Biomass and Bioenergy 105 (2017) 392–401

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Research paper

Seasonal variability of evapotranspiration and carbon exchanges over a biomass sorghum field in the Southern U.S. Great Plains

Sumit Sharma [a,1], Nithya Rajan [a,*], Song Cui [b,2], Kenneth Casey [c], Srinivasulu Ale [b], Russell Jessup [a], Stephen Maas [d]

[a] Department of Soil and Crop Sciences, Texas A&M University, College Station, TX 77843, USA
[b] Texas A&M AgriLife Research and Extension Center, Vernon, TX 76384, USA
[c] Texas A&M AgriLife Research and Extension Center, Amarillo, TX 79106, USA
[d] Department of Plant and Soil Science, Texas Tech University, Lubbock, TX 79409, USA

ARTICLE INFO

Article history:
Received 30 April 2017
Received in revised form
19 July 2017
Accepted 28 July 2017

Keywords:
Bioenergy
Eddy covariance
Sorghum bicolor
Net ecosystem production
Gross primary production
Ecosystem respiration

ABSTRACT

The eddy covariance method was used to investigate carbon fluxes and evapotranspiration (ET) from a high biomass forage sorghum (*Sorghum bicolor* L.) field in the Southern U.S. Great Plains for three growing seasons (2013–2015). Above normal precipitation and narrow row spacing (50 cm) led to higher biomass production (25 Mg ha^{-1}) and leaf area index (LAI = 7.2) development in 2014. This also resulted in higher carbon uptake or net ecosystem production (NEP) and ET during that year. Early and late season precipitation enhanced ecosystem respiration (R_{eco}) resulting in lower NEP in 2015. Shorter growing season (119 days) also contributed to lower cumulative NEP in 2015. Estimated gross primary production (GPP) in 2014 (1780 g m^{-2}) was 10% higher than the GPP in 2013 (1591 g m^{-2}) and 24% higher than the GPP in 2015 (1353 g m^{-2}). During all growing seasons, the site was a source of carbon (negative NEP) at the beginning and transitioned to a sink (positive NEP) later in the season. Biomass-GPP relationship indicated that approximately 65% of total GPP was allocated to above ground biomass (AGB). Average monthly ecosystem WUE (expressed as gross carbon gain per unit of ET) ranged from 1.7 g mm^{-1} to 4.2 g mm^{-1}. Results from our study indicate that weather conditions, growing season length and crop management are important factors in determining the magnitude of carbon uptake and release, and ET of this cellulosic biofuel feedstock crop in the Southern U.S. Great Plains.

1. Introduction

Fuel ethanol production in the U.S. has increased from 40 billion liters in 2009 to 55.6 hm^3 in 2015 [1]. Approximately 3.2 hm^3 of U.S. fuel ethanol was exported to more than 50 countries in 2015 [1]. Although U.S. is the largest exporter of fuel ethanol in the world, it also imported 0.36 hm^3 of ethanol in 2015. Majority of this imported ethanol came from Brazil. The main reason for the import was that the Renewable Fuel Standards (RFS) and the Low Carbon Fuel Standards of California and other states specify the use of biofuels with low greenhouse gas (GHG) emissions [2]. Based on life cycle analyses, GHG emissions from sugarcane (*Saccharum* spp.) cropping systems in Brazil are considered to have less GHG emissions compared to corn (*Zea mays*) cropping systems in the U.S., thus promoting its import [3]. The RFS statutory requirement for renewable fuel production is 113.6 hm^3 in 2020, of which at least 35% of total renewable fuels must be produced from cellulosic biofuels with low GHG emissions [4].

Cellulosic biofuels are produced from lignocellulosic biomass feedstocks using advanced conversion technological processes [5]. The main cellulosic biomass feedstocks include agricultural residues and dedicated herbaceous and woody energy crops [6,7]. Many cellulosic bioenergy crops are ideal candidates for growing in the Southern Great Plains due to their adaptation to water-limited and semi-arid environmental conditions. A potential bioenergy crop that is gaining popularity in the Southern Great Plains is sorghum (*Sorghum bicolor* L.). Several studies have reported the drought tolerance and high water use efficiency (WUE) characteristics of biomass and forage sorghums in the Southern Great Plains

* Corresponding author.
E-mail address: nrajan@tamu.edu (N. Rajan).
[1] Present Address: Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078, USA.
[2] Present Address: School of Agribusiness and Agriscience, Middle Tennessee State University, Murfreesboro, TN 37132, USA.

http://dx.doi.org/10.1016/j.biombioe.2017.07.021

[8–11]. In addition to agronomic characteristics such as high WUE and high biomass production, physical and chemical properties of the feedstocks also play a major role in determining their suitability for biofuel production [12–14]. The brown midrib (*bmr*) cultivars of forage sorghum have lower lignin content, and hence are ideal for ethanol production as lignin tends to prevent the enzymes from accessing cellulose [12,15,16]. Additionally, forage sorghum is cheaper to produce than corn [17]. Several new *bmr* cultivars of forage sorghum have already been successfully introduced in the Southern Great Plains region.

Changes in land surface properties and management practices due to land use change to cellulosic biofuel crops can significantly influence regional carbon and hydrologic cycles [18,19]. In recent years, eddy covariance systems with fast response instruments have been increasingly used for direct measurements of the exchange of CO_2 and water vapor between the vegetation surface and the atmosphere [20–22]. Using this method, CO_2 flux or net ecosystem production (NEP) is determined as the covariance between vertical wind velocity and CO_2 concentration. During the daytime, NEP measured using the eddy covariance method represents the balance between CO_2 absorbed by plants through photosynthesis (gross primary production, GPP) and CO_2 that is released through a combination of autotrophic and heterotrophic respiration (ecosystem respiration, R_{eco}). At night, NEP measurements represent R_{eco}. Similar to NEP, latent heat flux (LE) is determined as the covariance between vertical wind velocity and water vapor concentration. Latent heat is the energy flux used in evapotranspiration (ET). Scientists have established networks of experimental sites such as Ameriflux with eddy covariance systems for quantifying NEP and ET from key ecosystems in North America [23]. Data from these experimental sites are critical for gaining a proper understanding of regional and global carbon and hydrologic cycles. However, very few studies have been conducted to investigate ET and CO_2 fluxes of cellulosic biofuel crops such as sorghum [24]. In this three-year study (2013–2015), we examined half-hourly, daily, and seasonal ET and carbon flux dynamics of annual high biomass forage sorghum in the Southern U.S. Great Plains. Our results provide further insights into the dynamics of carbon fluxes and ET for this lesser studied, yet crucial, cellulosic biofuel cropping system in the Southern U.S. Great Plains.

2. Materials and methods

2.1. Study site

The study was conducted in a farmer's center-pivot irrigated field planted to high biomass forage sorghum for commercial seed production. The field was located approximately 4.5 km northeast of Plainview, TX in the Southern Great Plains region (34°12′34.70″ N and 101°37′50.85″ W, 1100 m elevation). The climate of the region is semiarid with long-term mean annual rainfall of 460 mm [25]. The total area of the center pivot field was 0.5 km^2 (50 ha) and sorghum was planted to half of the area (0.25 km^2). Remaining half of the field was planted to cotton (*Gossypium hirsutum* L.). The farmer practiced an annual rotation of sorghum and cotton in these two sections. The sorghum cultivar planted was Surpass XL *bmr* (Coffey Seed Company, Plainview, TX). The crop was planted on 20 May (DOY 140) in 2013 and 2014. Heavy rains in 2015 delayed planting, thus the crop was planted on June 4 (DOY 155) that year. In all three years, the planting density was approximately 120,000 plants per hectare. However, the row spacing was narrower in 2014 (50 cm) compared to 2013 and 2015 (100 cm). Urea (46-0-0) was broadcasted in the field in spring before planting at a rate of 325 kg ha^{-1}. In addition, triple superphosphate (0-45-0) was applied at a rate of 65 kg ha^{-1} prior to planting. For the first 40 days, the field was supplied with approximately 19 mm of water during each irrigation event. For the rest of the season, the field was irrigated with 38 mm of water during each irrigation event. Overall, the field was supplied with 400 mm of irrigation water in 2013 (12 irrigations) and 2014 (13 irrigations), and 267 mm of irrigation water in 2015 (7 irrigations). The field was harvested at physiological maturity for seed on 8 October in 2013 (DOY 282), 11 October in 2014 (DOY 285), and 1 October in 2015 (DOY 275). The growing season was 140, 147, and 119 days long in 2013, 2014, and 2015, respectively. Since the farmer practiced crop rotation, the field was disked in early spring to incorporate residues. The field was disked again before planting and was cultivated twice in June to control weeds. The major soil at the study site is Pullman Clay Loam (a fine, mixed, superactive, thermic Torrertic Paleustoll) with 0–1% slope.

2.2. Eddy covariance and ancillary data collection

Continuous measurements of CO_2 and water vapor were made using an eddy covariance flux tower established in the field at planting. Wind speed, CO_2, and water vapor concentrations were measured using IRGASON, which is an integrated open-path infrared gas analyzer (IRGA, Model EC-150, Campbell Scientific Inc., Logan, UT, USA) and sonic anemometer (Model CSAT-3A, Campbell Scientific Inc., Logan, UT, USA) system. These instruments were set up facing southwest (into the prevailing wind direction) at 2 m above the ground level at the beginning of the season. The instruments were raised to 2.6 m above the ground level as the average plant height increased to a maximum of 1.3 m. The movement of the irrigation system did not interfere with data collection as the height of the center-pivot system was over 3 m. The fetch (distance from boundary of the field to the tower) was about 200 m in east and west directions, and about 350 m in north and south directions. Data from the CSAT3A sonic anemometer and EC150 system were measured at 10-Hz sampling rate using a CR3000 datalogger (Campbell Scientific Inc., Logan, UT, USA). The raw 10-Hz wind velocity, CO_2, and water vapor data from CSAT3A sonic anemometer and EC150 were saved for further post-processing and analysis of NEP, GPP, R_{eco} and ET.

Other environmental variables measured include air temperature (T_{air}) and relative humidity (RH) (HMP50, Campbell Scientific Inc., Logan, UT, USA), net radiation (R_n) (NR-Lite net radiometer, Kipp & Zonen, Delft, The Netherlands), photosynthetically active radiation (PAR) (LI-200SL quantum sensor, LI-COR Biosciences, Lincoln, NE, USA), solar irradiance (LI-190SB pyranometer, LI-COR Biosciences, Lincoln, NE, USA), and precipitation (TE525 rain gauge, Campbell Scientific Inc., Logan, UT, USA). Soil temperature (T_{soil}) was measured using two averaging soil thermocouples installed at 2 and 6 cm below the surface (TCAV averaging soil thermocouples, Campbell Scientific Inc., Logan, UT, USA). Soil volumetric water content (VWC) at 4 cm below the surface was measured using two CS616 time domain reflectometer soil moisture sensors (Campbell Scientific Inc., Logan, UT, USA). Soil heat flux at 8 cm below the soil surface (G_{8cm}) was measured using four self-calibrating soil heat flux plates (HFP01SC, Hukseflux, Deft, The Netherlands). All the environmental variables were measured at 5 s interval. The CR3000 datalogger was programmed to calculate and save 30-min average values of these environmental variables.

Soil heat flux at the surface (G) was estimated every 30-min by adding soil heat storage above the heat flux plate (S) to the measured soil heat flux at 8 cm using Eq. [1].

$$G = G_{8cm} + S \quad (1)$$

Heat storage above the heat flux plates was calculated as follows: