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Net ecosystem carbon dioxide exchange of dedicated bioenergy feedstocks: Switchgrass and high biomass sorghum

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ABSTRACT

As switchgrass (*Panicum virgatum* L.) and high biomass sorghum (*Sorghum bicolor* L. Moench) acreages are expanding for cellulosic biofuels, it is critical to improve understanding of carbon dynamics of these two potential bioenergy crops. Eddy flux measurements from co-located switchgrass and high biomass sorghum fields during the 2012 and 2013 growing seasons were analyzed to quantify and compare net ecosystem CO_2 exchange (NEE) between two species. Monthly ensemble averaged NEE reached seasonal peak values of -36.9 ± 1.78 and -35.9 ± 2.32 μmol m^{-2} s^{-1} in switchgrass and sorghum, respectively. Similar magnitudes of NEE (-10 to -11 g C m^{-2} d^{-1}), gross primary production (GPP, 19–20 g C m^{-2} d^{-1}) and ecosystem respiration (ER, 10–12 g C m^{-2} d^{-1}) were observed in both ecosystems. Similarly, carbon fluxes of both ecosystems had similar response to air temperature and vapor pressure deficit (VPD). Carbon fluxes exhibited an optimum temperature of slightly over 30 °C and decreased markedly beyond 35 °C. The NEE decreased markedly at higher VPD (>3 kPa) because of the stomatal closure control of photosynthesis. The switchgrass field was a larger carbon sink, with a cumulative seasonal carbon uptake of -406 ± 24 to -490 ± 59 g C m^{-2} compared to -261 ± 48 to -330 ± 45 g C m^{-2} by the sorghum field. The switchgrass stand was a net carbon sink for four to five months (April/May–August), while sorghum appeared to be a net carbon sink for only three months (June–August). Our results imply that the difference in carbon sink strength between the two species was driven mainly by the length of the growing season.

1. Introduction

United States of America has one-third of the world's automobiles (230 million) and uses about 25% of the world's oil (NBAP, http://www1.eere.energy.gov/biomass/pdfs/nbap.pdf, accessed April 11, 2013). According to the projection of the U.S. Energy Information Administration (EIA), the reliance on foreign oil will increase 30% by 2030 and the transport sector's greenhouse gas emissions will rise by 40% (Annual Energy Outlook, 2007, ftp://ftp.eia.doe.gov/forecasting/0383(2007).pdf, accessed April 11, 2013). The demand and cost of energy are increasing while oil and gas reserves are declining (Sorrell et al., 2010). Moreover, the concentration of atmospheric CO_2 has increased substantially since the beginning of the Industrial Revolution. Most of the released CO_2 into the atmosphere is a result of burning fossil fuels (National Research Council, 2010). It is, therefore, necessary to produce alternative fuels from renewable sources to supplement transportation fuel requirement and to curb CO_2 emissions to the atmosphere. To expand current ethanol production from sugar/starch, alternate feedstocks sources are required. The U.S. has capability of producing about 1.3 billion dry tons of biomass each year (Perlack et al., 2005). Even though the biomass available consists of many different species, switchgrass (*Panicum virgatum* L.) and high biomass sorghum (hereafter referred to as sorghum) (*Sorghum bicolor* L. Moench) are two major dedicated cellulosic feedstocks (USDA, 2010).

The Energy Information Agency website (http://www.eia.gov) reports that biomass energy consumption has increased by 60% from 2002 to 2013. In 2013, renewable energy contributed to about 9.3% of current energy requirements in USA and 50% of this renewable energy is from biomass sources. This biomass energy translates to about 4614 trillion Btu's from biomass with about 2000 trillion Btu's toward biofuels. This growth is mainly due to increased consumption of biomass to produce biofuels, mainly ethanol blended

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Table 1
Monthly mean maximum temperature and monthly total rainfall in 2012 and 2013 in comparison with the 30-year mean (1981–2010) for Chickasha, Oklahoma, USA.

	2012		2013		30-year mean	
Month	Max T (°C)	Rain (mm)	Max T (°C)	Rain (mm)	Max T (°C)	Rain (mm)
January	13.56	49.78	11.67	37.85	10.06	33.5
February	13	16.26	12.6	73.41	14	45.2
March	21.66	112.52	16.65	27.18	18.83	71.9
April	24.11	78.74	19.45	268.73	24.06	91.9
May	29.48	150.37	26.48	76.2	28.06	133.1
June	33.51	71.37	32.14	112.52	32.39	104.6
July	37.98	48.01	33.26	145.03	35.28	53.6
August	36.04	42.67	34.3	24.13	34.56	69.3
September	31.56	117.35	32.68	48.51	30.61	91.4
October	22.61	13.72	23.46	66.55	24.89	98.6
November	20.3	21.84	14.56	37.33	17.06	54.4
December	12.19	21.84	8.14	7.37	11.5	48.5

with gasoline. Currently, corn (*Zea mays* L.) is the major feedstock for producing almost all ethanol produced in USA. However, cellulosic biofuel plants are making inroads with an existing capacity of 67.4 MMgy with another 129 MMgy proposed. The existing production capacity uses corn stover, corn cobs, switchgrass, and municipal solid waste. Through the USDA Biomass Crop Assistance Program (FSA, 2013), a total of about 20,000 ha have been planted to dedicated bioenergy crops such as switchgrass, miscanthus, and woody species. However, the production of energy crops, including switchgrass and sorghum, is expected to grow as most of the proposed ethanol plants will use energy crops for biofuel production and also as new pathways for sorghum biofuel production are approved by U.S. Environmental Protection Agency.

The benefits of dedicated energy crops are not only confined to transportation fuels, they also impact greenhouse gas emissions, soil erodability, soil carbon, microbial community changes, in essence impact ecosystem services. A recent study by Meehan et al. (2013) has demonstrated that integration of energy crops into agricultural landscapes promotes sustainability and they foster multiple ecosystem services (below ground carbon sequestration, pollinator abundance, biocontrol potential) and mitigate ecosystem disservices (e.g., phosphorous pollution, nitrous oxide emissions). The benefits to ecosystem services are region dependent. Evers et al. (2013) demonstrated that dedicated energy crops such as perennial warm-season grasses, after 4–5 years of management, can reduce the soil susceptibility to wind erosion but may not significantly increase soil organic carbon concentration in short term. Another ecosystem service of bioenergy crops in agroecosystems is in the area of soil microbial activity. Hargreaves and Hofmockel (2014) have demonstrated that having perennial crops such as switchgrass can affect the physiological capacity of microbial communities allowing for greater nitrogen retention and greater rates of decomposition that can lead to reduced nitrous oxide emissions and increased carbon sequestration.

The North American Carbon Program Science Plan (Wofsy and Harriss, 2002) emphasized that it is necessary to quantify carbon sink of the North America. In recent years, direct measurements of net ecosystem CO_2 exchange (NEE) have increased in a variety of ecosystems. Long-term eddy covariance monitoring networks such as AmeriFlux and EUROFLUX have been established to measure NEE across a range of land-use categories; and data from several ecosystems are available for scientific communities. However, very few studies on source-sink dynamics of young switchgrass stands have been reported (Skinner and Adler, 2010; Wagle and Kakani, 2014c; Zeri et al., 2011). These studies reported a consistent result that switchgrass stands act as sinks of carbon for at least the first few years of stand establishment if the field is not harvested or a small quantity of biomass is removed. However, these studies indicated that major removal of biomass could encourage the stand to act as a source of carbon when accounting for carbon loss from biomass harvest. To our understanding, no source-sink dynamics of sorghum have been reported. Here, we compare the magnitude and seasonality of NEE and its two components, gross primary production (GPP) and ecosystem respiration (ER), between co-located annual sorghum and perennial switchgrass during the 2012 and 2013 growing seasons. This comparative study not only provides better understanding of the minimally studied source-sink dynamics of switchgrass and sorghum, it also provides greater insight on how these two ecosystems respond to the same climatic conditions. This study has great importance as the southern Great Plains of the U.S. will contain large stands of the cellulosic feedstocks in the near future (Downing et al., 2011).

2. Material and methods

2.1. Site description

Eddy covariance measurements were performed over co-located switchgrass (cv. Alamo) and sorghum (cv. ES 5200) fields (eight hectares each) at the South Central Research Station, Chickasha, OK (latitude: 35.04°N, longitude: 97.91°W, and elevation: 330 m above sea level). The site has a deep and well-drained soil, formed from weathered loamy alluvium. The predominant soil series is Dale silt loam (a fine-silty, mixed, superactive, thermic Pachic Haplustoll). Switchgrass stand was established in spring 2010 and sorghum was planted around mid-May each year. Prior to switchgrass greening and sorghum planting, herbicides were applied: 2.3 L ha^{-1} of glyphosate + 1.2 L ha^{-1} LV6 + 2.5 mL L^{-1} squire in the switchgrass field and 2.3 L ha^{-1} of crop oil + 1.7 L ha^{-1} metalchlor + 1.1 kg ha^{-1} a.i. Atrazine in the sorghum field. Every year, urea and diammonium phosphate were applied to provide 75 kg N ha^{-1} for switchgrass in April and 112 kg N ha^{-1} for sorghum in May along with 39 kg P ha^{-1} for each.

2.2. Micrometeorological and biometric measurements

CO_2 fluxes from co-located switchgrass and sorghum fields were measured using the eddy covariance technique, equipped with a three-dimensional sonic anemometer (Model CSAT3, Campbell Scientific Inc., Logan, UT, USA) and an open path infrared gas analyzer (IRGA; model LI-7500, LI-COR Inc., Lincoln, NE, USA), during the 2012 and 2013 growing seasons. The eddy covariance systems were set up at the north end of the plots facing toward the prevailing wind direction, south. The fetch in the south and east-west direction was about 275 m. Sensor heights were adjusted according to the canopy height to avoid measuring fluxes in roughness sublayer. Other supplementary variables like photosynthetic photon flux density (PPFD – using LI-190, LI-COR Inc., Lincoln, NE, USA),