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Water Management and Cultivar Effects on Methane Emissions from Direct-seeded, Delayed-flood Rice Production in Arkansas

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Abstract

Methane (CH_4) emissions from rice (*Oryza sativa* L.) production are a source of concern in the environmental and agricultural communities. New and/or revised agronomic methodologies will be needed to identify production practice combinations that reduced CH_4 emissions without decreasing yields or milling quality. The objective of this study was to evaluate the effects of water management (i.e., full-season flood and mid-season drain) and cultivar (i.e., pure-line cultivar LaKast and the RiceTec hybrid XL753) on CH_4 fluxes and season-long emissions from rice grown in the direct-seeded, delayed-flood production system on a silt-loam soil in east-central Arkansas. Vented, non-flow-through, non-steady-state chambers were used to collect gas samples over a 60-min sampling interval for weekly measurements of CH_4 fluxes between flooding and harvest. Methane fluxes from all treatments started low then increased ($P < 0.01$) between 19 and 54 days after flooding (DAF), where the largest peak flux occurred from the full-season-flood/hybrid combination (229.3 mg CH_4-C m^{-2} d^{-1}) just after 50% of the panicles had emerged by 47 DAF. Methane fluxes from all four treatment combinations peaked between 47 and 54 DAF. After 54 DAF, CH_4 fluxes decreased ($P < 0.01$) in all treatment combinations leading up to flood release, with several treatment combinations exhibiting a temporary, at least numerically increased CH_4 flux just after flood release at 72 DAF. The full-season-flood (77.7 CH_4-C $ha^{-1}season^{-1}$) produced the greatest ($P < 0.01$), while the mid-season-drain (42.8 kg CH_4-C $ha^{-1}season^{-1}$) produced the lowest season-long CH_4 emissions. The mid-season-drain/hybrid combination exhibited the greatest ($P < 0.05$) emissions intensity (2.5 kg CH_4-C Mg $grain^{-1}$), while emissions intensity did not differ and averaged 6.4 kg CH_4-C Mg $grain^{-1}$ among the other three treatment combinations. Properly matching water management scheme with cultivar selection can provide a means to reduce CH_4 emissions from rice production in the direct-seeded, delayed-flood production system on silt-loam soils.

Keywords

Full-season flood, Mid-season drain, Hybrid rice, Pure-line rice, Greenhouse gas emissions, Silt loam

Introduction

As of 2005, agriculture was estimated to contribute about 47% of total anthropogenic CH_4 emissions, while the remaining non-agricultural sources of CH_4 production are from natural gas systems, landfills, and coal mining, which make up over 50% of the total CH_4 emissions in the US [1]. The main agricultural sources of CH_4 emissions in the US are enteric fermentation and manure management, with over 95% of total agriculturally related CH_4 emissions as of 2012, with rice (*Oryza sativa* L.) cultivation and field burning making up 3.7% of the total agricultural CH_4 releases [2]. As of 2013, atmospheric CH_4 inputs from enteric fermentation, manure manage-

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ment, rice production, and biomass burning contributed approximately 8.1% of total US anthropogenic GHG emissions to the environment [2]. As of 2011, CH_4 emissions from rice cultivation represented 1.1% of the total US CH_4 emissions to the atmosphere [2].

In 2015, estimated CH_4 emissions from rice cultivation were 11.2 million megatons (MMT) of CO_2 equivalents in the US [3]. However, CH_4 emissions from agricultural sources are closely tied to the regional geographic distribution of where rice production occurs, whereas Arkansas, California, Louisiana, and Missouri were the top four rice-producing states in the US in 2015 [4]. Based on rice yields, Arkansas produced an estimated 3.8 MMT CO_2 equivalents in 2015 from rice cultivation alone [3]. In Arkansas, rice grown in the direct-seeded, delayed-flood rice production system, is substantially different from other rice production systems in the US and worldwide. These production differences create unique difficulties as well as opportunities for improving management of soil and water resources needed to sustain rice production and protect the environment.

As a potent greenhouse gas (GHG), CH_4 is produced under anoxic conditions commonly associated with lowland rice production when carbon (C) from organic matter is consumed and converted to CH_4. Several biochemical processes exist where C is reduced to $CH_{4,}$ thus releasing energy for metabolic processes. Since soil organic matter (SOM) is generally concentrated near the soil surface in the A horizon, > 99% of the total soil-produced CH_4 is emitted from the topsoil [5]. The main mechanism of CH_4 release to the atmosphere from below a column of water has been via passive transport through the aerenchyma tissue of the rice plants themselves [6-9] while ebullition and diffusion are secondary and more minor emissions pathways [6,7].

Along with soil texture [10], management practices associated with rice production are one of the most important factors affecting CH_4 emissions. Cultivar selection, or the choice to plant either a conventional pure-line or a hybrid cultivar, plays a major role in not only yield, but also potential CH_4 emissions [11,12]. Hybrid cultivars have consistently shown decreased CH_4 emissions compared to pure-line cultivars grown on silt-loam [11,13,14] and clayey soils [10,12,13]. Hybrid rice cultivars typically have more vigorous root growth, as well as increased transport of atmospheric oxygen to the rhizosphere [8,15-17] to inhibit reduction of C in SOM and other C substrates (i.e., organic soil amendments) to CH_4, which only occurs after the soil's oxidation-reduction (redox) potential has decreased to approximately -200 mV from prolonged saturated soil conditions. Consequently, when hybrid rice is grown, the soil in the rhizosphere is kept from becoming anoxic longer and therefore lessens CH_4 production by methanogens.

Along with cultivar selection, which is a relatively easily implemented management practice option for rice producers, water management scheme also is a main controlling factor for CH_4 emissions from rice. However, water management alternatives are much less easily implemented compared to cultivar selection due to the potential constraints of water delivery to a field and the fact that rice is a semi-aquatic plant that is adapted for optimal growth under flooded-soil conditions. Rice in the US is generally grown under continuously flooded conditions throughout the growing season. Groundwater is used to irrigate over 74.1% of the rice acreage in Arkansas with the remaining acres irrigated with surface water obtained from reservoirs, streams, or bayous [18].

The primary irrigation practice in Arkansas is the use of the multiple-inlet irrigation, which uses poly-tubing as a means of irrigating rice to conserve water and labor. As of 2015, rice producers utilize multiple-inlet irrigation on 41% of the rice acreage in Arkansas [18]. In Arkansas, the drill-seeded, delayed-flood rice production system is the predominate production system, accounting for 85% of total planted-rice area. Utilizing a mid-season release of the flood (i.e., mid-season drain) has historically been used in rice production to control for straight head, a disorder that causes sterility of the spikelet's and reduces yield and decreases the bioavailability of arsenic to the plant by keeping the arsenic in a non-reduced state [2]. As an alternative water management practice, the mid-season drain aerates the topsoil and reduces the time that the topsoil experiences anoxic conditions, which are required for CH_4 production. Consequently, the mid-season drain may have positive implications for the sustainability of rice production if rice yields can be maintained, while reducing CH_4 emissions at the same time.

Since agriculture is responsible for 10 to 12% of total global anthropogenic GHG emissions, accounting for nearly 50% of global CH_4 emissions alone [1], mitigation of CH_4 production and release in agricultural settings, particularly in areas of concentrated rice production, has profound importance. Consequently, to reduce CH_4 emissions from rice production, field management practice combinations that promote reduced CH_4 emissions, without decreasing yields or milling quality, must be identified [19]. Therefore, the objective of this study was to evaluate the effects of water management (i.e., full-season flood and mid-season drain) and cultivar (i.e., a conventional pure-line and a hybrid cultivar) on CH_4 fluxes and season-long emissions from rice grown on a silt-loam soil in the direct-seeded, delayed-flood production system in eastern Arkansas. Based on previous field research results [10-12,20], it was hypothesized that the mid-season-drain/hybrid will have the lowest CH_4 emissions and the full-season-flood/pure-line treatment combination will have the largest season-long CH_4 emissions. It was also hypothesized that the mid-season-drain/hybrid will have the lowest CH_4 emissions per unit grain yield among the water management/cultivar treatment combinations.

Materials and Methods

Site description

Field research, similar to that conducted recently by Rogers, et al. [14], was conducted in 2015 at the University of Arkansas System Division of Agriculture Rice Research and Extension Center (RREC) near Stuttgart, Arkansas (34°27'54.5" N, 91°25'8.6" W). The soil throughout the study area was a DeWitt silt loam (fine, smectitic, thermic Typic Albaqualf) [21]. The study area has been managed in a rice-soybean (*Glycine max* L. [Merr.]) rotation, which is a common rotation for rice production in east-central Arkansas, for more than 25 years. The slope across the study area was approximately 0.2%. The regional climate throughout the study area is temperate with a mean annual air temperature of 17 °C, which ranges from a mean minimum of 12.7 °C to a mean maximum of 23.5 °C (NOAA, 2015). The mean annual precipitation is 1350 mm [22].

Treatments, experimental design, and agronomic management

The study area consisted of 16 field plots, 1.6-m wide by 5-m long, with nine rice rows planted with an 18-cm row spacing, arranged in a randomized complete block (RCB) design with four replications of each treatment combination. Eight plots (i.e., four pure-line and four hybrid-planted plots) were established in a full-season-flood bay and eight plots (i.e., four pure-line and four hybrid-planted plots) were established in a mid-season-drain bay. The pure-line rice cultivar 'LaKast' and the hybrid rice cultivar XL753 (RiceTec, Inc., Houston, TX) were drill-seeded on 6 May 2015. The flood was established on 10 June 2015 and was maintained at a depth of approximately 10 cm until maturity, at which time the flood was released on 24 October 2015 to prepare for harvest.

Recommended nitrogen (N) fertilization was used for optimal production of both cultivars [23]. The pure-line received 117 kg N ha^{-1} that was broadcast manually as urea (46% N) 24 hr before the flood was established (10 June 2015) and an additional split application of 45 kg N ha^{-1} was applied manually to the floodwater at beginning of internode elongation (1 July 2015) approximately 20 days after flooding (DAF). The hybrid cultivar received 134 kg N ha^{-1} pre-flood (10 June 2015) and a split application of 33 kg N ha^{-1} applied manually to the floodwater at the boot stage (14 July 2015) approximately 34 DAF.

Initial soil sample collection, processing, and analyses

Prior to flood establishment, two soil cores 4.8 cm in diameter were collected from the top 10 cm in each plot for a total of 32 cores collected from within the study area. Soil samples were dried at 70 °C for 72 hr, crushed, and sieved through a 2-mm mesh screen for soil property determinations. One set of soil samples per plot was used for determining bulk density and particle-size analyses using a modified 12-hr hydrometer method [24]. The second set of soil samples was analyzed by inductively coupled, argon plasma, atomic emissions spectrometry (Spectro Arcos, Spectro Analytical Instruments, Kleve, Germany) using a 1:10 soil-mass-to-extractant-volume ratio [25] for Mehlich-3 extractable nutrients (i.e., P, K, Ca, Mg, S, Na, Fe, Mn, Zn, and Cu). Total soil carbon (TC) and total nitrogen (TN) concentrations were measured by high-temperature combustion with a VarioMax CN analyzer (Elementar Americas, Inc., Mt. Laurel, NJ). Measured TC and TN concentrations were used to calculate C:N ratios on a plot-by-plot basis. Since the soil throughout the study site did not effervesce upon treatment with dilute hydrochloric acid, all measured soil C was assumed to be organic. Soil organic matter concentration was determined by weight-loss-on-ignition after 2 hr at 360 °C. Soil pH and electrical conductivity (EC) were analyzed potentiometrically in a 1:2 (m/v) soil-water suspension. Based on measured bulk densities in each plot and the 10-cm sampling interval, all measured concentrations (mg kg^{-1}) were converted to contents (kg or Mg ha^{-1}) for reporting purposes.

Soil oxidation-reduction potential and temperature measurements

Immediately after flooding of the field plots began (15 June 2015), soil oxidation-reduction (redox) potential (Eh) sensors (Model S650KD-OR, Sensorex, Garden Grove, CA) with Ag/AgCl reference solution were installed vertically to a depth of approximately 7 cm. One Eh sensor was installed in the bulk soil and a second sensor was installed adjacent to a gas-sampling-chamber base collar, described below, in each plot. In addition to the Eh sensors, chromel-constantan thermocouples were installed horizontally in the bulk soil at a depth of approximately 7 cm in each plot. All sensors were connected to a datalogger (CR 1000, Campbell Scientific, Inc., Logan, UT), protected by an environmental enclosure, to record soil Eh and soil temperature at 15-minute intervals, while mean data were output every hour. Measured sensor data were collected weekly. Soil Eh values were corrected to the standard hydrogen electrode by adding 199 mV to each field-measured value.

For the purposes of data reporting, both soil temperature and redox data from the hour during gas sample collection on each measurement data were extracted from the continuously recorded data for all replicate sensors. The individual hourly soil temperature and redox data from each weekly measurement date were subsequently used for statistical analyses.

Gas sample collection and analyses

Similar to procedures described in detail by Rogers, et al. [14], boardwalks were established throughout field plots and base collars were installed. Vented, non-flow-through, non-steady-state chambers [26] were used for the collection of gas samples for the determination of CH_4 fluxes. Schedule 40 polyvinyl chloride (PVC) was used in the construction of cylindrical base collars, 30 cm in diameter by 30-cm tall, that were inserted to a depth of approximately 10 cm. Chamber extensions, 40 and 60 cm in length, were used to facilitate rice growth during the season. Chamber caps were constructed with 10-cm tall cross sections of 30-cm diameter PVC, with a 5-mm thick sheet of PVC glued to the top and covered with reflective aluminum tape. Tire inner tube cross sections, approximately 10-cm wide, were also taped to the bottom of the caps to serve as a seal and attachment mechanism to the chamber base collar or extensions. A 15-cm long piece of 4.5-mm inside diameter (id) copper refrigerator tubing was installed on the side of each cap to maintain atmospheric pressure during use. On the top of the chamber caps, 12.5-mm diameter holes were created and plugged with gray butyl-rubber septa (Voigt Global, part# 73828A-RB, Lawrence, KS) for thermometer and syringe insertion. To ensure proper air mixing in the enclosed chamber, a 2.5-cm tall × 2.5-cm wide, battery-operated (9 V), magnetic levitation fan (Sunon Inc., MagLev, Brea, CA) was installed approximately 5 cm from the underside of the chamber and ran throughout the duration of gas sampling for headspace air mixing.

The collection of gas samples from the chambers was accomplished by using a 20-mL, B-D syringe with a detachable 0.5-mm diameter × 25-mm long needle (Beckton Dickson and Co., Franklin Lakes, NJ) that was inserted through the gray butyl-rubber septa installed in the chamber cap. After drawing a gas sample from the chamber, the collected sample was immediately injected into a pre-evacuated, 10-mL, crimp-top glass vial (Agilent Technologies, part# 5182-0838, Santa Clara, CA). Gas samples were collected at 20-minute intervals, beginning at 0 minutes when the chamber was capped and sealed, for 1 hr (i.e., the 0-, 20-, 40-, and 60-min marks). Gas sampling started 5 days after flood establishment in 2015 and continued weekly until flood release when sampling frequency changed to 1, 3, and 5 days after flood release. Similar to prior studies [14,20], all gas sampling occurred in the morning between 0800 to 1000 hours. During each chamber sampling event, ambient air temperature, relative humidity, and barometric pressure were measured with a multi-sensor device (model 00510SBDI, AcuRite, Lake Geneva, WI), while 10-cm soil temperature and the air temperature inside the chamber were recorded at every sampling interval (i.e., the 0-, 20-, 40-, and 60-min marks) using standard probe thermometer. At the end of gas sampling, the distance from the top of the chamber to the water level was recorded so that the interior chamber volume could be calculated.

Using a flame ionization detector (250 °C) equipped with a gas chromatograph (Model 6890-N; Agilent Technologies, Santa Clara, CA) with a 0.53-mm-diameter × 30-m HP-Plot-Q capillary column (Agilent Technologies, Santa Clara, CA), gas samples were analyzed for their CH_4 concentration within 48 hr of collection. Methane fluxes were calculated based on linear regression according to changes in concentrations in the chamber headspace over the 60-min sampling interval following procedures outlined by [20,27].

Season-long emissions were calculated on a chamber-by-chamber basis by linear interpolation between weekly sample dates. Emissions data were also divided into pre- and post-flood-release periods for data analyses due to differences in emissions mechanisms and to examine the impact of flood release and subsequent oxygenation on CH_4 emissions.

Plant sampling and processing

Seven days after the last gas sampling (i.e., 84 DAF), all aboveground biomass was collected from the interior of each base collar. Rice was harvested on 9 September 2015 (i.e.86 DAF) with a research-grade plot combine, at which time a sub-sample of rice grain was collected to determine harvest grain moisture. The combine yield was corrected to 12% grain moisture for yield-reporting purposes. Total season-long CH_4 emissions (i.e., pre- plus post-flood-release emissions) were divided by total rice grain yield on a plot-by-plot basis to express emissions on a per-unit-grain-yield basis (i.e., an emissions intensity metric).

Statistical analyses

Based on the RCB design with four replications of each treatment combination, a two-factor analysis of variance (ANOVA) was conducted using SAS (version 9.3, SAS Institute, Inc., Cary, NC) to determine pre-assigned treatment effects (i.e., cultivar, water management scheme, and their interaction) on initial soil properties (i.e., Mehlich-3 extractable P, K, Ca, Mg, S, Na, Fe, Mn, Zn, and Cu contents; soil pH and EC; SOM, TC, and TN contents; C:N ratio; bulk density; and sand, silt, and clay fractions) prior to flooding. A separate three-factor ANOVA was conducted to determine the effects of water management, cultivar, time (i.e., measurement date), and their interactions on CH_4 fluxes, soil temperature, and soil Eh. A separate two-factor ANOVA was conducted to determine the effects of water management, cultivar, and their interaction on rice grain yield; pre- and post-flood-release and total growing-season, area-based CH_4 emissions; and total growing-season, yield-based CH_4 emissions. All ANOVAs were conducted using the PROC MIXED procedure. When appropriate, means were separated by least significant difference (LSD) at the 0.05 level.

Results and Discussion

Initial soil properties

Initial soil properties in the top 10 cm prior to flooding were relatively uniform among pre-assigned treatment combinations throughout the study area (Table 1). Most initial soil properties (i.e., EC, extractable K, Fe, Mn, Mg, S, Cu, Zn, TN, and SOM, bulk density, sand, silt, and clay) were unaffected ($P > 0.05$) by water management practice (i.e., full-season-flood and mid-season-drain), cultivar (i.e., the pure-line cultivar LaKast and the hybrid cultivar XL753), or their interaction (Table 1) and were all within recommended ranges for optimal rice production on a silt-loam soil [28]. Sand, silt, and clay averaged 0.21, 0.72, and 0.07 g g^{-1} in the top 10 cm, confirming a silt-loam soil (Table 1). Soil organic matter, TC, and TN averaged 15.3, 7.6, and 0.92 Mg ha^{-1}, respectively for a mean C:N ratio of approximately 8:1. Extractable soil K and Zn (230 and 10.7 kg ha^{-1}) were within recommended optimum levels and extractable soil P (98.4 kg ha^{-1}) was above optimum for rice production on a silt-loam soil [23]. However, extractable soil Ca and Na, soil pH, and TC in the top 10 cm differed ($P \leq 0.01$) between water management schemes. Extractable soil Ca and Na were 120 and 36.5 kg ha^{-1}, respectively, and soil pH was 0.26 units greater in the full-season-flood than in the mid-season-drain water management scheme before flooding. Total carbon was also greater ($P < 0.01$) in the full-season-flood (7.77 Mg ha^{-1}) than in the mid-season-drain (7.49 Mg ha^{-1}). Despite the few differences in soil properties among pre-assigned treatments, all differences were small enough to cause no expected differences in rice growth or production. Consequently, any measured differences in CH_4 fluxes or emissions were assumed to be the result of actual treatment effects rather than due to inherent differences among plots.

Methane fluxes

Similar to other reports in Arkansas [10,12,14,29,30], CH_4 fluxes during the 2015 rice growing season followed a somewhat predictable temporal pattern throughout the rice growing season. Methane fluxes started low, increased to a numeric peak that ranged from 100 to 230 mg CH_4-C m^{-2} d^{-1} for the mid-season-drain/hybrid and

Table 1: Analysis of variance summary of the effects of rice cultivar, pre-assigned water management (WM) practice, and their interaction on soil physical and chemical properties from the top 10 cm of a Dewitt silt loam prior to flood establishment at the Rice Research and Extension Center near Stuttgart, Arkansas during the 2015 growing season. Overall means (n = 16) and standard errors (SE) are also reported.

Soil property	Cultivar	WM	Cultivar × WM	Overall mean (± SE)
	P			
Sand (g g^{-1})	0.22	0.34	0.31	0.21 (< 0.01)
Silt (g g^{-1})	0.24	0.68	0.3	0.72 (< 0.01)
Clay (g g^{-1})	0.45	0.15	0.65	0.07 (< 0.01)
pH	0.43	< 0.01	0.27	6.7 (0.05)
Bulk density (g cm^{-3})	0.7	0.33	0.7	1.38 (0.01)
Electrical conductivity (dS m^{-1})	0.62	0.24	0.69	315 (53)
Extractable nutrients (kg ha^{-1})				
P	0.87	0.19	0.59	98.4 (3.5)
K	0.92	0.25	0.86	230 (7.9)
Ca	0.88	< 0.01	0.28	1599 (21)
Mg	0.48	0.06	0.84	159 (2.0)
S	0.45	0.24	0.83	14.6 (0.54)
Na	0.44	< 0.01	0.87	148 (5.7)
Fe	0.51	0.27	0.89	646 (11)
Mn	0.25	0.68	0.98	293 (6.9)
Zn	0.54	0.25	0.28	10.7 (1.3)
Cu	0.73	0.31	0.43	1.3 (0.05)
Soil organic matter (Mg ha^{-1})	0.48	0.79	0.78	15.3 (0.01)
Total N (Mg ha^{-1})	0.28	0.64	0.42	0.92 (< 0.01)
Total C (Mg ha^{-1})	0.26	0.01	0.18	7.6 (0.01)
C:N ratio	0.06	0.66	0.88	8.3 (0.17)

full-season-flood/hybrid treatment combination, respectively, between 47 and 54 DAF, which was approximately 50% heading, and decreased thereafter until the flood was released at 68 DAF (Figure 1). The numeric peak flux from the full-season-flood/hybrid treatment combination was comparable to that of Brye, et al. [10] who reported a peak of 390 CH_4-C m^{-2} d^{-1} at 51 DAF from a pure-line cultivar "Taggart" grown on silt-loam soil under a full-season flood. In contrast, Simmonds, et al. [11] reported no relationship between the temporal pattern of weekly CH_4 emissions and the physiological growth stages of the rice crop. After flood release, CH_4 fluxes in all treatment combination at least slightly numerically increased within 5 days before decreasing to near zero by 81 DAF (Figure 1). This post-flood-release spike in CH_4 fluxes has been reported numerous times in both silt-loam and clay soils in Arkansas [10,14,29-31].

During the 2015 growing season, CH_4 fluxes differed ($P < 0.01$; Table 2) among water management/cultivar treatment combinations over time (Figure 1). Methane fluxes measured 5, 12, and 19 DAF in each treatment combination did not differ from a flux of zero. By 26 DAF, six days after flood re-establishment following the mid-season drain at 20 DAF, CH_4 fluxes from both mid-season-drain treatments did not differ from a flux of zero, while fluxes from both full-season-flood combinations increased from that at 19 DAF but did not differ from one another.

Table 2: Analysis of variance summary of the effects of cultivar, water management, time, and their interaction on methane fluxes and the effects of cultivar, water management, and their interaction on pre- and post-flood-release and season-long, area-scaled and yield-scaled methane emissions during the 2015 growing season at the Rice Research and Extension Center near Stuttgart, Arkansas.

Variable/Source of variation	P
Methane fluxes	
Cultivar	0.34
Water management	0.07
Time	< 0.01
Cultivar × water management	< 0.01
Cultivar × time	0.54
Water management × time	< 0.01
Cultivar × water management × time	< 0.01
Pre-flood-release, area-scaled emissions	
Cultivar	0.45
Water management	0.16
Cultivar × water management	0.48
Post-flood-release, area-scaled emissions	
Cultivar	0.11
Water management	0.02
Cultivar × water management	0.42
Season-long, area-scaled emissions	
Cultivar	0.40
Water management	0.01
Cultivar × water management	0.16
Season-long yield-scaled emissions	
Cultivar	0.43
Water management	0.01
Cultivar × water management	0.04

Between 33 and 72 DAF, CH_4 fluxes from the mid-season-drain/hybrid combination was lower than that from all other treatment combinations, with a peak average flux of 102.7 CH_4-C m^{-2} d^{-1} that occurred 47 DAF (Figure 1). The largest average peak flux occurred from the full-season-flood/hybrid combination (204.9 CH_4-C m^{-2} d^{-1}) between 40 and 47 DAF (Figure 1). The average peak fluxes for the mid-season-drain/pure-line and the full-season-flood/pure-line treatment combinations were 173.9 and 171.4 CH_4-C m^{-2} d^{-1}, respectively, which occurred at 54 to 61 and 40 to 47 DAF, respectively (Figure 1). From 47 to 68 DAF, CH_4 fluxes decreased from all treatment combinations. After flood release (i.e., 72 DAF), CH_4 fluxes from the full-season-flood/hybrid treatment increased from 67 (95.2 CH_4-C m^{-2} d^{-1}) to 75 DAF (141.5 CH_4-C m^{-2} d^{-1}). However, the other treatment combinations only had small, numeric increases in CH_4 fluxes between 68 and 75 DAF, which peaked at 150.9, 154.9, and 56.8 CH_4-C m^{-2} d^{-1} from the full-season-flood/pure-line and the mid-season-drain/pure-line and hybrid treatment combinations, respectively (Figure 1). The post-flood-release spike in CH_4 fluxes was consistent with similar previous reports [10,14,29]. Methane fluxes from the mid-season-drain/hybrid treatment did not differ from zero at 79 DAF, and, by 81 DAF, CH_4 fluxes from all treatment combinations did not differ from zero.

Soil temperature and redox potential fluctuations

At the time of flood establishment, soil temperatures at the 7-cm depth averaged 29 °C across both water management schemes, which then increased to the growing-season maximum of 33 °C in the first few days after flooding (Figure 2). The soil temperature remained relatively constant and uniform between water management treatments, except for when the mid-season-drain occurred at 15 DAF when the average soil temperature for the mid-season-drain (25.5 °C) was lower ($P < 0.01$) than that for the full-season-flood treatment (28 °C; Figure 2). The 7-cm soil temperature did not differ between water management treatments on any other measurement date during the 2015 rice growing season and was unaffected by rice cultivar ($P > 0.05$). The results of this study were similar to those reported by Rogers, et al. [20], where a maximum 7-cm soil temperature of 32 °C occurred at 19 DAF.

Similar soil temperature trends, but as expected, soil Eh started well-oxidized and decreased thereafter follow-

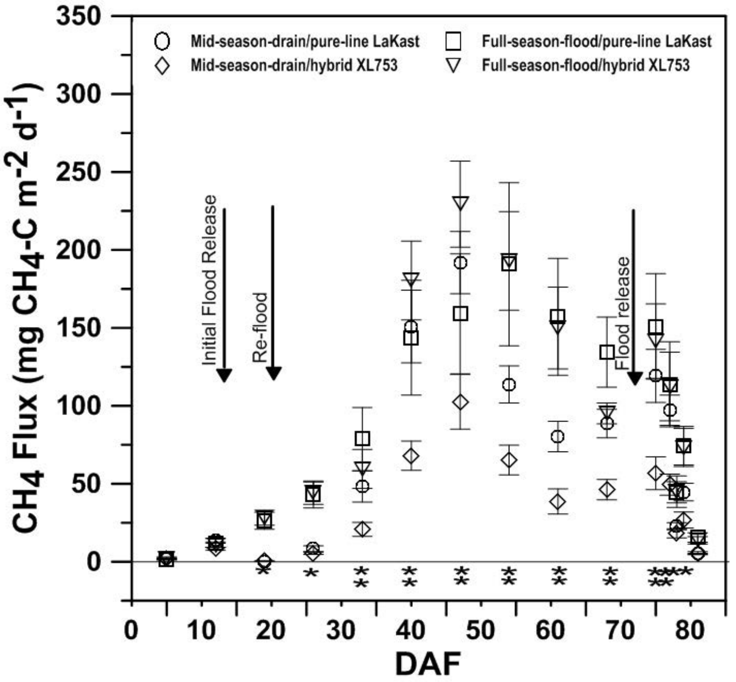

Figure 1: Season-long profile of methane (CH_4) flux trends over time for four water management scheme (mid-season-drain and full-season-flood) and cultivar (pure-line LaKast and hybrid XL753) treatment combinations from a DeWitt silt-loam soil during 2015 at the Rice Research and Extension Center near Stuttgart, Arkansas. The thick vertical lines indicate the timing of (1) Flood release at 15 days after flooding (DAF) for the mid-season drain; (2) Flood re-establishment at 22 DAF 7 days after the mid-season drain; and (3) Flood release at 72 DAF from all plots prior to harvest. Standard error bars accompany treatment means (n = 4). A single asterisk on a given measurement date indicates a significant ($P < 0.05$) difference exists among treatment combinations, while a double asterisk indicates the mid-season-drain/XL753 combination is significantly ($P < 0.05$) lower than all other treatment combinations.

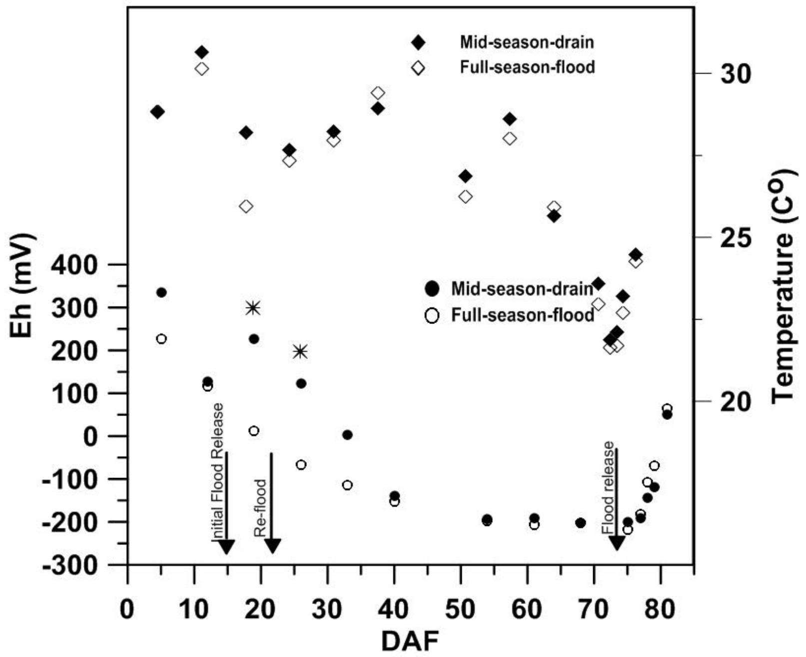

Figure 2: Season-long profile of soil temperature and oxidation-reduction potential (Eh) trends over time for the mid-season-drain and full-season-flood water management practices measured at a depth of 7 cm in a DeWitt silt-loam soil during 2015 at the Rice Research and Extension Center near Stuttgart, Arkansas. The thick vertical lines indicate the timing of (1) Flood release at 15 days after flooding (DAF) for the mid-season drain; (2) Flood re-establishment at 22 DAF 7 days after the mid-season drain; and (3) Flood release at 72 DAF from all plots prior to harvest. Asterisks indicates a significant difference in soil temperature or soil Eh between water management schemes ($P < 0.05$).

Table 3: Analysis of variance summary of the effects of water management, time, and their interactions on soil temperature and soil oxidation-reduction (redox) potential and the effects of cultivar, water management, and their interaction on rice dry matter and yield during the 2015 growing season at the Rice Research and Extension Center near Stuttgart, Arkansas.

Variable/Source of Variation	***P***
Soil temperature	
Cultivar	0.74
Water management	< 0.01
Time	< 0.01
Cultivar × water management	0.18
Cultivar × time	0.38
Water management × time	< 0.01
Cultivar × water management × time	0.99
Soil Redox	
Cultivar	< 0.63
Water management	< 0.16
Time	< 0.01
Cultivar × time	0.90
Cultivar × water management	0.02
Water management × time	0.04
Cultivar × water management × time	0.26
Rice dry matter	
Cultivar	0.39
Water management	0.94
Cultivar × water management	0.38
Rice yield	
Cultivar	0.87
Water management	0.61
Cultivar × water management	0.06

ing flood establishment (Figure 2). The soil redox level of approximately -200 mV is necessary for optimal CH_4 production [32]. Averaged across cultivar, soil Eh was greater (i.e., more oxidized; $P < 0.01$; Table 3) in the mid-season-drain than in the full-season-flood treatment at 19 and 26 DAF, whereas soil Eh was similar between water management treatments on each other weekly measurement date. Soil Eh at the 7-cm depth in the full-season-flood treatment decreased to < -200 mV by 54 DAF and remained < -200 mV until the flood was released at 72 DAF, while that in the mid-season-drain did not reach < -200 mV until two weeks later at 68 DAF. However, after 36 DAF, which was three weeks after flood re-establishment in the mid-season-drain treatment, soil Eh in both water management treatments had similar magnitudes and followed the same pattern for the rest of the growing season.

In contrast to soil temperature, which was unaffected by cultivar, soil Eh differed among water treatment-cultivar combinations ($P < 0.02$; Table 3). Soil Eh at the 7-cm depth was greater in the mid-season-drain/hybrid (-14.0 mV) than in the other three treatment combinations, which did not differ and averaged -72.1 mV. The increase in soil Eh in the mid-season drain demonstrates the synergistic effect of the combination of the alternative water management practice and use of a hybrid cultivar on soil redox potential due to enhanced root zone oxygenation [33].

In a similar study on a silt-loam soil in east-central Arkansas, Rogers, et al. [20] reported soil Eh rapidly decreased to < -200 mV by 25 to 30 DAF in a full-season-flood treatment. Soil Eh in the current study, averaged over cultivar, also differed among water treatments over time ($P < 0.04$; Table 3). However, in contrast to the soil Eh trends under the full-season-flood treatment, after decreasing following flood establishment, soil Eh in the mid-season drain increased from +128 mV at 12 DAF to +226 mV at 19 DAF then decreased to +122 mV at 26 DAF, clearly indicating that the drained soil became more oxidized than the soil under the continuous flood. Directly after the mid-season-drain, CH_4 fluxes from the mid-season-drain/hybrid treatment decreased and did not increase again until after the flood was reestablished at 20 DAF. The increase in soil Eh measured in the mid-season-drain was a significant increase compared to soil Eh measured in the full-season-flood treatment, which, over the same time, continued to decrease from +115 to -66 mV by 26 DAF. Soil Eh did not differ between the two water management practices for the remained of the rice growing season.

In the current study, the soil Eh trends over time under the mid-season-drain treatment at least partially explain the low CH_4 fluxes from the mid-season-drain/hybrid treatment combination throughout most of the rice growing season and indicated at least two weeks less time available for CH_4 production under the mid-season-drain than under the full-season-flood treatment. It would be expected that less time available for CH_4 production due to more-oxidized soil conditions for some time under the mid-season-drain would result in lower CH_4 emissions than from the full-season-flood treatment that had a longer time available for CH_4 production due to more prolonged reducing conditions.

Area-scaled methane emissions

Since the presence or absence of the flood itself affects the mechanism by which CH_4 is released from the soil, emissions were analyzed separately for these two periods of the rice growing season. Between initial flooding and flood release, CH_4 emissions were unaffected by water management scheme and cultivar ($P > 0.05$; Table 2). Pre-flood-release CH_4 emissions averaged 50.8 kg CH_4-C ha^{-1} across all treatment combinations. In contrast, post-flood-release CH_4 emissions differed ($P = 0.02$; Table 2) between water management schemes, where emissions from the full-season-flood 14.0 kg CH_4-C ha^{-1}) were 1.7 times greater than emissions from the mid-season-drain

Table 4: Summary of mean season-long, area-scaled methane (CH_4) emissions, rice yield, and methane emissions intensity for the various water management/cultivar treatment combinations and water management practices averaged across cultivars during the 2015 growing season at the Rice Research and Extension Center near Stuttgart, Arkansas.

Water management/Cultivar combination	**Methane emissions** **(kg CH_4-C ha^{-1} $season^{-1}$)**	**Rice yield** **(Mg ha^{-1})**	**Emissions intensity** **(kg CH_4-C Mg $grain^{-1}$)**
Mid-season-drain/LaKast	56.6	10.0	5.67a†
Mid-season-drain/XL753	28.9	11.5	2.52b
Mid-season-drain mean	42.8b†	10.7	3.99
Full-season-flood/LaKast	76.4	10.3	7.39a
Full-season-flood/XL753	79.1	12.6	6.29a
Full-season-flood mean	77.7a	11.4	6.79

†Values in same column followed by different letters are significantly different (P < 0.05); a and b show results of statistical analyses.

(8.2 kg CH_4-C ha^{-1}) treatment.

During the complete 2015 growing season and in contrast to that hypothesized, total season-long, area-scaled emissions differed between water management treatments ($P < 0.01$) but were unaffected ($P > 0.05$) by cultivar (Table 2). Season-long, area-scaled CH_4 emissions were 1.8 times greater from the full-season-flood (77.7 kg CH_4-C ha^{-1} $season^{-1}$) than from the mid-season-drain (42.8 kg CH_4-C ha^{-1} $season^{-1}$) water management scheme (Table 4). These results support the expected emissions differences between the two water management schemes based on the soil Eh trends (Figure 2).

Post-flood-release CH_4 emissions represented 18.0 and 19.2% and averaged 18.6% of total season-long emissions for the full-season-flood and mid-season-drain treatments. This proportion of post-flood-release emissions is larger than that reported in recent studies under a full-season flood in east-central Arkansas [10,20], which ranged from 3.4 to 13.2% from a silt-loam soil under a continuous flooding, but from different pure-line cultivars (i.e., 'Taggart' and 'Wells').

A similar study conducted by Simmonds, et al. [11] investigated water management effects on CH_4 emissions in east-central Arkansas, but, to the best of the authors' knowledge, this current study was the first to investigate the combination of mid-season-drain and full-season-flood water management schemes with pure-line and hybrid cultivars. Rogers, et al. [20] reported total season-long, area-scaled emissions from a full-season-flood on a silt-loam soil near Stuttgart, AR ranged from 54 kg CH_4-C ha^{-1} from N-fertilized bare soil to 220 kg CH_4-C ha^{-1} from an optimally N-fertilized pure-line cultivar 'Wells'. Simmonds, et al. [11] reported area-scaled CH_4 emissions from a silt-loam soil near Stuttgart, AR for a one-flush irrigation before continuous flooding and a continuous-flood regime ranged from 34 to 70 kg CH_4-C ha^{-1}, respectively, from the hybrid cultivar 'CLXP4534' and pure-line cultivars 'Francis', 'Jupiter', and 'Sabine'.

Rice dry matter and yields

Neither aboveground dry matter nor rice yields differed ($P > 0.05$) between water management schemes or cultivars (Table 3). Rice dry matter ranged from 27.8 Mg ha^{-1} in the full-season flood/hybrid treatment to 37.8 Mg ha^{-1} in the full-season flood/pure-line treatment and averaged 33.1 Mg ha^{-1} across all treatment combinations. Similarly, rice yields ranged from 10.0 Mg ha^{-1} from the mid-season-drain/pure-line to 12.6 Mg ha^{-1} from the full-season-flood/hybrid (Table 4) and averaged 11.1 Mg ha^{-1} across all treatment combinations. For comparison, based on Arkansas Rice Performance Trials in 2015, the average yields for continuous-flood regime on a Dewitt silt-loam soil near Stuttgart, AR were 10.6 and 7.5 Mg ha^{-1} for the hybrid 'XL753' and the pure-line 'LaKast', respectively [34].

Methane emissions intensity

Maintaining or increasing rice yields and improving C emissions intensity by reducing CH_4 emissions should be considered when developing new/alternative rice production management practice combinations, such as increasing the use of the mid-season drain for straight head control. Methane emissions intensity differed ($P = 0.04$) between water management schemes across cultivars (Table 2). Methane emissions intensity for the mid-season-drain/hybrid combination, which represented the smallest emissions intensity (2.52 kg CH_4-C Mg $grain^{-1}$) was more than 50% greater, where a low CH_4 emissions per unit grain yield value represented greater intensity, than that for the other three treatment combinations, which did not differ and averaged 6.45 kg CH_4-C Mg $grain^{-1}$ (Table 4). These results are similar to those of Simmonds, et al. [11], who reported an average CH_4 emissions intensity from a silt-loam soil near Stuttgart, AR for a one-flush irrigation before continuous flooding and continuous-flood water management regime of 5.57 and 9.72 kg CH_4-C Mg $grain^{-1}$, respectively, across the hybrid cultivar 'CLXP4534' and pure-line cultivars 'Francis', 'Jupiter', and 'Sabine'. However, Rogers, et al. [20] reported a decreased CH_4 intensity of 27.6 kg CH_4-C Mg grain^{-1} under a continuous flood with the pure-line cultivar 'Wells' compared to this study's full-season-flood/pure-line combination of 7.39 kg CH_4-C Mg grain^{-1}. The differences in emissions intensity could be attributed to yield differences between the various pure-line cultivars, coupled with the decreased season-long emissions for the particular study year compared to results of Rogers, et al. [20].

Potential implications

Alternative water management practices, as well as cultivar selection, have been shown to decrease CH_4 emissions, thereby providing opportunities to substantially conserve SOM, soil C, and water resources and reduce global warming potentials associated with rice production. Use of the mid-season-drain water management practice may have significant, positive effects on the future sustainability of rice production, soil health, water conservation, and climate change in specific US regions, such as in the Lower Mississippi River Valley which has concentrated rice production.

Along with potentially reduced water use, substantial reductions in CH_4 emissions from the mid-season-drain compared to the full-season-flood water management scheme will decrease the C footprint of rice, which may increase the marketability of rice as a staple food crop relative to other staple foods, such as potato (*Solanum tuberosum*). Reducing the C footprint may make rice more desirable for those who wish to reduce their personal climate-change impact on the planet, which may increase rice demand, thereby increasing profitability for rice producers, suppliers, and retailers in markets sensitive to climate-change awareness. However, with the mid-season-drain approach, there is the potential that nitrous oxide (N_2O) emissions may increase as the soil temporarily unsaturates and becomes partially re-oxidized. Considering that N_2O is an approximately 100 times more potent GHG than CH_4, exacerbating N_2O emissions with an alternative water management scheme may not be wise. Furthermore, from the same soil and location as the present study, Rector, et al. [35] reported numerically greater N_2O emissions from an intermittent wetting and drying scheme compared to a full-season flood, which highlight the potential for other non-CH_4 GHG emissions becoming relevant when traditional productions practices are altered from the standard full-season flood to mitigate CH_4, especially when fertilized with additional mineral N.

Conclusions

Results of this study confirmed the potentially positive impacts of reducing CH_4 fluxes and season-long emissions using alternative water management schemes and cultivar selection. Similar to that hypothesized, this study showed that, regardless of cultivar selection, mid-season draining of flood water significantly reduced season-long, area-scaled CH_4 emissions compared to the full-season-flood water management practice from rice grown in 2015 in the direct-seeded, delayed-flood production system on a silt-loam soil in east-central Arkansas. Similarly, this study also clearly showed that the mid-season-drain/hybrid (XL753) combination had the lowest CH_4 emissions per unit grain yield (i.e., the greatest emissions intensity) among all water management/cultivar treatment combinations evaluated. The reduction in CH_4 emissions per unit grain yield from the mid-season-drain/hybrid combination was magnified due to the significantly lower emissions from the mid-season-drain treatment coupled with the numerically greater yield from the hybrid cultivar compared to the full-season-flood treatment and pure-line cultivar, respectively. Based on reduced season-long CH_4 emissions, the mid-season-drain water management scheme, regardless of cultivar selection, appears to be a more environmentally sustainable agronomic practice compared to the full-season-flood scheme. Continued investigation, particularly with direct field measurements, is critically necessary to better understand the effects of various alternative water management practices, current rice cultivars, and their combinations on CH_4 emissions from silt-loam soils in Arkansas and other regions of concentrated rice production.

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