mos, M., Muylle, H., Nunn, C., Özgüven, M., Roldán-Ruiz, I., Schüle, H., Tarakanov, I., van der Weijde, T., Wagner, M., Xi, Q., Kalinina, O., 2016. Progress on optimizing miscanthus biomass production for the European bioeconomy: results of the EU FP7 project OPTIMISC. Front. Plant Sci. 7, 1–23. https://doi.org/10.3389/fpls.2016.01620.

Lowrance, R., Anderson, W., Miguez, F., Strickland, T., Knoll, J., Sauer, T., 2010. Landscape management and sustainable feedstock production: Enhancing net regional primary productivity while minimizing externalities. In: Braun, R., Karlen, D.L., Johnson, D. (Eds.), Sustainable Feedstocks for Advanced Biofuels: Sustainable Alternative Fuel Feedstock Opportunities, Challenges and Roadmaps for Six U.S. Regions. Soil and Water Conservation Society, Ankeny, IA, USA, pp. 1–19.

Meyers, T.P., Hollinger, S.E., 2004. An assessment of storage terms in the surface energy balance of maize and soybean. Agric. For. Meteorol. 125, 105–115. https://doi.org/10.1016/j.agrformet.2004.03.001.

Na, C.-I., Sollenberger, L.E., Erickson, J.E., Woodard, K.R., Vendramini, J.M.B., Silveira, M.L., 2015. Management of perennial warm-season bioenergy grasses. I. Biomass harvested, nutrient removal, and persistence responses of elephant grass and energy cane to harvest frequency and timing. BioEnergy Res 8, 581–589. https://doi.org/10.1007/s12155-014-9541-6.

Nunn, C., Hastings, A.F.S.J., Kalinina, O., Özgüven, M., Schüle, H., Tarakanov, I.G., Van Der Weijde, T., Anisimov, A.A., Iqbal, Y., Kiesel, A., Khokhlov, N.F., McCalmont, J.P., Meyer, H., Mos, M., Schwarz, K.-U., Trindade, L.M., Lewandowski, I., Clifton-Brown, J.C., 2017. Environmental influences on the growing season duration and ripening of diverse miscanthus germplasm grown in six countries. Front. Plant Sci. 8, 907. https://doi.org/10.3389/fpls.2017.00907.

Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W., Longdoz, D., Rambal, S., Valentini, R., Vesala, T., Yakir, D., 2006. Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: algorithms and uncertainty estimation. Biogeosciences 3 (4), 571–583. https://doi.org/10.5194/bg-3-571-2006.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Glob. Chang. Biol. 11, 1424–1439. https://doi.org/10.1111/j.1365-2486.2005.001002.x.

Song, Y., Jain, A.K., Landuyt, W., Kheshgi, H.S., Khanna, M., 2015. Estimates of biomass yield for perennial bioenergy grasses in the USA. BioEnergy Res 8, 688–715. https://doi.org/10.1007/s12155-014-9546-1.

U.S. Department of Agriculture, 2010. A USDA Regional Roadmap to Meeting the Biofuels Goals of the Renewable Fuels Standard by 2022. U.S. Department of Agriculture, Washington, DC, USA.

USA, 2007. The energy independence and security act of 2007 [WWW document]. (H.R.6). URL. http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf, Accessed date: 5 September 2018.

VanLoocke, A., Twine, T.E., Zeri, M., Bernacchi, C.J., 2012. A regional comparison of water use efficiency for miscanthus, switchgrass and maize. Agric. For. Meteorol. 164, 82–95. https://doi.org/10.1016/j.agrformet.2012.05.016.

Vickers, D., Mahrt, L., 1997. Quality control and flux sampling problems for tower and aircraft data. J. Atmos. Ocean. Technol. 14, 512–526. https://doi.org/10.1175/1520-0426(1997)014<0512:QCAFSP>2.0.CO;2.

Wagle, P., Kakani, V.G., 2014a. Seasonal variability in net ecosystem carbon dioxide exchange over a young switchgrass stand. GCB Bioenergy 6, 339–350. https://doi.org/10.1111/gcbb.12049.

Wagle, P., Kakani, V.G., 2014b. Environmental control of daytime net ecosystem exchange of carbon dioxide in switchgrass. Agric. Ecosyst. Environ. 186, 170–177. https://doi.org/10.1016/J.AGEE.2014.01.028.

Wagle, P., Kakani, V.G., Huhnke, R.L., 2015. Net ecosystem carbon dioxide exchange of dedicated bioenergy feedstocks: switchgrass and high biomass sorghum. Agric. For. Meteorol. 207, 107–116. https://doi.org/10.1016/j.agrformet.2015.03.015.

Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Q. J. R. Meteorol. Soc. 106, 85–100. https://doi.org/10.1002/qj.49710644707.

Wilczak, J.M., Oncley, S.P., Stage, S.A., 2001. Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorol 99, 127–150. https://doi.org/10.1023/A:1018966204465.

Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., Field, C., Grelle, A., Ibrom, A., Law, B., Kowalski, A., Meyers, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., Verma, S., 2002. Energy balance closure at FLUXNET sites. Agric. For. Meteorol. 113, 223–243. https://doi.org/10.1016/S0168-1923(02)00109-0.

Wutzler, T., Lucas-Moffat, A., Migliavacca, M., Knauer, J., Sickel, K., Šigut, L., Menzer, O., Reichstein, M., 2018. Basic and extensible post-processing of eddy covariance flux data with REddyProc. Biogeosciences 15 (16), 5015–5030. https://doi.org/10.5194/bg-15-5015-2018.

Zatta, A., Clifton-Brown, J., Robson, P., Hastings, A., Monti, A., 2014. Land use change from C3 grassland to C4 Miscanthus: effects on soil carbon content and estimated mitigation benefit after six years. GCB Bioenergy 6, 360–370. https://doi.org/10.1111/gcbb.12054.

Zeri, M., Anderson-Teixeira, K., Hickman, G., Masters, M., DeLucia, E., Bernacchi, C.J., 2011. Carbon exchange by establishing biofuel crops in Central Illinois. Agric. Ecosyst. Environ. 144, 319–329. https://doi.org/10.1016/j.agee.2011.09.006.

Zeri, M., Hussain, M.Z., Anderson-Teixeira, K.J., Delucia, E., Bernacchi, C.J., 2013. Water use efficiency of perennial and annual bioenergy crops in central Illinois. J. Geophys. Res. Biogeosci. 118, 581–589. https://doi.org/10.1002/jgrg.20052.

Zhuang, Q., Qin, Z., Chen, M., 2013. Biofuel, land and water: maize, switchgrass or Miscanthus ? Environ. Res. Lett. 8, 015020. https://doi.org/10.1088/1748-9326/8/1/015020.