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Carbon and evapotranspiration dynamics of a non-native perennial grass with biofuel potential in the southern U.S. Great Plains

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A R T I C L E I N F O

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A B S T R A C T

Old world bluestem cultivar WW-B Dahl [*Bothriochloa bladhii* (Retz.), S. T. Blake] is a non-native perennial C4 bunch grass with biofuel production potential grown predominantly in the Southern U.S. Great Plains. Although this is a popular introduced grass cultivar, data on carbon fluxes and evapotranspiration (ET) from this warm-season grass is rare. In this study, the eddy covariance method was used to measure CO_2 and ET from an established stand of bluestem for three years (2013–2015). Year 2015 had the highest gross primary production (GPP; 1358 ± 143 g C m^{-2}) followed by 2014 (1250 ± 31 g C m^{-2}) and 2013 (1024 ± 91 g C m^{-2}). The average loss of GPP as ecosystem respiration (R_{eco}) was 76%. Annual NEE sums were -302 ± 15 g C m^{-2} in 2013, -265 ± 41 g C m^{-2} in 2014, and -287 ± 32 g C m^{-2} in 2015. Results from this study show that the NEE in grasslands in years with normal precipitation that is well distributed may not vary from years with above-normal precipitation. This is because precipitation enhances R_{eco} along with carbon uptake, which may result in lower net carbon uptake in perennial grasslands in higher precipitation years than normal precipitation years. Gross primary production showed a linear relationship with ET (R^2 = 0.90) and above ground biomass (R^2 = 0.74). Only 26% of the GPP was allocated to above ground biomass indicating a higher allocation of carbon to below ground biomass. The water use efficiency of bluestem (2.9 g C kg^{-1} of water) matched well with that of native prairies and other dedicated biomass crops grown in the Southern Great Plains. As the demand for cellulosic biofuels is increasing, results from field experiments quantifying seasonal changes in carbon fluxes and ET could be important in understanding the contributions of large-scale production of novel biomass crops to regional carbon and hydrologic cycles.

1. Introduction

In addition to establishing food security, current U.S. agriculture is also challenged by improving energy security. The Energy Independence and Security Act of 2007 established the Renewable Fuel Standard (RFS) program which targets reducing greenhouse gas (GHG) emissions and expanding the renewable fuels sector in the U.S. (Bracmort, 2015). The RFS sets annual targets for biofuel production from various feedstocks that differ widely in production costs, GHG emissions and land-use requirements (Khanna et al., 2010). The RFS statutory requirement for renewable fuel production is 136 billion liters in 2022, of which at least 44% of total renewable fuels must be produced from cellulosic biofuels with low GHG emissions (USEPA, 2017). The majority of U.S. ethanol is produced from corn grain (*Zea mays* L.), which is capped at 57 billion liters. In 2016, the U.S. was the largest producer and exporter of fuel ethanol in the world with production reaching 58 billion liters (RFA, 2016). Although the U.S. was the largest exporter of fuel ethanol in the world, it also imported 363 million liters of fuel ethanol in 2015, majority of which came from Brazil. The Brazilian ethanol is produced from sugarcane (*Saccharum spp.*) which has less life-cycle GHG emissions compared to corn cropping systems in the U.S., thus promoting its import (Crago et al., 2010). To reduce the

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dependency on biofuel imports with lower GHG emissions, an increase in the production of fuel ethanol from advanced second generation bioenergy crops is anticipated in the future.

Old world bluestem cultivar WW-B Dahl [*Bothriochloa bladhii (Retz.), S. T. Blake*] (referred to as bluestem from hereon) is a C4 perennial bunch grass, native to India that had been introduced successfully in the Southern U.S. Great Plains in 1990s (Rajan et al., 2015a; Cui et al., 2013). Bluestem has many desirable characteristics as a biofuel crop, such as wide range of adaptation, water use efficiency (WUE) and high biomass productivity (Grabowski, 2000). In addition to favorable agronomic characteristics, physical and chemical properties of the feedstocks also play a major role in determining their suitability for large-scale biofuel production (Lewandowski et al., 2003). Buttrey et al. (2011) compared six perennial grasses including switchgrass (*Panicum virgatum*) and bluestem (*Bothriochloa ischaemum*) under irrigated and dryland conditions. The authors reported bluestem to be the best overall grass in terms of dry matter yield, forage quality and WUE. Venuto and Daniel (2010) reported similar energy values for switchgrass (16.8 GJ Mg^{-1}) and bluestem (16.6 GJ Mg^{-1}), though the energy values varied with timing of harvest. Venuto and Daniel (2010) concluded that land planted with bluestem spp. was the most productive in comparison to native mixed grasses in north western Oklahoma in the Southern U.S. Great Plains.

In recent years, groundwater levels have declined dramatically in the Southern Great Plains region due to excess water withdrawal from aquifers resulting in many farmers switching to production systems that use less water such as dryland farming or pastures (Rajan et al., 2015b). Among pasture grasses, WW-B Dahl blue stem is a popular choice. Current landscape in the Southern Great Plains is dominated by row cropping systems. In row cropping systems, management practices such as tillage and removal of harvested biomass can significantly influence carbon dynamics making them carbon sources in many cases (Schmidt et al., 2012). Increasing acreage of perennial crops such as bluestem in the Southern Great Plains may have positive implications on ecosystem services related to carbon gain. Natural and managed grasslands and pastures are known to play a major role in regional and global carbon dynamics. Perennial grasslands typically act as carbon sinks due to greater storage of carbon in soil (Frank and Dugas, 2001; Flanagan et al., 2002; Vleeshouwers and Verhagen, 2002; Rajan et al., 2013). However, grasslands can also act as net carbon sources due to changes in weather and disturbances such as fire and grazing (Flanagan et al., 2002; Jongen et al., 2011; Rajan et al., 2013). Such data from the perennial bluestem grass fields are limited.

An increase in area planted to bluestem grass in the Southern Great Plains can also affect regional surface energy balances. Changes in land cover can significantly affect latent heat (LE) and sensible heat (H) exchanges between the vegetation surface and the atmosphere through changes in leaf area, biomass, surface roughness and albedo. Latent heat is the amount of energy that is used in evapotranspiration (ET). Several studies found that ET from irrigated croplands contributed significantly to precipitation in semi-arid regions especially during the crop growing season (DeAngelis et al., 2010). A change in land use in the region from irrigated cropping systems to rainfed farming and grasslands could reduce the contribution of ET to precipitation in the region. Currently, there are limited data available on the ET dynamics of bluestem in the Southern Great Plains.

This research presents carbon and ET fluxes of bluestem measured using the eddy covariance method from 2013-2015. Through collaboration with a farmer, we established an eddy covariance system in a bluestem field in the Southern Great Plains. This provided us an opportunity to collect data under standard crop management practices followed under commercial production conditions in the Southern Great Plains. The objective of this study was to assess seasonal and inter-annual variation of net ecosystem exchange (NEE) of carbon dioxide (CO_2), ecosystem respiration (R_{eco}), gross primary production (GPP), and ET of bluestem grass in the Southern Great Plains. In addition, response of carbon and energy fluxes to the relevant environmental variables was also studied. Our research findings add to the understanding of carbon and ET dynamics of bluestem grass grown in the Southern Great Plains.

2. Materials and methods

2.1. Study site

This study was conducted from January 2013 to December 2015 in a farmer's field in the Southern U.S. Great Plains. The site was located about 5 km (34° 08′47″ N, 101° 25′48″ W, 1100 m elevation) west of Lockney, TX, USA in the Floydada County. This region has a semiarid climate with mean (30 yr) annual temperature of 14.9 °C and precipitation of 517 mm. About two-thirds of the annual precipitation is received during the crop growing season from May-October. Major soil mapping unit at the field is Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) with 0–1% slope. The field was established in 2007 and the cultivar of bluestem planted was "WW-B Dahl". This cultivar has upright growth habit and has better drought tolerance and WUE than conventional cropping systems in the Southern Great Plains (Allen et al., 2012). Prior to the establishment of bluestem grass, this field was in row crop agriculture. Total area of the site was about 42 ha. During the study period (2013–2015), the field was maintained as a low input system for seed production with no irrigation and fertilizer application. WW-B. Dahl bluestem remains vegetative for longer duration, with greening up in May, followed by peak growth in June and July, and blooming in mid to late September and shedding of seeds in October (Rajan et al., 2013). Hence, the period between 1-May until 31-October was considered for seasonal comparison of fluxes in this study.

2.2. Plant data

Four random plant and litter samples were taken biweekly from 0.25 m^2 area during the growing season. Green and yellow leaves were separated after samples were brought to the lab. Plant and litter samples were dried at 65 °C for a week. Dry weight of samples was taken immediately after removing the dried samples from the oven. Plant height was measured at the blooming stage when the plants achieved their maximum height of the season.

2.3. Eddy covariance data collection

A CSAT-3 A sonic anemometer (Campbell Scientific Inc., Logan, UT, USA) was used with a LI-7500 A open-path infrared gas analyzer (LI-COR Biosciences, Lincoln, NE, USA) to make continuous measurements of concentrations of CO_2 and water vapor, wind speed, and sonic temperature. These instruments were set up facing southwest (prevailing wind direction) at a height of about 2.1 m from the ground surface. The system was set such that the minimum fetch was about 200 m in all directions. Other environmental variables measured included net radiation (R_n) (Model NR-Lite, Kipp & Zonen, Delft, The Netherlands), air temperature (T_{air}), relative humidity (RH), and vapor pressure deficit (VPD) (Model HMP50, Campbell Scientific Inc., Logan, UT, USA), solar irradiance (Model LI-190SB, LI-COR Biosciences, Lincoln, NE, USA), photosynthetic photon flux density (PPFD) (Model LI-200SL, LI-COR Biosciences, Lincoln, NE, USA), precipitation (Model TE525, Campbell Scientific Inc., Logan, UT, USA), and soil volumetric water content (VWC) at 10, 20 and 40 cm depths (Model CS-655, Campbell Scientific Inc., Logan, UT, USA). Self-calibrating soil heat flux plates (HFPSC-01, Hukseflux, Deft, The Netherlands) were used to measure soil heat flux at 8 cm depth from the soil surface (G_{8cm}). Additional soil VWC measurements (Model CS-616, Campbell Scientific Inc., Logan, UT, USA) were made at 4 cm below the surface in between a pair of heat flux plates. Average soil temperature (T_{soil}) between 2 and 6 cm depths below the surface (above the heat flux plate) were measured using averaging soil thermocouples (Model TCAV, Campbell Scientific Inc., Logan, UT, USA). Data from the sonic anemometer and infrared gas analyzer were measured at 10-Hz sampling rate using a CR3000 datalogger (Campbell Scientific Inc., Logan, UT, USA). All other environmental variables were measured at 5 s interval. The datalogger was programmed to calculate and save 30-min average values of all environmental variables. The raw 10-Hz data from the sonic anemometer and infrared gas analyzer were saved for further post-processing and analysis of CO_2 and energy fluxes.

2.4. Data Processing, gap filling and analysis

Fluxes (NEE, LE and H) were computed using the open source EddyPro 5.2.1 software (LI-COR Biosciences, Lincoln, NE, USA). The sign convention used was a positive flux represents flux from the ecosystem to the atmosphere, while a negative flux represents flux from the atmosphere to the ecosystem. Calculation of fluxes requires raw data filtering and applications of algorithms for correcting fluxes. Some of the corrections include spike removal, corrections for air density fluctuations (Webb et al., 1980) and spectral corrections for flux losses (Moncrieff et al., 1997). EddyPro assigns flags for quality control based on tests for steady state and turbulence (Foken et al., 2004; Göckede et al., 2007). High quality fluxes are indicated by flag '0', intermediate quality fluxes are flagged as '1' and poor quality fluxes are flagged as '2'. Data were also screened and filtered for implausible values occurred during maintenance, precipitation and low turbulence conditions (friction velocity < 0.10 m s^{-1}). Occasional gaps in the flux data occurred during power failure or maintenance. The amount of data which was either missing or did not meet the quality check criteria was about 32, 16 and 25% of the total data in 2013, 2014, and 2015, respectively. After screening data for the above mentioned filtering criteria, the CarboEurope and Fluxnet eddy covariance gap-filling on-line tool (http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/) was used for gap filling and flux partitioning (Reichstein et al., 2005). This tool uses recognized and widely used flux partitioning procedures to provide estimations of half-hourly GPP and R_{eco} (Falge et al., 2001). A detailed uncertainty analysis was conducted for all three years. Major sources of uncertainties related to gap filling and u* thresholds were determined according to the methods suggested by Hunt et al. (2016) and Wutzler et al. (2018).

After gap filling, we examined the energy balance to assess the quality of eddy covariance flux data. The main components of energy balance include R_n (W m^{-2}), LE (W m^{-2}), H (W m^{-2}) and soil heat flux at the surface (G in W m^{-2}). The energy partitioning can be expressed as follows:

$$R_n - G = LE + H \tag{1}$$

The slope of the regression between R_n - G and sum of LE and H is an indication of the degree of energy balance closure. A slope of 1 indicates complete closure and a slope < 1 indicates partial energy balance closure. Soil heat storage (S) above the heat flux plates and measured soil heat flux at 8 cm (G_{8cm}) were added to obtain G. Heat storage above the soil heat flux plates was calculated using the following equation:

$$S = \frac{\Delta T_s C_s d}{t} \tag{2}$$

where S is the storage term, ΔT_s is the change in soil temperature (difference between two consecutive 30 min measurements), *Cs* is the heat capacity of moist soil, *d* is depth of soil in meters above the heat flux plate, and *t* is time in seconds. For the energy balance assessment, good quality original data (flag '0') for LE and H were used when all the energy balance components were available. The slopes of the linear regression between the available energy (R_n – G) and the sum of LE and H during the growing season ranged from 0.84 to 0.85 with coefficient of regression (r^2) more than 0.90 during all years of the study. Energy balance closures ranging from 84 to 85% in our study fall within the range (70–90%) generally reported for grasslands, pastures, and crop lands (Stoy et al., 2013; Rajan, 2007).

To understand the impact of environmental conditions on the photosynthetic response of the bluestem grass, rectangular hyperbola models were developed during the peak growing season relating daytime (PPFD > 10 µmol m^{-2} s^{-1}) NEE with PPFD (Flanagan et al., 2002; Hussain et al., 2011).

$$NEE = \frac{NEE_{\max} PPFD}{PPFD + \left(\frac{1}{\alpha}\right) NEE_{\max}} + R \tag{3}$$

where NEE_{max} is the maximum net CO_2 exchange (µmol CO_2 m^{-2} s^{-1}), PPFD is the photosynthetic photon flux density (µmol photons m^{-2} s^{-1}), α is the initial slope of the light response curve, NEE_{max}/α is the PAR associated with half of the maximum NEE rate, and R is the intercept term, which is the average daytime R_{eco} (µmol CO_2 m^{-2} s^{-1}).

To understand the response of R_{eco} to T_{soil}, an exponential relationship between weekly average night-time R_{eco} and T_{soil} was established:

$$R_{eco} = ae^{bT_{soil}} \tag{4}$$

where, R_{eco} is the weekly average night-time ecosystem respiration, T_{soil} is the corresponding soil temperature, and a and b are model parameters. Only original data was used for this analysis. The factor Q_{10} indicates the sensitivity of the R_{eco} to T_{soil} (increase in respiration in response to a 10 °C rise in temperature) and was computed as:

$$Q_{10} = e^{10b} \tag{5}$$

where b is the constant fitted using Eq. (4).

Ecosystem Water use efficiency (WUE) was calculated in terms of gross carbon uptake per unit water lost by dividing GPP with daytime ET at different temporal scales. Statistical analyses and evaluation of regression models were performed using SigmaPlot Version 13.0 (Systat Software, Inc.).

3. Results and discussion

3.1. Weather conditions

The environmental variables, T_{air}, T_{soil}, PPFD, and VPD followed a similar trend during the three years (2013-15) of this study (Fig. 1). Average annual temperature recorded at the field was 14.4 °C, 14.0 °C, and 15.0 °C in 2013, 2014, and 2015, respectively. The recorded annual average temperatures were close to the mean annual 30-year (1981–2010) air temperature (14.9 °C) recorded in Floydada county. Major differences in the amount and distribution of precipitation were observed over the three years of the study (Fig. 2). Year 2013 and 2014 received normal amount of rainfall (509 mm in 2013 and 520 mm in 2014) and year 2015 received almost double the amount of normal precipitation (820 mm). Nearly 75% of the precipitation in 2015 was received by the first week of July followed by an extended dry period from mid-July to late September (Fig. 2). Soil moisture was sensitive to the magnitude and timings of precipitation (Fig. 2). Above normal rainfall during the early growing season resulted in the highest average seasonal VWC at 10 cm depth in 2015 (0.28), followed by 2014 (0.26) and 2013 (0.24). The driest months of the season were May in 2013 (VWC of 0.19), August in 2014 (VWC of 0.17) and 2015 (VWC of 0.20). Year 2013 recorded more days with VPD greater than 2.5 kPa followed by 2014 and 2015. Average seasonal VPD was the highest in 2013 (1.5 kPa). Average seasonal VPD was similar in 2014 and 2015 (1.1 kPa). Seasonal (May 1- October 31) PPFD accumulation was the highest in 2013 (1616 MJ) due to less number of cloudy days followed by 2014 (1552 MJ) and 2015 (1538 MJ). Average seasonal T_{soil} was the highest (22.5 °C) in 2013, while it was similar in 2014 (20.4 °C) and 2015 (20.1 °C). This could be due to the shade provided by early growth

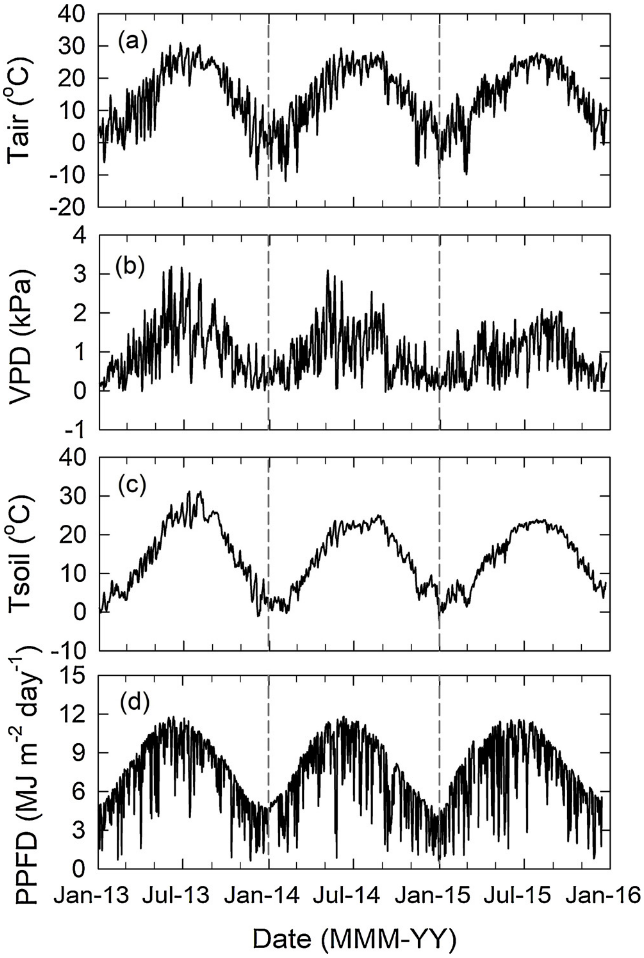

Fig. 1. Daily averages of meteorological variables for 2013, 2014 and 2015. (a) Air temperature (T_{air}) in °C, (b) vapor pressure deficit (VPD) in kPa, (c) soil temperature (T_{soil}) in °C and (d) photosynthetic photon flux density (PPFD) in MJ m^{-2} day^{-1}. Grey dashed lines separate years from each other.

in 2014 and 2015 due to precipitation, which lowered the soil temperatures in the field in comparison to 2013. However, the average annual T_{soil} was similar (14.1 °C in 2013, 13.8 °C in 2014, and 14.0 °C in 2015) for all the years of the study.

3.2. Phenology

Bluestem achieved a maximum height ranging from 90 to 110 cm. Biomass of the crop increased rapidly following rainfall events. Peak aboveground biomass (AGB) for different seasons was achieved at different times. Maximum AGB observed was about 7.3, 10.2, and 10.3 Mg ha^{-1} in 2013 (DOY 303), 2014 (DOY 274), and 2015 (DOY 223), respectively (Fig. 3). Biomass production of bluestem in this study was lower than that reported by Dalrymple (1991) (15 ton ha^{-1}) and Buttrey et al. (2011). The possible reason for lower biomass in our study could be the absence of management including irrigation and nutrient application, whereas the above reported studies were well managed plots with multiple harvests per season. In comparison to dedicated biomass crops, biomass production of bluestem from this study is lower than what has been reported for switchgrass by Wagle et al. (2015) (17 ton ha^{-1}) in Oklahoma, U.S. and Eichelmann et al. (2016) (12 tons ha^{-1}) in Canada under dryland conditions, and Sanderson et al. (1996) (26 ton ha^{-1}) in Alabama.

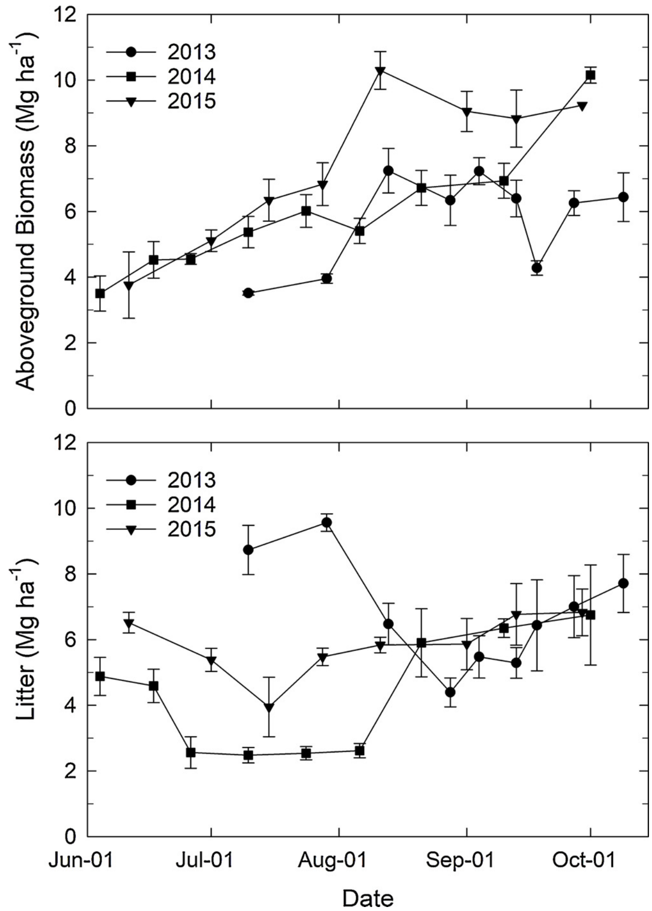

Fig. 3. Seasonal evolution of aboveground biomass (AGB) and litter in 2013, 2014, and 2015. The data was collected randomly from a 0.25 m^2 area with four replications. Error bars represent the standard error of the mean.

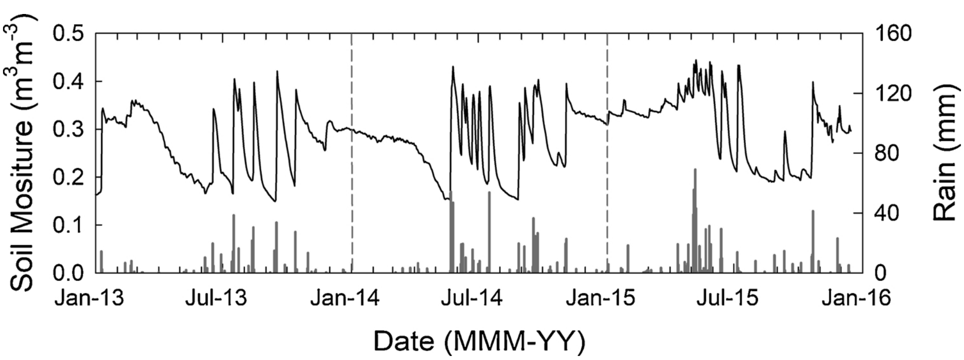

Fig. 2. Daily average soil moisture (volumetric water content) and weekly sum of rain measured at the study site during 2013, 2014 and 2015. The vertical bars represent precipitation and horizontal lines represent soil moisture. Grey dashed lines separate years from each other.

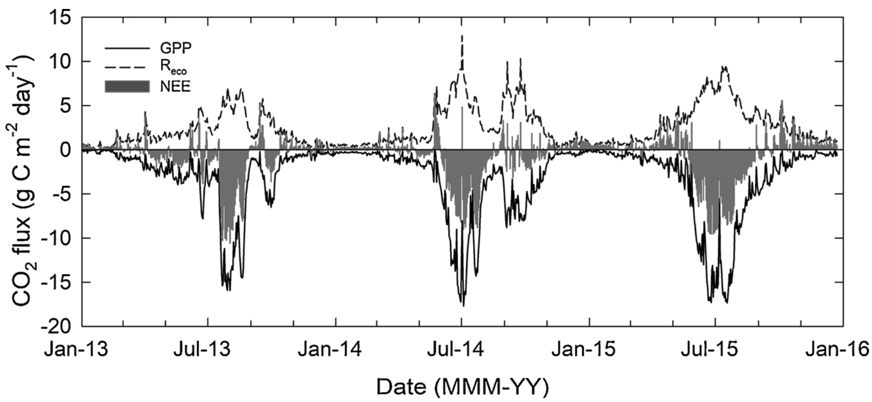

Fig. 4. Thirty-minute average net ecosystem exchange (NEE), gross primary production (GPP) and ecosystem respiration (R_{eco}) of bluestem field in the Southern U.S. Great Plains for 2013, 2014 and 2015. Carbon uptake was denoted as negative and carbon release was denoted as positive. The growing season was defined as the period from 1 May to 31 October every year as the crop started greening in the first week of May and was completely senesced by the last week of October. Grey dashed lines separate years from each other.

Table 1
Cumulative seasonal and annual gross primary production (GPP), net ecosystem exchange (NEE), ecosystem respiration (R_{eco}), evapotranspiration (ET) ecosystem water use efficiency (WUE), and rain (mm) in bluestem. Values in parenthesis with annual sums represent uncertainty estimates for corresponding fluxes.

Year	GPP	NEE	Reco	ET	WUE	Rain
	g C m^{-2}			–mm–	g C kg^{-1} water	–mm–
Seasonal						
2013	−877	−314	563	326.6	2.7	445
2014	−1140	−317	823	383.8	3.0	450
2015	−1233	−372	860	442.9	2.8	676
Annual						
2013	−1024(143)	−302(15)	722(160)	398.8(23)	–	509
2014	−1250(31)	−265(41)	984(79)	443.0(27)	–	520
2015	−1358(91)	−287(32)	1072(126)	530.3(30)	–	820

3.3. Carbon fluxes

Fig. 4 shows daily carbon flux exchanges at the bluestem site throughout the study period and Table 1 presents the seasonal cumulative values for NEE, GPP and R_{eco} fluxes. Non-growing season for bluestem was from January-April in the beginning and November-December towards the end of the year, covering winter, early-spring and late-fall periods. Although perennial grasses such as bluestem leave a thick mat of residue on the ground resulting in less weed pressure during fallow seasons compared to conventionally tilled agricultural fields, winter annual weeds such as horseweed (*Erigeron canadensis*) were sparsely present in the site generating slight photosynthetic activity during the off-season. During the growing seasons, carbon flux dynamics of bluestem varied depending on the magnitude and timing of precipitation. The photosynthetic activity started with new growth in May every year and progressed towards maxima during the peak growing season in July. Bluestem showed a typical C4 grass response to precipitation and warm conditions during the growing season, with increased photosynthetic activity and biomass production as the season progressed in June and July. Early growing season in 2013 and the preceding season in 2012 were dry due to severe drought in the region. This resulted in poor growth of bluestem at the beginning of this study in 2013. Early season precipitation in 2014 and 2015 caused vigorous growth in June and July (Fig. 4). As a result, GPP was the lowest in 2013, followed by 2014 and 2015. Early season precipitation also resulted in periods of enhanced R_{eco} fluxes in early growing season in 2014 and 2015 despite initiation of growth and photosynthetic activity. The seasonal R_{eco} was 64% of GPP in 2013, 72% in 2014 and 70% in 2015.

Maximum daily NEE observed during the growing season was -10.6 g C m^{-2} on DOY 214 in 2013, -9.0 g C m^{-2} on DOY 185 in 2014, and -9.5 g C m^{-2} on DOY 176 in 2015. Maximum GPP was also observed on similar DOY, which was -15.9 g C m^{-2} in 2013, -17.7 g C m^{-2} in 2014, and -17.3 g C m^{-2} in 2015. Maximum R_{eco} observed was 7.0 g C m^{-2} on DOY 211 in 2013, 12.9 g C m^{-2} on DOY 183 in 2014, and 9.4 g C m^{-2} on DOY 194 in 2015. The maximum daily GPP values in our study are lower than those reported (-21.5 g C m^{-2} day^{-1}) by Zhou et al. (2017) for *Bothriochloa caucasia* C. E. Hubb. in the Oklahoma region of the Southern Great Plains in the U.S. However, peak R_{eco} values in 2014 were comparable to peak R_{eco} values reported (12 g C m^{-2} day^{-1}) by Zhou et al. (2017). Seasonal carbon uptake for bluestem in our study are higher than those reported by Rajan et al. (2013) (164 g C m^{-2}) for the same bluestem site in the 2010 growing season with above normal precipitation. The field was grazed during the 2010 growing season. According to Zhou et al. (2017), photosynthetic activity decreases following removal of green biomass either through grazing or harvest for baling, which explains lower cumulative values of GPP in Rajan et al's study.

Annual net ecosystem carbon uptake of 2013 was the highest, followed by 2015 and 2014. Strong seasonal R_{eco} in 2014 and 2015 resulted in lower annual NEE values in those years. The annual R_{eco} was 70% of annual GPP in 2013, and 79% in 2014 and 2015. It should also be noticed that R_{eco} during the non-growing season was slightly higher in 2015, probably due to accumulation of residue from the previous year and relatively more wet conditions. Annual NEE for bluestem in our study (Table 1) are within the range of those reported for native prairies by Suyker and Verma (2004) (-274 g C m^{-2}) in Oklahoma, Suyker and Verma (2001) (-268 g C m^{-2}) for a tall grass prairie in Oklahoma and Zeri et al. (2013) (-344 g C m^{-2}) in Illinois. These values also matched well with those reported for rainfed high biomass sorghum (-261 to -330 g C m^{-2}) in the Oklahoma region of the Southern Great Plains in the U.S. by Wagle et al. (2015). However, these values were lower than that reported (-406 to -490 g C m^{-2}) for switchgrass in a similar study by Wagle et al. (2015). These findings suggest that carbon dynamics of non-native bluestem not only matches the carbon dynamics of native prairies, but also match the net carbon uptake values of high biomass sorghum (annual cellulosic bioenergy crop) under rainfed conditions in the Southern Great Plains of the U.S. This is important as perennial nature of bluestem eliminates standard agronomic practices required for row crops such as sorghum, thereby could provide better ecosystem services related to improved soil and water quality in the long-term.

A strong linear relationship between AGB and GPP was developed (R^2 = 0.74) where AGB was the response variable to GPP (Fig. 5). According to Venuto and Daniel (2010), carbon content of bluestem biomass was 43.2 g C Kg^{-1} or 43.2%. We used this carbon content in the AGB to obtain a relationship between carbon accumulated in AGB (green and yellow leaves) on a given day of growing season and accumulated GPP during the corresponding time period. The slope of this relationship was 0.23, which indicated that 23% of the GPP was allocated to AGB. Overall, the GPP is distributed among AGB, below ground biomass and autotrophic respiration (Sharma et al., 2017). Therefore,

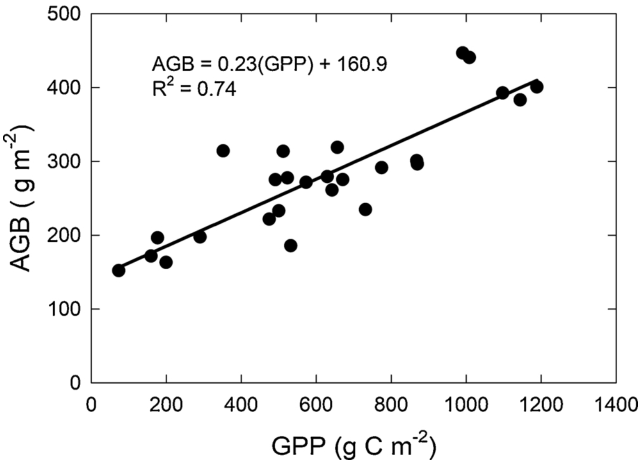

Fig. 5. Cumulative aboveground biomass (AGB) plotted versus gross primary production (GPP).

the remaining GPP was part of litter, below ground biomass and autotrophic respiration. Campioli et al. (2015) reported similar relationships for croplands, grasslands and forests. The authors concluded that more GPP is distributed to belowground biomass in unmanaged grasslands, to better explore soil volume for nutrients and moisture. Several studies have concluded greater allocation of biomass in unmanaged grasslands to belowground biomass, which is consistent with our findings (Scurlock and Hall, 1998; Ni, 2002). In a previous study, Sharma et al. (2017) reported a 65% allocation of GPP to AGB in well managed irrigated high biomass sorghum in the same region. Greater allocation of GPP to below ground biomass in bluestem is important as soils in the Southern Great Plains are low in organic carbon due to continuous row crop production. This suggests that production of perennial grasses such as bluestem may help in the building of soil organic carbon reserves in these soils. However, long term studies specifically targeting soil organic carbon accumulation and above and belowground biomass productions are required for better understanding of GPP allocation.

The biomass of this field was not harvested for commercial biofuel production. Harvesting all AGB from the field for commercial energy production could result in a net release of CO_2. However, it should be noted that the bluestem field was maintained with minimal agronomic management operations. Agronomic practices such as tillage, nutrient application and irrigation also have implications on deciding the overall carbon source/sink status of a cropping system (Balafoutis et al., 2017). Therefore, more investigation is needed to determine the lifecycle carbon budget of the bluestem grass by accounting for various sources of carbon emissions and sequestration.

3.4. Evapotranspiration

Fig. 6 shows the regular seasonal pattern of ET during all growing seasons. Average daily ET during the non-growing season of all years was 0.5 mm day^{-1}. The trends in ET in bluestem were in agreement with carbon uptake, which was largely driven by precipitation. When plotted against each other across all growing seasons, monthly GPP and ET showed a strong linear (R^2 = 0.94) relationship (Fig. 8). Similar agreement between carbon uptake and ET have been reported by Rajan et al. (2015a) and Eichelmann et al. (2016), suggesting the importance of precipitation in carbon uptake and ET dynamics of perennial grass systems. Seasonal ET of bluestem was comparable to those reported by Burba and Verma (2005) for a tall grass prairie in Oklahoma.

Table 1 shows the cumulative values of seasonal and annual ET. The seasonal ET was 74, 85, and 65% of the seasonal precipitation received during 2013, 2014, and 2015, respectively. The annual ET was 79, 85 and 64% of the annual precipitation received during 2013, 2014, and 2015, respectively. The possible reason for lower proportion (in 2013 and 2015) of annual ET with respect to seasonal as well as annual precipitation could be the loss of rain water through runoff when the surface soil was saturated (Fig. 2). Water use efficiency calculated is also presented in Table 2. Ecosystem water use efficiency of bluestem was lower than that of 3.3–4.1 g C kg^{-1} water reported by Skinner and Adler (2010) for switchgrass in northeast U.S., 3.8 g C kg^{-1} water observed by Eichelmann et al. (2016) in Canada, and 3.1 g C kg^{-1} water by Abraha et al. (2016) in Illinois, U.S. The slope of monthly GPP and ET relationship also represents WUE, which was 2.9 g C kg^{-1} water (Fig. 7).

Lower WUE of bluestem in comparison to switchgrass in our study than the studies conducted in northern latitudes could be attributed to lower temperatures and VPD which lead to lower ET requirement for equal amount of carbon uptake in Northern latitudes (Eichelmann et al., 2016). However, values of WUE in our study fall within the range of 2.5–3.1 g C kg^{-1} water observed by Wagle et al. (2016) for a young switchgrass stand in Oklahoma, USA. Also, WUE of bluestem in our study fall within the range reported by Beer et al. (2009) (2.1–4.4 g C kg^{-1} water) for grasslands and croplands. Comparable WUE of bluestem and switchgrass under similar environmental conditions (Wagle et al., 2016) suggests similar ecosystem productivity of bluestem and switchgrass in the Southern Great Plains. Though, it should be noticed that growing season length of switchgrass in Wagle et al.'s study was at least a month longer than bluestem in our study, and therefore produced greater biomass than bluestem despite similar WUE.

3.5. Temperature sensitivity of ecosystem respiration

We also examined the impact of environmental variables on carbon fluxes. Temperature and moisture are well known controlling factors of R_{eco} and have been reported in several previous research studies (Xu and Qi, 2001; Xu and Baldocchi, 2004; Suyker and Verma, 2012; Rajan et al., 2013). When plotted against night-time T_{soil}, weekly average night-time R_{eco} showed a strong exponential dependence (Fig. 8). Temperature sensitivity (Q_{10}) value for the bluestem field was 2.6, 3.0, and 3.0 in 2013, 2014 and 2015, respectively. Fig. 8 also shows the decline in respiration during low moisture conditions. Ecosystem respiration includes both autotrophic and heterotrophic respirations. Precipitation events restore soil moisture, thus enhancing microbial activity and R_{eco} (Sharma et al., 2017). Ecosystem respiration was the lowest when VWC was in the range of wilting point (0.19 m^3 m^{-3}). Also, this explains the greater R_{eco} in early growing seasons of 2014 and 2015 following precipitation events. Suyker et al. (2004) and Rajan et al. (2013) reported similar observations of declining R_{eco} under low soil moisture conditions. These results suggest that despite the favorable impact of precipitation on carbon uptake in the grassland ecosystems, it also exacerbates carbon release from the system.

3.6. Influence of vapor pressure deficit on GPP and ET

As discussed previously, GPP declined under dry conditions in the bluestem field. When plotted against VPD, GPP increased quickly until 10:00 am (GMT +6:00 h) and declined thereafter in the afternoon without any limitation to PPFD. For example, Fig. 9 shows the relationship between GPP, NEE and ET with rising VPD for three clear days (DOY 226, 232 and 233) in August 2014. Average VWC at 10 cm depth was 0.19 m^3 m^{-3} during those days. Carbon uptake peaked up to 1.7 kPa VPD and declined thereafter. While GPP and NEE declined with rising VPD, ET was rising with VPD until it plateaued. This suggests that GPP is more sensitive to dry conditions than ET and is more likely to be affected by VPD than ET. Similar results have been observed by Cabral et al. (2013) for C3 and C4 crops and Rana et al. (2016) for cardoon, a perennial bioenergy crop. The decline in GPP and NEE with rising VPD during dry conditions could be explained by increasing stomatal resistance, which reduces CO_2 gas exchange between stomatal cavity and

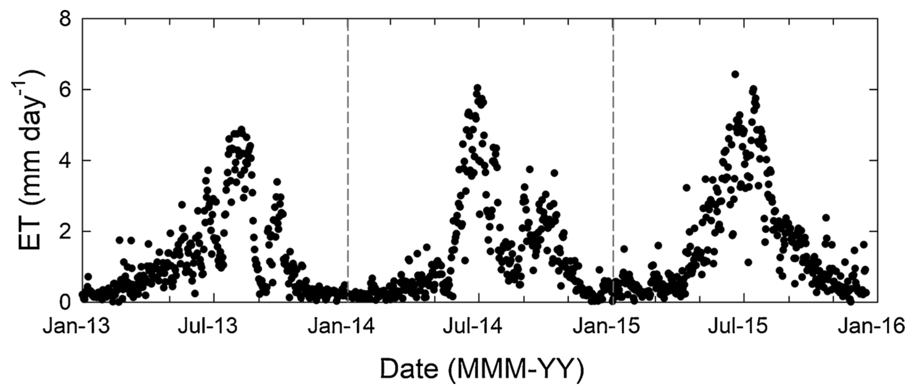

Fig. 6. Thirty-minute average evapotranspiration (ET) of bluestem in the Southern U.S. Great Plains during the three study years (2013–2015). Grey dashed lines separate years from each other.

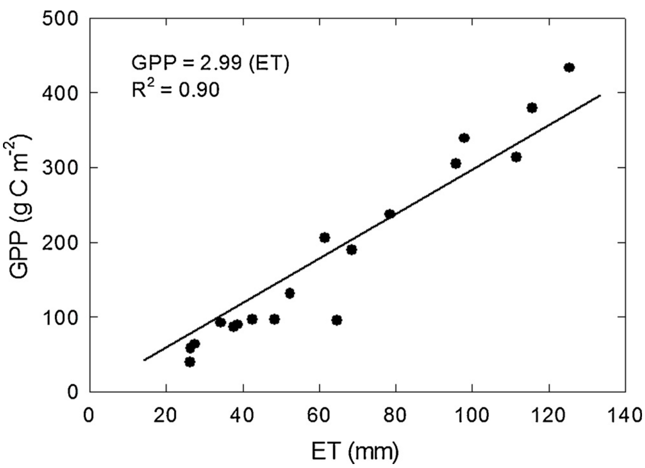

Fig. 7. Linear relationship between monthly gross primary production (GPP) and evapotranspiration (ET) during the active growing season (May-October) across all three years.

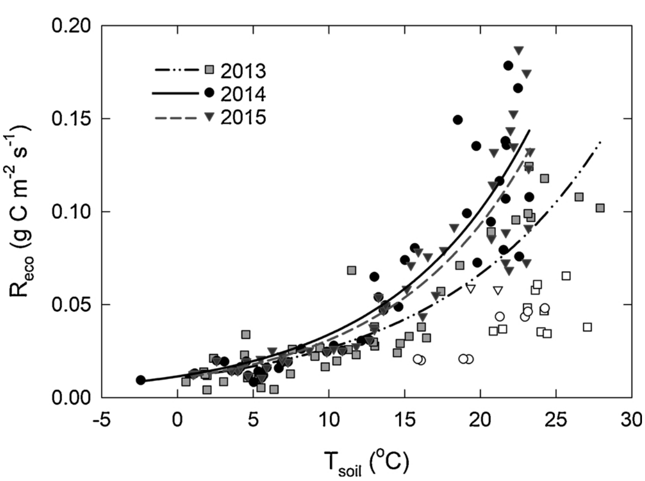

Fig. 8. Exponential relationship between weekly average night-time soil temperature (T_{soil}) and night-time ecosystem respiration (R_{eco}) for year 2013 ($R_{eco} = 0.0107e^{0.0915T_{soil}}$), 2014 ($R_{eco} = 0.0114e^{0.1090T_{soil}}$), and 2015 ($R_{eco} = 0.0.103e^{0.0110T_{soil}}$). Only original data was used for the relationship. Coefficient of determination (R^2) was 0.85 in 2013, 0.81 in 2014 and 2015. The white data points refer to R_{eco} during dry period (volumetric water content < 0.19 $m^3\,m^{-3}$), and were not included in regression analysis.

atmosphere, thereby reducing photosynthesis. According to Cabral et al. (2013), the possible reason behind low sensitivity of ET to rising VPD could be due to added evaporation from soil and transpiration

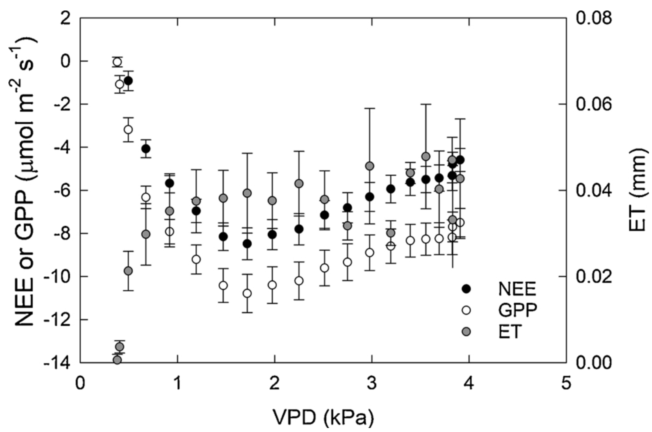

Fig. 9. Relationship between half-hourly diurnal averages of net ecosystem exchange (NEE), gross primary production (GPP) and evapotranspiration (ET) with corresponding vapor pressure deficit (VPD) during warm and dry conditions (volumetric water content = 0.19 $m^3\,m^{-3}$) in old world bluestem field for selected days (DOY 226, 232, and 233) in 2014. Error bars represent the standard error of the mean.

from cuticle, which compensates the decline in transpiration during stomatal closure, as the driving factor for ET is VPD.

4. Conclusions

Carbon and ET dynamics of Old World Bluestem were measured from a producer field in the Southern Great Plains region of the United States. Growing season precipitation was influential in carbon and ET dynamics, where early season precipitation was advantageous in promoting vigorous growth than mid-season precipitation. Carbon fluxes of bluestem in our study were comparable to those of perennial native grass species, as well as rainfed biomass sorghum in the Southern Great Plains. Additionally, greater allocation of GPP to below ground biomass by bluestem indicates benefits for building soil organic carbon in the Southern Great Plains compared to row crops. This would also help alleviate the impact of biomass removal from the field for biofuel production as bluestem may be retaining significant amount of carbon below ground. However, further research is necessary to validate this conclusion. The WUE and ecosystem productivity of bluestem matched well with that of switchgrass in the Southern Great Plains. Measured carbon fluxes and ET were sensitive to VPD and PPFD. Our data shows that carbon uptake was more sensitive to VPD than ET. This conclusion may vary for different grass species and growing conditions due to varying physiological properties and resilience of different species.

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