Research Article

Evaluation of the Plant's Role in Greenhouse Gas Emissions in Furrow-irrigated Rice

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Abstract

The role of rice (*Oryza sativa*) plants themselves at facilitating methane (CH_4) emissions from flood-irrigation has been well-established. However, as alternate water management schemes, such as furrow-irrigation, grow in use, the role of rice plants facilitating CH_4 and nitrous oxide (N_2O) emissions needs to be evaluated. The objective of this study was to characterize the effect of rice plants (i.e., with plants and bare soil) on CH_4, N_2O, and carbon dioxide (CO_2) fluxes, season-long emissions, and global warming potential (GWP) estimates in furrow-irrigated rice on a silt-loam soil (Typic Albaqualfs) in eastern Arkansas during 2019. Carbon dioxide and CH_4 fluxes were generally greater ($P < 0.05$) from the with-plants than the bare-soil treatment over time, while, averaged over time, N_2O flux from bare soil (0.15 mg m^{-2} hr^{-1}) was 1.7 times greater ($P < 0.05$) than with plants (0.085 mg m^{-2} hr^{-1}). Season-long CO_2 and CH_4 emissions were at least 3.2 times greater ($P < 0.05$) from the with-plants treatment. Three-gas (i.e., CH_4, N_2O, and CO_2) GWP estimates were approximately 13,000 kg CO_2 eq. ha^{-1} season^{-1} greater ($P < 0.05$) from the with-plants than the bare-soil treatment, but two-gas (i.e., only CH_4 and N_2O) GWP estimates were unaffected ($P > 0.05$) by treatment. Results of this study indicate that, at least in the up-slope position, CH_4 and N_2O emissions measured in the with-plant area atop beds are reasonably representative of both the with-plant, top-of-bed area and the furrow area of a furrow-irrigated rice field with few to no plants present.

Keywords

Methane, Nitrous oxide, Carbon dioxide, Global warming potential, Rice production, Arkansas

Introduction

Agriculture, forestry, and other associated land uses account for an estimated 24% of global greenhouse gas (GHG) emissions, where ~16% of global GHG are methane (CH_4) [1]. It has also been estimated that rice (*Oryza sativa*) cultivation specifically accounts for a significant portion (~11%) of global annual CH_4 emissions, which has led to rice being globally identified as a major GHG-producing crop [1]. In the United States (US), Arkansas is the leading rice-producing state, where ~8.3 Mg grain ha^{-1} were produced in 2022, which represented 50.1% of the total US rice production [2].

Rice is typically grown using flood-irrigation, which consists of installing levees to retain water then permanently flooding the field 28 to 34 days after planting, or once the rice plants reach the 4- to 5-leaf stage [3]. Flood-irrigation is used to create a layer of stagnant surface water that helps to reduce weeds and disease, thus increasing profitability [4]. However, flood-irrigation uses large quantities of water, which contributes to depleted aquifers in the Lower Mississippi River Valley and creates an anaerobic soil environment that leads to abundant CH_4 emissions [5,6]. Alternative water management schemes (i.e., furrow-irrigation or alternate wet and dry) have been shown to minimize GHG emissions, namely CH_4, and reduce rice's global warming potential (GWP) [6-8].

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Furrow-irrigation consists of creating raised beds along a gently sloping landscape, allowing irrigation water to flow by gravity in furrows between raised beds from the up- to the downslope position, which wets the raised beds, thus watering the rice plants [4]. In Arkansas, furrow-irrigation accounts for ~10.5% of planted-rice area and, as recent trends have shown, furrow-irrigation is expected to continue to expand in use due to documented water conservation without a significant effect on yield [4]. However, in contrast to flood-irrigation, furrow-irrigation reportedly creates variable field conditions of oxidation-reduction (redox) potential and soil moisture, which can minimize CH_4 emissions, but potentially increase nitrous oxide (N_2O) emissions, for which each molecule of N_2O has a nearly 10-fold greater GWP than CH_4 [6,9,10].

An increase in N_2O emissions in furrow-irrigated rice is influenced primarily by soil moisture content, which impacts oxygen (O_2) availability and microbial processes [11,12]. Elevated, but not saturated, soil moisture contents (i.e., > 60% water-filled pore space), similar to soil moisture contents in furrow-irrigated rice fields, create an O_2-limited environment that is ideal for denitrifying bacteria, which are the primary source of N_2O production in soil [13]. However, in anaerobic environments (i.e., flooded-soil conditions), the relatively quick development of reducing conditions causes denitrification to nearly cease and methanogenic microorganisms begin decomposing soil organic matter to produce and release CH_4 [14,15].

It has been demonstrated that, under flood-irrigation, the rice plant itself acts as a conduit to facilitate gas transfer between the soil and the atmosphere through aerenchyma tissue [16], providing a means for O_2 to be transported into the soil to the rhizosphere and for CH_4 trapped in the soil below the flood water to be released to the atmosphere. In Arkansas, Rogers, et al. [17] quantified season-long CH_4 emissions from flood-irrigated rice on a silt loam, specifically evaluating the effects of optimally fertilized rice and non-fertilized bare soil. Results showed that the fertilized, with-plants treatment emitted four times more CH_4 than the unfertilized, bare-soil treatment [17]. Similarly, Brye, et al. [18] evaluated the effects of soil texture (i.e., silt loam and clay) and plant presence on CH_4 fluxes and emissions in flood-irrigated rice in Arkansas. Results showed that CH_4 emissions between flooding and harvest were 6.1 and 20.9 times greater when rice plants were present in the silt-loam and clay soils, respectively [18].

Despite the reported substantial CH_4 emissions reduction from bare soil (i.e., without plants present) compared to plants being present in flood-irrigated rice, coupled with the expanding use of furrow-irrigated rice production, the potential role of the rice plant itself at facilitating gas exchange between the soil and atmosphere under furrow-irrigation, where there is no flood, warrants evaluation. Therefore, the objective of this study was to quantify the effect of the presence of rice plants (i.e., with and without plants) on GHG (i.e., CO_2, CH_4, and N_2O) fluxes, season-long emissions, and GWP estimates at an up-slope site position under no-tillage (NT) in furrow-irrigated rice on a silt-loam soil in eastern Arkansas. It was hypothesized that the presence of rice plants will increase CO_2, CH_4, and N_2O fluxes, season-long emissions, and GWP estimates compared to bare soil without plants.

The GHG flux and emissions data constituting the with-plants treatment in this study were previously reported as part of two larger-scale field studies [7,19]. However, paired with the previously reported with-plants data from only the up-slope position until NT management, the combined dataset with bare-soil results represents a new dataset, where new statistical analyses address a different objective than what has previously been evaluated.

Materials and Methods

The current study was conducted in the same production-scale, furrow-irrigated rice field and at the same time as several other field studies [6,7,9,19]. The other field studies evaluated multiple aspects of furrow-irrigated rice, such as the effects of site position and tillage treatment effect on near-surface soil property variations (i.e., oxidation-reduction potential, soil temperature, and soil moisture), rice agronomic response, GHG fluxes over time, and season-long GHG emissions [6,7,9,19].

Site Description, Treatments, and Experimental Design

Similar to Della Lunga, et al. [6,7,9] and Slayden, et al. [19], the current study was conducted at the Rice Research and Extension Center (34.46°N, -91.46°W), near Stuttgart, AR in Arkansas County, between May and September 2019. The specific study site was in the up-slope region of a 16-ha, production-scale, furrow-irrigated rice field, 91-m north of the south end of the field, which was the field's highest point of elevation. The soil throughout the study area is mapped as a poorly drained Dewitt silt loam (fine, smectitic, thermic Typic Albaqualfs) [20]. The specific study area was conducted in a strip of NT (i.e., stale seedbed) soil management that was 6-m wide and extended the ~ 140m of the up-slope study area with a 2% slope. The 30-yr (1991-2020) annual average air temperature in the region is 17.3 °C [21]. The 30-yr (1991-2020) annual mean precipitation is 128.8 cm [22].

This study was established as a completely random design. Two experimental treatments were evaluated, a vegetated soil surface and bare soil. Each treatment was spatially replicated three times.

Field Management

As described in more detail by Della Lunga, et al. [6,7], the hybrid cultivar '214-Gemini' (Rice Tec Inc., Alvin, TX) was planted on 30 April, 2019 with a 19-cm row spacing at a rate of 21 kg seed ha^{-1}. The previous years' raised beds had been maintained and were treated with a NT furrow-runner implement (Perkins Sales Inc., Bernie, MO) to ensure the furrow was open for unobstructed water flow during irrigation. On 16 May, 2019, at approximately the 2- to 3-leaf stage, the study received 101 kg P ha^{-1} as triple superphosphate, 67 kg K ha^{-1} as muriate of potash, 11 kg Zn ha^{-1} as Zinc 20, and 23 kg N ha^{-1} and 27 kg S ha^{-1} as ammonium sulfate. On 3 June, 2019, at approximately the 3- to 4-leaf stage, the study received

168 kg N ha^{-1} of urease-inhibitor-coated urea (46% N). All fertilizers were mechanically broadcast-amended to the soil surface.

Immediately after rice planting, six, 30-cm diameter by 30-cm tall, polyvinyl chloride (PVC) base collars for gas sampling, with a beveled bottom and four, 12.5-mm-diameter holes drilled 12 cm up from the beveled end to allow free movement of water, were installed by pounding the collar into the ground with a mallet atop raised beds in the study area. Three base collars were installed in the to-be vegetated area atop alternating raised beds to constitute the with-plants treatment, while three additional base collars were installed atop the raised beds between where the with-plants collars were installed to constitute the bare-soil treatments. Thus, all six base collars were in a 6-m-long row, perpendicular to the predominant field slope, with base collars representing the two treatments for gas sampling on alternating raised beds in the six total raised beds that comprised the strip of NT field management. Once emerged, rice plants were manually removed from the bare-soil collars and were maintained plant-free for the remainder of the growing season.

The study area was furrow-irrigated approximately weekly throughout the growing season, but more frequently if needed, from 13 June, 2019 to 4 September, 2019 using a 30-cm-diameter lay-flat polypipe that was placed parallel to the study site at the south end of the field, where a tail-water pump at the north/down-slope end of the field returned surface water back to the upper crown of the field [23]. Weeds were managed as needed with various herbicide applications, where additional details regarding weed management throughout the growing season were reported in Slayden, et al. [19].

Greenhouse Gas Measurements

Similar to Della Lunga, et al. [6,7] gas sampling occurred 16 times throughout the growing season, approximately weekly, from three weeks after rice planting to harvest [i.e., 21, 28, 35, 42, 49, 56, 63, 70, 77, 84, 91, 98, 105, 112, 118, and 125 days after plating (DAP)]. Immediately prior to gas sampling from single base collar, the four, 12.5-mm-diameter holes were plugged with 1.3-cm diameter rubber stoppers (part #73828A-RB, Voigt Global, Lawrence, KS) and a PVC cap (i.e., 10-cm tall by 30-cm diameter) was placed atop the base collar and sealed with a rubber flap to create a closed chamber. On the underside of the cap, a small fan was mounted that was powered with a 9-V battery to circulate the air inside the enclosed headspace. On the side of the cap, a 15-cm-long piece of copper refrigerator tubing was installed to provide pressure equilibration with the outside, ambient air. On the top of the cap, two septa were installed, one to serve as the gas extraction point and one to serve as a thermometer insertion point to monitor the air temperature inside the closed chamber during gas sampling. When necessary, chamber extensions were mounted on top of the base collars prior sampling to accommodate the growth of the plants during the growing season. Caps and extensions were covered in reflective aluminum tape to reduce temperature variations inside the closed chambers during sampling. Gas

samples were collected three times over a 1-hour period, at the 0-, 30-, and 60-minute marks, using a 25-mL syringe. Collected gas samples were transferred from the syringe to pre-capped (20-mm headspace crimp cap; part #5183-4479, Agilent Technologies, Santa Clara, CA), pre-evacuated 10-mL glass vials (part #5182-0838, Agilent Technologies, Santa Clara, CA).

Within generally 48 hours after collection, gas samples were analyzed on a Shimadzu GC-2014 ATFSPL 115-V gas chromatograph (GC; Shimadzu North America/Shimadzu Scientific Instruments Inc., Columbia, MD). For CH_4 and CO_2 concentration measurements, a flame ionization detector was used, while an electron capture detector was used to quantify N_2O concentrations. Helium was the carrier gas used for sample analyses. Gas fluxes from a given chamber on a given sample date were calculated as the linear slope among the three gas sample concentrations from the 0-, 30-, and 60-minute marks during which the chamber was sealed with the cap.

Similar to Della Lunga, et al. [7] and Slayden, et al. [19], season-long emissions were estimated on a chamber-by-chamber basis using linear interpolation between individual flux measurements on consecutive sample dates. Global warming potentials were calculated on a chamber-by-chamber basis using conversion factors of 34 and 298 for CH_4 and N_2O, respectively, from the Intergovernmental Panel on Climate Change (IPCC) 5th GHG emissions assessment [1] and conversion factors of 28 and 265 for CH_4 and N_2O, respectively, from the IPCC 6th assessment [24] to obtain CO_2 equivalents [7]. A conversion factor of 1 was assigned to CO_2 under both assessments. Two sets of GWPs were calculated based on both the 5th and 6th assessments: i) CH_4 and N_2O only, and ii) CH_4, N_2O, and CO_2. Global warming potentials were calculated using conversion factors from IPCC's 5th and 6th assessments to facilitate comparison to past reports that used conversion factors from IPCC's 5th or 6th assessments. Flux and emissions data from the three replicate base collars for the with-plants treatments were taken from Della Lunga, et al. [6,7].

Statistical Analyses

Based on a completely random design for the field treatment, a two-factor analysis of variance (ANOVA) was conducted using PROC GLIMMIX in SAS (version 9.4, SAS Institute, Inc., Cary, NC) to evaluate the effect of field treatment (i.e., with plants and bare soil), time (i.e., sample date), and their interaction on CO_2, CH_4, and N_2O fluxes. A one-factor ANOVA was conducted in SAS to evaluate the effect of field treatment (i.e., with plants and bare soil) on season-long CO_2, CH_4, and N_2O emissions and the four GWP-related parameters. All data were analyzed using a gamma distribution. Significance was judged at $P < 0.05$ and, when appropriate, means were separated by least significant difference at the 0.05 level.

Results and Discussion

Gas fluxes

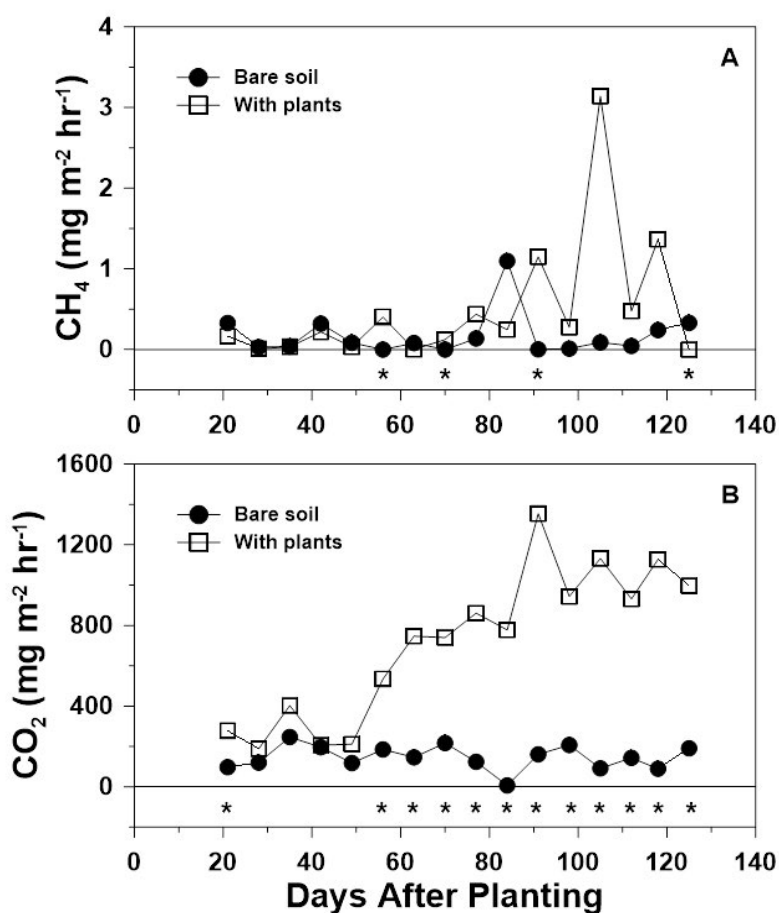CH_4: Methane fluxes in both treatments started relatively

Figure 1: Methane (CH_4) and carbon dioxide (CO_2) fluxes from each treatment (i.e., bare soil and with plants) measured over time during the 2019 growing season from furrow-irrigated rice under no-tillage management on a silt-loam soil in east-central Arkansas. Lines between data points are for visual representation, not to indicate rate of change. Asterisks (*) indicate dates where a significant difference ($P < 0.05$) of methane (CH_4) or carbon dioxide (CO_2) flux between the bare soil and with plants treatment is present.

low at the beginning of the growing season (0.33 and 0.16 mg m^{-2} hr^{-1} for the bare-soil and with-plants treatment at 21 DAP, respectively), but the bare-soil CH_4 fluxes remained below 0.32 mg m^{-2} hr^{-1} and relatively constant until a numeric flux spike at 84 DAP, followed by a numeric decrease and plateau for the remainder of the growing season (Figure 1A). In contrast, the with-plants treatment slowly increased throughout the growing season to a peak at 91 DAP, then to a greater peak numeric flux at 105 DAP, followed by a general numeric decrease to the end of the growing season (Figure 1A). Methane fluxes from the bare-soil treatment ranged from 0 mg m^{-2} hr^{-1} at 56 and 70 DAP to 1.02 mg m^{-2} hr^{-1} at 84 DAP, while CH_4 fluxes from the with-plants treatment ranged from 0 mg m^{-2} hr^{-1} at 125 DAP to 3.14 mg m^{-2} hr^{-1} at 105 DAP (Figure 1A).

Methane fluxes differed ($P < 0.01$) between the bare-soil and the with-plants treatments over time throughout the 2019 growing season (Table 1). For the bare-soil treatment, seven sample dates (i.e., 28, 35, 56, 70, 91, 98, and 112 DAP) had CH_4 fluxes that were greater ($P < 0.05$) than a flux of zero, while, for the with-plants treatment, five sample dates (i.e., 28, 35, 49, 56, and 125 DAP) had CH_4 fluxes that were greater than a flux of zero. Methane fluxes differed between

Table 1: Analysis of variance summary of the effects of treatment (i.e., bare soil or with plants), time (i.e., sample date), and their interaction on methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) fluxes over the course of the 2019 growing season from furrow irrigated rice under no-tillage management on a silt-loam soil in east-central Arkansas.

Source of Variation	CH_4	N_2O	CO_2
		P	
Treatment	< 0.01	0.01	< 0.01
Time	< 0.01	< 0.01	< 0.01
Treatment × Time	< 0.01	0.20	< 0.01

treatments on four of the 16 sample dates (i.e., 56, 70, 91, and 125 DAP; Figure 1A). Methane fluxes did not differ between treatments until the sixth sample date (i.e., 56 DAP), then did not differ again until two weeks later (i.e., 70 DAP), which was followed by three sample dates until differing again (i.e., 91 DAP), and then a final five weeks where no difference was observed until the last sample date (i.e., 125 DAP; Figure 1A).

The role of plants in the release of CH_4 was highlighted by the days during which significant difference between treatments was reported and were most concentrated

in the second half of the growing season, starting at 56 DAP when, during tiller growth, the aerenchyma tissue gets fully developed [3]. Methane fluxes from the with-plants treatment were indeed larger than from the bare-soil treatment on three of the four sample dates where a significant difference between treatments occurred, which was likely due to enhanced CH_4 transport from the soil to the atmosphere through the aerenchyma tissue of the rice plants themselves [16,17] along with direct diffusion since there was no overlying layer of flood water to travel through under the furrow-irrigated conditions.

Other studies have evaluated CH_4 fluxes in furrow-irrigated rice. Similar to the results of this study, Della Lunga, et al. [6] evaluated relationships between greenhouse gas fluxes (i.e., CH_4, N_2O, and CO_2), GWP, soil properties, and environmental factors in furrow-irrigated rice on the same field as the current study over the 2018 and 2019 growing seasons. Results showed that CH_4 fluxes were < 2 mg m^{-2} hr^{-1} during the first half of the 2018 growing season and CH_4 fluxes were > 2 mg m^{-2} hr^{-1} around the end of the growing season [6]. However, in contrast to the results of this study, during the 2018 growing season, the CH_4 flux maximum was observed 10 days later and the CH_4 flux minimum was observed about 40 days earlier for the up-slope, NT treatment with-plants [6]. Timing differences were likely due to variability in irrigation application and rainfall [6]. Furthermore, similar to the results of the current study, Della Lunga, et al. [7] reported that CH_4 fluxes differed over time during both the 2018 and 2019 growing seasons. In contrast to the current study, Hang, et al. [25] evaluated the effects of direct seeding and water management schemes (i.e., traditional flood, furrow, and drip irrigation) on rice yield and CH_4 and N_2O emissions on a poorly drained soil in Yinchuan City, Ningxia Province, China. Results showed that CH_4 flux maximum of approximately 6 mg m^{-2} hr^{-1} and generally greater CH_4 fluxes from the furrow-irrigated treatment throughout the 120-day study period than from the with-plants treatment of the current study [25]. Differences in CH_4 fluxes from the current study and the furrow-irrigated treatment in Hang, et al. [25] were likely due to differing soil water contents, which could be due to the lowland site-position used in Hang, et al. [25] or rainfall differences. Furthermore, Karki, et al. [26] quantified grain yield and CH_4 and N_2O fluxes from furrow-irrigated rice on a silty-clay soil in northeast Arkansas and reported generally lower CH_4 fluxes than the current study.

N_2O: Nitrous oxide fluxes were relatively low and steady throughout the 2019 growing season, but three distinct numeric peak N_2O fluxes were observed at 56, 77, and 118 DAP (Figure 2). Nitrous oxide fluxes from the bare-soil treatment ranged from 0.02 mg m^{-2} hr^{-1} at 35 DAP to 1.9 mg m^{-2} hr^{-1} at 56 DAP, while N_2O fluxes from the with-plants treatment ranged from 0.01 mg m^{-2} hr^{-1} at 28 DAP to 1.4 mg m^{-2} hr^{-1} at 56 DAP. However, in contrast to CH_4, N_2O fluxes were greater ($P < 0.05$) than a flux of zero on only three of the sixteen sample dates (i.e., 56, 77, and 118 DAP; Figure 2).

In contrast to CH_4, N_2O fluxes differed over time ($P < 0.01$) and differed between treatments ($P = 0.01$) throughout the 2019 growing season (Table 1). Averaged across treatment, N_2O fluxes were numerically largest at 56 DAP and did not differ from N_2O fluxes at 77 and 118 DAP, which were at least 2.8 times greater than all other N_2O fluxes (Figure 2). However, of the three numeric peaks, only the N_2O flux at 118 DAP did not differ from the N_2O flux at 105 DAP (Figure 2). Furthermore, N_2O fluxes were numerically smallest at 28 DAP,
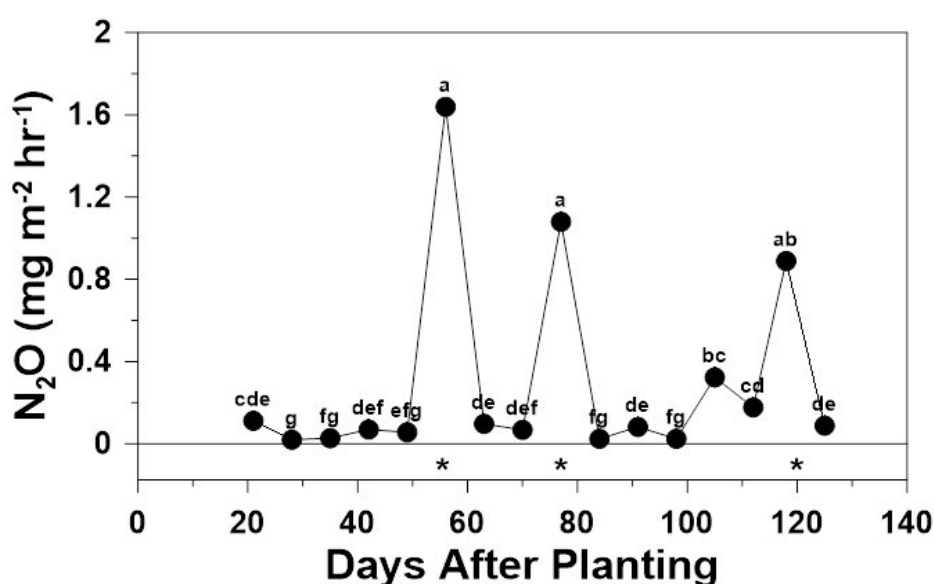

Figure 2: Nitrous oxide (N_2O) fluxes averaged between treatment (i.e., bare soil and with plants) throughout the 2019 growing season from furrow-irrigated rice under no-tillage management on a silt-loam soil in east-central Arkansas. Lines between data points are for visual representation, not to indicate rate of change. Asterisks (*) indicate dates when the mean N_2O flux differed ($P < 0.05$) from a flux of zero. Different letters indicate differences ($P < 0.05$) between measurement dates. Nitrogen fertilization occurred at 16 and 34 days after planting.

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which did not differ from 35, 49, 84, and 98 DAP (Figure 2). In contrast to CH_4, the lack of difference between treatments over time was likely because N_2O emissions do not occur predominantly through the plants themselves, but rather through simple diffusion from the soil to the atmosphere. The fluctuating, moist to wet, yet aerobic, soil conditions created by furrow-irrigation [9] are an ideal environment for the coupled nitrification-denitrification processes to produce N_2O as a by-product of incomplete denitrification, which converts NO_3^- to N_2O gas [13]. The peak N_2O fluxes reported in this study coincided with spikes in volumetric soil water contents in the NT/up-slope portion of the larger field, highlighting the fundamental role of environmental parameters at regulating gaseous-N losses [7,9].

Averaged across time, the whole-season mean N_2O flux from the bare-soil (0.15 mg m^{-2} hr^{-1}) was 1.7 times greater than the with-plants (0.085 mg m^{-2} hr^{-1}) treatment. It is likely that N_2O flux from the bare-soil treatment was greater than from the with-plants treatment because the absence of plants in the bare-soil treatment allowed all applied N to be used as denitrification substrate by microbes, thus causing a greater N_2O flux. However, with plants present, the majority of applied N was likely assimilated by the plants, making much of the applied N unavailable for microbes to carry out denitrification, leading to a lower N_2O flux.

Nitrous oxide fluxes during the 2018 growing season under NT at the up-slope position with plants ranged from < 0.01 mg m^{-2} hr^{-1} at 108 DAP to 6 mg m^{-2} hr^{-1} at 33 DAP [6,19], which was about three times greater than the N_2O flux maximum reported in the current study, but similar to the N_2O flux minimum recorded for the current study. In addition, similar to the results of the current study, Slayden, et al. [19] reported that N_2O fluxes differed over time during both the 2018 and 2019 growing seasons. Hang, et al. [25] reported generally greater N_2O fluxes throughout their study period than in the current study, but the N_2O flux maximum from the current study was approximately eight times greater. The difference in flux maxima may be explained by differences in fertilizer-N applications between the two studies [6,25] where the largest N application in Hang, et al. [25] was 96 kg ha^{-1} as urea, which was 1.75 times less than the largest N application in the current study. In addition, Karki, et al. [26] reported a peak N_2O flux one week after the second fertilizer-N application of approximately 2.2 mg m^{-2} hr^{-1}, which was similar to the peak N_2O flux measured in the current study.

CO_2: As expected, CO_2 fluxes in both treatments started relatively low at the beginning of the growing season (97 and 277 mg m^{-2} hr^{-1} for the bare-soil and with-plants treatment at 21 DAP, respectively), but the bare-soil CO_2 fluxes remained steady for the remainder of the growing season (Figure 1B). In contrast, the with-plants treatment generally increased throughout the growing season to a peak numeric flux at 91 DAP, followed by a numeric decrease and plateau at approximately 100 DAP to the end of the season (Figure 1B). Carbon dioxide fluxes from the bare-soil treatment ranged from 7 mg m^{-2} hr^{-1} at 84 DAP to 247 mg m^{-2} hr^{-1} at 35 DAP, while CO_2 fluxes from the with-plants treatment ranged from 188 mg m^{-2} hr^{-1} at 28 DAP to 1355 mg m^{-2} hr^{-1} at 91 DAP (Figure 1B).

Similar to CH_4, but in contrast to N_2O, CO_2 fluxes differed ($P < 0.01$) between the bare-soil and with-plants treatments over time throughout the 2019 growing season (Table 1). For both treatments, all CO_2 flux means over time were greater ($P < 0.05$) than a flux of zero. Additionally, CO_2 fluxes differed between treatments on 12 of the 16 sample dates (i.e., 21, 56, 63, 70, 77, 84, 91, 98, 105, 112, 118, and 125 DAP), where the CO_2 flux from the with-plants was greater than the bare-soil treatment on all 12 dates (Figure 1B). Carbon dioxide fluxes differed between treatments on the first sample date of the 2019 growing season (i.e., 21 DAP), were then similar between treatments for the next four sample dates, then differed between treatments on all sample dates from 56 DAP to the end of the growing season (i.e., 125 DAP; Figure 1B).

Similar to CH_4, differences in CO_2 fluxes between the bare-soil and with-plants treatment were due to plant presence/absence, where the with-plants treatment had a greater CO_2 flux because of the root respiration contribution to the total CO_2 flux. Furthermore, the contribution of root respiration to the total CO_2 flux also explains why CO_2 fluxes from the with-plants treatment were greatest towards the end of the growing season. The steep initial increase in CO_2 fluxes followed by fluxes leveling off some matches the rate of metabolic processes rice plants go through, where the rate is greater during the vegetative phase (i.e., first half of the growing season) and lower during the reproductive phase (i.e., second half of the growing season) [3].

Della Lunga, et al. [6] reported that CO_2 fluxes for the 2018 growing season ranged from 58.7 mg m^{-2} hr^{-1} at 27 DAP to 1101 mg m^{-2} hr^{-1} at 89 DAP under NT in the up-slope position, which was similar to the timing of the CO_2 flux maximum and minimum (i.e., 28 and 91 DAP, respectively), but was smaller than the minimum and maximum CO_2 flux values (i.e., 188 and 1355 mg m^{-2} hr^{-1}, respectively) from the current study. In addition, similar to the results of the current study, Della Lunga, et al. [7] reported that CO_2 fluxes differed over time during both the 2018 and 2019 growing seasons. Furthermore, Xu, et al. [27] evaluated water management strategies (i.e., continuous flooding, flooded and wet intermittent irrigation, and flooded and dry intermittent irrigation) and cultivar effects on GHG emissions from a silty clay loam in Huqiao, Hubei Province, China. Results showed an average CO_2 flux between two cultivars of 509 mg m^{-2} hr^{-1} from the flooded and wet intermittent irrigation treatment throughout the 117-day field study, which fell within the CO_2 flux range reported in the with-plants treatment in the current study (Figure 1B) [27].

Season-Long Gas Emissions

Season-long CH_4 and CO_2 emissions differed ($P < 0.05$), while season-long N_2O emissions did not differ ($P > 0.05$) between treatments (Table 2). Season-long CH_4 emissions were 3.2 times greater from the with-plants than from the bare-soil treatment (Table 2). Similar to CH_4, season-long CO_2 emissions were 4.9 times greater from the with-plants than from the bare-soil treatment (Table 2). In contrast, season-long N_2O emissions were unaffected by treatment and averaged 8.4 kg ha^{-1} $season^{-1}$ (Table 2).

Table 2: Summary of the treatment (i.e., bare soil and with plants) effect on season-long methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) emissions and several global warming potential (GWP) parameters over the course of the 2019 growing season from furrow-irrigated rice under no-tillage management on a silt-loam soil in east-central Arkansas. Global warming potentials were evaluated using CH_4 and N_2O conversion factors from both the 5th (IPCC, 2014) and 6th (IPCC, 2021) Intergovernmental Panel on Climate Change assessments.

Greenhouse Gas Parameter	*P*-value	Treatment		Overall Mean
		Bare Soil	With Plants	
CH_4 (kg ha^{-1} season^{-1})	0.01	4.1 b[†]	13.2 a	-
N_2O (kg ha^{-1} season^{-1})	0.18	10.9	6.0	8.4
CO_2 (kg ha^{-1} season^{-1})	< 0.01	3,625 b	17,728 a	-
GWP 5th ($CH_4 + N_2O$; kg CO_2 eq. ha^{-1} season^{-1})	0.24	3,391	2,228	2,810
GWP 5th ($CH_4 + N_2O + CO_2$; kg CO_2 eq. ha^{-1} season^{-1})	< 0.01	7,016 b	19,957 a	-
GWP 6th ($CH_4 + N_2O$; kg CO_2 eq. ha^{-1} season^{-1})	0.23	3,006	1,952	2,479
GWP 6th ($CH_4 + N_2O + CO_2$; kg CO_2 eq. ha^{-1} season^{-1})	< 0.01	6,631 b	19,681 a	-

[†]Means in a row with different letters are different at *P* < 0.05

Similar to CH_4 fluxes, season-long CH_4 emissions were clearly related to CH_4 transport differences between treatments, where the aerenchyma cells in the plants themselves provide the conduit for CH_4 release from the soil and O_2 transport to the roots. Della Lunga, et al. [6] reported that season-long CH_4 emissions from the 2018 growing season at the up-slope position under NT management ranged from 6 to 13.3 kg ha^{-1}, which was similar to season-long CH_4 emissions from the with-plants treatment in the current study (13.2 kg ha^{-1} season^{-1}; Table 2). Furthermore, similar to the results of the current study, Della Lunga, et al. [7], which evaluated season-long GHG emissions and GWP between conventional-tillage and NT treatments on the same field as the current study, reported that season-long CH_4 emissions between tillage treatments averaged approximately 10 kg ha^{-1} season^{-1}. Rogers, et al. [17], who quantified CH_4 fluxes and season-long emissions in eastern Arkansas from a fertilized, bare-soil treatment and an optimally fertilized, with-plants treatment on a silt-loam soil in flood-irrigated rice, reported that season-long CH_4 emissions from the fertilized, with-plants treatment were 4.1 times greater than from the fertilized, bare-soil treatment. In addition, Karki, et al. [26] reported season-long CH_4 emissions of approximately 1.7 kg ha^{-1} season^{-1}, which was approximately eight times lower than reported for the current study, likely due to major differences in soil texture. Karki, et al. [26] was conducted on a silty-clay soil, whereas the current study was conducted on a silt-loam soil, and soil surface texture has been shown to have a substantial effect on GHG fluxes and emissions, where clayey soils consistently have lower GHG fluxes and season-long emissions than more loamy soils [18].

Similar to CO_2 fluxes, season-long CO_2 differences were likely due to differences in root respiration between treatments. Xu, et al. [27] reported that season-long CO_2 emissions between two cultivar treatments in flood- and wet-intermittent irrigation ranged from 12,137 to 15,467 kg ha^{-1} season^{-1}, which was similar to the season-long CO_2 emissions reported from the with-plants treatment in the current study (Table 2). Furthermore, similar to the results of the current study, Della Lunga, et al. [7] reported season-long CO_2 emissions in the up-slope position during the 2018

growing season as ~15,000 kg ha^{-1} season^{-1}. Although the CO_2 emissions in the current study do not represent net ecosystem exchange (NEE) [28], the magnitude of the CO_2 efflux suggests that soil respiration could represent a greater loss of C in rice fields than previously considered [29,30]. The vented, non-flow-through, closed, dark-chamber approach is considered a reliable method to measure CO_2 emissions, although a method bias needs to be considered [30]. Considering that grain is harvested and removed from rice fields and that crop residues are often burned before the beginning of the next growing season, soil respiration obtained with the closed, static-chamber method during the growing season should represent a process that is included in the C budget, independent from photosynthetic CO_2 uptake.

In contrast to N_2O fluxes, season-long N_2O emissions did not differ between treatments, which could be explained by soil redox potential behavior and that rice plants do not primarily facilitate N_2O release from the soil to the atmosphere. Della Lunga, et al. [9] evaluated soil redox potential, soil water content, soil temperature, and other properties throughout the 2018 and 2019 growing seasons on the same field as the current study and reported that, during the 2019 growing season in the up-slope-NT combination, soil redox potential at the 7.5-cm soil depth from 21 to 97 DAP ranged from 105 to -19 mV and, at 102 DAP, anaerobic conditions were present and were maintained until 122 DAP. Thus, soil redox potential was low enough that CH_4 and N_2O could be produced at times, but, because rice plants do not facilitate a large proportion of N_2O release from the soil, it is reasonable that season-long N_2O emissions were unaffected by the presence or absence of plants, while season-long CH_4 emissions were greatly affected by the presence or absence of plants. Furthermore, Slayden, et al. [19] evaluated site position and tillage treatment effects on season-long N_2O emissions and fluxes on the same field as the current study during the 2018 and 2019 growing seasons and reported season-long N_2O emissions, averaged across site position, during the 2018 growing season were 15.9 kg ha^{-1} season^{-1} with plants present, which was nearly two times greater than the season-long N_2O emissions reported in the current study. This result may have been related to lower rainfall during

the 2018 growing season, which may have created more optimal conditions for incomplete denitrification and N_2O production. In addition, Karki, et al. [26] reported season-long N_2O emissions of 11.6 kg ha^{-1} season^{-1} with plants present, which were similar to season-long N_2O emissions reported from the both the with-plants and bare-soil treatment in the current study. The magnitude of N_2O emissions across multiple years of furrow-irrigated rice production suggests that the amount of substrate alone available for nitrification-denitrification does not constitute a reliable indication of potential gaseous-N emissions unless certain environmental properties, such as soil moisture, create favorable conditions for denitrification to even occur [7,9,19].

Global Warming Potential

Global warming potential combines the effects of all GHGs considered into a single metric. In this study, GWP was estimated with two (CH_4 and N_2O) and with all three gases (CH_4, N_2O, and CO_2) using conversion factors from both the 5th [1] and 6th [24] IPCC GHG emissions assessments.

In this study, GWP estimates for just CH_4 and N_2O from both the IPCC's 5th and 6th assessments were unaffected ($P > 0.05$) by treatment, while GWP estimates for CH_4, N_2O, and CO_2 combined from both the IPCC's 5th and 6th assessments differed ($P < 0.05$) between treatments (Table 2). Averaged across treatments, the GWP for CH_4 and N_2O combined was 2,810 and 2,479 kg CO_2 eq. ha^{-1} season^{-1} from the IPCC's 5th and 6th assessments, respectively (Table 2). However, accounting for CH_4, N_2O, and CO_2, the GWP estimate based on the 5th assessment was 2.8 times greater from the with-plants than from the bare-soil treatment and was three times greater from the with-plants than from the bare-soil treatment based on the 6th assessment (Table 2). These results demonstrate the substantial impact of the season-long CO_2 emissions difference between bare soil and when plants are present to contribute to soil respiration (Table 2).

The lack of a treatment difference for estimated GWP when CO_2 is not accounted for (i.e., CH_4 and N_2O only) may have been a result of a combination of factors. The bare-soil treatment produced numerically, though not significantly, greater N_2O emissions than the with-plants treatment (Table 2), which may have been related to microbes utilizing a portion of the fertilizer-applied N for partial denitrification. In addition, rice plants in the with-plants treatment likely assimilated some, if not all, of the fertilizer-N additions, to reduce the amount of N substrate available for nitrification-denitrification processes, as evidenced by the numerically, though not significantly, lower N_2O emissions from the with-plants than the bare-soil treatment (Table 2). Furthermore, the with-plants treatment had greater CH_4 emissions than the bare-soil treatment (Table 2). The combined result of these factors left both two-gas GWP estimates unaffected by treatment, while both three-gas GWP estimates differed between treatments due to root plus microbe respiration in the with-plants treatment, where the bare-soil treatment had CO_2 emissions only from microbial respiration.

Similar to the current study, Della Lunga, et al. [7] reported three-gas (i.e., CH_4, N_2O, and CO_2) GWP estimates at the up-slope position of ~20,000 kg CO_2 equivalents (eq.) ha^{-1} season^{-1} during the 2018 growing season. Furthermore, similar to the two-gas GWP estimate average between treatments in the current study, Karki, et al. [26] reported a two-gas (i.e., CH_4 and N_2O) GWP estimate of 3,122 kg CO_2 eq. ha^{-1} season^{-1} from the up-slope position of a furrow-irrigated rice field on a silt-clay soil in northeast Arkansas. In addition, in a study that evaluated effects of water management practice (i.e., intermittent-flood and traditional flooding) and cultivar on N_2O emissions and GWP from a DeWitt silt-loam soil at the RREC near Stuttgart, AR, Rector, et al. reported a CH_4 plus N_2O GWP estimate of 2,046 kg CO_2 eq. ha^{-1} season^{-1} and 4,836 kg CO_2 eq. ha^{-1} season^{-1} for a hybrid and pure-line cultivar, respectively, from an intermittent-flood treatment. Global warming potential results of Rector, et al. [31] were within to above the range of the two-gas GWP estimates reported in this study and highlighted the importance of rice cultivar on GWP via cultivar effects on CH_4 emissions [32].

Implications

Due to the complexities in GHG fluxes, season-long emissions, and GWP estimates, mechanisms of GHG emissions in furrow-irrigated rice fields appear to be driven by multiple different pathways (i.e., transport through plant tissue for CH_4, diffusion from incomplete bacteria-mediated denitrification for N_2O, and diffusion from root respiration for CO_2). However, the lack of difference in two-gas GWP estimates (i.e., $CH_4 + N_2O$) between the bare-soil and with-plants treatment indicates that CH_4 and N_2O measurements from the tops of beds are representative of the entire field area, not just the partial field area occupied by the tops of raised beds. Consequently, results of this field study suggest that it is not necessary to report differential CH_4 and N_2O fluxes, season-long emissions, and/or GWP estimates for furrows compared to atop beds in a furrow-irrigated rice production system where rice planting is concentrated on top of raised beds, at least in the up-slope position. Furthermore, studies that evaluate GHG emissions in furrow-irrigated rice systems may be able to reasonably assume that CH_4 and N_2O measurements from the tops of beds apply to the entire up-slope field area. However, a major difference with three-gas GWP estimates (i.e., $CH_4 + N_2O + CO_2$) still exists between bare-soil and with-plants areas due to large differences in CO_2 emissions from root respiration. Notably, as this study evaluated a bare-soil treatment from the top of raised beds, further research should evaluate GHG emissions from the tops of beds and specifically the within-furrow area of not only furrow-irrigated rice systems, but also other upland cropping systems that use raised beds with furrow-irrigation, as soil moisture contents, redox potentials, and soil temperatures within the furrows may differ from atop raised beds, which may affect GHG emissions differently than demonstrated in the current study.

Results of this study also support that the use of the dark, closed-chamber method, with plants present inside the collars, represents a valid approach to obtain a more detailed and complete C budget. Closed-chamber methods, where the chamber remains dark with minimal temperature variations throughout the typical 1-hr measurement

period, minimizes potential photosynthetic CO_2 uptake and minimizes disruptions to other plant and soil biotic and abiotic processes that respond to increasing temperatures. In contrast, closed-chamber methods that are clear allow for light penetration, continued photosynthetic CO_2 uptake, and increased temperature that can alter metabolic processes rates during the measurement period. Consequently, studies like the current can supplement datasets that can be used to obtain reliable estimates of gaseous-C losses from the soil to the atmosphere.

Furthermore, results of this study suggest that the use of off-season vegetation, such as cover crops as an erosion-control, climate-smart agricultural conservation practice, between growing seasons in furrow-irrigated production systems may need careful management attention and further research. It is possible that increased GWPs may occur due to the extended presence of growing cover-crop plants. However, leaving a field fallow, without establishing a cover crop, may not reduce potential soil erosion compared to the presence of a cover crop.

Conclusions

This study quantified CO_2, CH_4, and N_2O fluxes, season-long emissions, and GWP estimates between a with-plants and bare-soil treatment at an up-slope position under NT in a furrow-irrigated rice field on a silt-loam soil in eastern Arkansas. Similar to that hypothesized, the with-plants treatment frequently had greater CO_2 and CH_4 fluxes over time, greater season-long emissions, and greater three-gas (i.e., CH_4 + N_2O + CO_2) GWP estimates than the bare-soil treatment. However, in contrast to that hypothesized, N_2O fluxes were not greater from the bare-soil treatment and season-long N_2O emissions were unaffected by treatment. In addition, two-gas GWP estimates (i.e., CH_4 + N_2O) did not differ between the bare-soil and with-plants treatments. Thus, results of this study indicate that, at least in the up-slope position, CH_4 and N_2O emissions measured in the with-plant area atop beds are reasonably representative of both the with-plant, top-of-bed area and the furrow area of a furrow-irrigated rice field with few to no plants present.

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