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Comparison of carbon budget, evapotranspiration, and albedo effect between the biofuel crops switchgrass and corn

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ABSTRACT

Interest in biofuels produced from perennial crops like switchgrass (*Panicum virgatum* L.) has increased over the past decades. It has been suggested that perennial biofuel crops have additional climate benefits compared to annual crops, such as carbon sequestration and albedo increase, but these effects have not been quantified in field studies. We compared carbon dioxide and water exchange results from eddy covariance measurements and surface albedo over a switchgrass and a corn field in Southwestern Ontario, Canada, for the year 2014. Results for the carbon budget showed more carbon uptake for switchgrass compared to corn (annual net ecosystem exchange NEE of -336 ± 40 vs $+64 \pm 41$ g C m^{-2}). Switchgrass was a small sink of carbon with a net ecosystem carbon balance (NECB) of -66 ± 59 g C m^{-2} but corn was a source for a scenario where corn grain only is harvested (NECB 393 ± 44 g C m^{-2}) and a 1.5 times larger source if both corn grain and stover are harvested (NECB 699 ± 47 g C m^{-2}). Switchgrass had, however, a lower yield 568 ± 93 g m^{-2} than either corn scenario (751 ± 40 g m^{-2} for grain only and 1439 ± 52 g m^{-2} for grain plus stover). Results from the albedo measurements showed a negative radiative forcing on an annual basis for the switchgrass field compared to corn. Differences in albedo were especially pronounced during spring and fall when radiative forcing values of -10.2 and -5.5 W m^{-2} were observed, respectively. Qualitative analysis of the carbon budget, evapotranspiration, and albedo results from this study suggests that biofuel produced from switchgrass can have more climate benefits than biofuel produced from continuous corn cropping systems.

1. Introduction

Concerns about rising atmospheric CO_2 levels and energy security have led to renewable fuel standard (RFS) policies being implemented by many countries around the globe (Mabee, 2007). In Canada and the US, RFS policies require a certain percentage of transportation and heating fuel to be produced from renewable energy sources (e.g. biofuels). Most of the biofuel produced in the US is currently made from corn grain (United States Department of Agriculture, 2015). Since biofuel produced from corn grain faces competition from food and feed production, interest in cellulosic ethanol produced from perennial biofuel crops has increased with increasing biofuel demand (Liebig et al., 2005; McLaughlin et al., 2002; McLaughlin and Walsh, 1998; Schmer et al., 2008).

Some of the advantages of perennial biofuel feedstock are high productivity across large regions of North America, low management input requirements, carbon sequestration, improvement of soil and water quality, providing wildlife habitat, and a cooling effect on local climate (Bransby et al., 1998; Georgescu et al., 2011; McLaughlin and Adams Kszos, 2005; McLaughlin and Walsh, 1998; Parrish and Fike, 2005; Zeri et al., 2011). Switchgrass, a perennial warm-season C4 grass native to North-America, has been evaluated as a feedstock for cellulosic ethanol production under the US RFS (Schnepf and Yacobucci, 2013). Young switchgrass stands have shown greater potential for carbon sequestration than corn and provide a climate benefit beyond fossil fuel displacement (Skinner and Adler, 2010; Wagle and Kakani, 2014; Zeri et al., 2011).

Abbreviations: BD, soil bulk density; DM, dry matter; EBC, energy balance closure; EC, eddy covariance; ET, evapotranspiration; EWUE, ecosystem water use efficiency; GEP, gross ecosystem productivity; GHG, greenhouse gas; GPP, gross photosynthetic production; HWUE, harvest water use efficiency; NEE, net ecosystem exchange; Re, ecosystem respiration; RF, radiative forcing; RFS, renewable fuel standard; Rn, net radiation; SOC, soil organic carbon; WUE, water use efficiency; λE, latent heat flux.

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However, Eichelmann et al. (2015) showed that the average carbon budget of a mature switchgrass stand is close to neutral, which is in contrast to published studies on young stands. It is therefore important to compare the carbon sequestration potential of mature switchgrass and corn.

When implementing policies for large scale biofuel feedstock production, many factors have to be considered. Direct climate feedback mechanisms through a change in albedo and energy partitioning have largely been ignored in past studies of perennial and annual biofuel crops, however, their impact can be significantly larger than the carbon savings from displaced fossil fuel (Georgescu et al., 2011). Radiative forcing effects on climate through changes in albedo have been recognized as important climate feedback mechanisms in the past (Betts, 2000; IPCC, 2013). Perennial crops display a higher albedo than annual crops due to earlier green-up in spring and an extended growing season in fall (Georgescu et al., 2011). A switch in partitioning of net radiation from sensible to latent heat through increased evapotranspiration (ET) can lead to a local cooling effect (Georgescu et al., 2011). However, the interdependencies of the various energy fluxes result in complex feedback mechanisms influencing the local surface and air temperature, atmospheric water vapour content, cloud formation, and other climate variables (Bagley et al., 2014; Baldocchi and Ma, 2013). It is important to quantify how the land use change associated with switching from annual to perennial biofuel feedstock crops affects local and regional climate (Bagley et al., 2014). The changes in local climate induced by large scale perennial biofuel feedstock production can help alleviate climate change if they result in a net cooling effect. Changes in albedo and energy balances by large scale switchgrass production have to be considered to get a more comprehensive view of the climate benefits of switchgrass biofuels. However, observational data on biophysical parameters such as albedo for perennial biofuel crops is scarce (Georgescu et al., 2011). Only few studies have reported field scale measurements of these parameters (Miller et al., 2015).

Changes in evapotranspiration can not only impact the local climate, but also the local and regional water budget. Previous studies have shown that switchgrass has the potential to be productive in drought conditions (Eichelmann et al., 2015; Wagle and Kakani, 2014a), but high productivity might be coupled with increased evapotranspiration (Eichelmann et al., 2016). Water demand and associated implications on the local water budget need to be considered when comparing different crops for biofuel production especially with the predicted increase in frequency of droughts in the future over large parts of North America (Cook et al., 2015; Dai et al., 2004). Water use efficiency (WUE) of a crop is a measure of the water cost of carbon uptake or biomass production and can help in evaluating the drought tolerance and water use intensity of a crop. Previous studies have shown that switchgrass can have high water use efficiency (Skinner and Adler, 2010; Wagle and Kakani, 2014a). WUE is, however, dependent on a variety of environmental conditions and can fluctuate on a daily, monthly, and annual basis (Eichelmann et al., 2016). For intercomparison of WUE between crops it is therefore important to ensure consistent environmental conditions between the study sites.

Most studies on carbon sequestration and water balance of biofuel feedstock crops in large scale fields representative of commercial production have focused on a single crop species rather than comparison of multiple biofuel feedstocks. Zeri et al. (2011) conducted the first side-by-side study of the carbon cycle of multiple perennial biofuel crops using the eddy covariance method, which enables continuous monitoring of CO_2 and water fluxes (Baldocchi et al., 1988). Comparison of results from studies conducted over multiple years or in different climatic regions are difficult due to environmental differences such as air temperature, precipitation, and soil conditions between studies, which have a large influence on carbon and water cycling (Pielke et al., 1998; Sellers, 1997). To make informed decisions about the climate benefits of different biofuels, studies are needed that directly compare continuous measurements of carbon and water cycling and other climate feedback mechanisms of different biofuel feedstock crops grown at commercial scales and experiencing similar environmental conditions.

The objectives of this study were to compare the carbon budget, evapotranspiration, water use efficiency, and albedo effect of the biofuel feedstock crops corn and switchgrass under similar climatic conditions. We conducted eddy covariance measurements of CO_2 and H_2O fluxes along with measurements of surface albedo on a mature switchgrass field on a commercial farm and a large scale corn field on a research farm during the year 2014. The fields are located in Southern Ontario, Canada, and experienced similar environmental conditions during the study year.

2. Materials and methods

2.1. Measurement sites

Measurements were conducted in 2014 for switchgrass and corn fields situated at two locations in Southwestern Ontario, Canada, a region dominated by agricultural activity. The switchgrass site was located on a commercially farmed field (60 ha in size) in Seaforth, ON, (43° 35′0.89″ N, 81° 26′47.55″ W, approximately 300 m a.s.l.). Switchgrass (*Panicum virgatum* L.) had been planted on this field in spring 2006 and reached full production yield in 2008. Throughout the site history, annual management inputs involved nitrogen fertilization in spring and switchgrass cutting in fall. In 2014, switchgrass emerged on May 10 and fertilizer was applied in the form of urea at 84 kg N ha^{-1} on May 23. The switchgrass was cut on October 28, 2014, and left on the field in windrows over winter. Switchgrass was baled and removed from the field in the following spring (April 15, 2015), yielding 568 g m^{-2}. For a detailed description of the switchgrass field layout and management history see Eichelmann et al. (2015).

The corn site was located on the University of Guelph Agricultural Research Farm in Elora, ON, (43° 38′33.94″ N 80° 24′54.08″ W, approximately 375 m a.s.l., approximately 83 km distance to switchgrass field). The corn field had been in continuous corn production for 2 years prior to the study year (2012 and 2013). Before that, spring barley was planted on the field in 2011, soybeans in 2010, and continuous corn again from 2007 to 2009. During the last two years of corn production (2012/2013), the field received liquid dairy manure application every year in the fall after harvest. The manure was broadcast applied and incorporated the day after application. In the fall previous to the study year, the field received 84.1 m^3 ha^{-1} of dairy manure at a total N rate of 105 kg N ha^{-1} on November 13, 2013. The corn field was disked on May 12, 2014 and corn (*Zea mays* L.) of the variety N20Y3220 was planted on May 27, 2014. Corn emerged on June 4, 2014 and was harvested on November 4, 2014, yielding a total dry biomass of 1439 g m^{-2} of which 751 g m^{-2} was grain and 688 g m^{-2} was stover. In the fall of the study year, the field received 82.8 m^3 ha^{-1} of dairy manure at a total N rate of 87 kg N ha^{-1} on November 10, 2014. The site selected for measurements of corn was 4 ha in size and located in the northern corner of a 30 ha corn field. The eddy covariance sampling system was located in the southeastern border of the 4 ha plot. For a detailed description of the corn field site setup and treatments see Abalos et al. (2015). Eddy covariance data from the corn site was not filtered for wind direction since the eddy covariance tower was surrounded by corn for more than 100 m in all directions and by more than 200 m in the direction of the predominant wind (i.e. from the west of the tower). The eddy covariance flux