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RESEARCH ARTICLE

Daily soil surface CO_2 flux during non-flooded periods in flood-irrigated rice rotations

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Abstract Carbon dioxide (CO_2) emitted from the soil, as a result of root and microorganism respiration, is a major process in the global carbon cycle. Since CO_2 production is dependent on oxygen availability, prolonged saturated soil conditions in rice (*Oryza sativa*) can decrease the quantity of soil carbon released in the form of CO_2 over time. At present, a deficiency exists in the scientific literature on soil surface CO_2 flux in well-established, flood-irrigated rice systems, which are flooded for approximately 3 months a year during the rice growth period. Plenty of studies have examined soil surface CO_2 flux in dryland cropping systems and methane emissions in paddy-grown rice, but flood-irrigated rice does not easily fall into either of these categories due to the cyclic nature of seasonal flooding. Therefore, this is the first study to examine daily soil surface CO_2 flux during non-flooded periods in well-established, flood-irrigated rice rotations. For a comprehensive analysis, soil surface CO_2 flux was measured for 2 years on 10 different rice-based rotations, which had been managed using conventional tillage or no-tillage for 10 and 11 years. Rotations included continuous rice and various combinations of rice rotated with soybean (*Glycine max*), corn (*Zea mays*), and/or winter wheat (*Triticum aestivum*) and were located on a silt-loam soil in the Mississippi River Delta region of Arkansas in the USA. Results showed that 7 of the 16 measurement dates differed in daily soil surface CO_2 flux among tillage and/or crop rotations. However, these differences were determined to be from crop maturity, in relation to early- or late-season planting, instead of patterns of long-term flood irrigation. Years that rice was grown reduced the cumulative CO_2 emissions, but substantial differences over time were minimized in rotations with soybean or corn. Findings from this experiment are valuable in the scientific understanding of carbon gas cycling in rice-based cropping systems because the aerobic periods between flooding were evaluated, which is the time period often ignored when examining carbon gas emissions in rice. Overall, this study provides evidence that the commonly used rice-based cropping systems reach a somewhat equilibrium state in daily CO_2 fluxes over time, regardless of the frequency in periodic soil saturation.

Keywords Soil surface CO_2 flux · Soil carbon · Rice rotations · Flood irrigation · Tillage · Long-term crop rotations

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1 Introduction

The concept of global warming is attributed to an array of different factors but is primarily attributed to three main greenhouse gases that are present both naturally and from anthropogenic influences: CO_2, methane, and nitrous oxide (Climate Change 2007). The most influential of these components contributing to atmospheric warming is CO_2 (Climate

Change 2007; Le Treut et al. 2007). Since the 1850s, the global concentration of CO_2 in the atmosphere has steadily increased from 280 ppm to over 400 ppm in 2013 (Kimble et al. 2002; National Oceanic and Atmospheric Administration - Earth System Research Laboratory 2013). In total, CO_2 emissions represent approximately 77 % of the anthropogenic greenhouse gas emissions (Climate Change 2007). The unnatural enrichment of CO_2 in the atmosphere is partly due to elevated fossil fuel combustion since the Industrial Revolution and in part due to land use changes associated with agriculture. Agricultural operations contribute roughly 25 % of the total anthropogenic CO_2 emissions (Duxbury 1995), and a sizeable portion of this percentage is attributed to soil cultivation, expansion into natural ecosystems, and the mineralization of soil organic carbon (Kimble et al. 2002).

The flux of CO_2 from the soil is a major process in the global carbon cycle and is a significant portion of the terrestrial carbon budget. Generally, soil air is greater in CO_2 (1–10 %) and lower in oxygen (5–10 %) than the atmosphere, which is a result of the decomposition of soil organic matter and by the respiration of roots and microbes (Montgomery et al. 2000; Piñol et al. 1995). Soil organic matter is a one of the main reservoirs of soil organic carbon in the biosphere. Follett (2001) estimated that approximately 1,550 Pg of soil organic carbon are stored in the world's soils, which is more than two times the carbon contained in living vegetation (560 Pg) or in the atmosphere (750 Pg; Sundquist 1993). Land management practices have the potential to enhance carbon accumulation, thereby easing the gaseous carbon load to the atmosphere and enriching the soil (Lal 2004).

Net carbon sequestration can be accomplished with any practice that returns large amounts of plant biomass to the soil, decreases soil disturbance, maintains soil structure, and conserves nutrient and water usage (Follett 2001; Paustain et al. 2000). Agricultural practices that can accomplish this include reducing or eliminating tillage, decreasing or ceasing fallow periods, discontinuing residue burning, winter cover cropping, switching from monoculture to rotation cropping, and altering fertilizer applications to increase production (Farquhar et al. 2001; West and Post 2002).

One of the key factors in the process dynamics and management responses of soil organic matter is the presence or absence of oxygen. Generally, an abundant oxygen supply promotes rapid soil organic matter decomposition, whereas a deficiency in oxygen results in a substantially lower decomposition rate (DeBusk et al. 2001; Shaffer and Ma 2001), with the carbon mineralization rates in aerobic conditions being as much as three times faster than under anaerobic conditions (DeBusk and Reddy 1998). Thus, the presence of saturated soil conditions that occur in rice-based cropping systems can affect the release rates and patterns of carbon gas emissions from the soil.

In agricultural row cropping systems, flood-irrigated rice is grown under nearly to completely saturated soil conditions (Norman et al. 2003). However, flood-irrigated rice soils are different from common wetland soils in that the soil is dry between harvesting and planting periods and between crop rotations. Rice is a high-residue-producing crop that is capable of producing 6.5 Mg ha^{-1} of aboveground biomass under optimal nitrogen fertilization (United States Department of Agriculture- National Agricultural Statistics Service 2012). Crop rotations involving high-residue-producing crops, such as rice and corn (8.0 Mg ha^{-1}), typically show a substantial increase in soil organic carbon, and the anaerobic conditions under which rice is grown affects the breakdown and retention of these crop residues, which in turn impacts the total soil organic carbon content in the soil (United States Department of Agriculture USDA National Agricultural Statistics Service NASS 2012; Witt et al. 2000). Soils continuously cropped with flood-irrigated rice have been reported to sequester 11 to 12 % more carbon than soils that support a dry season maize and flood-irrigated rice rotation within the top 15 cm of a clay soil in the Philippines (Witt et al. 2000).

While there have been numerous studies conducted on carbon gas emissions, predominantly methane, in rice during the flooded period, studies conducted on soil respiration from rice-based crop rotations during the non-flooded periods, such as during pre-flood, post-flood release, and between crop rotations, are practically nonexistent. Most of the studies that have been performed to investigate the long-term effects of crop rotations on CO_2 emissions have been evaluated in crops such as soybean, corn, and wheat (Al-Kaisi and Yin 2005; Omonode et al. 2007; Brye et al. 2006b). However, due to the cyclic anoxic conditions that result from rice production, these dryland crop studies do not pertain to crop rotations that include flood-irrigated rice. Furthermore, a majority of the rice research on soil organic carbon storage and carbon gas emissions that is available has been conducted on paddy-grown rice in Asia, which varies from upland rice by flooding regimes, in addition to the planting techniques used, such as transplant water seeding as opposed to dry seeding, harvesting methods, and residue management (De Datta 1981). These production differences, combined with the information that climatic differences account for a large variation in the amount of carbon gas loss due to soil organic matter decomposition (Carter 1996), result in findings from paddy rice not being directly applicable to flood-irrigated rice in the geographic area of the Mississippi River Delta region of the southern and mid-southern USA, which is where 81 % of the rice production occurs in the USA (United States Department of Agriculture National Agricultural Statistics Service 2012).

Therefore, the objectives of this study were to (i) evaluate the effects of rice-based crop rotations that include corn, soybean, and/or winter wheat and conventional tillage or no-tillage and on soil surface CO_2 flux after 10 and 11 years of consistent management (Fig. 1), and (ii) since soil CO_2 respiration rates have shown to be positively correlated with both soil temperature and soil moisture (Franzluebbers et al. 1995; Raich and Schlesinger 1992), evaluate the degree to which soil temperature and soil moisture control soil respiration in the Mississippi River Delta region of eastern Arkansas.

It was hypothesized that soil surface CO_2 flux would be (1) greater under conventional tillage than no-tillage in response to greater soil disturbance and aeration caused from tillage, (2) greater in rice during the post-flood than pre-flood period due to the accumulation of soil organic matter during the cropping period, (3) greater in crop rotations with corn than with soybean during the growing period due to larger biennial inputs of soil organic matter from crop residues, (4) greater in rotations that are double-cropped with winter wheat compared to single-cropped rotations due to an overall greater annual contribution to the soil organic matter pool from biannual inputs of crop residues, and (5) positively correlated with both soil temperature and soil moisture levels.

2 Materials and methods

2.1 Site description

This field study was conducted during 2009 and 2010 at the University of Arkansas Rice Research and Extension Center near Stuttgart, Arkansas, which lies at 34° 27′ N, 91° 24′ W and is located in the Mississippi River Delta region of eastern Arkansas in an area known as the Grand Prairie (United States Army Corps of Engineers 2000). Measurements were performed in a long-term experiment that was initiated in 1999 on a Dewitt silt loam, which is classified as a fine, smectitic, thermic, and Typic Albaqualf and is characteristic of Grand Prairie soils used for rice production (NRCS 2008).

Prior to 1999, the study site had been fallow for a number of years due to the absence of irrigation capabilities. Vegetation covering the site consisted of a mixture of grasses and weeds that were managed by periodic mowing during the growth period. To prepare for the study, the site was land-leveled to a 0.15 % grade in fall 1998. Land leveling consisted of removing the top 10 cm of soil, mechanically leveling the field to grade, and redistributing the topsoil evenly over the field. This land leveling procedure is a common practice in the Mississippi River Delta region, especially in areas that are heavily concentrated in rice production in order to enable an even distribution of flood irrigation water.

The climate of the region is warm and wet with a 30-year mean annual temperature minimum of 0.22 °C in January and maximum of 33.1 °C in July. The 30-year mean annual precipitation is 132 cm (Southern Region Climate 2012).

2.2 Experimental design and field treatments

This field study was comprised of two tillage treatments, which included conventional tillage and no-tillage, and 10 rice-based cropping systems arranged in a randomized complete block design with four replications. Each replicate block occupied an area of 9120 m^2 within the 1.9-ha experimental site and was partitioned as a strip-plot, whereas the whole plot variable consisted of the two tillage treatments and the 10 rice-based crop rotations were stripped across each tillage treatment. There were a total of 80 individual plots evaluated, with each tillage-rotation combination under optimal fertility and unchanged annual crop varieties representing an experimental unit.

Crop varieties included in the rice-based rotation treatments consisted of major agronomic crops grown in Arkansas and are commonly used in rice-based rotations. The 10 crop rotations included 1-, 2-, and 3-year rotations with soybean and corn, and some of rotations included winter wheat (Fig. 1). The following rotations were evaluated: (1) continuous rice, (2) rice-soybean, (3) soybean-rice, (4) rice-corn, (5) corn-rice, (6) rice (wheat), (7) rice (wheat)-soybean (wheat), (8) soybean (wheat)-rice (wheat), (9) rice-soybean-corn, and (10) rice-corn-soybean.

Early-season crops were fallow during the winter and included rice, soybean, and corn grown in the following rotations: continuous rice, rice-soybean, soybean-rice, rice-corn, corn rice, rice-soybean-corn, and rice-corn-soybean. Late-season crops produced wheat during the winter and included rice and soybean in the following rotations: rice (wheat), rice (wheat)-soybean (wheat), and soybean (wheat)-rice (wheat). In late-season crop rotations, wheat is represented in parentheses to indicate the winter production period, as opposed to the summer production period in which rice, soybean, and corn crops are grown.

Planting generally occurred in mid-April for the long-season crops and mid-June for short-season crops (Table 1). Rice, soybean, and wheat were sown into 19-cm rows using an Almaco NT drill (Almaco Inc., Nevada, IA, USA). Rice was drill-seeded at a rate of 100 kg seed ha^{-1}, soybean at a rate of 56 kg seed ha^{-1}, and wheat at a rate of 67 kg seed ha^{-1}. Corn was planted in 76-cm rows at a plant population of 79,000 seeds ha^{-1}.

Crop fertilization followed an optimal fertility recommendation based on the analysis of soil samples that were collected in spring 1999. The annual soil fertility treatment consisted of P_2O_5 applied as triple super phosphate and K_2O applied as muriate of potash, with both fertilizers broadcast pre-plant and pre-tillage with a spreader. Specific fertilizer rates for each crop are listed in Motschenbacher et al. (2014). Urea was used as the nitrogen fertilizer source, which was applied with a hand spreader pre-flood at the five-leaf stage of rice growth approximately 1 month after planting. Phosphorous and

Fig. 1 *Top left* to *right* and *bottom left* to *right*: experimental field plots planted in rice (*Oryza sativa*), soybean (*Glycine max*), corn (*Zea mays*), and winter wheat (*Triticum aestivum*) on a silt-loam soil at the Rice Research and Extension Center near Stuttgart, AR, USA. Experimental field plots in the pictures were some of the plots used to evaluate soil surface CO_2 flux and are part of a long-term study on 10 different rice-based crop rotations under conventional tillage or no-tillage management. There were a total of 80 experimental field plots evaluated in the study, each measuring 6 by 19 m

potassium were incorporated into the soil under conventional tillage and were left at the surface under no-tillage. Following nitrogen fertilization, a permanent flood of 5 to 10 cm was established on the rice crop, which was maintained annually until the crop reached physiological maturity. All other summer crops present in a given year were flood-irrigated on an

Table 1 Summary of the crop rotations and planting, rice flooding, rice flood release, and harvest dates during the 2009 and 2010 study periods at the Rice Research and Extension Center near Stuttgart, AR, USA

Rotation	Annual crop management dates							
	2009			Harvest	2010			Harvest
	Plant	Flood[a]	Release		Plant	Flood[a]	Release	
Continuous rice	07 Apr	02 June	24 Aug	03 Sep	14 Apr	26 May	10 Aug	25 Aug
Rice-soybean	07 Apr	02 June	24 Aug	03 Sep	23 Apr	–	–	26 Aug
Soybean-rice	01 June	–	–	20 Oct	14 Apr	26 May	10 Aug	25 Aug
Rice-corn	07 Apr	02 June	24 Aug	03 Sept	21 Apr	–	–	04 Oct
Corn-rice	07 Apr	–	–	29 Sep	14 Apr	26 May	10 Aug	25 Aug
Rice (wheat)[b]	25 June	09 July	02 Oct	21 Oct	18 June	28 July	20 Sep	15 Oct
Rice (wheat)-soybean (wheat)[b]	25 June	09 July	02 Oct	21 Oct	24 June	–	–	28 Oct
Soybean (wheat)-rice (wheat)[b]	28 June	–	–	04 Nov	18 June	28 July	20 Sep	15 Oct
Rice-soybean-corn	01 June	–	–	20 Oct	21 Apr	–	–	04 Oct
Rice-corn-soybean	07 Apr	–	–	29 Sep	23 Apr	–	–	26 Aug

Crop management dates are summarized for the crops grown during the summer growing period. Crops in parentheses were grown during the winter. Rotations with flooding and flood release dates represent rotations that had rice planted during the growing season

[a] Flooding dates listed are approximate flooding dates

[b] Rotations that include wheat were planted/harvested on 13 November 2008/16 June 2009 and 28 October 2009/08 June 2011

as-needed basis approximately three to four times annually, which was based on the amount of rainfall received and the development of the crop. Winter wheat was rain-fed only without irrigation.

Crop management practices for rice (Slaton 2001), soybean (Ashlock 2000), corn (Espinoza and Ross 2003), and wheat (Kelley 1999) followed the University of Arkansas Cooperative Extension Service recommendations for stand establishment, irrigation management, weed control, and pest management. In conventional tillage plots, crop residues were incorporated into the soil generally 1 to 2 months following harvest by disking two times. Prior to planting in the spring, plots were tilled by disking once, followed by multiple passes of a Triple K field cultivator (Kongskilde Industries, Inc., Hudson, IL, USA) to achieve the desired seedbed for rice planting. In no-tillage treatments, crop residues were left on the surface after harvest and were not manipulated by any means prior to planting in the spring.

2.3 Soil CO_2 sampling

Similar to Brye et al. (2006a), soil surface CO_2 flux was measured on the tillage-rotation treatment combinations using a LI-COR 6400XT portable photosynthesis system equipped with a 10-cm-diameter CO_2 flux soil chamber (LI-COR, Inc., Lincoln, NE, USA; Fig. 2). Measurements were conducted 6 times during the 2009 growing season and 10 times during the 2010 growing season, with the first measurement each year made prior to spring planting in May and the last measurement made following harvest in November. Sampling dates for 2009 were made on the following dates: 25 May, 30 June, 13 July, 27 July, 06 September, and 10 November. Sampling dates for 2010 were made on the following dates: 16 April, 07 May, 23 June, 01 July, 15 July, 27 July, 11 August, 18 August, 04 September, and 13 November.

For rotations planted in rice, measurements were made up until the plots were flooded and after the flood was released, whereas rotations with corn or soybean planted had measurements made throughout the entire growing season. Soil surface CO_2 flux was measured along with the 2- and 10-cm soil temperatures using a pencil-type thermometer and the volumetric water content in the top 6 cm using a Theta Probe (Model TH20, Dynamax, Houston, TX, USA). In order to uniformly measure the soil surface CO_2 flux in each plot, the soil chamber was placed vertically on a 10-cm-diameter plastic collar that was previously inserted into the ground to an approximate depth of 2 cm. The collars were placed between rows and were moved to another location in each plot every month to ensure an accurate representation of the plot.

2.4 Data analyses

The effects of tillage and crop rotation on soil surface CO_2 flux were evaluated by analysis of variance using the GLM procedure in SAS® (version 9.2, SAS Institute, Inc., Cary, NC, USA). Tillage and rotation treatments were considered as fixed effects and blocks were a random effect. Soil surface CO_2 flux data were analyzed separately for each measurement date. A single comprehensive analysis for all crop rotations over the 2-year study period was not practical because soil surface CO_2 flux could only be measured in non-flooded, tillage-rotation treatment combinations. Therefore, tillage-rotation combinations that were flooded during the dates evaluated were not measured and included in the data set for statistical analyses. Due to the combination of 1-, 2-, and 3-year crop rotations included in the study, and the 2-year duration of the study, the 3-year rotations of rice-soybean-corn and rice-corn-soybean were the only crop rotations that were evaluated during both years. This is because the rice-soybean-corn and rice-corn-soybean rotations produced dry-land crops, i.e., corn and soybean, consecutively during the 2 years of evaluation (Table 1). All other rotations were flooded either during the summer growing season every year, i.e., continuous rice and rice (wheat), or during 1 of the 2 years of evaluation, i.e., rice-soybean, soybean-rice, rice-corn, corn-rice-corn, rice (wheat)-soybean (wheat), and soybean (wheat)-rice (wheat), with the flooding dates varying between the early- and late-season crops (Table 1).

For analyses on dates pre-flood, during the dryland crop growing season, and post-flood release, both years were combined in order to have enough measurements for a statistical analysis. The pre-flood measurements were made prior to any flooding on early-season rice, the measurements during the dryland crop growing season were only made on the non-flooded rotations producing soybean or corn during the summer growth period, and the post-flood release period was measured after floods were released in all treatments. Furthermore, the effects of soil moisture and 2- and 10-cm soil temperatures on soil surface CO_2 flux were evaluated using the SAS® linear regression analysis. When appropriate, means were separated using Fisher's protected least significant difference at the 0.05 level on all statistical analyses.

Soil surface CO_2 flux measurements from each measurement date were used to calculate annual CO_2 flux over the summer growing period. Daily CO_2 values on dates not sampled during each annual evaluation period, which was from 25 May 2009 to 10 November 2009 and 16 April 2010 to 13 November 2010, were calculated by taking the difference between two of the closest measurement dates and calculating a running average of increases or decreases in flux over time using an Excel spreadsheet (version 10, Microsoft, Inc. Redmond, WA, USA). Annual CO_2 fluxes emitted during the growing period were calculated for each tillage-rotation

Fig. 2 Measuring soil surface CO_2 flux in a rice-based crop rotation planted in corn (*Zea mays*; *top*) using a LI-COR 6400XT portable photosynthesis system (*bottom left*) equipped with a 10-cm-diameter CO_2 flux soil chamber and a 10-cm-depth soil thermometer (*bottom right*)

treatment combination. Due to the presence of anoxic conditions during the growing period in rice, values were set as 0 g $CO_2 m^{-2}$ day^{-1} from the date flooding occurred until the flood was released.

3 Results and discussion

3.1 Initial soil properties

Soil samples collected in 1999, prior to any tillage or rotation treatments, showed that soil properties in the top 10 cm were generally uniform among the 20 pre-assigned, tillage-rotation treatment combinations. Statistical analyses performed on 1999 soil samples indicated that the pre-assigned tillage-rotation treatment combinations did not differ among soil bulk density, soil organic matter contents, soil organic carbon contents, total nitrogen, the partitioning of soil organic carbon and total nitrogen within soil organic matter, and carbon-to-nitrogen ratios at the significance level of 0.05. Furthermore, soil particle size distribution did not differ among any treatment combinations when measured in 2010 at the significance level of 0.05. Detailed soil property values after 11 years of management are reported in Motschenbacher et al. (2014).

3.2 Tillage and rotation effects on soil CO_2 flux within sampling dates

After 10 and 11 years of consistent crop rotation and 9 and 10 years of conventional tillage or no-tillage management, soil surface CO_2 flux was infrequently affected by tillage and/or crop rotation. Of the 16 measurement dates across 2 years of observations, soil CO_2 flux was affected by tillage and rotation on two dates in 2010, tillage alone on one date in 2009, and rotation alone on two dates in 2009 and two dates in 2010, for a total of 7 out of the 16 dates measured. There were no independent tillage or rotation treatment effects during the same date. As displayed in the variability of all soil surface CO_2 flux measurements within the same sampling date generally increased throughout the cropping season until after harvest. In accordance with past research (Amos et al. 2005), increasing soil surface CO_2 flux throughout the growth period was expected due to crop maturing and soil temperature increases related to seasonal changes.

3.2.1 Tillage and rotation effects on soil surface CO_2 flux

The tillage-rotation combinations differed in soil surface CO_2 flux on 23 June 2010 (P=0.031) and 15 July 2010 (P=0.004). On 23 June 2010, soil surface CO_2 flux was greater in the rice-soybean rotation under both conventional tillage and no-tillage, with values of 8.76 and 7.54 μmol $CO_2 m^{-2} s^{-1}$, respectively, than that in the late-season cropping systems rotated with wheat, including rice (wheat), rice (wheat)-soybean (wheat), and soybean (wheat)-rice (wheat), under both tillage treatments and rice-corn under conventional tillage, which had values ranging from 0.11 to 1.49 μmol $CO_2 m^{-2} s^{-1}$. With the exception of the rice-soybean rotation under both conventional tillage and no-tillage, all other rotations under both tillage treatments measured on 23 June 2010 did not differ at the 0.05 level. During the time of sampling, early-season rotations growing rice in 2010, which included continuous rice, soybean-rice, and corn-rice, were not measured because rice had already been flooded for the growing season.

Smaller soil surface CO_2 flux in the late-season crops compared to the early-season crops may be explained by the different growth stages of crops during the time of sampling (Amos et al. 2005). Root respiration has been estimated to constitute 40 to 60 % of the CO_2 emitted from the soil (Raich and Schlesinger 1992), so soils containing more mature crops have the ability to produce greater soil surface CO_2 emissions due to increased root respiration from greater photosynthetic rates (Kuzyakov and Cheng 2001; Amos et al. 2005). On 23 June 2010, late-season crops had been planted 3 days prior to CO_2 flux measurements, whereas the non-flooded, early-season rotations had been planted approximately 3 weeks prior to measurement on this date (Table 1). Therefore, early-season crops were substantially more developed than the late-season crops which greatly explains the differences in soil surface CO_2 flux measurements.

On 15 July 2010, soil surface CO_2 flux was also lower in some of the late-season cropping systems, including rice (wheat), rice (wheat)-soybean (wheat), and soybean (wheat)-rice (wheat) under conventional tillage and rice (wheat) under no-tillage, which all ranged from 3.07 to 4.08 μmol $CO_2 m^{-2} s^{-1}$, than that in the rice-soybean, rice-corn, rice-corn-soybean under conventional tillage, and rice-soybean-corn under no-tillage, which all ranged from 6.74 to 9.01 μmol $CO_2 m^{-2} s^{-1}$. Like the 23 June 2010 sampling date, smaller quantities of soil surface CO_2 flux in late-season crops could be associated with crop maturity during the time of measurement (Raich and Schlesinger 1992; Kuzyakov and Cheng 2001; Amos et al. 2005). In that, the late-season rice and soybean crops were less mature than the early-season rice, soybean, and corn crops.

3.2.2 Tillage effects on soil surface CO_2 flux

Tillage can affect CO_2 loss from the soil by aerating the soil through physical disturbance from mechanical manipulation (West and Post 2002). However, averaged across all rotation treatments, there was only 1 out of the 16 sampling dates that differed in tillage alone, which was measured on 10 November 2009 (P=0.025). On this date, no-tillage had 47 % greater soil surface CO_2 flux than that under conventional tillage, with respective readings of 1.07 and 0.73 μmol $CO_2 m^{-2} s^{-1}$. Results from this sampling date are different from what was expected based on past studies that reported greater CO_2 flux under conventional tillage than that measured under reduced and no-tillage treatments (Reicosky and Lindstrom 1993; Reicosky et al. 1997; West and Marland 2002). These results were also contrary to results in a study evaluating a soybean-wheat rotation on a silt-loam soil in a similar geographic location of east-central Arkansas, which reported a 38 % greater soil surface CO_2 flux under conventional tillage than from that under no-tillage (Brye et al. 2006b). However, greater soil surface CO_2 flux under no-tillage than that under conventional tillage observed in this study on 10 November 2009 was similar to tillage effects on CO_2 emissions in a sorghum (*Sorghum bicolor* L.)-based cropping system study conducted in Georgia (Hendrix et al. 1988). Hendrix et al. (1988) reported greater soil surface CO_2 flux under no-tillage than that under conventional tillage, which was justified as a result of measurement timing. In that, tillage affects the time at which CO_2 is released from the soil rather than the total CO_2 production from the treatment, meaning that CO_2 emissions are expected to be greater immediately following the soil disturbance from tillage and not necessarily during the time of measurement. Therefore, a reasonable assumption for the greater soil surface CO_2 flux in no-tillage on 10 November 2009 may also be related to the timing of CO_2 measurements following mechanical soil manipulation under conventional tillage.

Despite soil surface CO_2 flux differences reported in previous studies in relation to tillage, there was only 1 out of the 16 measurement dates that actually showed any differences in soil surface CO_2 flux between conventional tillage and no-tillage treatments. Thus, the measured soil surface CO_2 flux in each sampling date over time does not provide strong support that performing conventional tillage was the foremost contributing factor influencing daily soil surface CO_2 flux across the 2 years of measurements. While greater soil surface CO_2 flux under conventional tillage would be expected immediately after tillage, these losses would occur rather rapidly. Therefore, measurements from this study suggest that increases in soil surface CO_2 flux under conventional tillage are not constant throughout the season.

3.2.3 Rotation effects on soil surface CO_2 flux

Rotation can affect soil surface CO_2 flux by increasing the plant and microbial biomass content in the soil and through root respiration of the crops being grown (Kuzyakov and Cheng 2001; Al-Kaisi and Yin 2005; Brye et al. 2006b; Omonode et al. 2007). However, averaged across tillage treatments, rotations differed in only 4 of the 16 sampling dates, which were 30 June 2009 (P=0.007), 06 September 2009 (P<0.001), 16 April 2010 (P=0.015), and the 01 July 2010 (P<0.001).

During 2009, patterns of soil surface CO_2 flux among rotations differed within each measurement date. On 30 June 2009, rotations growing corn, specifically corn-rice and rice-corn-soybean, had two times the quantity of soil surface CO_2 flux than those growing soybean, specifically rice-soybean-corn, soybean (wheat)-rice (wheat), and soybean-rice, with values ranging from 4.69 to 5.71 and 2.34 to 2.79 μmol CO_2 m^{-2} s^{-1}, respectively. However, during the 06 September 2009 measurement date, rotations growing soybean had two to three times greater soil surface CO_2 flux than the rotations growing corn, with values ranging from 4.10 to 5.18 and 1.61 to 1.82 μmol $CO_2 m^{-2}$ s^{-1}, respectively. Thus, the 30 June 2009 and 06 September 2009 dates had reversed values of significance for corn verses soybean crops in rotation. Rotations that were flooded and not compared in analyses included continuous rice, rice-soybean, rice-corn, rice (wheat), and rice (wheat)-soybean (wheat) during the 30 June 2009 measurement date and rice (wheat) and rice (wheat)-soybean (wheat) during the 06 September 2009 measurement date.

Similar to measurements conducted in 2009, patterns of soil surface CO_2 flux among rotations in 2010 varied among measurement dates. On 16 April 2010, the rice (wheat) and rice (wheat)-soybean (wheat) rotations, which ranged from 3.02 to 3.39 μmol $CO_2 m^{-2}$ s^{-1}, had greater CO_2 flux than the other eight rotations, which ranged from 0.99 to 1.96 μmol $CO_2 m^{-2}$ s^{-1}. Furthermore, the soybean (wheat)-rice (wheat) rotation had a CO_2 flux of 1.96 μmol $CO_2 m^{-2}$ s^{-1}, which was greater than that of the continuous rice, rice-soybean, soybean-rice, rice-soybean-corn, and rice-corn-soybean rotations, which ranged from 0.99 to 1.44 μmol CO_2 m^{-2} s^{-1}. Being that the 16 April 2010 measurement date was early in the season, early-season crop rotations had been just planted with summer crops and late-season crop rotations still contained winter wheat during the time of measurement. Thus, greater soil respiration would be expected in the late-season crop rotations due to the influence of root respiration from wheat as opposed to the absence of crop growth in recently planted rotations that had been fallow for the winter. However, on the 01 July 2010 measurement date, rotations planted with early-season soybean, specifically rice-soybean and rice-corn-soybean, had greater CO_2 flux than that in all late-season rice or soybean rotations, with values ranging from 7.38 to 8.35 and 2.61 to 3.07 μmol $CO_2 m^{-2}$ s^{-1}, respectively.

3.3 Pre-flood and post-flood soil surface CO_2 flux in rice

For an evaluation of the rotations that produced rice during the summer growing period, soil surface CO_2 flux was compared between pre-flood and the post-flood sampling dates for each tillage-rotation combination (Table 1). When sampling years were combined, there were no differences in CO_2 flux between pre-flood or post-flood periods in the rotations growing rice for any of the tillage, rotation, or tillage-rotation combinations at the 0.05 level (Table 1). These results suggest that the buildup of soil organic matter, and thus soil organic carbon available for CO_2 production, during the anaerobic period when the rice field is flooded, combined with the input of fresh crop residues following harvest, did not result in soil surface CO_2 flux differences pre-flood and post-flood periods in rice. Similar to the lack of differences between tillage treatments that was explained by Hendrix et al. (1988), the lack of differences among pre-flood and post-flood could quite possibly be a result of measurement timing following the release flood waters.

3.4 Soil surface CO_2 flux in rotations with soybean and corn planted during the growth period

When compared across both sampling years, there were no differences in rotations that contained soybean and/or corn during 2-year or 3-year rotations at the 0.05 level. Furthermore, there were no differences in soil surface CO_2 flux in relation to which crops were produced during the growth period, i.e., soybean or corn. These results are unexpected considering the varied quantities of biomass inputs from soybean and corn crop residues annually. Rotations with greater frequencies of corn add significantly more biomass to the soil than rotations with greater frequencies of soybean. Furthermore, the large roots of corn, as opposed to the smaller roots of soybean, create large differences in soil surface CO_2 flux associated with root respiration (Kuzyakov and Cheng 2001; Al-Kaisi and Yin 2005; Brye et al. 2006b; Omonode et al. 2007).

3.5 Soil moisture and temperature effects on soil surface CO_2 flux

When combined across measurement dates, tillage treatments, and crop rotations, soil surface CO_2 flux was affected by soil moisture and soil temperature at both the 2- and 10-cm soil depths ($P<0.001$). Despite this statistical relationship, there was a very weak predictive relationship of soil surface CO_2 flux ($r^2=0.311$). The regression equation for the predictive relationship of soil surface CO_2 flux is represented by $y=-14.217+55.784x_1+0.587x_2+0.797x_3$, where y is the soil surface CO_2 flux, x_1 is the volumetric water content, x_2 is the 2-cm spoil temperature, and x_3 is the 10-cm soil temperature. The association between soil moisture and soil temperature on soil surface CO_2 flux has been well documented throughout the years, whereas warmer temperatures and adequate soil moisture with proper drainage increase soil surface CO_2 flux (Schlesinger 1997; Davidson et al. 2002). However, though significant enough when combined with soil temperature to be included in the regression equation, soil moisture was not a strong predictive variable ($P=0.735$) as both 2-cm ($P<0.001$) and 10-cm soil temperatures ($P<0.001$) when evaluating each variable separately within the model equation.

In general, the numerical values for soil moisture content were similar among sampling days, despite large variations in soil surface CO_2 flux during the same days. Soil surface CO_2 flux was also greater in 2009 than in 2010, which could be associated with above normal rainfall amounts during the 2009 sampling year and below average rainfall amounts during the 2010 sampling year (USDA-ARS 2011). The weakness of the soil moisture variable relative to soil temperature in the predictive value of soil surface CO_2 flux has been evaluated in a previous CO_2 study conducted in a similar geographic location. Brye et al. (2006a) reported a slight relationship between soil moisture content and CO_2 flux in a soybean-winter wheat rotation, which was assumed to be contributed to climatic factors during the years of observation.

For this analysis, the measured environmental variables of 2- and 10-cm soil temperatures and the volumetric water content were the only variables used to determine the predictive relationship between soil surface CO_2 fluxes. The treatment effects of tillage and rotation were eliminated from the model due to a lack of consistent differences in measured CO_2 flux within individual sampling dates that were associated with tillage and/or rotation treatment effects. Furthermore, the inability to measure rice during the flooded period limited the ability to fully evaluate all tillage-rotation treatment combinations over a large fluctuation of soil temperature and moisture throughout the year. Thus, the rationale behind the elimination of managed treatment effects was to get a predictive equation of soil surface CO_2 flux based solely on environmental factors.

3.6 Estimation of soil surface CO_2 flux during the growth period

Estimations of soil surface CO_2 flux during summer growing period displayed substantially greater CO_2 emissions under rotations not flooded during the estimation period, which

Table 2 Summary of the estimated soil surface carbon dioxide (CO_2) flux during the 2009 and 2010 summer growing periods on a silt-loam soil at the Rice Research and Extension Center near Stuttgart, AR, USA

Rotation	CO_2 flux (g m^{-2} growing season^{-1})			
	2009		2010	
	Conventional tillage	No-tillage	Conventional tillage	No-tillage
Continuous rice	514±101	663±89	575±145	676±147
Rice-soybean	824±117	873±106	3362±320	2586±304
Soybean-rice	1976±201	2189±173	659±167	606±96
Rice-corn	743±78	949±90	2475±193	1832±93
Corn-rice	2239±178	1434±145	654±78	582±113
Rice (wheat)	121±63	521±61	957±132	1254±89
Rice (wheat)-soybean (wheat)	239±45	424±68	1692±222	1614±153
Soybean (wheat)-rice (wheat)	2161±249	2530±307	993±58	953±198
Rice-soybean-corn	1945±182	2241±137	2346±146	2038±217
Rice-corn-soybean	1509±134	1867±102	2461±243	2285±347

Values represent different rice-based crop rotations that were continuously managed for 10 or 11 years using conventional tillage or no-tillage. Rice was either continuous or rotated with soybean and/or corn, and some rotations also included wheat. Crops in parentheses were grown during the winter. Flood irrigation occurred in the continuous rice, rice-soybean, rice-corn, rice (wheat), and rice (wheat)-soybean (wheat) rotations in 2009 and the continuous rice, soybean-rice, corn-rice, rice (wheat), and soybean (wheat)-rice (wheat) rotations in 2010 ranged from 25 May to 10 November in 2009 and 16 April to 13 November in 2010 (Tables 1 and 2). However, dissimilarities in these values were expected due to pre-establishing daily CO_2 flux values as 0 g $CO_2 m^{-2}$ day^{-1} during times when flooded conditions were present. Estimates calculated in 2009 on rotations not flooded during the growing season ranged from 1434±145 g $CO_2 m^{-2}$ in the corn-rice rotation under no-tillage to 2530±307 g $CO_2 m^{-2}$ in the soybean (wheat)-rice (wheat) rotation under no-tillage (Table 2). Similarly, estimates calculated in 2010 on rotations not flooded during the growing season ranged from 1614±153 g $CO_2 m^{-2}$ in the rice (wheat)-soybean (wheat) rotation under conventional tillage to 3362±320 g $CO_2 m^{-2}$ in the rice-soybean rotation under conventional tillage (Table 2). Rotations that were flooded at some time period during the growing season had much lower estimated rates of soil surface CO_2 flux during the summer growth period. Soil surface CO_2 flux values ranged from 121±63 g $CO_2 m^{-2}$ in the rice (wheat) rotation under conventional tillage to 949±90 g $CO_2 m^{-2}$ in the rice-corn rotation under no-tillage during the summer growing period in 2009, and soil surface CO_2 flux values ranged from 575±145 g $CO_2 m^{-2}$ in continuous rice under conventional tillage to 993±58 g $CO_2 m^{-2}$ in rice (W)-soybean (W) under conventional tillage in during the summer growing period in 2010 (Table 2).

4 Conclusion

Results of this study demonstrated that annual periodic soil saturation from flood irrigation in rice decreases the annual emissions of soil surface CO_2 by decreasing the oxygen availability during the rice crop growth period, when compared to dryland crop rotations. However, decreases in soil surface CO_2 flux that result from soil saturation did not substantially and consistently affect daily soil surface CO_2 flux during non-flooded periods when the management practices have occurred over a long-term period.

This study evaluated periodic sampling dates over the course of two summer growing seasons as opposed to continuous measurements during a short period of time. While no-tillage, high-residue-producing crops, and rotations producing winter wheat, as opposed to remaining fallow, have been shown to sequester an overall greater amount of carbon in the soil (Motschenbacher et al. 2014), this study suggests that emission rates of CO_2 from the soil essentially become more uniform over time regardless of the amount of carbon stored in the soil from past management conditions. Therefore, root respiration associated with crop maturity could be the leading variable in soil surface CO_2 flux during the growing season in non-flooded, rice-based crop rotations, as opposed to the decomposition rate of soil organic matter.

The results of this experiment are significant to the scientific community because they indicate that over the course of time, rice-based crop management systems can reach a somewhat equilibrium state of daily CO_2 emissions regardless of the frequency of periodic flooding. Findings from this experiment are also valuable to the scientific understanding of carbon cycling in flood-irrigated, rice-based cropping systems during the non-flooded periods. Evaluating aerobic periods in flood-irrigated systems, which includes the time before flooding, the time after the flood is released, and periods that rice is in rotation with a dryland crop, is just as important as evaluating carbon cycling during the flooded periods. In flood-irrigated systems that produce one rice crop annually, the soil is only saturated for about 25 % of the year, and this percentage goes up substantially if a dryland crop is added as an annual rotation. Despite the time flood-irrigated rice soils are in non-flooded conditions, this dry period has often been overlooked in past studies evaluating carbon gas emissions in rice-based cropping systems. Thus, the omission of this evaluation highlights the importance of this experiment and indicates that this time period in rice-based crop rotations needs to be given greater attention in future scientific studies relating to comprehensive carbon gas emissions in rice.

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