Methane emissions reductions from alternate wetting and drying of rice fields detected using the eddy covariance method

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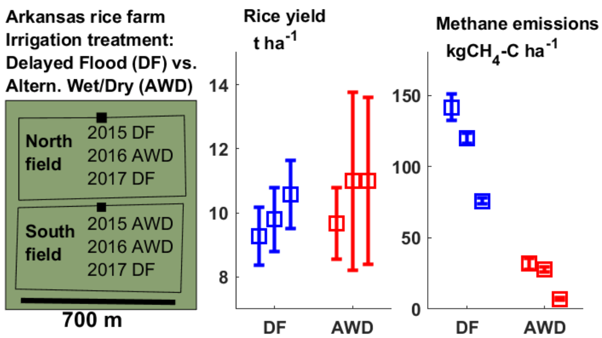

Abstract

Rice cultivation contributes 11% of the global 308 Tg CH_4 anthropogenic emissions. The Alternate Wetting and Drying (AWD) irrigation practice can conserve water while reducing CH_4 emissions through the deliberate, periodic introduction of aerobic soil conditions. This paper is the first to measure the impact of AWD on rice field CH_4 emissions using the eddy covariance (EC) method. This method provides continuous, direct observations over a larger footprint than in previous, chamber-based approaches. Seasonal CH_4 emissions from a pair of adjacent, production-sized rice fields under delayed flood (DF) and AWD irrigation were compared from 2015 to 2017. Across the two fields and three years, cumulative CH_4 emissions in the production season were in the range from 7.1-31.7 kg CH_4-C ha^{-1} for the AWD treatment and in the range 75.7-141.6 kg CH_4-C ha^{-1} for the DF treatments. Correcting for field-to-field differences in CH_4 production, the AWD practice reduced seasonal CH_4 emissions $64.5 \pm 2.5\%$. The AWD practice is increasingly implemented for water conservation in the U.S. Mid-South; however, based on this study, it also has great potential for reducing CH_4 emissions.

Introduction

Globally, 160 million hectares of land are under rice cultivation, with 1.2% of total production in the United States[1]. Within the U.S., Arkansas contains over 50% of total land planted to rice – 0.6 million hectares[2]. Global rice production generates 11% of anthropogenic CH_4 to the atmosphere[3]. CH_4 has 28 to 34 times the radiative forcing capacity of CO_2 over a 100 year time horizon[4] and recent rises in the atmospheric CH_4 concentration are largely due to anthropogenic activities[3]. Rice is the staple food of over 3 billion people[5], and its production is expected to increase. While reducing CH_4 emissions in rice production is important, any modifications to rice cultivation and field water management must not significantly affect yield.

Nearly all the rice grown in the United States is irrigated and flooded during a portion of the growing season, as is approximately 75% of world rice production[6]. The U.S. generates a rice yield (8.36 t ha^{-1}) nearly twice the world average (4.48 t ha^{-1})[1]. The majority of water needed to sustain rice production in Arkansas comes from pumping already depleted alluvial aquifers[7] and from capturing surface water in reservoirs[8,9]. Typical irrigation practice in Arkansas is to implement delayed flood (DF) following drill seeding, in which an initial flood is established at 4 to 5 leaf stage (beginning tillering) and then maintained at 5-10 cm until about two weeks before harvest[10].

Some producers aim to decrease irrigation water use in these systems by implementing the alternate wetting and drying (AWD) practice, in which the field is allowed to dry down before reapplying irrigation water. This method was developed and tested in Asia[11,12] and is economically viable in Arkansas[13]. In addition to enhanced water conservation, in longer dry down periods, AWD better interrupts anaerobic soil conditions, thereby reducing CH_4 emissions[14–16]. AWD can be more successful on zero-grade fields (no slope) that enhance water delivery options and timing, and enable efficient capture of rainfall. Although only about 12.3% of total rice in Arkansas is grown on zero-grade fields, the practice is growing due to the potential to save 40% of irrigation water applications[17,18], to serve as a carbon-offset credit option[19], and additional economic benefits[20,21]. AWD is under consideration as a Clean Development Mechanism to reduce CH_4 production from rice agriculture in developing countries[22], and should reduce net CH_4 emissions regardless of field grade.

AWD can reduce CH_4 emissions from rice fields either without affecting yield or with relatively minimal losses[23–27]. A one week, mid-season drainage event can interrupt soil anaerobic decomposition enough to reduce CH_4 emissions by 64% with no evident effect on yield[28]. Moderate AWD irrigation management can increase yield and plant growth[29] and has benefits for the rhizosphere[30]. Verification tests of reduced CH_4 emissions from AWD have been performed with the static vented chamber method on potted rice or in plot trials[31–33,24,34]. If used optimally, chamber measurements are easy to use and detect low flux rates[35]. Unfortunately, chamber measurements capture small footprints (several plants), risking to miss natural spatial variation in soil, plant, or growth conditions. Spatial variability can lead to large uncertainty levels of 40 - 60 % in the calculated flux values due to uneven fertilizer spreading or localized variation in water level[36]. Additionally, typical weekly sampling rates in chamber studies often fail to capture daily variations in weather and plant growth that affect gaseous emissions[37].

The goal of this study was to determine the degree of reduction in field CH_4 emissions that could result from AWD in a typical U.S. Mid-South rice production system via direct measurement. The use of the eddy covariance (EC) method with paired fields of AWD and delayed flood (DF) rice production is unique to this study. The results presented here are based on three growing seasons of data and provide a base for future research efforts to reduce agricultural water consumption and corresponding greenhouse gas emissions without affecting the yield.

Materials and Methods

Site information. Two commercially farmed, adjacent rice fields (34° 35' 8.58" N, 91° 44' 51.07" W) located in Lonoke County, Arkansas, were used for this research in 2015, 2016, and 2017 (Figure 1). Each field was approximately 26 ha: 350 m from north to south and 750 m from east to west. In 2015, the North field was managed with delayed flooding (DF) and the South field was managed with the AWD system, facilitating a direct comparison of the two irrigation practices with minimal spatial separation. To test each irrigation practice under similar climate conditions, in 2016 both fields were under AWD management and in 2017 both fields were under DF management. The fields were zero-grade leveled in 2006, have also been in continuous rice production, and have similar historical harvest yields. The sites were tilled before the 2016 planting with a shallow disc harrow and were flooded each winter for two months for waterfowl habitat and hunting. The soil mapping unit in 100% of the North field and 93.2% of the South field is a poorly-drained Perry silty clay; with 2 ha of the southwest corner of the South field mapped as a Hebert silt loam soil[38].

In each study year, the fields were drill-seed planted with CL XL745 hybrid seed (Rice Tec., Alvin, TX), similar in its CH_4 production to other hybrids and demonstrated to generate less CH_4 than pure-line cultivars[39]. Planting and harvest dates, field water conditions, and wetting treatments, are in Table 1. In 2016, wet conditions delayed seeding about two weeks later than the other years; harvesting was similarly delayed. Cumulative time under inundation is defined as a water depth above the surface for more than one day since shorter inundation periods are either unintentional (i.e., are from rain) or associated with an irrigation flush to incorporate urea fertilizer. In most dry-down events the water depth was 10-15 cm below the surface prior to re-application of water. Urea application rates were 144 kg urea-N ha^{-1} in 2015 in three doses; 155 kg urea-N ha^{-1} in 2016 in two doses; and 155 kg urea-N ha^{-1} in 2017 in three doses. Diammonium phosphate (DAP) was applied at 18 kg DAP-N ha^{-1} (2016) and 20 kg DAP-N ha^{-1} (2015; 2017). Additional agronomic information such as fertilizer and pesticide application dates and rates is in Table S1.

Gas flux measurements. The fluxes of CH_4, CO_2, latent energy (LE), and sensible heat (H) were measured using the EC technique[40] within the Delta-Flux network[41]. The two identical measurement systems consisted of a 3D sonic anemometer (CSAT3, Campbell Scientific, Inc, U.S.), an open-path CO_2/H_2O infrared gas analyzer (LI-7500A, LI-COR Inc., Lincoln, NE, U.S.), and an open-path CH_4 analyzer using wavelength modulation spectroscopy (LI-7700, LI-COR

Inc.). The gas analyzers were calibrated before and after each season with a zero gas (0.0001%) and spanned and checked using gases from AmeriFlux traceable to World Meteorological Organization standards[42]. The instruments were installed on towers at each field, at 2.2 m (North field) and 2.1 m (South field) above the soil surface.

Measurements were recorded at 20 Hz through an Analyzer Interface Unit (LI-7550, LI-COR Inc.) with the LI-COR SMARTflux™ automated processing system. Each tower, equipped with EC sensors and other low-frequency biometeorological sensors, was located at the north end of each field, approximately in the center by east and west. The dominant southern winds enabled a data collection footprint over each targeted field. The flat, uniform terrain and extensive fetch (> 350 m) are well suited for micrometeorological observation. In each growing season, EC and biometeorological data were collected within three days after drill-seeding until within three days before harvest. In 2015, CH_4 measurements in the South field started five weeks later, on 15 May, due to instrument challenges.

Microclimate, plant, and soil measurements. The microclimate measurements were recorded with data loggers (CR3000 & CR1000, Campbell Sci., U.S.) and were taken on or near the EC tripod. Soil and water temperatures were measured using thermistors (107, Campbell Sci., U.S.) at depths of 4 cm (2015) and 2 cm (2016-17) under the soil surface (with three replicates near the tower site), at the soil-water interface (one sensor), and on top of the water surface (one sensor). These measurements were used to correct the ground heat flux term for heat storage above soil heat flux plates installed at 8 cm depth in 2015 and 4 cm in 2016-17 (HFP01SC, Hukseflux, Netherlands). Additional sensors measured air temperature and relative humidity (HMP155, Vaisala, Finland), 2-D wind vectors (05103-5 propeller wind monitor, R.M. Young U.S.), atmospheric pressure (Barometer 278, Setra, U.S.), and the four components of net radiation (CNR4 radiometer, Kipp and Zonen, Netherlands). Water depth was recorded with capacitive level transmitters (Nanolevel, Keller America, U.S.). The North field's water depth measurements were interpolated during 12-25 June 2015 due to data logging errors, but field observations showed that the field remained inundated during this period. In 2016 water depth data were gap-filled when data points were missing through a linear regression with collected dissolved O_2 concentrations at the soil-water interface (MiniDOT Logger, PME, U.S.). In 2017 water depth data were gap-filled via linear regression with gap-less data series from piezo-resistive ceramic loggers (Troll 100, In-Situ, U.S.A.) placed in the irrigation ditch on the field corners.

A GPS-enabled John Deere (U.S.) GreenStar 3 2630 Harvest Monitor recorded location-based wet and dry harvest weights from both fields, with measurements approximately 2 m apart. Yields were reported on a 13% moisture basis. Replicate grain samples from 2015 were analyzed by the University of Arkansas Rice Quality Laboratory[43]. Milled Rice Yield (MRY), the mass percentage of rough rice that remains as milled rice, and Head Rice Yield (HRY), the mass percentage of rough rice that remains as head rice, were determined for the 2015 harvest.

Prior to rice emergence, 7 April 2015, soil samples were collected along an equally spaced (100 m) N-S transect of the centerline of each field to determine soil chemical and physical properties. Four locations were sampled per field, with one additional point 100 m to the east. Five push probe samples at each location were aggregated for each of 0-10 cm and 10-20 cm depth intervals. Each field was then more extensively sampled on 17 October 2016 and 23 March 2017, with aggregated push probe samples taken on a 100 m grid spacing in the two depth increments. Samples were taken from 30 and 21 locations from the North and South fields, respectively, in 2016 and in 21 locations in each field in 2017. From these samples a number of analyses were performed at the Agriculture Diagnostic Laboratory of the University of Arkansas. Organic matter concentrations in the soil were measured by loss-on-ignition (LOI) after 2 h at 360 °C; electrical conductivity was measured on a saturated paste extraction. Elemental sodium concentrations were determined following Mehlich III extraction and analyzed on a Spectro Arcos ICP. Soil texture was determined using the hydrometer method[44]. Samples from the latter two dates were analyzed for carbon and nitrogen content using combustion and analysis on an Elementar VarioMax CN. Soil bulk density was also determined after drying and weighing replicates of 5 cm diameter core samples of known volume from each of the 0-5 cm and 5-10 cm depth intervals at three points per field from the N-S transect during the 7 April 2015 sampling.

Data processing. High-frequency data collected from the EC system was processed and quality controlled using EddyPro software (v. 6.2, LI-COR Inc., Lincoln, NE, U.S.) to compute half-hourly fluxes of CH_4, CO_2, latent energy (LE), and sensible heat (H). The high-frequency wind vector was corrected for flow distortion due to transducer shadowing[45]. Across both fields and all three seasons of data, the average increase from this correction was 3.6% for H, 3.5% for LE, 3.5% for the CO_2 flux, and 4.8% for the CH_4 flux, as indicated by the slope of the regression line between the corrected and non-corrected flux estimates. Typical EC corrections were applied within EddyPro using adjusted advanced settings, e.g., for spike removal, sensor separation distances, and lag detection[46–51]. Data were removed when the CH_4 analyzer's Relative Signal Strength Indicator was less than 10, for wind directions between 265° and 95°, for friction velocity ($u*$) < 0.1 m s^{-1}, when the quality flag was greater than 5 on a 9-point scale[52], and when random uncertainty errors in CH_4 flux were greater than 0.2 μmol m^{-2} s^{-1}. The output from footprint models in EddyPro[53,54] was used to keep data where 90% of the flux contribution was within 350 m of the tower, to prevent drift of flux source area from outside the field.

After filtering for wind directions, footprint size, and periods when the sensors either were without power or failed to produce an output, 29-41% of the half-hourly CH_4 flux data was available, depending on the field and season. After filtering for data quality, 21.7-26.9% of each growing season measurement period was represented with direct measurements. The majority of data was removed due to the friction velocity filter and the quality flag. For the CO_2, LE, and H fluxes, data coverage was higher, ranging from 23.1% to 34% of each measurement period. The energy balance was tested using the net radiation data, ground heat flux corrected for storage, and the H and LE fluxes. The average energy balance closure rate on 30-minute time scales were 0.73, 0.75 and 0.69 (North field, 2015-17) and 0.89, 0.69, and 0.82 (South field, 2015-17), respectively. The estimated energy balances were comparable to other EC study reports for wetlands (0.76 ± 0.13)[55,56] where soil heat flux and storage terms are especially difficult to measure. Spectral correction factors for the CH_4 flux were calculated and applied in EddyPro, and were similar between fields and years, with median values of 1.226 and 1.225 in 2015, of 1.224 and 1.231 in 2016, and of 1.224 and 1.237 in 2017, for the North and South fields, respectively.

The turbulent flux data were gap-filled using artificial neural networks (ANN), similar to recent EC research[57,58]. The ANNs use data equally apportioned into training, testing, and validating groups from natural data clusters identified using a k-means method. The procedure was replicated across 20 resampling runs with the median prediction used for gap-filling. Conservative uncertainty bounds for the seasonal budget were calculated using the 95% confidence interval of cumulative flux variations from the separate runs. The ANN models for CO_2, LE, and H fluxes included the following explanatory variables: decimal day since the start of the study period, leaf area index and plant height interpolated using growing degree day, u_*, air temperature, incoming solar radiation (R_g), vapor pressure deficit (VPD), and water depth. Soil variables such as moisture, temperature, and nutrient status were not explicitly included due to gaps in their time series. However, water depth directly impacts soil moisture conditions as well as redox state and oxygen availability, and air temperature is closely related to soil temperature. A lookup table approach was used to gap-fill the R_g and VPD time series[59]. Fuzzy transformation sets representing seasonality and the time of day were included[60]. The net CO_2 exchange was modeled separately for night and day values (separated by R_g = 5 W m^{-2}), where R_g and VPD were not included in the night values. Explanatory variables for gap-filling CH_4 flux included barometric pressure and the gap-filled turbulent flux time series of CO_2, LE, and H.

The ANN models for CO_2, LE, and H fluxes compared favorably (in coefficient of determination R^2 and root mean square error RMSE) to gap-filling with a standard moving-window lookup table approach that correlates flux magnitudes to common meteorological variables[59]. The ANN method also performed better than the moving-window method as the clustering algorithm helped avoid edge effects. The gap-filling model fit the North field's CH_4 flux data, for each year (2015-17) with R^2 of 0.81, 0.91, and 0.97 and root-mean-square error (RMSE) of 0.065, 0.016, and 0.019 µmol m^{-2} s^{-1}, while for the South field the CH_4 model fit with R^2 of 0.75, 0.23, 0.95 and RMSE of 0.026, 0.013, and 0.019 µmol m^{-2} s^{-1}. The R^2 in 2016 was lower for the South field since its fluxes were low relative to other years and to their variance. All H, LE, and CO_2 models had R^2 values greater than 0.90.

Statistical treatment and experimental design. In 2015, the two fields were treated nearly identically for 55 days after planting (see the agronomic calendar S1). Therefore, the 2015 season may be treated as a before-after-control-impact (BACI) change detection experiment[61,62], to better examine the impact of mid-season drainage by discriminating the field-to-field effect. Thus, this study in 2015 has replication in the "before" period, but not of the AWD impact itself. The "before" period allows a comparison of a time series of baseline CH_4 exchange prior to drainage. This method is subject to caveats, including temporal autocorrelation and missing replication in space or time[63]; however, the fields displayed similar qualitative responses, and the fields experienced near-identical meteorological conditions due to their adjacency. The effects of temporal autocorrelation and variation were small regarding the primary objective: the magnitude of CH_4 emissions reduction by AWD. Field differences were assessed, and field correction terms were generated in this period using two models. First, linear regression was fit to the "before" period to generate a slope for comparison between the two fields for each turbulent flux (CH_4, CO_2, H, and LE). These initial regression slopes were used to generate an estimate of field effects separate from treatment effects. Second, the ratio of cumulative modeled flux from each field during this initial period was used to remove the impact of uneven sampling from the data-generated regression estimate. Both ratios were tested as factors to be applied across the full growing season to estimate a counterfactual "control" scenario for the AWD-treated field's potential CH_4 emissions under an imagined delayed flooding but with its CH_4 production potential. This alternate scenario is used to compare between measured CH_4 emissions under AWD and DF to generate the treatment effect targeted in our research in a "BACI Model".

The treatment effect was investigated in the following two years, when the fields are treated similarly (AWD in 2016 and DF in 2017). The third year enables a full-season control as a second model titled the "Full Season Model", where field-to-field differences are assessed over the full growing season rather than the early growing season alone. The Full Season Model has two main benefits over the BACI Model: first, a field-effects factor based only on a period with low fluxes has greater uncertainty, and second, field differences in the early season may not be representative of field differences across the whole season. The field-effect derived from the 2017 growing season is then used to find a treatment effect for the AWD-DF experiment in 2015. The 2016 experiment is used to generate additional estimates of growing season CH_4 emissions during AWD conditions, but field effects in that year are difficult to disentangle from the treatment effect.

Results

Agronomic and environmental conditions. Meteorological conditions for the three growing seasons were compared to the 30-year (1981-2010) climate normal for Stuttgart, AR (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, compiled through the Southern Regional Climate Center, Louisiana State University, August 2018). Monthly mean temperatures were always within 1 °C of the 30-year normal except July 2016 was 1.2 °C higher, April 2017 was 1.6 °C higher, July 2017 was 1.1 °C lower, and August 2017 was 1.5 °C lower than the normal. Rainfall from Apr-Aug was wetter than normal (492 mm) in all three years, with values of 505 mm (2015), 627 (2016) and 868 mm (2017). In all years, daily maximum temperatures frequently exceeded 30 °C and the soil temperatures at 4 cm depth nearly always exceeded 20 °C.

Soil clay contents of the 0-10 cm depth differed between the two fields and were 60 ± 2.0% (standard deviation) and 41 ± 10% for the North and South fields, respectively ($p < 0.005$, $\alpha = 0.05$). At 10-20 cm depth, clay content was 62 ± 4% and 43 ± 7%, respectively ($p < 0.002$). In the North field all samples were classified as clay in the USDA soil triangle; in the South field most samples were silty clay or silty clay loam, one was clay and three were clay loam. Soil organic matter in the North field (3.6 % - 4.5 %) was significantly greater in the 0-10 cm depth than in the South field (2.5 % - 2.9 %), which was also true in the 10-20 cm depth (Table S2). The North field also had greater electrical conductivity, sodium, carbon, and nitrogen levels. Soil bulk densities in the 0-5 cm depth did not differ significantly between fields and averaged 1.34 ± 0.09 g cm^{-3} ($p > 0.05$). At 5-10 cm depth, the North field had significantly less dense soil (1.95 ± 0.19 g cm^{-3} for North field vs. 1.60 ± 0.12 g cm^{-3} for South field; $p = 0.003$).

The fields generated comparable yields with mean harvest yield not significantly different, and within 4-7% between fields (Table 2) in 2015 and 2017. In 2016, the yield monitor failed to capture the northern half of either field. A sub-area in the southern half of each was used to extrapolate a full-field yield estimate based on the ratio of the sub-area's yield to the full yield in the other two years (Figure S3; S4). The 2016 yield estimate was greater than the other years but also had a greater standard error (>2.5 t ha^{-1} vs. ca. 1 t ha^{-1}). Both sites experienced a West-East gradient in productivity, with some regions yielding > 12 t ha^{-1} and others yielding < 8 t ha^{-1}. This gradient is likely due to land leveling a decade previously, which moved topsoil and created higher soil fertility on the more productive east side. In 2015, the fields had milling yields that were similar and typical, where the North, DF-irrigated field had MRY of 72.1% and HRY of 58.1% and the South, AWD-irrigated field had MRY 71.9% and HRY 56.8%.

CH_4 fluxes. During the first 55 days in 2015, 216 half-hourly flux measurements passed all quality filters for the DF-treated field and 318 for the AWD-treated field. Of these, n = 103 were coincident at both fields and were well correlated ($R^2 = 0.75$) indicating similar mechanisms controlling CH_4 emissions, though they differed in magnitude (Figure 2 and Figure S1). The slope was 0.43 ± 0.03, indicating that the CH_4 production potential of the South (AWD-treated) was likely less than half that of the North (DF-treated) field. Cumulative, gap-filled fluxes during this time indicated that the South field emitted $40 \pm 16\%$ of the CH_4 emitted by the North field, and this ratio is used in the BACI Model. The other turbulent fluxes were more similar (Figure S2) with slopes ranging from 0.88 to 1.11 and R^2 from 0.94-0.96. Prior to the first dry-down in 2016 (26 April to 24 June), field CH_4 emissions were uncorrelated ($R^2 = 0.00$) with a slope of 0.01 ± 0.03, because the flux rates were very low, less than 0.08 μmol m^{-2} s^{-1} and most often less than 0.02 μmol m^{-2} s^{-1}. In 2017, the full growing season could be considered as a control with both fields under DF management. The fluxes were highly correlated ($R^2 = 0.71$) and had a slope of

0.61 ± 0.01. The ratio of cumulative, modeled fluxes in 2017 from the South field to North field was 0.63 ± 0.01, and this ratio is used in the Full Season Model.

During the full 2015 growing season, CH_4 fluxes were consistently higher from the DF-treated field than the AWD-treated field (Figure 3). Each dry-down period significantly reduced CH_4 emission, and fluxes generally took from one to three weeks after the new flooding to recover to the baseline emission rate, likely due to the time to re-establish reduced soil conditions and methanogenesis. Over the whole 2015 season, the South field emitted 31.7 ± 4.1 kg CH_4-C ha^{-1}, or 22.4% of the CH_4 emitted by the North field (Table 2). As stated earlier, the CH_4 production capacity of the AWD-treated field was 40-43% that of the DF-treated field. Using the BACI Model we then attributed CH_4 emissions reductions of 44 ± 22% to the AWD irrigation practice, using – conservatively – the error term associated with the gap-filled cumulative flux estimate of the field effect, rather than the slope method (with a lower error term).

The full-growing season results from 2016 (with both fields treated with AWD) and 2017 (with both fields treated with DF) are consistent with the 2015 observation of lower CH_4 emissions in the South field. The South field had emitted 26% and 63% of the North field's CH_4 in 2016 and 2017, respectively. The 2017 results indicate that the full-season field-to-field effect is less than modeled from the 2015 BACI analysis; using 2017's field ratio of 63 ± 1% resulted in an AWD treatment-induced emissions reduction of 64.5 ± 2.5% in the 2015 comparison. That the full-season emissions in 2017 are closer between fields than modeled from the 2015 data alone may have several causes. First, methanogens may take longer to become active in the South field, possibly due to soil texture or microbial community differences that impact redox chemistry and CH_4 production potential[64–66]. Second, differences early in the season may derive from differences in remnant litter or organic material found on the field at the onset of the growing season[67,32,68]. Third, early-season drainage is known to enable aerobic digestion of labile organic matter, leaving less available for later methanogenesis[69].

The 2016 results are harder to interpret for field-effects as the AWD treatments were not identical; the South field had more drying events, which may explain its lower CH_4 production relative to the North field. The CH_4 emissions in 2016, in the early, flooded period, were much lower than in the other years, possibly because of the tillage before planting in 2016 (only), which created soil mixing and better aeration. Plow tillage has been seen elsewhere to reduce CH_4 production due to reduced dissolved organic carbon content and a reduced methanogen community in the soil water[70]. On the other hand, it can also increase labile C availability from easily decomposable compounds of incorporated litter (thus increasing CH_4 emissions)[71]. Additionally, the later planting date may have induced more aerobic respiration of available litter prior to inundation in this case.

Flux dynamics. Following field flooding, CH_4 fluxes in both fields and in all years tended to increase slowly. The CH_4 emission time series were both punctuated by shorter, one- or two-day periods of higher CH_4 releases during active lowering of the water depth. This phenomenon – higher CH_4 emissions following a lowered water depth – occurred in both fields following the final drain event at the end of each studied growing season and several times in the 2015 season following drying events. A brief drying of the surface on the DF-treated field provoked a significant release of CH_4, with half-hourly emissions reaching 1.1 µmol CH_4 m^{-2} s^{-1} mid-day on 14 July 2015. A similar flush of CH_4 from the AWD-treated field was measured soon after the drying event on 20 July 2015 generating a peak flux of 0.45 µmol CH_4 m^{-2} s^{-1}. This type of abrupt CH_4 release was again seen when the DF field's water level dips below the surface for one half-day and measured emission rates of 0.8 µmol CH_4 m^{-2} s^{-1} are seen on both 1 and 2 August 2015. The neural network model predicts such peaks again during the final drainage period following 12 August 2015, though northeastern winds prevented measurement in this time. These flux peaks exist in both 2016 and 2017 at the final draining, with higher rates in the North field than the South field. These peak emission events after the loss of the water barrier may have been caused by a rapid loss of entrapped CH_4 in the soil and are also reported by other authors[72,73,24]. As seen in other studies[58,74], the spike in emissions in the immediate period following a drainage or dry down event has magnitude and timing dependent on soil texture, with some evidence that soils with greater clay content may entrap more CH_4 for release following field drying[72].

Discussion

This study is the first to compare DF to AWD treatments using the EC method in a field-scale rice production site, capturing greater spatial and temporal resolution (half-hourly) than chamber-based techniques. The main finding, that AWD can reduce growing season methane emissions by 64.5 ± 2.5%, is within the range of estimates for the U.S. Mid-South generated through chamber campaigns on trial plots. This past research has shown CH_4 emission reductions ranging from 48% to greater than 90% for AWD, depending on the duration and number of drying cycles[13,24]. A recent literature review identified reduction factors in the U.S. of 39% and 83% for single- and multiple-drain AWD, respectively[34]. In Asia 60% reductions of CH_4 emission are reported from AWD or mid-season drainage practices[31,32,68,69]. While both chamber and EC methods require filling gaps between acceptable measurements, the EC method captured different types of temporal variability that would be difficult to detect using a chamber-based approach. These variations include diurnal fluctuations in emissions, quick responses to draining and flooding events, and period where CH_4 fluxes initially ramp up. These variations can be further used to improve modeling efforts to predict irrigation effects on CH_4 emissions[75–77]. Spatially, the EC method smooths localized flux variances by integrating across its measurement footprint. It is, therefore, less prone to location bias but also reduces the nuanced spatial perspective of chamber methods.

There are several potential, and potentially interacting, factors that may drive field differences in CH_4 production and emission. High clay contents in the soil can impact CH_4 emissions by creating a physical barrier for gases to escape to the surface and are a potential buffer for redox potential following the imposed flood[78,79]. The greater clay content in the North field may induce poorer drainage and less aeration of that soil. CH_4 production from clay soils can be 23% less than in similarly managed silt loam fields[80] and has explained 25-41% of variability in CH_4 emissions in a recent meta-analysis[34]. There are additional differences regarding drying rate and mineralogical effects on redox dynamics. Therefore, it is not ideal for this experiment's analysis that the fields differed in terms of their methane emission potential, though the lower CH_4 emissions under AWD are quantifiably significant. Further field studies are needed to fully quantify the CH_4 emissions reduction potential of the AWD method.

Similarly, higher salinity levels may represent a potentially inhibiting factor for CH_4 production[81–84]. The North field emitted much larger amounts of CH_4 despite both higher clay content and soil salinity, which lends additional support to the effectiveness of the AWD irrigation practice in reducing CH_4 emissions. The North field soils do have higher organic matter content (indicated as LOI and percent carbon content), which is known to increase CH_4 flux potential by serving as a methanogenic substrate[85,32]. The North field has above average organic matter content relative to other studies in rice or soil properties in Arkansas (3.5-4.5% in the top horizon), likely correlated to the higher clay content[86,87]; compared to the South field (2.5-2.9%).

The DF treatment seasonal emissions (75.7, 120.0, and 141.6 kg CH_4-C ha^{-1}) are in line with other studies (71-195 kg CH_4-C ha^{-1}) on silt loam soils in Stuttgart, AR[24,73]. They are within the range (16.5–149 kg CH_4-C ha^{-1}) of growing season CH_4 emissions reported across the U.S. Mid-South rice region in a review of chamber studies taken on replicated small plots[88]. Using the IPCC emission factor[32,89] of 0.97 kg CH_4-C ha^{-1} day^{-1}, and applying it conservatively over inundated days, the IPCC estimate of 71-91 kg CH_4-C ha^{-1} is in range with the measured emissions. The present study's results represent only three growing seasons, but inter-annual variations in meteorological conditions, especially higher surface and soil temperatures, can significantly vary emissions by up to an order of magnitude. For example, an EC study of a flooded rice paddy in California reported a range of 25-111 kg CH_4-C ha^{-1} over seven growing seasons[58].

AWD appears to be an effective strategy for reducing CH_4 emissions from rice production in the U.S. Mid-South. While reducing CH_4 emissions is a major benefit of AWD, from a greenhouse gas perspective, the aerobic cycles of AWD can generate higher N_2O emissions than traditionally flooded rice fields[90–93]. However, based on previous studies, these N_2O emissions are generally not enough to outweigh CH_4 reductions in terms of global warming potential[24,94,95]. Although water management during the growing season in an AWD irrigated field could result in yield reductions with extreme soil drying (below 60% of saturated volumetric water content[24]), there was no yield reduction noted in this study. The direct measurements provide a platform for further process-based, mechanistic modeling of CH_4 production under different management regimes[96]. This study quantified the impacts of drying cycles by the most direct method known for vertical gaseous transport. This direct, production-scale knowledge will enable better communication between farmers, carbon credit programs, and other sustainability platforms. As other studies have indicated, AWD can help reduce water use by agricultural production in the already-depleted Mississippi River Valley Alluvial Aquifer[13,97,98]. AWD can increase economic gains to the producer by saving water applications and their associated energy costs[13]. The AWD management system, if implemented globally where appropriate, could greatly reduce annual CH_4 production and opens new opportunities for carbon trading.

Associated content

An agronomic calendar of farm activities (Table S1), a comparison of the turbulent fluxes of CH_4 (Figure S1), H, LE, and CO_2 (Figure S2) during the identical-treatment phase harvest yield calculations, soil information (Table S2) and yield calculations (Table S3, Figures S3 and S4).

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Table 1: Planting, harvest, irrigation, and inundation information, where the number of inundation cycles refers to the number of separate periods where the field was continuously under inundation. Irrigation treatments are abbreviated as DF (Delayed Flood) and AWD (Alternate Wetting and Drying).

Year	Field	Treatment	Date planted	Date harvested	Growing season length, days	Days inundated	Number of inundation cycles	Percent of season inundated
2015	North	DF	8 April	19 Aug	133	93	6	70%
2015	South	AWD	7 April	19 Aug	134	57	8	42%
2016	North	AWD	23 April	13 Sep	143	69	4	48%
2016	South	AWD	23 April	13 Sep	143	57	6	40%
2017	North	DF	10 April	26 Aug	138	72	5	52%
2017	South	DF	9 April	27 Aug	140	84	3	60%

Table 2: Harvest yield estimation by field and year, derived from GPS-enabled combine monitor (and normalized to 13% moisture content); CH_4 emissions are measured by eddy covariance and gap-filled by artificial neural network models. Yield in 2016 is more uncertain due to errors in combine recording and modeling whole-field yield from a better-measured sub-area (see SI). Data from AWD treatments are in italicized fonts. Errors in the cumulative flux indicate the 95% confidence interval based on the gap-filling procedure.

Yield, ton ha^{-1}	**2015**	**2016**	**2017**
North field	9.3 ± 0.9	*11.0 ± 2.8*	9.8 ± 1.0
South field	*9.7 ± 1.1*	*11.0 ± 2.6*	10.6 ± 1.1
Cumulative CH_4-C flux, kg CH_4-C ha^{-1}			
North field	141.6 ± 9.2	*27.7 ± 1.7*	120.0 ± 3.4
South field	*31.7 ± 4.1*	*7.1 ± 0.8*	75.7 ± 2.1
Flux per yield, kg CH_4-C ton^{-1}			
North field	15.3 ± 2.0	*2.5 ± 0.7*	12.2 ± 1.3
South field	*3.3 ± 0.7*	*0.6 ± 0.2*	7.2 ± 0.8

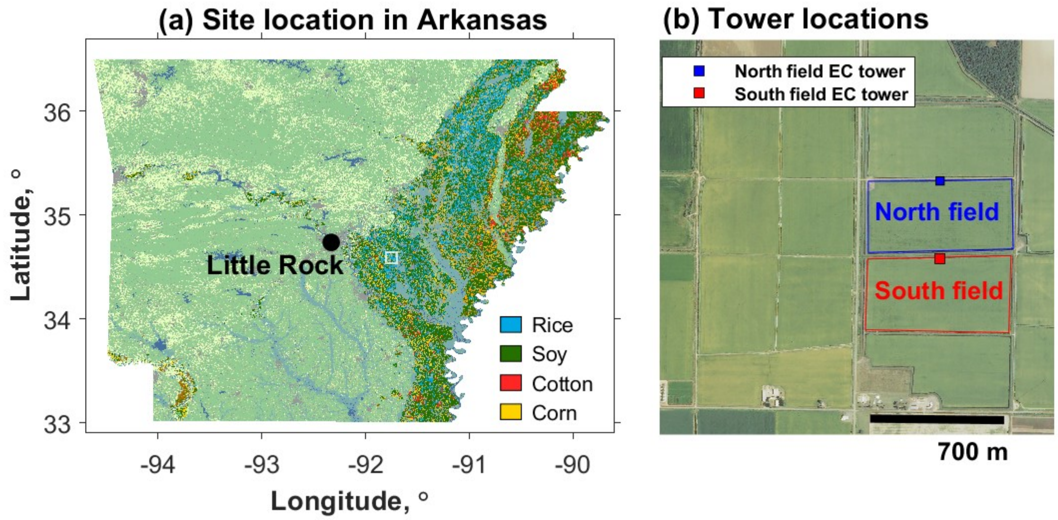

Figure 1: a. Field location (marked by white square near the town of Humnoke, Lonoke County, Arkansas) on the 2015 CropScape crop cover dataset from the National Agricultural Statistics Service*[99]* with selected crops in legend. b. The locations of the eddy covariance (EC) towers are marked on the north side of fields. The fields are separated by a drainage canal and two levees (North field: 34° 35'19.82 N, 91° 45'06.00" W; South field: 34° 35'06.71 N, 91° 45'06.10" W). The fields are roughly 26 ha each. Predominant winds are from the south. The background image is from the USDA-FSA-APFO Aerial Photography Field Office within the National Agriculture Imagery Program (NAIP) and was taken 22 August 2013.

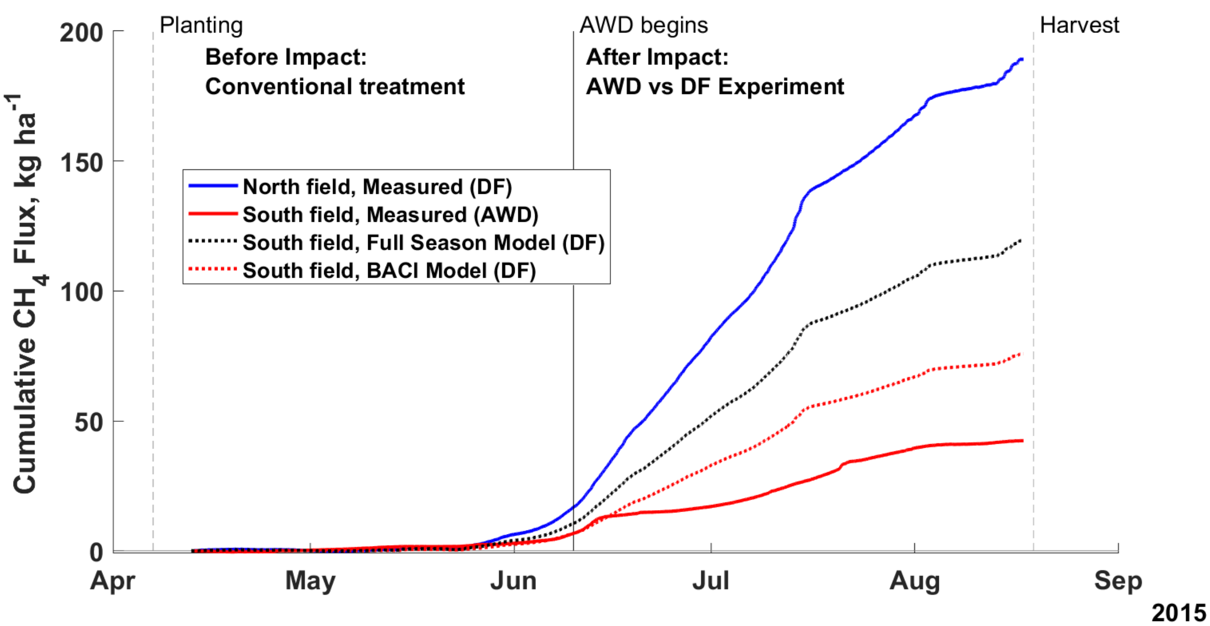

Figure 2: Cumulative, measured and gap-filled turbulent CH_4 flux observations from the two fields (full lines). Two counterfactual scenarios are presented (dashed lines) that represent modeled emissions of the South field under an imagined delayed flooding irrigation treatment on its same soil conditions. The BACI Model uses data from the initial period of 2015 and the Full Season Model uses data from the full 2017 growing season as a control, when both fields had DF treatment.

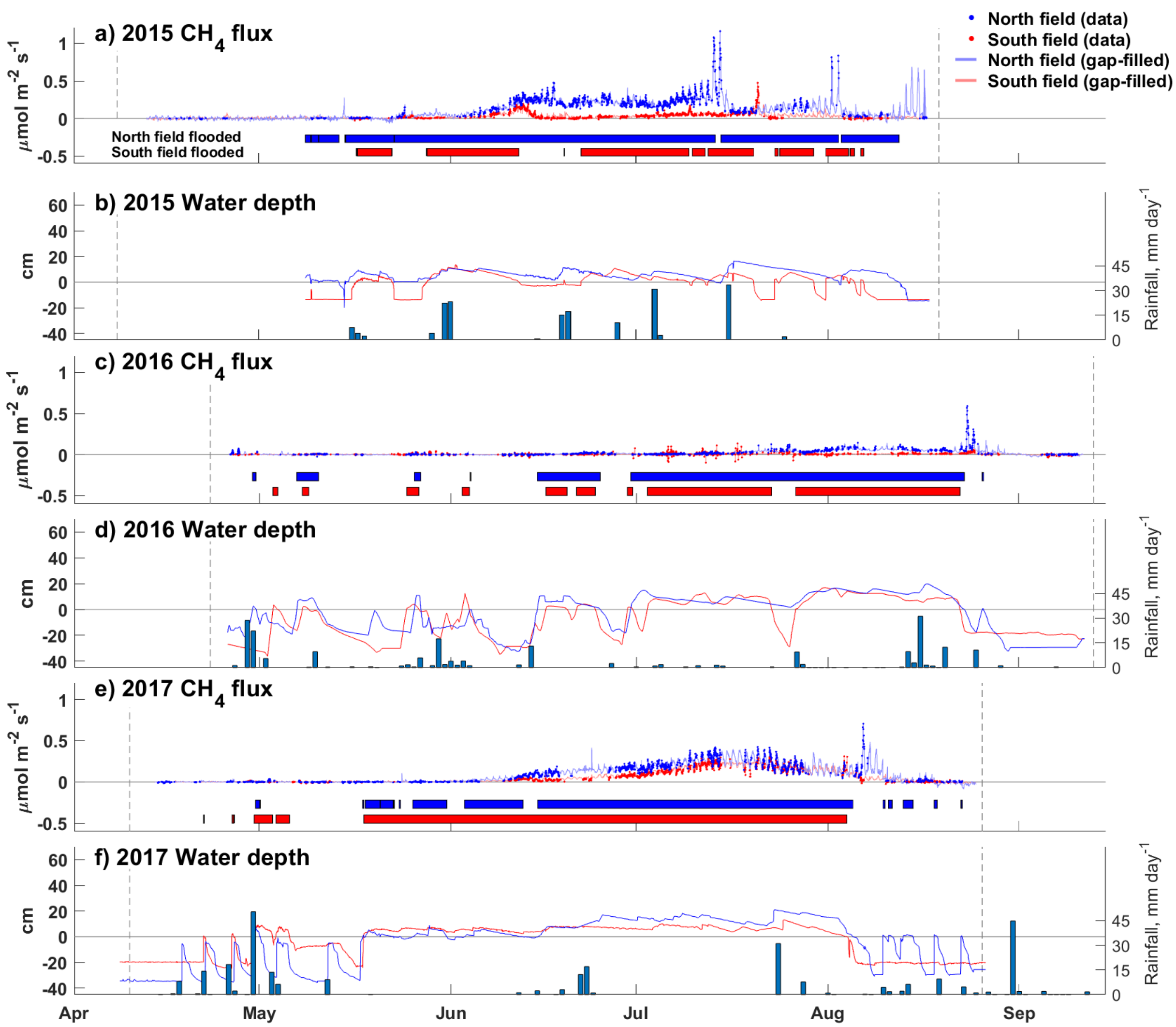

Figure 3: (a, c, e) Methane fluxes for the each growing season at two adjacent fields under different management regimes, with the inundation periods (defined where water depth was above the soil surface) indicated by bars below the CH_4 fluxes. Dots represent measured points and the lines represent the gap-filled model. (b, d, f) Water depth and rainfall.