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The effect of water management and ratoon rice cropping on methane emissions and yield in Arkansas

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ABSTRACT

Sustainable intensification of rice farming is crucial to meeting human food needs while reducing environmental impacts. Rice production represents 8% of all anthropogenic emissions of CH_4, a potent greenhouse gas. Cultivation practices that minimize the number of days the rice fields are flooded, such as irrigation using the alternate wetting and drying (AWD) technique instead of continuous flooding (DF) can potentially reduce CH_4 emissions. Ratoon cropping, wherein a second crop of rice is grown from the harvested stubble of the first crop, can produce additional yield with minimal labor but may generate more CH_4 than single cropping. The objectives of this study were first to test different water management regimes for their impact on yield and CH_4 emissions, and second to investigate CH_4 emissions from a ratoon crop and perform an exploratory economic analysis of ratoon cropping. Two adjacent fields in Lonoke County, Arkansas were compared under different irrigation treatments from 2015 through 2020; the 2020 season also included a ratoon crop. Field-scale CH_4 emissions were measured using the eddy covariance method at each field. AWD reduced CH_4 emissions by 79.5% on average in comparison to DF for the main seasons. Across the field-seasons, the emissions from the main crop ranged from 77.2 to 132.5 kg CH_4-C ha^{-1} under DF and from 7.1 to 40.7 kg CH_4-C ha^{-1} under AWD. The ratoon crop generated emissions from 39.7 to 50.7 kg CH_4-C ha^{-1}, up to a 3.6-fold increase from the main crop of the same year. CH_4 emissions from the ratoon crop in this study were much lower than those found in previous ratoon studies. The ratoon crop yield was 13% that of the main crop yield on average but there was no significant difference in yield between irrigation treatments for the main seasons.

1. Introduction

Agriculture is a major contributor to atmospheric greenhouse gas (GHG) emissions that drive climate change (Ciais et al., 2013). Climate change threatens global food security, increasing the magnitude and duration of severe weather events, leading to floods, droughts, and crop damage (Meehl et al., 2000). The result is an agricultural system of unpredictable productivity in a world of increasing population, which makes sustainable intensification crucial. Sustainable intensification can be defined as increasing agricultural productivity while limiting the environmental impact of production (Garnett et al., 2013). This aim requires improving the yield of staple crops while preventing environmental contamination, minimizing the destruction of natural habitats, and reducing anthropogenic GHG emissions. Rice farming is responsible for 8% of anthropogenic CH_4 emissions because the flooded conditions under which it is usually grown create an anaerobic environment that promotes the growth of methanogenic bacteria (Banker et al., 1995; Ciais et al., 2013; Cole et al., 1997; Saunois et al., 2020).

Within the growing season, irrigation management practices have potential to reduce CH_4 emissions by decreasing the total duration of field inundation. The alternate wetting and drying (AWD) practice, where rice fields are flooded and then periodically allowed to dry down before reflooding, significantly reduces CH_4 emissions compared to delayed, continuous flooding (DF) (Balaine et al., 2019; LaHue et al., 2016; Linquist et al., 2015, 2018; Runkle et al., 2019). Delayed flooding is defined here as a form of continuous flooding where the field is managed under aerobic conditions for a short time after sowing, in this case until the plants grew to the 5-leaf stage, then continuously flooded until just before harvest. Drying periods that allow the water level to drop lower than 15 cm below the surface show greater reductions in

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emissions than less severe drying periods, although long drying periods can also decrease yield by 5–22% (Balaine et al., 2019; Carrijo et al., 2017; Linquist et al., 2015). Given the possibility of yield loss, moderate drying periods may provide the best balance between reducing GHG emissions and producing a profitable harvest.

Ratoon cropping, which is the practice of inducing the growth of a second crop from the harvested stubble of the first crop by flooding and fertilizing the stubble, has the potential to increase yield without much extra investment since very little labor is involved in managing the ratoon crop (Santos et al., 2003). This practice could be an effective way to increase yield, but the environmental impact needs to be evaluated before it can be considered a form of sustainable intensification. Ratoon crops can emit from two to four times as much CH_4 as the main crop (Lindau and Bollich, 1993; Lindau et al., 1995), likely as a result of the decomposition of rice straw remaining in the field, the additional fertilizer applied, and the high temperature of the early months in which the ratoon crop is grown (Linquist et al., 2018). However, when the emissions are yield-scaled and the decreased labor required for the ratoon crop is considered, the overall GWP can be less than that of a conventional crop (Firouzi et al., 2018; Yuan et al., 2019).

The objective of this study is to determine the effect of rice water management and ratoon cropping on yield and field CH_4 emissions in a production setting in Arkansas. This state is responsible for roughly half the US rice production and includes products for both domestic and international consumption (Childs, 2021). The CH_4 emissions are measured using the eddy covariance (EC) technique to conduct a full field-scale, paired-field experiment using different irrigation treatments and ratoon cropping on similar rice fields in Lonoke County, Arkansas from 2015 to 2020. This study extends previous work at these sites that focused primarily on the effect of water management on GHG emissions from 2015 to 2017 (Runkle et al., 2019). This study is also one of very few to use the EC technique to evaluate ratoon crop CH_4 flux in rice. The EC technique allows for continuous measurements, can be used to generalize over larger, production-scale areas, and does not disturb the field-atmosphere interface (Schrier-Uijl et al., 2010). Using this technique on a full field scale has limitations, namely the lower number of replications per season, but it allows for the measurement of emissions on an ecosystem level which is necessary for a complete understanding of CH_4 flux. Our aims are (1) further understanding of the effect of varying degrees of AWD on yield and CH_4 emissions, as the number and duration of drying events differed between fields and seasons, (2) report CH_4 emissions from a ratoon rice crop managed with AWD.

2. Site description and methods

2.1. Site description

This study was conducted on a pair of commercially farmed, adjacent 26 ha rice fields (34°35′ 7.84″ N, 91°45′ 6.02″ W) in Lonoke County, Arkansas during the 2015 through 2020 growing seasons (Fig. 1). Each field was assigned a single irrigation treatment and was assumed to be spatially homogenous. The fields were predominately (>90%) Perry silty clay, zero-grade leveled, and continuously planted in rice since 2006. The fields were burned to remove previous crop residue each fall, except in 2020 where ratoon crop was grown, and were flooded each winter for two to three months for waterfowl habitat and hunting. The fields were planted with CLXL745 hybrid seed by drill-seeding in 2015, 2016, 2017, and 2018, and aerial water seeding in 2019 and 2020 (Rice Tec., Alvin, TX). Drill-seeded fields were sown at a rate of 25 kg ha^{-1} while water-seeded fields were sown at a rate of 28 kg ha^{-1}. Seeds for the water-seeded fields were pre-germinated. The two fields and instrumentation set-up have been previously described and are registered with Ameriflux as US-HRC and US-HRA for the North and South field, respectively (Reba, 2021; Runkle, 2021; Runkle et al., 2019; Suvočarev et al., 2019).

In 2015, the North and South fields were flooded on May 15 and May 16, respectively, and were managed with a delayed flooding (DF) regime in the North field and an alternate wetting and drying (AWD) regime in the South field. In the DF system, rice is dry seeded, briefly flushed with water to encourage growth, and allowed to grow to the 5-leaf stage before being continuously flooded for the rest of the season in contrast to AWD, where the flooding period is interrupted by shorter drying periods. In 2016, seeding, and therefore flooding and harvest, was delayed due to wet conditions, and both fields were flooded on June 14 and managed with an AWD regime. In 2017, both fields were flooded on May 18 and managed with a DF regime. In 2018, the North and South fields were flooded on June 3 and both were managed with an AWD regime. In recent work (Karki et al., 2023) it was reported that the North field in 2018 was managed with a DF regime, but there were three periods where the water level dropped more than 2 cm below the soil surface for at least 24 h (Fig. 3d), which was the criteria we used in this paper for determining the number of drying events for fields managed with AWD. For this reason, here we considered the field to be managed with AWD. In 2019 and 2020, the fields were flooded prior to planting to facilitate water seeding but were managed with an AWD regime throughout the main season. The fields managed with water seeding were allowed to dry for a short period after seeding to allow the rice to establish roots, flushed with water, and then reflooded at the 5-leaf stage. In 2019 the

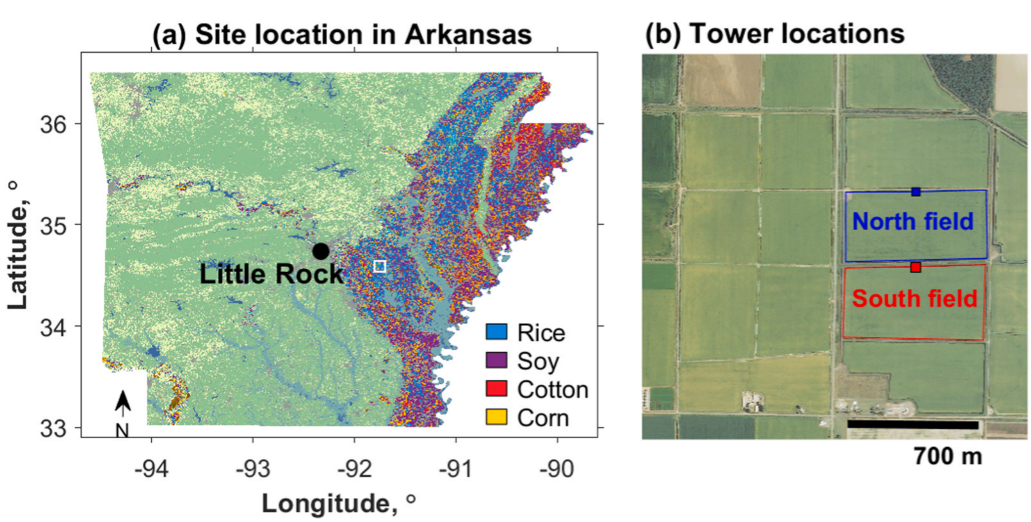

Fig. 1. : (a) The study site, a pair of fields in Lonoke County, Arkansas, marked by a white square and showing the 2015 CropScape crop cover data set from the National Agricultural Statistics Service (Han et al., 2014) (b) The locations of the eddy covariance (EC) towers are marked on the north side of the fields. The background image is from the USDAFSA- APFO Aerial Photography Field Office within the NAIP and was taken August 22, 2013. Versions of this figure have been previously presented (Runkle et al., 2019; Suvočarev et al., 2019).

North field was reflooded on June 14 and the South field was reflooded on June 16. In 2020 both fields were reflooded on May 17. A ratoon crop was grown in both fields in 2020 and was managed with AWD. The 2020 main crop was cut to a height of 40 cm upon harvest and the residue of the main crop was left on the field. The fields were reflooded within two days of cutting.

Fertilizer was applied as urea and diammonium phosphate (DAP) throughout May and June for all main seasons except 2020 which had an application of DAP in late April and an application of urea in early July. Fertilizer was applied to the ratoon crop at the beginning of the ratoon season. Total urea application rates were 144 kg N ha^{-1} for 2015, 155 kg N ha^{-1} for 2016, 2017, 2018, and 2019, 245 kg N ha^{-1} for the 2020 main crop, and 77 kg N ha^{-1} for the 2020 ratoon crop. Agrotain (a urease inhibitor) was used in the first urea application to protect against ammonia volatilization. Total DAP application rates were 20 kg N ha^{-1} for 2015, 2017, 2018, and the 2020 main crop, 18 kg N ha^{-1} for 2016, and 22 kg N ha^{-1} for 2019. No DAP was applied to the ratoon crop..

2.2. Equipment and measurements

The CH_4, CO_2, latent energy (LE), and sensible heat (H) fluxes were measured using the EC technique as part of the Delta-Flux network (Baldocchi et al., 1988; Runkle et al., 2017). Equipment used on the EC towers included data loggers (CR3000 and CR1000, Campbell Scientific, Inc., Logan UT, USA), temperature and relative humidity sensors (HMP155, Vaisala, Vantaa, Finland), an atmospheric pressure sensor (Barometer 278, Setra, Boxborough, MA, USA), a 2D wind vector sensor (05103 −5 propeller wind monitor, R.M. Young, Traverse City, MI, USA), sensors measuring the four components of net radiation (CNR4 radiometer, Kipp & Zonen, Delft, Netherlands), a 3D sonic anemometer (CSAT3, Campbell Scientific, Inc., Logan, UT, USA), an open path CO_2/H_2O infrared gas analyzer (LI-7500A, LI-COR Inc., Lincoln, NE, USA), and an open-path CH_4 using wavelength modulation spectroscopy (LI-7700, LI-COR Inc., Lincoln, NE, USA). The sonic anemometer wind vector and gas analyzer concentration measurements were recorded at 20 Hz through an Analyzer Interface Unit (LI-7550, LI-COR Inc., Lincoln, NE, USA) with the LI-COR SMARTflux automated processing system. The equipment was installed at the north end of each field, on tripods 2.2 m (North field; US-HRC) and 2.1 m (South field; US-HRA) above the ground. Precipitation and temperature data for Stuttgart, AR were downloaded from the PRISM database (PRISM Climate Group, 2014) and compared to average values from the last 30 years.

Soil temperature was measured at 2 and 4 cm below the soil surface near the towers using thermistors (107, Campbell Scientific, Inc., Logan, UT, USA). Water temperature was also measured using thermistors placed on top of the water and at the soil-water interface. The water level was measured with capacitive level transmitters (Nanolevel, Keller America, Newport News, VA, USA). Dissolved O_2 concentrations were measured at the soil-water interface using a miniDOT logger (PME, California, USA). A GPS-enabled John Deere GreenStar 3 2630 Harvest Monitor recorded location-based wet harvest weights from both fields, with measurements approximately 2 m apart (John Deere, IL, USA). Yields were reported on a 13% moisture basis. The equipment setup for this site and study has been previously described (Runkle et al., 2019).

2.3. Data processing

The raw data from the EC system was processed as half-hourly measurements using EddyPro software (v. 7.0.6, LI-COR Inc., Lincoln, NE). Further processing was performed using MATLAB software (v. R2019b, MathWorks Inc., Natick, MA) to remove poor quality data and to gap-fill missing values. CH_4 flux data obtained by the EC method is prone to large gaps due to inadequate turbulence, periods where the wind is not blowing over the area of interest, and technical problems (Irvin et al., 2021). The 2018–2020 CH_4 flux data was evaluated during data processing to determine the major causes of gaps. The 2015–2017 CH_4 flux data was acquired pre-processed from a previous study (Runkle et al., 2019). In other studies, CH_4 datasets with data coverage as low as 17% have been successfully gap-filled using an artificial neural network (ANN) (Irvin et al., 2021). Flux data in 2019 was limited due to problems with the equipment and was excluded from further analysis. We proceeded with gap-filling the remaining dataset using an ANN approach with a set of meteorological, phenological, and flux predictor variables. For further information about the criteria used for processing the raw data and for gap-filling, see the Supplemental Material.

2.4. Data analysis

Cumulative emissions from irrigation treatments were grouped and tested for normality using the Shapiro-Wilks test and for equivalence of variance using an F-test. The cumulative CH_4 emissions were of equal variances but not normally distributed when grouped by irrigation treatment, so a Mann-Whitney U test, a nonparametric equivalent of a t-test, was used to compare emissions between irrigation treatments. The data for each main (i.e., not ratoon) field-season was also compared by regressing the cumulative CH_4 emissions with the length of flooding events. Flooding and drying events of at least 24 h were counted beginning with the initiation of the first flood at the 5-leaf stage and ending with the final drain before harvest. Additional tests were performed with adjustments to the cumulative CH_4 emissions to account for the possible influence of year-to-year effects. Cumulative CH_4 emissions from the main and ratoon field-seasons were compared by not analyzed for significant differences because the small number of replicates for the ratoon treatment would render most statistical methods prone to error.

A previous study on the same fields for 2015 through 2017 used the 2017 season as a control to determine the impact of field-to-field differences on cumulative CH_4 emission, where the season-long South-to-North CH_4 emissions ratio was 0.67. (Runkle et al., 2019). We chose not to do so here as we explored it and found it did not qualitatively impact the results of this study. The cumulative growing degree days were used

Table 1
Planting dates, harvest dates, and field management practices for all years. Abbreviations: MS (main season), RS (ratoon season), DF (delayed flooding), and AWD (alternate wetting and drying). Dashes show that the field-season was a ratoon crop and was regrown from a main crop rather than seeded. Days under inundation was defined as the cumulative time the field spent inundated from sowing to harvest. Drying events were defined as periods where the water level fell at least 2 cm below the soil surface for a minimum of 24 h. Individual drying events with less than 24 h of flooded conditions between them were considered to be a single drying period. Only drying events after the initial flooding event and before the final draining event were counted.

Year	Irrigation treatment		Days under inundation		Number of drying events		Start of season		End of season	
Field	North	South	North	South	North	South	North	South	North	South
2015	DF	AWD	93	57	0	4	8-Apr	7-Apr	19-Aug	19-Aug
2016	AWD	AWD	76	63	1	4	23-Apr	23-Apr	13-Sep	13-Sep
2017	DF	DF	75	84	0	0	10-Apr	9-Apr	27-Aug	27-Aug
2018	AWD	AWD	66	36	3	3	30-Apr	30-Apr	15-Sep	31-Aug
2019	AWD	AWD	42	42	1	2	13-May	13-May	12-Sep	12-Sep
2020 – MS	AWD	AWD	77	90	1	2	2-Apr	2-Apr	19-Aug	18-Aug
2020 – RS	AWD	AWD	51	49	2	2	20-Aug	19-Aug	8-Nov	9-Nov

to normalize the cumulative annual CH_4 emissions for a possible year effect. Since the primary difference between years that can be accounted for with the data available is the climate, we divided the cumulative CH_4 emissions for each field-season by the cumulative growing degree days for each field-season, thus creating a "year-adjusted emissions" estimate. The temporal aspect of emissions was investigated by breaking the flux data for each field-season into vegetative, reproductive, and maturation stages based on predictions from the DD50 Rice Management Program (Hardke, 2022). Further information on the growth stages can be found in the Supplemental Material (Supplemental Table 3). A t-test was used to test the effect of irrigation method and field on the yield because the yield data between irrigation methods and fields was normal and of equal variance.

To determine whether the ratoon crop was cost-effective in this study, we performed an exploratory analysis of the cost of its production. The cost and net return of the ratoon crop was estimated using a rice crop enterprise budget (University of Arkansas Division of Agriculture Research and Extension, 2022), which considered the costs of the amount and method of application of pesticide, herbicide, and fertilizer, the fuel required for operating machinery and pumping water, hourly labor, equipment maintenance, and the expected return based on average price per yield.

2.5. Literature synthesis

Because rice ratoon cropping is not common in Arkansas, we performed a literature review and synthesis of recent rice ratoon studies that reported both main and ratoon yields. The literature search was performed using the University of Arkansas library database and spanned 1993 through 2021 encompassing 11 studies, 199 sites, and 2 countries. Only articles that included both the main and ratoon crop yield were included in the synthesis. Sites where the ratoon yield exceeded the main season yield were excluded. Poor main season yield in those papers resulted from lodging or other crop damage, and the purpose of this review was to gain a clearer picture of ratoon yield under good conditions. Data on fertilizer treatment and cultivar were also recorded when available.

3. Results

3.1. Climate

All seasons had greater annual precipitation than the 30-year average (1288 mm) with a range of 1411–1925 mm (PRISM Climate Group, 2014). The main growing season precipitation, defined as the precipitation from April through September, was greater than the 30-year average of 598 mm for all years except 2015, which was 390 mm (Supplemental Table 4). The 2020 ratoon season precipitation, defined as precipitation from August through November, was 506 mm, greater than the 30-year average of 381 mm (Supplemental Table 4). The monthly average minimum, maximum, and mean temperatures for the study years were not that different (within 1 °C) from the 30-year average except for 2016 which had an average annual minimum temperature 1.2 °C higher than the 30-year average. Compared to the 30-year average monthly mean temperatures, this study's main growing seasons were 1.1–3.9 °C warmer for April and July of 2015, June, July, and September of 2016, April of 2017, May and June of 2018, and May and September of 2019 (Supplemental Table 5). The average monthly mean temperature was 1.3–1.9 °C cooler than the 30-year average for August of 2017, and April, October, and November of 2020 (Supplemental Table 5).

3.2. Yield

For the main seasons, the yield varied little by year, with most yields in the range of 9–11 t ha^{-1} (Table 2, Supplemental Fig. 2). Both fields from the 2016 season had greater yields (11.0 t ha^{-1}) than the other field-seasons. The North field in 2018 suffered crop damage due to weeds and had the lowest yield of all the field-seasons (7.1 t ha^{-1}). Yield did not vary significantly by irrigation treatment ($p > 0.05$ using the t-test) or field ($p > 0.05$ using the t-test) (Supplemental Fig. 2). The ratoon yield for 2020 was 11.9% of the main yield for the North field and 13.9% of the main yield for the South field.

Table 2
Yield (13% moisture content) for the North and South fields during each season (ton ha^{-1}). Yield data was derived from a GPS-Enabled Combine Monitor, processed by Greenway Equipment (AR, USA).

Year	North field yield (t ha^{-1})	South field yield (t ha^{-1})
2015	9.3	9.7
2016	11.0	11.0
2017	9.8	10.6
2018	7.1	9.3
2019	9.1	8.6
2020 – Main Season (MS)	10.9	10.8
2020 – Ratoon Season (RS)	1.3	1.5

The literature review focused on ratoon cropping found studies from China and the United States. Seeding and irrigation methods varied between different studies – Chinese studies frequently transplanted rice, rather than directly seeding on either wet or dry ground as in our study and the other studies from the United States. While the irrigation method was not always stated, when available it was most commonly delayed or continuous flooding (i.e., without AWD). Main crop yields ranged from 5.6 to 12.1 t ha^{-1} and ratoon crop yields ranged from 0.6 to 7.4 t ha^{-1}, or 7.4–95.1% that of the main crop (Supplemental Table 6). Instances where the ratoon crop yield was higher than the main crop yield were attributed to damage to the main crop and were excluded from the synthesis. When split by location, the ratoon crop yielded 20.9–76.2% that of the main crop in the United States and 7.4–95.1% that of the main crop in China. The yields for our study were similar, with our main crop yields falling within the upper range of the synthesis main crop yields and our ratoon crop yields falling within the lower range of the synthesis ratoon crop yields (Supplemental Fig. 3).

Compared to the main crop, the financial input for the ratoon crop in this study was minimal. Herbicide was applied aerially to the main crop 7 times, but only once to the ratoon crop. Similarly, 112 kg ha^{-1} of diammonium phosphate (DAP) and 532 kg ha^{-1} of urea were applied to the main crop, while no DAP and only 168 kg ha^{-1} urea was applied to the ratoon crop. The ratoon crop required much less fuel for the use of heavy equipment than the main crop because the field was plowed only before the main crop. The ratoon crop enterprise budget had a net profit of 66.28 USD ha^{-1} for the South field and 5.74 USD ha^{-1} for the North field, making it cost-effective. The South field had a higher profit than the North field despite having only a slightly higher yield because the yield for the North field was 1.3 t ha^{-1}. The yield required for the farmer to breakeven for the field, with the cost of management and the income from the crop being the same, was 1.28 t ha^{-1} which is only slightly lower than the North field yield. The average profit for an Arkansas rice field in 2021 was 496.85 USD ha^{-1} (University of Arkansas Division of Agriculture Research and Extension, 2022); as expected the ratoon crop returned a lower profit than the main crop.

3.3. CH_4 flux dynamics

Most of the field-seasons followed a similar general pattern of low CH_4 flux early in the season, a gradual increase reaching a maximum in mid-to-late summer, and a decrease until the final draining period followed by a large spike (Figs. 2–4). Spikes were characterized by a sudden sharp increase in CH_4 flux followed by an equally sharp decrease. Spikes had a short duration—generally less than 3 days—and were determined by visual inspection of the CH_4 flux data. An exception to this pattern was the North field during 2015 (Fig. 2a), which had a

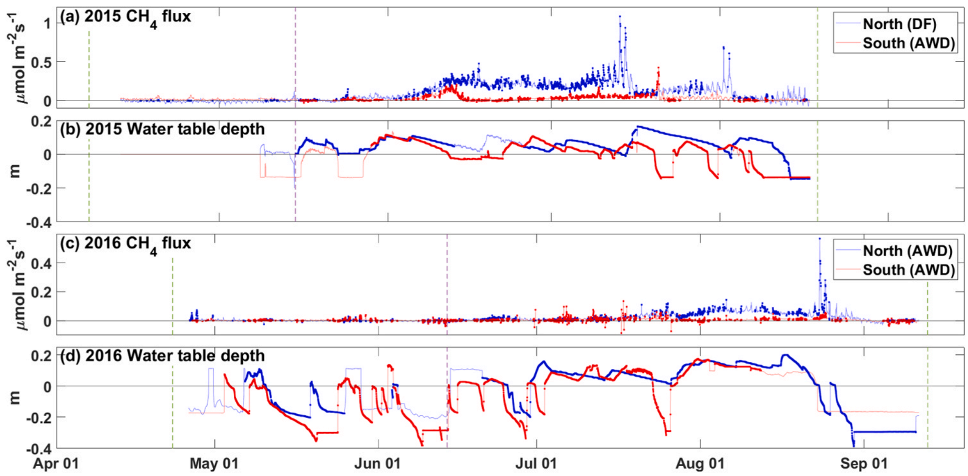

Fig. 2. : (a) Interpolated, gap-filled daily CH_4 flux for 2015. (b) Water level measurements for 2015. (c) Interpolated, gap-filled daily CH_4 flux for 2016. (d) Water level measurements for 2016. The North field in 2015 was managed with DF while the South field in 2015 and both fields in 2016 were managed with AWD. Note change in the y-axis scaling between (a,b) and (c,d). Darker points indicate observed data while paler lines indicate modelled data. Green dashed lines indicate planting and harvest dates. Purple dashed lines indicate flood initiation dates.

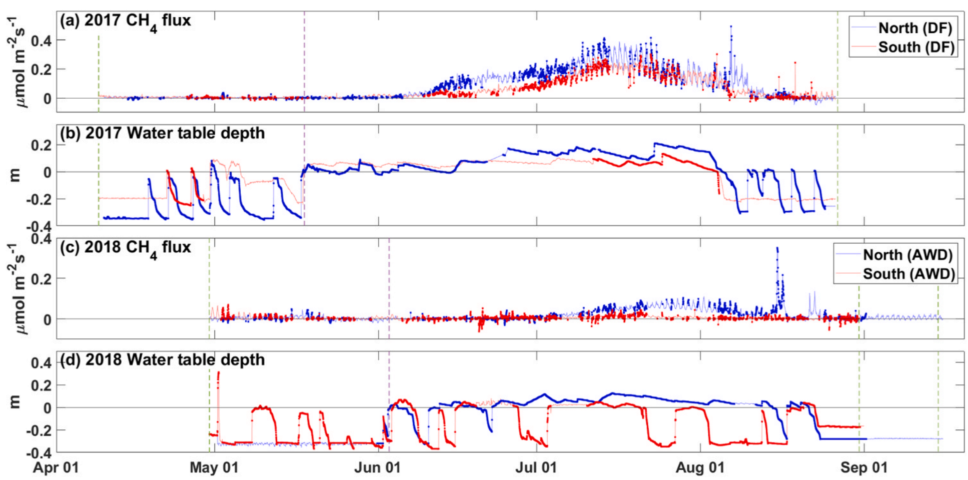

Fig. 3. : (a) Interpolated, gap-filled daily CH_4 flux for 2017. (b) Water level measurements for 2017. (c) Interpolated, gap-filled daily CH_4 flux for 2018. (d) Water level measurements for 2018. Both fields in 2017 were managed with DF while both fields in 2018 were managed with AWD. Note change in the y-axis scaling between (a,b) and (c,d). Darker points indicate observed data while paler lines indicate modelled data. Green dashed lines indicate planting and harvest dates; note that in 2018 the North field was harvested two weeks after the South field. Purple dashed lines indicate flood initiation dates.

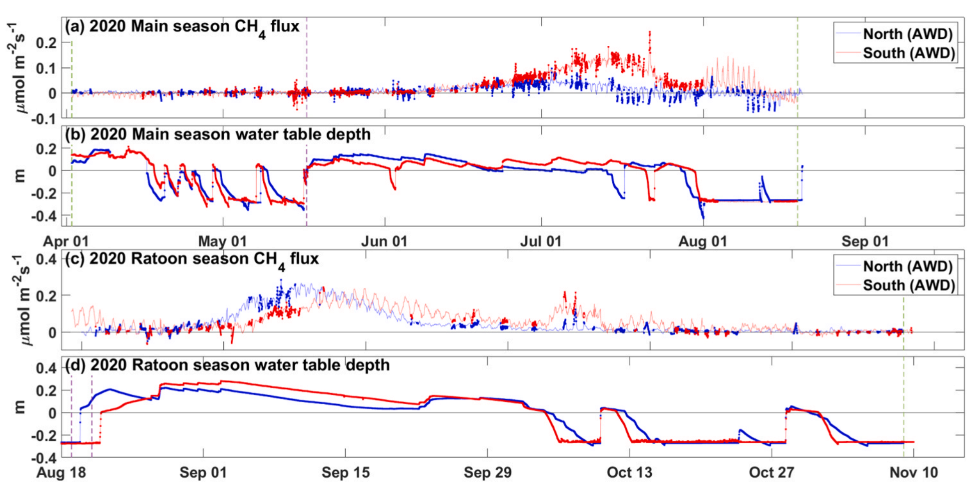

Fig. 4. : (a) Interpolated, gap-filled daily CH_4 flux for the 2020 main season. (b) Water level measurements for the 2020 main season. (c) Interpolated, gap-filled daily CH_4 flux for the 2020 ratoon season. (d) Water level measurements for the 2020 ratoon season. The main season and ratoon season fields were managed with AWD. Darker points indicate observed data while paler lines indicate modelled data. Note change in the x-axis and y-axis scaling between (a,b) and (c,d). Green dashed lines indicate planting and harvest dates. Purple dashed lines indicate flood initiation dates.

second period of increasing flux followed by a second peak before the final draining period. Additionally, the South field in 2015 (Fig. 2a), the South field in 2018 (Fig. 3c), and the North field in 2020 (Fig. 4a), all lacked the end of season flux spike. For all years except 2020, the North field had greater baseline flux levels than the South field for most of the season, regardless of irrigation treatment.

The CH_4 flux was related to the water level in the field as it tended to increase during flooded periods and at the beginning of drying events. Periods where CH_4 flux slowly increased corresponded to prolonged flooded periods, while most CH_4 spikes corresponded to the beginning of a drying event, as in mid-July for the South field in 2015. The drying events that corresponded to a flux spike occurred after longer flooded periods, and so were primarily during the latter half of the season. Early season drying events were not associated with CH_4 spikes. For field-seasons with multiple spikes, the post-spike fluxes were always lower than the pre-spike fluxes, suggesting that the drying periods did lower the flux rates, despite the initial increase. The field-seasons that did not have CH_4 spikes after the final draining event had drying events within the last month of the season, suggesting that CH_4 production was disrupted and unable to recover in the short period of time between the previous drying event and the final drain.

Spikes not associated with a drying event have other potential explanations. The spikes during July and August in the North field in 2015 (Fig. 2a) are associated with instances where the water level dipped below the soil surface briefly, suggesting that even without a complete drying event the water level was low enough to release the CH_4 trapped in the soil or water column. The spikes during August in the South field in 2017 (Fig. 3a) occur following the final drain and may be caused by remaining pockets of trapped CH_4 being released as the soil dries further. For all years, spikes from field-seasons treated with a DF regime (ranging from 0.1 to 1.1 μmol m^{-2} s^{-1}) rather than an AWD regime (ranging from 0.1 to 0.6 μmol m^{-2} s^{-1}) were larger.

The CH_4 flux rate increased more quickly during the early part of the 2020 ratoon season than the 2020 main season, reaching the same level as the maximum steady flux rate of the main season within three weeks (Fig. 4a, Fig. 4c). CH_4 flux during the main season took more than a month to reach this level (Fig. 4a, Fig. 4c). The field patterns for the ratoon season were also different from the main season: the South field flux was higher than the North field flux throughout most of the main season but was overtaken by the North field during mid-September of the ratoon season. Note that there is a disconnect between the low South field CH_4 flux at the end of the 2020 main season and the higher South field CH_4 flux at the beginning of the 2020 ratoon season. This disconnect results from separately gap-filling the ratoon and main seasons, and the South field lacked observed CH_4 data for that transition period.

The ratoon season responded to the irrigation treatment similarly to the main seasons, with spikes in both fields following the first drying event (here, on October 4). Then, the North field did not have a spike following the second drying event on October 11, possibly because the two drying events were close together, with only 1.6 days of flooding between events (Fig. 4b, Fig. 4d). Neither field had a spike following the final drain event on October 30, which was 9 days before the ratoon harvest.

3.4. Cumulative CH_4 Emissions

For all seasons except 2020, cumulative CH_4 emissions were greater from the North field than the South field (Table 3). Fields managed with DF produced greater emissions in general (Fig. 5). Fields managed with AWD produced lower emissions, though the magnitude varied depending on the duration and frequency of the drying periods. The North field in 2015 produced the highest emissions and had the greatest number of days under inundation (Table 1). The South field in 2018 produced the least emissions and had the least number of days under inundation (Table 1). The range of emissions from the DF treatments was 77.2–132.5 kg CH_4 ha^{-1} and the range of emissions from the main season AWD treatments was 5.8–40.7 kg CH_4 kg CH_4 ha^{-1}.

The ratoon season emissions in the North field were 2.6 times higher than the main season (Table 3). The ratoon season emissions in the South field were 24.6% higher than the main season (Table 3). On a yield-scaled basis, the ratoon seasons produced 8.9–30.5 times the CH_4 emissions of the main season (Table 3).

The irrigation treatment had significant ($p < 0.05$) impact on the cumulative CH_4 emissions, with emissions from field-seasons managed with AWD being 79.4% less than DF emissions on average for unadjusted CH_4 emissions and 79.6% less for year-adjusted emissions (Fig. 5). For 2015, which had paired AWD and DF irrigation treatments, the cumulative emissions from the field managed with AWD were 73.4% less on average than emissions from the DF field.

Seasons where the fields were managed with the same irrigation treatment still showed variation. The South field produced 75.5% and 78.2% less CH_4 than the North field in 2016 and 2018 respectively, when both seasons were managed with AWD. The reverse was true in 2020, with the North field producing 73.0% less CH_4 than the South field (Fig. 6). In 2016, the South field had 3 more drying events than the North field, and in 2018, the South field had longer drying events than the North field, with an average drying event length of 15 days for the South field and 5 days for the North field. In 2020 the North field water level was near or below the soil surface for approximately 26 days from mid-June to mid-July. The water level did not drop low enough to be considered a drying event but may have been sufficiently low to interrupt methanogenesis. For all 3 seasons the field with the greater number of cumulative days under inundation had higher cumulative CH_4 emissions (Table 1, Fig. 6).

The drying event length was approximately 3–5 days for most field-seasons with about 0–3 days standard deviation. However, in 2018 and 2020, the South field had drying events that did not fall within these ranges: in 2018 a long drying event lasted 29.7 days during late July and mid-August and in 2020 a short drying event lasted 1.1 days during early June. The length of flooding events for all field-seasons managed with AWD ranged from 1.5 to 54.7 days, with the average for each field ranging from 8.5 to 30.1 days. The length of these flooding events varied more than the length of the drying events, though the North field in 2016 had the longest flooding event in AWD-treated fields which lasted 54.7 days during June through August. The shortest flooding events occurred in June of 2016 and 2018, with the South field having an event of 1.5 days in 2016 and the North field having an event of 1.5 days in 2018. The length of continuous flooding for field-seasons managed with DF ranged from 71.2 to 88.4 days.

The cumulative CH_4 emissions for each flooding event and the length of the flooding event were significantly related ($r^2 = 0.77$, $p < 0.01$ using the F-test), with emissions increasing exponentially with the duration of the event for all fields managed with AWD (Fig. 7). The relationship was even more significant ($r^2 = 0.91$, $p < 0.01$ using the F-test) when extended to include fields managed with DF with only a slight change in the rate of increase (Fig. 7). We applied this second model with the events from the DF-managed fields to only the flooding events during the AWD-managed cases as a form of validation, and it dropped the r^2 to 0.67 and raised the root mean square error from 4.60 to 5.44 kg ha^{-1}. Flooding events in 2016 and 2018 were consistently below the line of best fit, while events in other years were more evenly distributed (Supplemental Fig. 4). The ratoon-season emissions associated with the longer flooding events in those seasons are approximately 2.3–2.6 times as high as the model would predict (Fig. 7).

Emissions were similar during the reproductive and maturation stages and were lowest during the vegetative stage (Table 4 and Fig. 8). The North field in 2015 was an outlier in both the vegetative and

Table 3
Management practices, cumulative CH_4 emissions, and yield-scaled CH_4 emissions for each field-season. Abbreviations: MS (main season), RS (ratoon season), DF (delayed flooding), and AWD (alternate wetting and drying). Uncertainty ranges were calculated from the 95% confidence interval of cumulative emissions variations from the 40 gap-filling runs, as in (Runkle et al., 2019), where errors due to gap-filling were significantly greater than the relative uncertainty of measured values.

Year	Irrigation treatment		CH_4 emissions, kg CH_4-C ha^{-1}		Yield-normalized emissions, kg CH_4-C ton^{-1}	
Field	North	South	North	South	North	South
2015	DF	AWD	132.5 ± 3.5	35.3 ± 5.6	14.2	3.6
2016	AWD	AWD	29.0 ± 1.1	7.1 ± 0.6	2.6	0.6
2017	DF	DF	114.5 ± 1.5	77.2 ± 2.2	11.7	7.3
2018	AWD	AWD	26.6 ± 1.5	5.8 ± 0.3	3.7	0.6
2020 - MS	AWD	AWD	11.0 ± 0.5	40.7 ± 1.5	1.0	3.8
2020 - RS	AWD	AWD	39.7 ± 1.0	50.7 ± 2.4	30.5	33.8

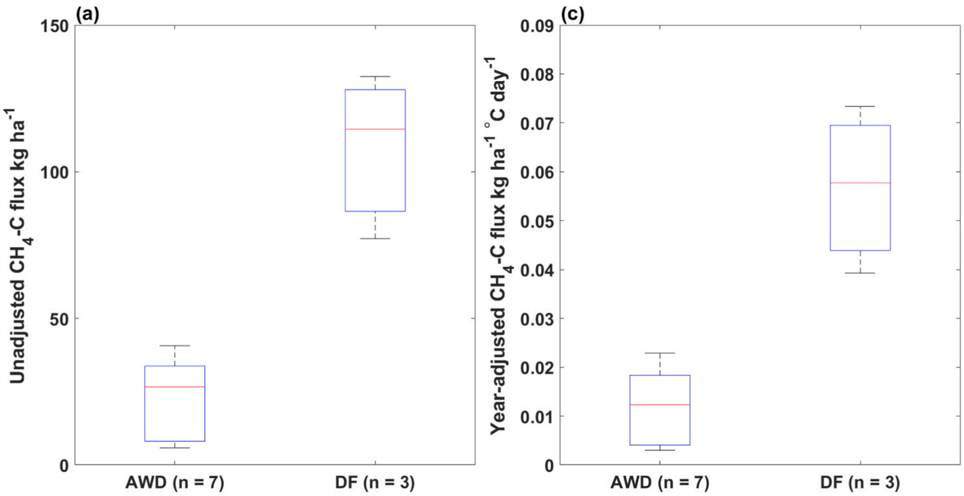

Fig. 5. **:** Plot of the ranges of (a) unadjusted cumulative CH_4 emissions and (b) year-adjusted cumulative CH_4 emissions under different irrigation treatments for the main seasons. Abbreviations: DF (delayed flooding), and AWD (alternate wetting and drying).

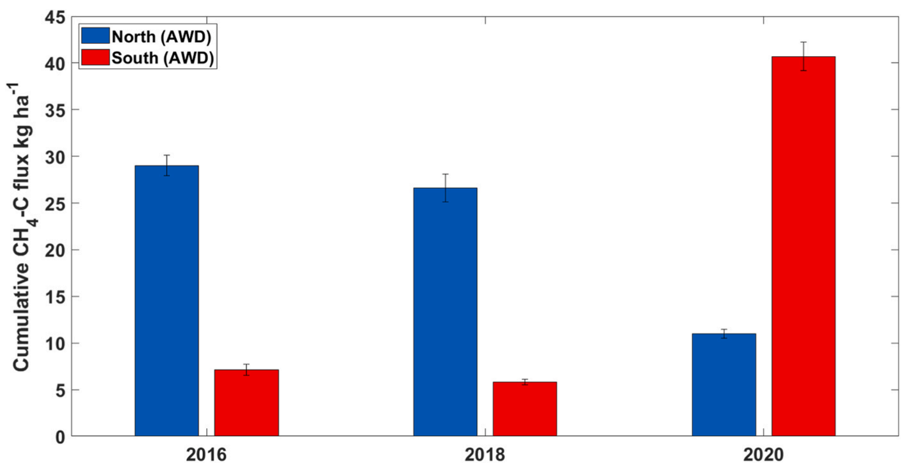

Fig. 6. **:** Plot of cumulative CH_4 emissions ranges for all seasons where both fields were managed with AWD.

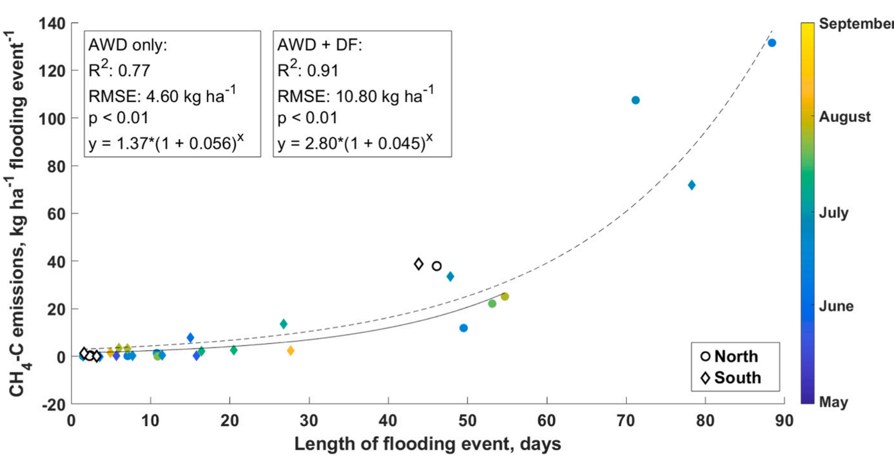

Fig. 7. **:** Cumulative CH_4 emissions per each flooding event for all field-seasons managed. The dashed line indicates the relationship for all main field-seasons (26 independent flooding events) while the solid line indicates the relationship for all main field-seasons managed with AWD (23 independent flooding events). The black outlined points indicate flooding events during the ratoon season and were not included in model creation. Each main season flooding event is color-coded by the month at the midpoint of the event. Note that the cumulative emissions include the 2 days following each event to catch any spike in emissions at the beginning of the drying event that is attributable to the release of trapped CH_4 generated during the flooding event.

reproductive stages, having the highest CH_4 emissions of all other field-seasons for the reproductive stage and the second-highest emissions for the vegetative stage (Fig. 8). The South field in 2015 was also an outlier in the vegetative stage, with the highest emissions of all field-seasons for that stage (Fig. 8). The outlier field-seasons were managed with different irrigation treatments, with the North field being managed with DF and the South field being managed with AWD. The South field in 2020 acted as a CH_4 sink during the vegetative stage, which can happen when the methanotrophic bacteria in the soil are more active than the methanogenic bacteria (Banker et al., 1995).

Table 4
Cumulative CH_4 emissions for each main field-season broken into vegetative, reproductive, and maturation growth stages. Uncertainty ranges were calculated from the 95% confidence interval of cumulative emissions variations from the 40 runs, as in (Runkle et al., 2019).

Year	Vegetative stage CH_4 emissions, kg CH_4-C ha^{-1}		Reproductive stage CH_4 emissions, kg CH_4-C ha^{-1}		Maturation stage CH_4 emissions, kg CH_4-C ha^{-1}	
Field	North	South	North	South	North	South
2015	8.4 ± 1.9	9.0 ± 5.3	80.0 ± 0.5	14.0 ± 0.5	45.2 ± 2.2	11.9 ± 1.7
2016	0.8 ± 0.7	1.1 ± 0.3	4.6 ± 0.3	2.8 ± 0.3	23.6 ± 0.8	3.3 ± 0.3
2017	1.2 ± 0.4	2.9 ± 1.5	51.4 ± 0.4	34.2 ± 0.4	61.7 ± 1.2	40.1 ± 0.9
2018	1.2 ± 0.4	1.6 ± 0.2	5.4 ± 0.1	1.8 ± 0.05	20.6 ± 1.2	2.7 ± 0.1
2020	2.0 ± 0.3	-0.4 ± 0.7	10.0 ± 0.1	21.2 ± 0.1	-0.6 ± 0.4	19.4 ± 1.2

4. Discussion

4.1. Management effects on CH_4 fluxes and yield

This study considered the effect of multiple management practices on rice yield and CH_4 emissions in Arkansas. While it is difficult to fully separate the individual treatment, field, and season effects, we used several complementary approaches to draw our conclusions. First, we minimized interference by selecting similarly treated fields and/or time periods for comparison. Second, we adjusted data for year-to-year variation when necessary. Third, we tested patterns across both separate and combined datasets to more carefully attribute changes to seasonal emissions.

Some differences in cumulative CH_4 emissions cannot be attributed to irrigation management. The paired fields were adjacent, zero-grade-levelled, and grown under the same climate conditions during each season, but in all seasons except 2020 the North field emitted more cumulative CH_4 than the South field, even when irrigation treatments were the same for both fields. This effect may be partly due to differences in soil composition between fields. Both fields had soil that was at least 90% Perry silty clay, but additional soil texture analysis reported in Runkle et al. (2019) showed significantly higher clay content in North field than South field (60 vs. 41% at 0–10 cm depth). Soils with a lower clay content are generally assumed to have greater potential for CH_4 emissions, as clay soils tend to trap CH_4 below the surface (Le Mer and Roger, 2001; Linquist et al., 2018). However, the North field, which had the higher clay content, emitted more CH_4 than the South field. It is possible that during short drying events, the field (North) with higher clay content retained more moisture than the field (South) with lower clay content, leading to greater CH_4 production and emission. Other differences in soil composition between fields such as different levels of soil organic matter and different soil microbiomes may also affect CH_4 emissions. Soil with high organic matter content has greater potential for methanogenesis than soil with low organic matter content (Cao et al., 1995), and the North field had significantly higher soil organic matter than the South field (Runkle et al., 2019).

The highest steady CH_4 flux rates occurred in July and August, which were the months with the highest mean temperatures, as well as the months when the rice plants had reached maximum vegetative growth and moved into the reproductive and maturation stages (Hardke et al., 2020). When broken down by growth stage, emissions generally increased during the later stages, reaching a maximum during the reproductive stage or the maturation stage. Methanogenesis is enhanced under high temperatures, and CH_4 transport from the soil to the atmosphere is most often mediated by the aerenchyma of the rice plants (Le Mer and Roger, 2001; Linquist et al., 2018). In later growth stages the plants also have higher biomass and therefore produce higher levels of the root exudates that provide substrate for methanogenic bacteria (Neue et al., 1997). The combination of favorable conditions for methanogenesis and high rates of plant transport likely led to high rates of CH_4 flux during the late summer at the Arkansas rice fields.

Irrigation practices had a significant effect on CH_4 emissions in this study, with AWD reducing emissions by 73.4% with respect to the DF treatment; similar to our previous, comparable results for 2015–2017 (Runkle et al., 2019). Both studies had emissions reductions within the range of other AWD studies performed with the chamber technique on United States rice fields, between 39% and 83% (Karki et al., 2023; Linquist et al., 2018). The level of emission reduction was not the same for all AWD field-seasons and cumulative CH_4 emissions from fields under the same treatment differed (Fig. 6). This difference indicates that AWD management was not consistent between fields. There were variations in the length and duration of drying events between fields, and reducing the time the field is inundated can reduce CH_4 emissions (Balaine et al., 2019; Linquist et al., 2015). It is also possible that differences in seeding method between years influenced emissions, as some studies have found water seeded rice to produce higher CH_4 than dry seeded rice (Hang et al., 2014; Ko and Kang, 2000; Tao et al., 2016). As we only had CH_4 data for one water seeded year we were unable to determine if there was any significant difference in emissions between the two seeding methods.

The flooding event duration was significantly, positively related to CH_4 emissions. As longer flooding events also imply fewer or shorter drying events, the extension of this result is that fewer or shorter drying

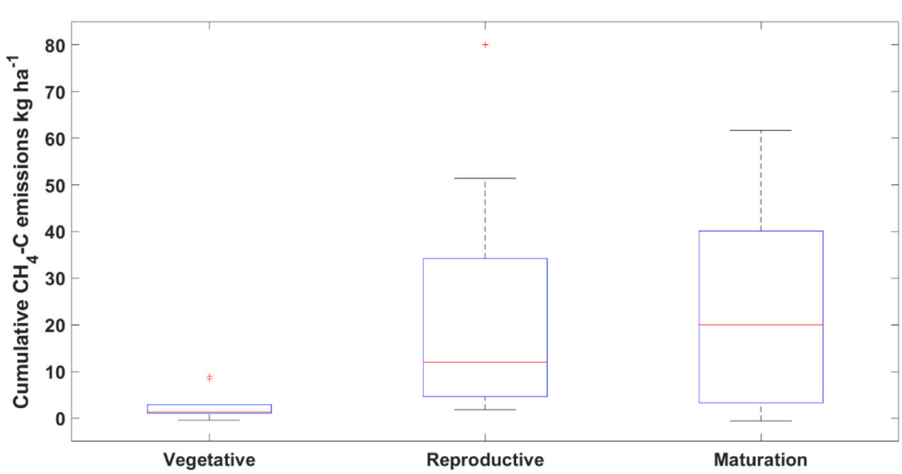

Fig. 8. : Cumulative CH_4 emissions for the main seasons during each growth stage, across all field-seasons and irrigation treatments.

events result in higher CH_4 emissions than longer or more frequent drying events. This finding is similar to Perry et al. (2022) which reported an 18% greater reduction in CH_4 emissions compared to a DF control for a 12-day drying event than an 8-day drying event and a 26% greater reduction in CH_4 emissions for a 12-day drying event than a 5-day drying event. That the relationship remained significant when fields managed with DF were included suggests this relationship is generalizable to other forms of irrigation treatment, which means it has potential to be developed into a model for estimating CH_4 emissions from rice fields.

Unlike Perry et al. (2022), we found that the length of the flooding and drying events also interacted with the timing of those events. All the flooding events associated with high CH_4 emissions occurred during the latter part of the season, though not all flooding events that occurred late in the season were associated with high emissions. Late-season flooding events that did not produce high emissions were of shorter duration, usually less than 15 days. The South field in 2018 had the lowest cumulative emissions in the study and the longest drying event of 29.7 days. This drying event occurred from late July to mid-August, during the maturation stage when emissions are highest. The North and South fields in 2020 both had long flooding events of 49.3 days and 47.8 days respectively, but North field had lower overall emissions. The long flooding event for the North field in 2020 occurred earlier in the season, during the vegetative and reproductive stages, while the long flooding event for the South field in 2020 occurred later, during the reproductive and maturation stages. The soil at our sites is mostly clay, and clay soils take a longer time after a flooding event to develop reducing conditions than silt loam soils (Brye et al., 2013), so longer flooding periods enhance methanogenesis, while interrupting them decreases it.

Some studies have found that irrigation treatments that reduced the overall time the field spent flooded resulted in lower yield, as forms of AWD with long drying periods resulted in water stress, weed growth, and susceptibility to disease (Bidzinski et al., 2016; Carrijo et al., 2017; de Vries et al., 2010; Linquist et al., 2015). Other studies found that AWD treatment had no effect on the yield with respect to DF (Balaine et al., 2019; Carrijo et al., 2018). This study did not find any significant difference in main season yield between AWD and DF. Another possible drawback is that the aerobic conditions such as those induced by AWD favor the production of N_2O, which is also a GHG (Akiyama et al., 2005; Kritee et al., 2018; Zou et al., 2007). However, several studies measuring N_2O emissions under AWD and DF found that there was no significant difference between irrigation treatments when N fertilizer application was managed appropriately (Chidthaisong et al., 2018; Karki et al., 2023; LaHue et al., 2016). When N fertilizer was applied during flooded periods and drying events occurred only after most of the N had been taken up by the crop, N_2O emissions were limited (Chidthaisong et al., 2018; LaHue et al., 2016). Karki et al. (2023), which was performed on the same fields used in this study during 2015–2019, attributed the similarity of N_2O emissions between irrigation treatments to the split application of N fertilizer which limited the amount of excess N in the soil.

4.2. Ratoon cropping

Guidelines from Texas and Louisiana extension offices say that farmers should expect the ratoon yield to be between 25% and 33% that of the main crop yield, while an overview of international studies found that the ratoon yield could be between 34% and 64% (Saichuk, 2014; Wang et al., 2020; Way, 2010). Our own analysis of recent studies in China and Texas found that the ratoon crop could vary significantly, yielding anywhere from 7.4% to 95.1% of the main crop under good conditions (Supplemental Fig. 3). When split by location the range of yields for studies in Texas was narrower than the range of yields for studies in China. The inconsistency of reported yields suggests that ratoon cropping depends strongly on location and management factors and highlights the need for further research.

The yield from our study's 2020 ratoon season was within the lower range of plausible values from the literature synthesis, but much lower than would be expected from the guidelines from the extension offices in neighboring states. Ratoon cropping is strongly influenced by timing. In temperate climates, the earlier the main crop is planted, the higher the likelihood of a successful ratoon crop (Dou et al., 2016). By extension, the harvest date of the main crop is also important since it determines the amount of time the ratoon crop will have to mature. The latest recommended main harvest date to initiate ratoon cropping in Louisiana is August 15 (Saichuk, 2014). Our fields were harvested 3–4 days later, on August 18 and 19. October of 2020 was 1.3 °C colder than average, and growth of the ratoon crop may have been slowed during that month due to the low temperatures. This mechanism could be further elucidated in follow-up studies with more ratoon-season data to compare. Ratoon cropping in the United States is also more common in Louisiana and southern Texas, which are areas with higher average temperatures and longer warm seasons than Arkansas (Bollich and Turner, 1988). Guidance for ratoon cropping suggests using early maturing varieties and planting early enough to avoid the negative effects of late-season cold weather (Saichuk, 2014; Way et al., 2014). Stubble height can also affect yield, with low to moderate stubble heights of 30 cm or less being generally considered to produce the highest ratoon yield (Beuzelin et al., 2012; Dong et al., 2020; Torres et al., 2020; Way et al., 2014). The stubble height for this study was deliberately cut higher than recommended in order to shorten the regrowth time and increase the likelihood of harvest before first frost (personal communication, Mark Isbell, 2022).

The 2020 ratoon season's CH_4 emissions were compared to the 2020 main season rather than other years' fallow season emissions because fallow season emissions tend to be much lower than growing season emissions (Reba et al., 2019). Fallow season emissions are highest during winter flooding (Reba et al., 2019), but winter flooding for the other years did not start until November which is when the ratoon season ended. We assumed CH_4 emissions during the equivalent fallow period (mid-August to early November) were negligible in most other years due to the lack of sustained flooding and the reduced level of biomass on the field due to the post-harvest burning of residual litter, the common practice in the years without a ratoon crop.

That the cumulative CH_4 emissions from the ratoon crop for this study were higher than the main crop emissions may be due to the August timing of the main crop harvest. August had the second highest mean and maximum temperatures for 2020. Between the continuously flooded conditions in the early part of the ratoon season, the high temperatures, and the ample substrate for bacterial growth provided by the residue from the main crop left on the field, conditions were favorable for methanogenesis. The ratoon emissions ranged from 39.7 to 50.7 kg CH_4-C kg ha^{-1}, which was comparable to the main crop emissions from other years with AWD treatment as in the South field in 2015 and 2020. The yield-scaled ratoon emissions, however, ranged from 30.5 to 33.8 kg CH_4-C ton^{-1} and were greater than yield-scaled main season emissions from any year in this study.

Ratoon season emissions in this study were higher than that of the main season, but they were relatively low when compared to the ratoon studies from the literature synthesis, which showed emissions ranging from 45 to 267 kg CH_4-C ha^{-1}. It is difficult to compare ratoon emissions because they differed greatly between studies. Some studies reported higher emissions, with ranges from approximately 67 to 307 kg CH_4-C ha^{-1} (Xu et al., 2022), or 294–1990 kg CH_4-C ha^{-1} (Lindau and Bollich, 1993), and rates of 188.62 kg CH_4-C ha^{-1} (T. Wang et al., 2021). Others reported lower emissions, from 0.59 to 32.6 kg CH_4-C ha^{-1} (Ding et al., 2021). Though the highest emissions came from a field managed with DF (C. Lindau and Bollich, 1993), the difference in range of emissions could not be directly contributed to irrigation management, as Xu et al. (2022) and T. Wang et al. (2021) studied ratoon crops managed with AWD, while Ding et al. (2021) studied ratoon crops managed with both DF and AWD but found no significant difference between them. Overall, the emissions from our ratoon season (39.7–50.7 kg CH_4-C ha^{-1}) fit within the broad range established by other studies.

The EC technique allows for continuous measurements of CH_4 flux over a large, field-scale spatial domain but it is not without limitations. The method is not suited for experiments with small-scale spatial heterogeneity (Baldocchi, 2014), and the data is subject to error due to interference with the operating of the sensors and field conditions that violate the assumption of homogeneity of the field (Chu et al., 2021). We minimized errors in the data by extensive filtering of problematic data points, the details of which can be seen in the Supplementary Material. Applying the EC technique on a full field also limits the number of possible replicates of a given treatment, which makes analysis between treatments difficult. Field-scale experimental studies with the EC technique are rare and, due to the cost of equipment and the limited number of available production-scale fields available. We believe that the data we have presented here is valuable as it is a rare ecosystem level analysis of CH_4 emitted from a ratoon crop managed with AWD. We cannot state whether it is representative of all ratoon fields under AWD conditions simply because the replicate number is low and the sites do not represent the conditions of the regions in Texas and Louisiana where ratoon cropping is more prevalent in the U.S.

5. Conclusion

This study expanded on the results of previous research by demonstrating a significant relationship between the length of flooding events and cumulative CH_4 emissions, as well as a general pattern of higher CH_4 emissions occurring later in the season. It is also one of few such studies performed on full production-scale fields using the EC method. Furthermore, we found these relationships may be useful for informing model building in the future. With the addition of more field-seasons of data or a different type of model we may be able to estimate emissions with a simple metric such as the length of flooding and drying events or the number of days under inundation. The CH_4 emissions increase between the ratoon and main crop was unambiguous but was also based on two sites from a single year, and additional years of ratoon cropping under EC are necessary to establish a baseline for CH_4 emissions from ratoon rice cropping in Arkansas.

We found no difference in yield between irrigation treatments. The ratoon crop was financially viable and ratoon crop emissions were low compared to previous studies in Louisiana, though yield from the ratoon crop was also low compared to the average of other studies from the literature review. Additional seasons of research to develop a standard for CH_4 emissions from ratoon rice under AWD and a better understanding of methods to increase ratoon yield without increasing emissions are necessary if ratoon cropping is to be considered as a sustainable intensification practice.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Benjamin R. K. Runkle reports financial support was provided by US Geological Survey, the University of Arkansas Water Resources Center, the National Science Foundation, and the US Department of Agriculture.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108652.

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