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Soil Carbon Dioxide Respiration in Switch Grass Fields: Assessing Annual, Seasonal and Daily Flux Patterns

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Abstract

Quantifications of annual soil CO2 respiration in switch grass systems are limited to the growing season or coarse-scale temporal sampling. This study evaluates daily and seasonal soil CO2 respiration in switch grass croplands. Hourly measurements during 12 month period were taken for soil CO2 flux, soil temperature, and soil moisture. Although both soil temperature and moisture were positively correlated with soil CO2 flux rates, soil temperature was the primary driver of soil respiration. During winter, lower soil temperatures corresponded with significant decreases in average daily CO2 flux rates, however, CO2 pulses associated with precipitation events increased flux rates up to three times the seasonal daily average. Soil temperature influenced both daily and seasonal flux patterns where the highest flux rates, up to 31.0 kg CO2 ha-1 h-1, were observed during the warmest hours of the day (13:00 to 15:00) and during the warmest season (Summer). Summer and Spring emissions combined accounted for 80.1% of annual flux, indicating that exclusion of non-growing season time periods may result in an underestimation of total annual CO2 efflux. Our results indicate that inclusion of the non-growing season and a fine-resolution temporal sampling approach provides more accurate quantifications of total annual CO2 emissions in switch grass croplands.

Keywords: Carbon dioxide, Flux, Soil respiration, Switch grass

1. Introduction

On a global scale, release of carbon dioxide (CO2) through soil respiration is estimated to contribute more than ten times the amount of carbon (C) to the atmosphere than anthropogenic fossil fuel emissions (Dornbush and Raich 2006; Raich and Schlesinger 1992). Consequently, changes in land use and management practices that affect soil respiration rates can have a significant impact on atmospheric CO2 concentrations and soil C pools (McNally et al. 2015). In the United States, agriculture alone occupies 51.3% (1.16 billion acres) of the total land area (Nickerson et al. 2011) and is among the largest net sources of atmospheric C resulting from land use change (US EPA 2004). In recent years, the cultivation of bioenergy crops has been embraced by greenhouse gas (GHG) reduction efforts to not only mitigate atmospheric CO2 emissions through the reduction of fossil fuel use, but to also promote C sequestration in agricultural soils (Lemus and Lal 2005; Sartori et al. 2006).

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Evidence suggests that bioenergy crops can promote soil C capture and storage (Sartori et al. 2006), however, a better understanding of soil CO2 emissions, the primary mechanism of soil C loss in agricultural landscapes (Parkin and Kaspar 2003), is needed to determine the net C sequestration potential of these systems.

Bioenergy crops are often regarded as C neutral or C sink systems due to their ability to offset fossil fuel GHG emissions, fix and deposit atmospheric C into soils, and recapture C released during utilization in crop production in subsequent growing seasons. Quantification of actual offsets generated by these crops has progressed to include many components of atmospheric C release and capture including soil and plant studies as well as complexities of the cultivation process (Adler et al. 2007; Smith et al. 2014). These assessments can be used to identify the most efficient bioenergy crops for meeting C offset and sequestration goals from

various perspectives of production. In terms of GHG offsets, switch grass has emerged a highly effective bioenergy resource, reducing GHG emissions from fossil fuels by 115% compared to 85% and 40% by reed canary grass and corn, respectively (Adler et al. 2007). Studies assessing soil processes also indicate that although soil respiration in switch grass fields can account for 44% of total plant biomass C loss, the increase in soil C content in these systems results in a greater net C uptake by soils than has been observed for some other biofuels (Zeri et al. 2011; Frank et al. 2004). Soil CO2 respiration studies assessing switch grass croplands in the southeastern United States are, however, often limited either to data collected at a coarse temporal scale (weekly or biweekly) or to the growing season including only warmer months.

Extensive research has demonstrated that soil respiration rates are positively correlated with temperature (Dornbush and Raich, 2006; Raich and Schlesinger, 1992; Wang et al., 2008; Chang et al. 2012) and soil moisture (Bauer et al., 2008; Hernandez-Ramirez et al., 2009; Lee et al., 2007; Lloyd and Taylor, 1994; Raich and Potter, 1995; Sainju et al., 2010), both of which vary diurnally, seasonally, and episodically. Fine-resolution temporal data, i.e. multiple measurements per day, is required to assess episodic events, such as precipitation, to capture pulses of soil CO2 respiration in responses to soil wetting (Hernandez-Ramirez et al. 2009; Sainju et al. 2010), which would be missed using a weekly to bi-weekly sampling approach (Savage and Davidson 2003). With respect to seasonal variation, although cooler soil temperatures are associated with a decrease in soil CO2 rates, soil respiration has been shown to continue in even snowy, winter conditions (Miao et al. 2012). Omission of soil flux data during non-growing seasonal periods could thus significantly affect the net annual CO2 flux estimated for the system. These limitations in soil CO2 flux studies in switch grass croplands create potential to inaccurately estimate annual loss of C through soil respiration.

Although some studies do report switch grass soil CO2 flux rates based on fine-scale and long term data, these studies have been conducted in regions outside of the southeastern United States (Frank et al. 2004, Qi and Xu 2001, Tufekcioglu et al. 2001), which differ significantly in annual climate regimes that affect soil temperature and soil moisture patterns. Applying these rates to switch grass systems located in the southeastern U.S. may also misrepresent soil C losses within the region. Switch grass production in East Tennessee has increased significantly through efforts to cultivate biofuel crops to offset fossil fuel production and use in the region. Consequently, geographically targeted studies are needed to accurately develop C sequestration values for switch grass production in East Tennessee.

This study investigated diurnal and seasonal variation in soil CO2 flux for a switch grass cropland in East Tennessee, and assessed the role of soil moisture and soil temperature as controls on soil CO2 flux rates. First, we hypothesized that soil CO2 flux rates are higher than those reported for the Pacific Northwest and Central Plains regions of the United States due to the warmer climate and annual precipitation patterns in E TN. Further, we hypothesized that soil temperature was a more significant control on soil CO2 flux rates than soil moisture due to the relative consistent annual precipitation regime coupled with significant thermal changes throughout the seasons. A fine-scale, i.e. hourly, temporal sampling approach was used for one full year to provide a better understanding of soil respiration responses to diurnal, episodic, and seasonal conditions.

2. Methods

2.1 Site Description

The study was conducted in an Alamo switch grass plot at the University of Tennessee Plant Science Experiment Station (UT PSES) and at the University of Tennessee Holston Dairy Farm (UT HDF) both located in Knoxville, Tennessee (35o 58’ N, 83o 56’ W). Soil properties for both sites are listed in Table 1.

Regional climatic conditions are humid subtropical with an average annual precipitation of 121.9 cm and weekly averages ranging from 3.0 cm to 5.5 cm. The mean annual temperature is 14°C with the hottest month, July, ranging 21oC to 32oC and the coldest month, January, ranging -1oC to 8oC.

Table 1. Soil properties of the study site.

	UT PSES[1]				UT HDF[2]			
Depth	**0-5cm**	**5-10cm**	**10-15cm**	**15-30cm**	**0-5cm**	**5-10cm**	**10-15cm**	**15-30cm**
Soil Classification	Loam				sandy clay			
pH	5.61	5.46	5.52	5.02	5.535	5.715	6.15	6.375
CEC (meq/100g)	10.20	9.36	8.96	8.95	7.85	7.57	8.85	8.75
% Organic Carbon	1.45	1.21	1.03	0.75	1.19	0.81	0.53	0.47

[1]University of Tennessee Plant Science Experiment Station
[2]University of Tennessee Holston Dairy Farm

The study was initiated at the UT PSES in well-established switchgrass plots plantad in 1992. Crop management at this site, however, did not incorporate the use of nitrogen fertilizer which is outlined in University of Tennessee (UT) Extension recommendations and commonly practiced in the southeastern United States to increase crop yield. Flux measurements at the UT HDF site began in mid-November and continued at this location through the completion of the experiment. UT HDF switchgrass plots were established in 2004 and managed according to UT Extension recommendations which included the application of 67 kg ha-1 y-1 of nitrogen annually.

With the exception of the use of nitrogen fertilizer, site characteristics at both the UT PSES and UT HDF sites were comparable to reduce error resulting from differences in site environmental conditions. In addition to similar soil profiles and regional climatic conditions, both sites adhered to a similar cropping and harvesting regime in which grass was cut between 10 and 15 centimeters once per year in early November. Although the use of nitrogen fertilizer improves switch grass crop production, this practice has been shown to have a nominal impact on soil CO_2 flux (Sainju et al. 2010; Hernandez-Ramirez et al. 2009; Raich and Schlesinger 1992).

2.2 Soil Properties

Chemical soil properties for both UT PSES and UT HDF are listed in Table 1. The laser diffraction method (LDM) was employed to confirm soil classification based on particle size and ratio. Soil type classification was consistent within the first 30 cm of the soil profile with UT PSES characterized by a Loam and UT HDF by Sandy Clay. Chemical soil analyses included soil pH, cation-exchange capacity (CEC) and soil organic carbon (SOC) content. CEC was determined using the soil testing protocol developed by the Clemson soil testing with mineral extraction performed using a Perkin-Elmer 5300 Dual View Inductively Coupled Plasma spectrometer. SOC was determined using the dry combustion method described in Sparks et al. (1996). All soil chemistry analyses were performed at the University of Tennessee Soil, Plant and Pest Center in Nashville, TN.

2.3 Soil Respiration Measurements

Daily CO_2 flux measurements were taken once per hour from 00:00 to 23:00 throughout the duration of the experiment with the exception of the cool season (December to March) in which measurements were taken once every two hours due to solar power limitations during this season. Flux rates determined from hourly data were used to assess annual, seasonal, and daily soil flux patterns. Soil CO_2 flux was measured using the LICOR LI-8100 Automated Soil CO_2 Flux system comprised of an infrared gas analyzer control unit and multiplexer capable of supporting continuous flux measurements for up to eight LICOR 8100 long-term closed chambers. Total of six chambers were established at the UT PSES study site. Three chambers were positioned atop switch grass crowns to represent covered areas (Cover) and the other three chambers were positioned in the interspaces between crowns to represent bare soil (Bare).

The LICOR LI-8100 long term CO_2 flux chambers were installed to implement the closed chamber method for estimating soil respiration of CO_2. In this method, the LI-8100 Analyzer control unit estimates soil respiration rates by measuring the increase or decrease (flux) of gaseous CO_2 concentrations in the chamber headspace over time. The observation length of all measurements was 90 seconds to minimize chamber CO_2 concentration changes during analysis and a 30 second dead band was programmed to allow for equilibration of the chamber pressure upon closure. All measurement protocols were programmed using a LICOR 8100 palm wireless controller linked with the LI-8100 Analyzer control unit.

Each flux chamber has an internal volume of 4076.1cm3 with an exposed soil area of 317.8cm2. The whole system dimensions are 48.3cm long by 38.1 cm wide by 33 cm high. To reduce error from lateral diffusion of CO_2 in the soil column, PVC soil collars measuring 20.3cm in diameter were inserted to a depth of 3 cm to 5 cm and extended approximately 6 cm to 10 cm above the soil surface. A double gasket system sealed the chamber outside the soil collar andbetween the chamber and mounting plate to minimize CO_2 leaks and wind effects (Healy et al., 1996). Between measurements, the chamber head moved away from atop the measurement collar to minimize perturbations to the natural microclimate. Vegetation height was maintained at 5 cm in each chamber to allow for automated chamber movement, though we do recognize that clipping vegetation for maintenance may result in an underestimation of soil CO_2 flux rates due to decreased soil C accumulation (Riedell et al. 2010). Soil temperature and moisture was also recorded at the time of each measurement. Soil temperature was monitored using Omega T-handled Type E thermocouples with 6.4mm diameter and 250mm immersion length inserted to a depth of 250mm. Volumetric soil moisture was measured using 5 cm long EH2O Model EC-5 dielectric sensors.

A cubic polynomial regression analysis was applied to hourly measurements to evaluate diurnal patterns in soil CO_2 flux with changes in soil moisture and temperature (SAS, Inc. Cary, NC) for both Cover and Bare plots separately. Seasonal and annual flux patterns were determined using daily average flux rates calculated from hourly measurements. Seasonal assessment were represented as Spring (March 20 to June 20), Summer (June 21 to September 22), Fall (September 23 to December 21), and Winter (December 22 to March 19). To determine annual flux patterns, averaged daily CO_2 flux values were summed with Cover and Bare sites representing 75% and 25%, respectively, of the total land area.

3. Results and Discussion

3.1 Annual CO_2 Flux

The total annual soil CO_2 emission for Cover and Bare sites were 81.17 Mg CO_2 ha-1 y-1 and 51.69 Mg CO_2 ha-1 y-1, respectively. These values were used to determine an average weighted annual CO_2 emission of 73.80 Mg CO_2 ha-1 y-1 for the switchgrass plot, where Cover is representative of 75% and Bare 25% of the total land surface area. This equates to a loss of 20.14 Mg C ha-1 y-1. The total annual soil CO_2 flux measured here for switchgrass is significantly greater than estimations of annual soil CO_2 efflux reported for other perennial grasses (Zhang et al. 2011; Maljanen et al. 2001). Comparative to other crop grasses, annual loss of CO_2–C flux for switchgrass is five times greater than has been observed for barley, 4.0 Mg C ha-1 y-1 and more than two times greater than reports for crops such as wheatgrass, 8.65 Mg C ha-1 y-1 (Zhang et al. 2011). In some instances, however, annual soil flux under annual and perennial crop grasses have been shown to range between 14.8 MgCO_2–C ha-1 y-1 and 20.3 MgCO_2–C ha-1 y-1 during the growing season alone (Sainju et al. 2010). This may be due to differences in climate, environmental conditions and species types. The warm, humid climate in the East Tennessee region may provide conditions conducive to higher average soil respiration rates compared to other switchgrass croplands in other regions. This supported by lower estimated annual flux rates reported from other regions such as North Dakota (10.8 Mg CO_2-C ha-1 y-1) (Frank et al. 2004), Iowa (10.2 Mg CO_2-C ha-1 y-1) (Tufekcioglu et al. 2001), and Louisiana (3.72 Mg CO_2-C ha-1 y-1) (Blazier et al. 2012). Consequently, although switchgrass croplands in the East Tennesseeregion have been suggested to function as C sinks or C neutral land areas our results suggest that loss of soil C through CO_2 respiration may exceed an annual SOC accumulation rate of 7.55 Mg C ha-1 (Soro 2011). These finding demonstrate the need for a more detailed analysis of total net ecosystem exchange of C in East Tennesse switchgrass croplands to better understand the role of these systems in local and regional C budgets.

3.2 Seasonal CO2 Flux

Seasonal flux trends for total cropland area show a positive correlation between average seasonal temperatures and soil CO2 respiration rates. The highest seasonal CO2 fluxes were observed during the warmest season (summer) and the lowest fluxes during the coolest (winter) (Figure 1). Average daily CO2 respiration rates increased and decreased throughout the Spring and Fall seasons, respectively. Increasing ambient and soil temperatures in the Spring stimulate both plant growth and microbial activity previously dormant during the Winter. The creation of plant litter and movement of new roots through the soil supply fresh carbon and oxygen to soil microbes, resulting in a steady increase in soil CO2 respiration during the Spring transition from Winter to Summer. Similar soil temperature ranges were observed during the Spring and Fall transitions, however, higher soil flux rates were observed during the Spring. Lower flux rates in the Fall coincide with generation of organic material with matured plants and decreasing ambient and soil temperatures, which can slow respiration from microbial and autotrophic processes (Wang et al. 2008; Dornbush and Raich 2006). Further, average daily Spring soil moisture was greater than in the Fall at 25.8% and 19.2%, respectively. Greater soil moisture content has been shown to correlate with higher soil C content (Sainju et al. 2010; Hernandez-Ramirez et al. 2009) which may also contribute to the greater flux rates during the Spring. Summer alone accounted for approximately 47.4% of annual CO2 emissions while Spring and Summer combined was representative of 80.1% of the annual flux. The Fall and Winter seasons contributed least to the overall annual soil CO2 flux, 13.3% and 6.6% of respectively. However, representing close to 20% of total annual emissions, exclusion of these seasons may result in a significant underestimation of total annual soil CO2 respiration.

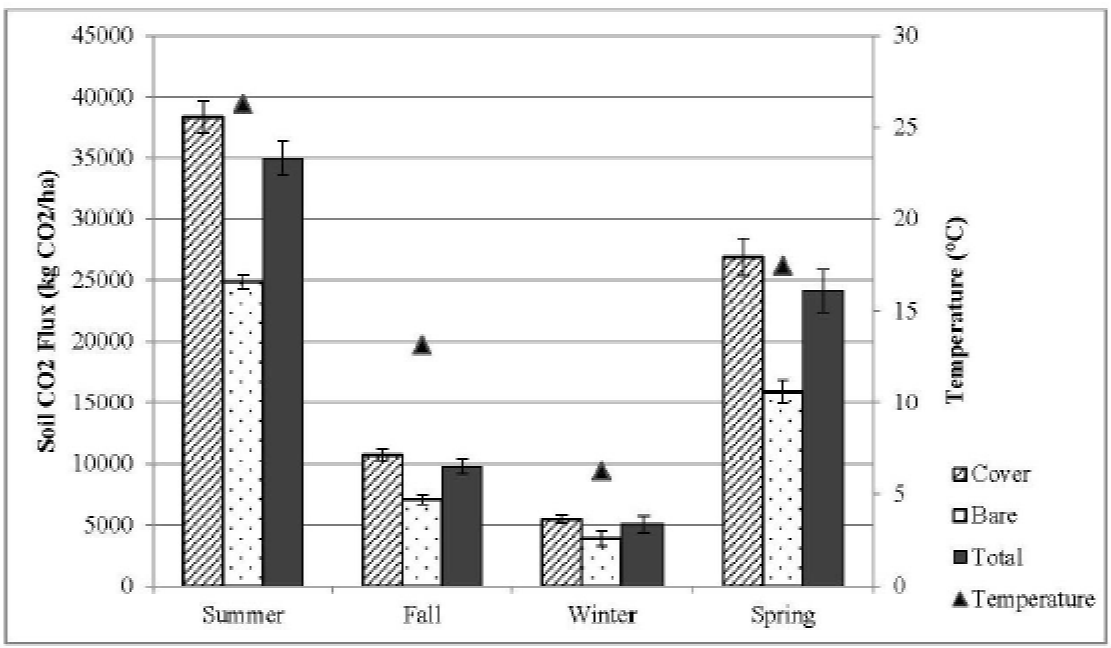

Figure 1. Average seasonal CO2 flux rates (kgCO2 ha-1y-1).

Seasonal patterns for Cover and Bare sites were similar to total area soil CO2 flux trends. Average respiration rates at Cover sites were greater than at Bare sites for every season (Figure 1), with the greatest flux rate offsets between site types observed during Spring and Summer. Previous studies have shown that vegetated soils can exhibit higher rates of soil respiration which can be correlated with larger microbial communities (Song et al. 2012; Thomson et al. 2010). Results of this study are consistent with these findings, with higher soil CO2 respiration under Cover due to greater plant biomass, including switch grass crowns and root structure, as well as increased microbial activity due to in situ litter supplied by the switch grass crowns. Reduced flux variation between Cover and Bare during Winter was mostly likely the result of reduced microbial activity due to cooler soil temperatures, in spite of higher soil moisture content during this season.

3.3 Daily CO2 Flux

Daily CO2 flux patterns were positively correlated with diurnal soil temperature shifts. During all seasons except winter, the highest and lowest daily flux rates were observed during the warmest and coolest hours of the day, respectively (Figure 2).

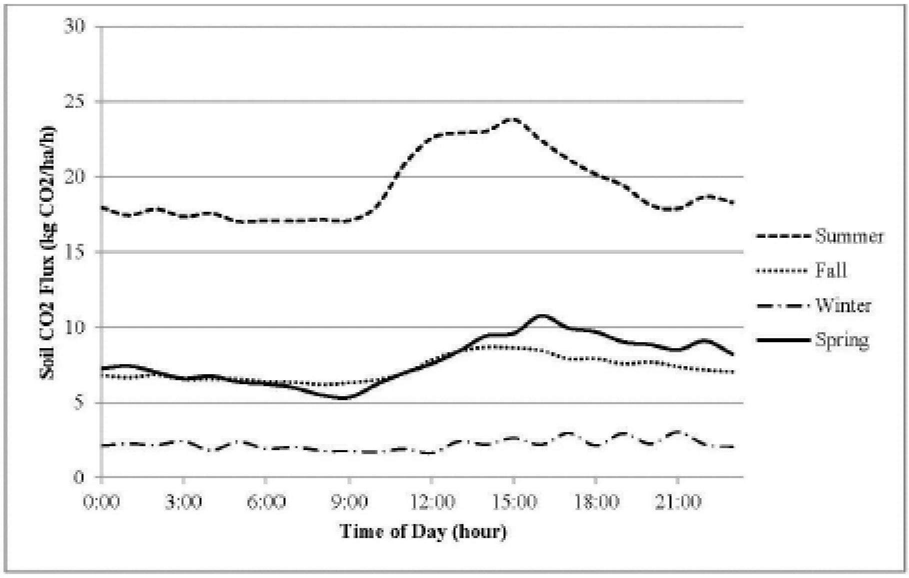

Figure 2. Daily variations in CO2 flux for each season.

During Spring, Summer and Fall the highest average daily fluxes occurred between 13:00 and 16:00 while the lowest flux rates were measured between 00:00 and 09:00. The greatest diurnal variation in hourly flux rates was observed during the summer with an average daily range of 6.79 kg CO2 ha-1h-1. The highest average hourly flux rates for the total switchgrass cropland area were measured during June and ranged from 20.6 kg CO2 ha-1h-1 at 05:00 and 31.0 kg CO2 ha-1h-1 at 15:00. The smallest daily variation in hourly flux rates was observed during the winter with an average daily range of 1.39 kg CO2 ha-1h-1. Diurnal flux trends were consistent with the positive correlation between soil temperature and soil CO2 respiration discussed with respect to seasonal trends. Higher temperatures during the daylight hours corresponded with daily peak soil respiration rates. Conversely, the decrease in CO2 flux throughout the evening correlated well with decreasing daily soil temperatures which slow biological processes. In addition to lower average soil temperatures, reduced diurnal variations in soil temperature during this season resulted in more consistent conditions from day to night and contributed to reduced variation in diurnal flux rate trends. Reduced daily variations in soil temperature under wetter soil conditions combined with cool season temperatures have been shown to be correlated with decreased soil respiration variability (Grahammer et al. 1991). The cool, wet winters of the East Tennessee climate are consistent with these conditions, as are the results of this study.

3.4 Soil Moisture and Soil Temperature

Figure 3 and 4 show the annual CO2 flux along with soil temperature and moisture. Overall, CO2 flux corresponds well with soil temperature change, while soil moisture was not a primary factor controlling CO2 flux in our study.

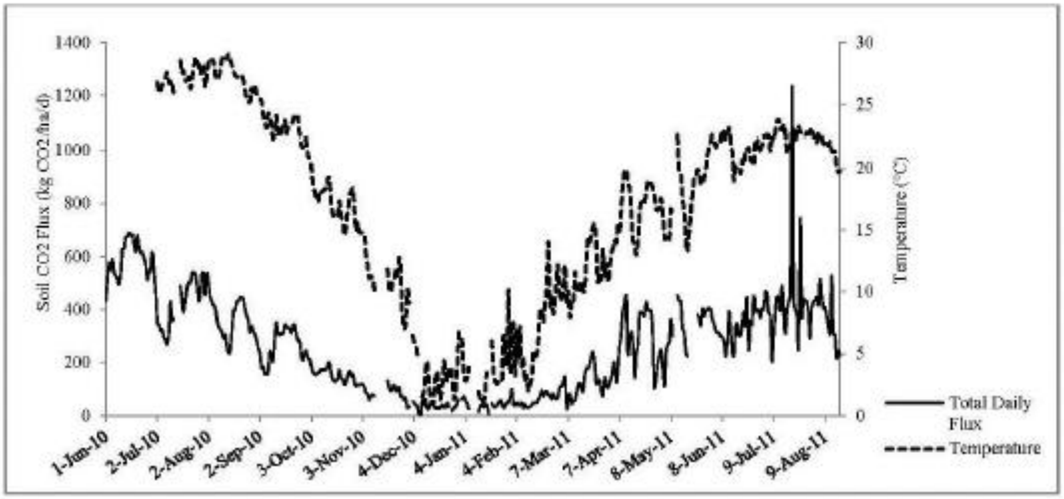

Figure 3. Annual CO2 flux as a function of soil temperature.

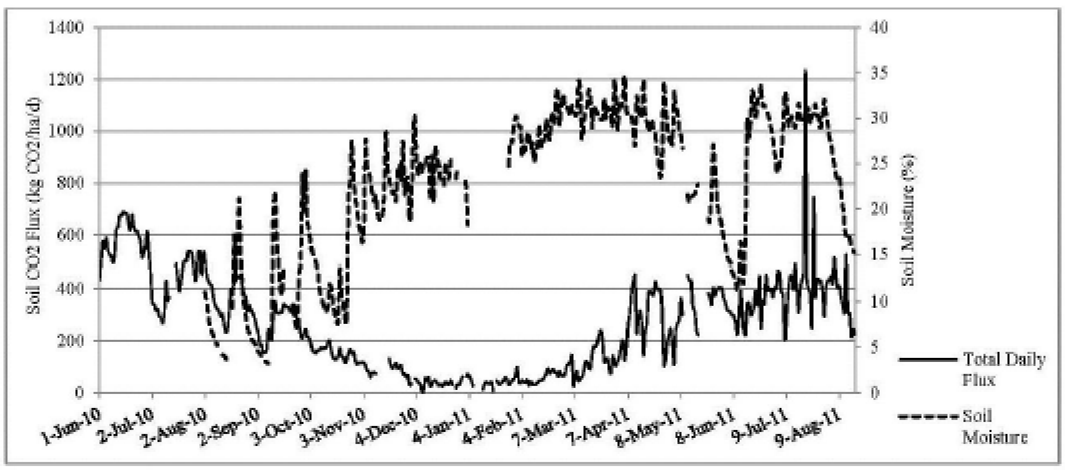

Figure 4. Annual CO2 flux as a function of soil moisture.

A cubic polynomial regression model showed that soil temperature accounted for 75% and 69% ($P<0.0001$) of soil CO2 flux variability for Cover and Bare sites, respectively (Figure 5). The positive relationship between higher flux rates and increases in soil temperature corresponded with previous studies in which increased rates of microbial and plant activity with warmer soil temperatures resulted in increased soil CO2 respiration (Trevors 1985; Dornbush and Raich 2006;Chang et al. 2012). When applied to determine the impact of soil moisture on soil CO2 respiration, the regression model accounted for only 6% of Cover flux variability and 9% for Bare ($P<.0001$). Figure 3 shows the annual CO2 flux as a function of soil moisture. These results were inconsistent with some previous studies that demonstrated a more significant positive correlation between soil moisture and soil CO2 flux (Sainju et al. 2010; Hernandez-Ramirez et al. 2009; Lee et al. 2007; Raich and Potter, 1995).

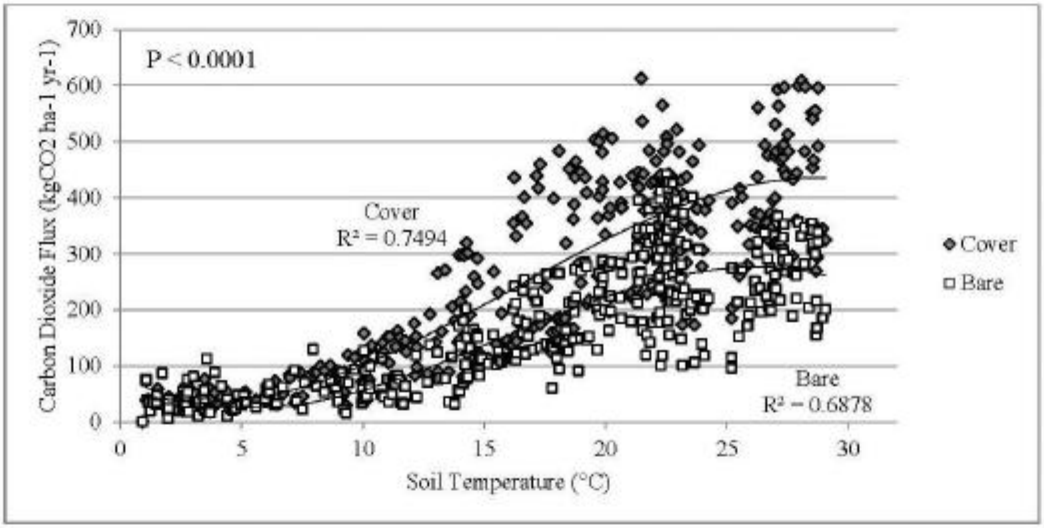

Figure 5. A cubic polynomial regression analysis of CO2 flux relative to soil temperature. Data are representative of individual measurements collected throughout the entire study period.

Sainju et al. (2010), for instance, showed that irrigation in some croplands increased CO2 flux rates by up to a 50% due to a correlated increase in soil moisture. A notable difference in our study, however, is that the highest average soil moisture (~34%) was observed during Spring but CO2 flux did not follow the soil moisture pattern. (Figure 4). Conversely, the warmer months were characterized by less frequent and less intense precipitation events resulting in a lower average soil moisture content, 21.5% during Summer, and more consistent soil moisture conditions. Figure 6 shows the annual precipitation and soil moisture. In all seasons, soil moisture increased immediately following precipitation events which simultaneously corresponded with episodic CO2 pulse events (Figure 7). Although the average daily soil CO2 flux during Winter was 60 kg CO2 ha-1, precipitation-induced pulses stimulated increases in daily flux rates of up to 178 kg CO2 ha-1.

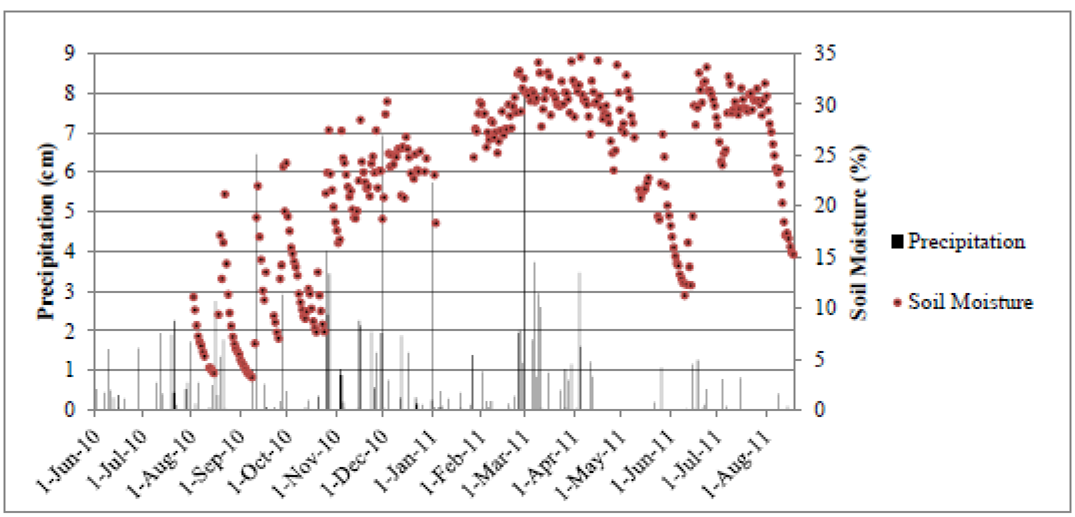

Figure 6. Annual precipitation and soil moisture.

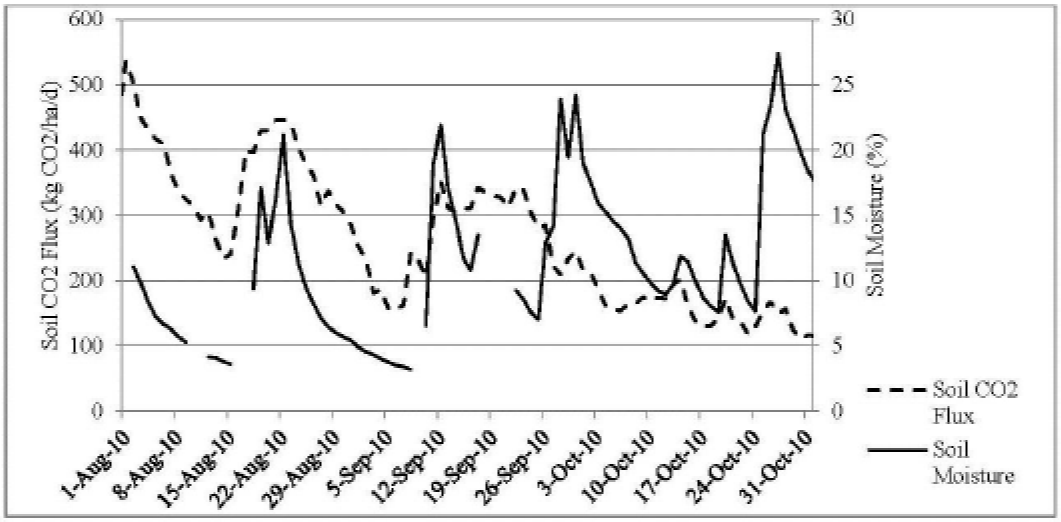

Figure 7. Sporadic CO2 flux response to soil moisture.

Further, decreased CO2 flux rates were observed at soil moisture contents of 5% or below. These results suggest that while soil moisture is less significantly correlated to soil CO2 respiration than soil temperature in this system, episodic wetting and drying events do influence smaller scale flux rate variations. Our results indicate that soil temperature is a primary driver of soil CO2 flux rates in Switchgrass croplands in East Tennessee. As the interactive effects of soil temperature and moisture influence soil biological activity (Grahammer et al. 1991), the lower variability in soil moisture during warmer months may have enhanced heterotophic and autotrophic respiration sensitivity to soil temperature variations during the peak soil CO2 flux seasons (Spring and Summer). Still, the combination of both soil temperature and moisture increased the regression model's ability to explain flux variance for Cover and Bare sites to 82.7% and 81.5% ($P<.0001$), respectively. This suggests that while soil temperature plays a more significant role in soil respiration in this system, the interaction between soil temperature and moisture should be considered in flux rate models.

4. Conclusions

In this study, the majority (~93%) of the annual soil CO2 efflux was observed during the Spring, Summer and Fall seasons. During the Winter, episodic precipitation events induced pulses of CO2 respiration indicating that significant respiration continues throughout the entire year. The growing season for switchgrass excludes Winter and portions of Spring and Fall suggesting that studies limited to only this time period may underestimate annual CO2 by more than 10%. Soil temperature was the primary driver of soil respiration rates during all seasons except Winter, during which soil moisture was more influential on average daily flux rates. CO2 flux rates at Cover sites were consistently greater than flux rates observed at Bare sites; however, significant soil respiration at Bare sites demonstrates the importance of including bare ground interspaces in soil CO2 flux assessments for switchgrass croplands. The total annual CO2 efflux reported here is greater than has been reported for other perennial grasses and greater than CO2 flux data reported for switchgrass in other regions in the United States. Greater annual CO2 flux result from the wet, warm subtropical-temperate climate of the region. Our results suggest that geographically focused studies, which include the growing and non-growing seasons, are critical to estimations of annual soil CO2-C soil losses needed for the development of more accurate carbon offset values for switchgrass production as a bioenergy crop in Tennessee.

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