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Research article

Eddy covariance assessment of alternate wetting and drying floodwater management on rice methane emissions

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A R T I C L E I N F O

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A B S T R A C T

Reducing methane emissions and water use is critical for combating climate change and declining aquifers on food production. Reductions in irrigation water use and methane emissions are known benefits of practicing alternate wetting and drying (AWD) over continuous flooding (CF) water management in lowland rice (*Oryza sativa* L.) production systems. In a two-year (2020 and 2021) study, methane emissions from large farm-scale (~50 ha) rice fields managed under CF and AWD in soils dominated by Sharkey clay (Sharkey clay, clay over loamy, montmorillonitic non-acid, thermic Vertic halauepet) were monitored using the eddy covariance method (EC). In the EC system, an open-path laser gas analyzer was used to monitor air methane gas density in the constant flux layer of the atmosphere over the rice-crop canopies. Total water pumped into the field for floodwater management was higher in CF compared to AWD by 24 and 14% in 2020 and 2021, respectively. Considerable variations between seasons in the amount of methane emitted from the CF and AWD treatments were observed: CF emitted 29 and 75 kg ha^{-1} and AWD emitted 14 and 34 kg ha^{-1} methane in 2020 and 2021, respectively. Notwithstanding, the extent of reduction in methane emissions due to AWD over CF was similar for each crop season (52% in 2020 and 55% in 2021). Rice grain yield harvested differed by only ±2% between AWD and CF. This investigation of large-scale system-level evaluation, using the EC method, confirmed that by practicing AWD floodwater management in rice, water pumped from aquifers could be reduced by about a quarter and methane emissions from rice fields could be cut down by about half without affecting grain yields, thereby promoting sustainable water management and greenhouse gas emission reduction during rice production in the Lower Mississippi Delta.

1. Introduction

Highly productive lowland rice, from seedling emergence until harvest, is normally grown in bunded fields filled with water; for that reason, the crop is considered the largest water-consuming cultivated food crop [1–3]. About half of the global population subsists on rice for their daily food-nutrition needs; as such, production demand for this commodity increases with the increasing population [2,4]. In addition to the evapotranspiration (ET) loss of water from croplands, water requirements for growing lowland flooded rice

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include water infiltration and deep percolated out of the rice root zone from floodwater-ponded soils [5–7]. Lowland flooded rice-based cropping systems were estimated to consume about 2–3 times more water than other irrigated crops [8]. The declining availability of blue water supplies for sustaining irrigated agriculture is already threatening vital food supply chains in the world [9]. Water used in irrigated rice production accounts for about 70% of this blue water supply globally [10]. After accounting for the re-use of floodwater that runoff from fields, it was estimated that rice crops can still consume 34–43% of the world's irrigation water supplies [8,11].

Alternate wetting and drying (AWD) is a floodwater management practice in rice and has proven to enhance water use efficiencies [12]. The International Rice Research Institute (IRRI) recommends the adoption of AWD as a rice water use reduction practice over continuous flooding (CF) systems [13]. In AWD, the field is initially flooded to about 5 cm ponding and left to dry down, whenever the water table in the soil drops down to about 15 cm below the soil surface, the field is irrigated back to the same level. However, to avoid water stress that can reduce grain yield, the 5 cm ponding needs to be continuously maintained for about a week before and after maximum crop flowering. Reductions in water use by about 40–70% under AWD water management in rice production over conventional CF systems were reported, while not significantly affecting grain yields [14]. The AWD rice systems require 25–70% less water than traditional CF systems without yield reduction [1].

In addition to the water consumption issues, agriculture also contributes to about a quarter of all the greenhouse gases (GHG) emitted from human enterprises, and about a tenth of all the methane emissions were from flooded rice fields [15–20]. An anaerobic environment is critical for CH_4 producing bacteria and the subsequent catalyzing methane synthesis and emissions from landscapes. Continuously flooded rice fields provide an environment that fosters these bacteria development [21, 22]. Consequently, water management, especially ponding level in the field, and field residue management practices significantly impact methane (CH_4) emissions [16,18].

Compared to carbon dioxide (CO_2), methane emissions are roughly 30% more potent a greenhouse gas and can stay unaltered in the atmosphere for over a hundred years [23]. The United Nations and the IPCC (Intergovernmental Panel on Climate Change) alerted the world to take immediate actions to reduce its emissions from anthropogenic sources [24,25]. Water-saving technologies such as AWD can also reduce the time rice fields remain submerged, thereby slowing down the anaerobic reactions in the soil environments that control methane production and emissions [13,20]. Notwithstanding, there were considerable differences between reported water use and methane emission potentials of AWD and CF fields that were related to climate, soils, landscapes, the scale of experiments, and instrumentation used for measuring fluxes of water and methane under flooded fields [13,20,26]. Recognizing the various levels of methane and water use reductions of AWD reported from field experiments [12], investigated methane emissions and reported a reduction of 49% in methane emissions (closed chamber measurements) and 42% in water used by the crop without compromising grain yield returns. In a three-year, closed chamber study [27], reported about 60–87% methane emission reductions by adopting AWD.

Numerous studies investigated methane emission potentials and water footprints of many flooded rice production systems across the world; however, they were spot measurements using closed-top chambers, so with limited spatial representation [16,26–31]. Large uncertainty hovers around the point-measured water consumption and methane emission values when scaling to larger farm-scale systems. In addition to the low spatial representation, the inability to continuously sample gases in such measurements has been recognized as a shortcoming when using those results to make management recommendations. Fast response, laser-based methane gas analyzers, and infrared gas analyzers for measuring water vapor densities coupled with 3-D anemometers enable continuously quantifying water vapor and methane fluxes from large-scale rice cropping systems and landscapes [32,33]. [31] compared methane emissions from rice fields measured using closed chambers and eddy covariance technology and reported consistent and comparable results. However [33], reported deviations between chamber and eddy covariance measurements during the mid-rice crop season.

In the Lower Mississippi Delta region (LMD), the largest continuous crop production area in the USA, rice is one of the important crops [34]. Water is normally pumped from the Mississippi River Valley Alluvial Aquifer (MVAA) to meet the irrigation water demands of crops grown in the region. The MVAA was reported to be declining at fast rates threatening the region's continued sustainable irrigated agricultural production [35]. Therefore, the major objective of this study was to use eddy covariance technology to monitor and compare continuous methane fluxes and water use in large systems-level evaluations of rice produced under CF and AWD flood water management systems in the LMD.

Table 1
Average physical and chemical properties of soils under continuous flooding (CF) and alternate wetting and drying (AWD) flood water treatments in the experiments in 2020 and 2021.

Soil Depth (cm)	Soil Texture	pH	Organic matter, %	CEC, Meq 100 g $^{-1}$	Mehlich-3 Extractable Nutrients (mg kg^{-1})							
					P	K	Ca	Mg	Zn	S	Cu	K_{zf}, cm hr^{-1}
Field used in 2020												
0–15	Clay	7.0	2.1	26.9	60	381	5550	1219	3.1	10.3	5.2	0.09
15–30	Clay	7.1	1.6	27.4	45	425	6732	1348	3.3	32.1	6.0	–
30–45	Clay/Silt loam	6.9	1.8	27.2	34	352	5067	1214	3.5	31.8	6.5	–
Field used in 2021												
0–15	Clay	6.4	1.6	24.0	25.0	183	3085	616	5.5	6.6	4.4	0.08
15–30	Clay	6.3	1.3	22.6	27.0	188	3080	628	4.2	7.1	4.2	–

K_{zf} = field saturated hydraulic conductivity, CEC = cation exchange capacity.

2. Methods and materials

2.1. Experiment

Studies were conducted in 2020 and 2021 on large-scale rice (approx. 25 ha fields for both CF and AWD systems) about 25 km from the USDA-ARS Water Management Research Unit's experimental farm in Leland, Mississippi, USA (33° 27′ N, 90° 91′ W, ~32 m elevation above sea level). The climate of the location is humid subtropical with warm summers and mild winter temperatures [59]. To a depth of about 1.2 m, the soil of the experimental farm is dominated by Sharkey clay (clay over loamy, montmorillonitic non-acid, thermic Vertic halauepet) (Table 1). The land and the crop belonged to a farmer, so all the soil-crop-water management practices followed for the crop cultivation were those generally recommended by the Mississippi State University extension service and followed by regional producers (http://extension.msstate.edu/agriculture/crops/rice). Fields were conventionally tilled using a shallow disc harrow in the fall after soybean (*Glycine max* L.) was harvested and tilled again before planting rice in March–April. Rice cv. 'Thad' was planted with a grain drill at a row spacing of 15 cm. The seeding rate was about 2,200,000 seeds per ha. 'Thad' is a medium-grain size, mid-maturity, medium height, and long-grain rice hybrid developed at the Mississippi Agricultural and Forestry Experiment Station, Mississippi State University, Stoneville, Mississippi. The fields were zero-grade leveled for rice planting. The CF and AWD fields were about 1 km from each other in 2020 and side by side in 2021. The fields used were under a soybean-rice rotation.

In both AWD and CF systems, the crop was planted on May 6, 2020, emerged after eight days and reached physiological maturity 110 days after planting (DAP). In 2021, the crop was planted on April 5, emerged after nine days, and reached physiological maturity 126 DAP. The fields were flooded using multiple side inlet and pipe planner designs for even-water distribution out of lay-flat poly pipes (https://www.deltaplastics.com/). Flood water application was a cascade distribution in which irrigation was applied at the head of the paddy field. Water-flow meters were used to measure the amount of water applied in AWD and CF treatments.

The CF field was kept to about 5–10 cm ponding depth by turning the pump on and off as needed. The AWD field was allowed to fall to a much lower water level before restarting pumping but never allowed to go mud-dry, keeping in view the region's blast disease sensitivity to aerobic soils. Authors did not have ponded flood water depth in the field measured using water level recorders due to technical difficulties; instead, soil water sensors were used (HydraProbe, Stevens Water Monitoring Systems Inc., Portland, OR, USA) at 10 cm depth in AWD and CF fields.

The Mississippi State University extension service's package and practices were followed for herbicide, fungicide, and insecticide applications, if necessary, and the fields were maintained weed and insect-free (https://extension.msstate.edu). Fertilizer applications were based on soil tests in both crop seasons. In 2020 and 2021, there were three applications of urea (NH_4N_2O) at 112 kg ha^{-1} and one application of ammonium sulfate $(NH_4)_2SO_4$ at 224 kg ha^{-1}. The same amount of fertilizer was applied in CF and AWD systems.

3. Plant measurements

Leaf area index (LAI) was measured fortnightly (cloud-free days only) using an AccuPAR LP-80 LAI meter (METER Group Inc., USA). Plant heights were monitored weekly. These measurements were replicated at 4 to 10 random locations in the field and averaged. Combine harvesters were used for harvesting and weighing rice grains from farms. The AWD and CF treatments were harvested separately. Grain weights were reported at 13% moisture.

3.1. Eddy covariance measurements for methane

In the eddy covariance method, the vertical flux of an entity of interest from the cropping system is represented as a covariance between the vertical velocity of air eddies originating from the system and the concentration of the entity of interest in it [36]. Detailed physical principles and derivation of the equations used for quantifying fluxes using the EC method, and limitations of the method and techniques used to overcome those limitations are available elsewhere [36–40].

One tower for siting eddy covariance (EC) sensors was placed in the middle of each field to have adequate fetch for gas analyzers and 3-D wind and other micrometeorological sensors installed on the tower. The average maximum height of the rice crop was 1 m, and the EC sensors were located constantly at 2.5 m above the plant canopy to measure fluxes in the constant flux layer for turbulence above the crop canopy [36]. The CF and AWD treatments were instrumented with identical sensors and sensor placement heights. As the EC towers carrying the sensors were centrally located in the large farm-scale (~ 25 ha) field, further investigations on directional wind impacts on footprints of the methane gas detected by the sensors were not investigated further under the given windspeed footprint of the gas remain constant in all directions around the EC tower.

In EC systems, the velocity of vertical transport of eddies from the cropping system (vertical component of the horizontal wind vector) was measured using a Gill Windmaster 3D sonic anemometer (Gill Instruments, Lymington, UK). Open-path LI-7500-DS infrared gas analyzers (LI-COR Inc., Nebraska, USA) were used for measuring water vapor density (for quantifying water and latent heat energy flux) in the vertically propagated EC tower. Methane concentration in the same EC tower was measured and quantified using a wavelength modulation spectroscopy-based LI-7700 laser gas analyzers (LI-COR Inc., Nebraska, USA). The anemometers and gas analyzers were mounted on telescopic, hydraulic height-adjustable towers. All the eddy flux measurements were recorded at 10 Hz frequency using an LI-7500 interface unit (LI-COR Inc., Nebraska, USA). The EC measurements started from the day of rice seedling emergence and continued until physiological maturity.

The authors also collected data for quantifying the impact of microclimate on rice growth and water and methane emission dynamics and quantifying solar and earth radiation energy balances in response to AWD and CF systems. Solar and earth radiation

(CNR4-L 4-component, Kipp & Zonen B.V., The Netherlands), air humidity and temperature (Vaisala, Finland), soil heat flux (Hukseflux, Finland), and rainfall (Tipping bucket rain gauge (Texas Electronics, USA), and photosynthetic photon flux density (Quantum Sensor, LI-COR, USA) were measured. The micrometeorological data were averaged and recorded on a data logger (Sutron Xlite, Germany).

The EddyPro v 7.0.9 installed in a Smartflux microcomputer (LI-COR Inc., USA) processed the raw eddy covariance (10 Hz frequency) data to compute fluxes at 30 min intervals. The Smartflux system installed on the EC tower received both the EC flux data and micrometeorological data for processing and flux computations. Quality control and further post-processing of the water, latent heat, sensible heat, and methane flux output from the Smartflux were carried out using Tovi™ software (LI-COR Inc) based on the OzFlux method [39] (https://www.licor.com/env/support/Tovi/topics/configurable-mds-gap-filling.html). The [41] procedure was used to eliminate periods with mild air turbulence due to calm wind speeds. The marginal distribution sampling technique developed by Ref. [42] was used to fill gaps in the latent heat, sensible heat, and methane flux data. The air temperature was selected as the driver for gap-filling methane flux as those data were without gaps and of the best quality.

4. Results and discussion

4.1. Crop canopy microclimate

When the primary source of flood water for growing rice crops in the LMD depends on groundwater, the water input from naturally occurring rainfall is paramount in easing pumping pressure on the aquifers. Observed rainfall during rice growth varied considerably between 2020 and 2021 (Fig. 1). From the emergence of rice seedlings to harvest, crops received 36.9 cm of rain in 111 days in 2020 and 44.5 cm in 124 days in 2021. Daily rainfall amounts varied between 0.01 and 6.5 cm in 2020 and 0.01–5.6 cm in 2021. The number of rainy days (days with rainfalls recorded above 0.01 cm) was 34 in 2020 and 49 in 2021. Most of the rainfall received was conserved and stored in fields with levies for ponding water.

Next to water inputs from natural rainfall, air temperature is another weather variable that drives crop growth, development, grain yield, and consumptive water demands (evapotranspiration, ET). Daily averaged air temperature (Ta) on the day of rice crop seedling emergence in 2020 was 18.3 °C, which increased to 23.5 °C when the crop reached physiological maturity, 112 days after seedling

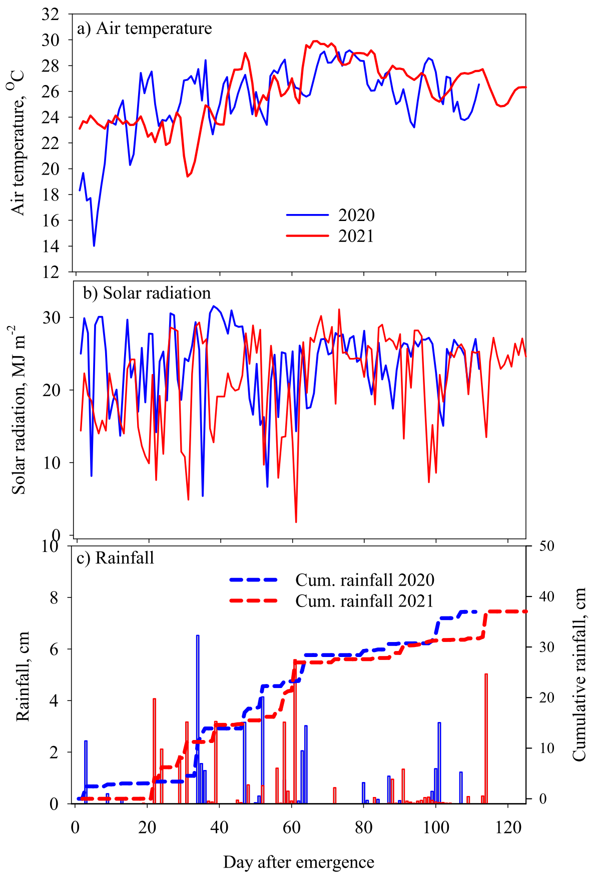

Fig. 1. Daily a) average air temperature (Ta), b) global solar radiation (Rg), c) total rainfall, and cumulative (cum.) seasonal rainfall during the rice crop season in 2020 and 2021.

emergence (DAE) (Fig. 1a). In 2021, similarly, the daily averaged Ta at seedling emergence was 23.1 °C, which increased to 27.6 °C at physiological maturity. The highest daily average Ta measured was 29.2 °C (on 76 DAE) during the 2020 crop growing period and 29.9 °C in 2021 (on 69 DAE). The daily average lowest temperature was 14.0 °C in 2020 (on 14 DAE) and 19.4 °C (on 31 DAE) in 2021.

Solar radiation is another natural resource critical for the fundamental plant growth process of photosynthesis (photosynthetically active radiation) and biomass accumulation in crop plants. Due to the LMD's humid climate, the experimental fields received considerable rainfall, as discussed above. The frequent clouding and rain events affected the amount of solar radiation falling on the crop canopy, which, across the two seasons, varied between 7 and 31 MJ m^{-2} d^{-1} (Fig. 1b and c). Owing to the higher number of rain events and associated overcast, the crop season in 2021 received lower amounts of solar radiation than in 2020, especially at the beginning of the season (Fig. 1b and c).

4.2. *Rice growth and grain yield*

As crops were grown stress-free with ample water and N applications across CF and AWD systems in 2020 and 2021, there were no appreciable differences in LAI measured (Fig. 2a and b). In 2020, rice grown under the AWD tended to develop slightly higher LAI at the beginning of the season but coincided with LAI in CF towards the end of the season (Fig. 2a). The maximum LAI measured in 2020 was 6.3 m^2 m^{-2} on 96 days after seedling emergence (DAE) under AWD and 6.1 m^2 m^{-2} on 92 DAE under CF. In 2021, the maximum LAI measured was 6.4 and 6.1 m^2 m^{-2} on 77 DAE under AWD and CF management, respectively (Fig. 2b).

Harvested rice (grain) yield was 2.2% greater under AWD in 2020 than CF (12.1 Mg ha^{-1} under CF vs. 12.4 Mg ha^{-1} under AWD) (Table 2). In 2021, rice grain harvested in AWD was 2.3% less than CF (14.5 Mg ha^{-1} under CF vs. 14.2 Mg ha^{-1} under AWD). Over the past century, the agricultural water management community noticed excessive water requirements for ponding in paddy rice fields for growing flooded rice [43]. Still, the need for this staple food crop for billions of people across the globe necessitated its continued cultivation with the growing scarcity for freshwater from fast-declining aquifers [44]. examined the efficacies of a CF with intermittent irrigation applied when water in the soil depleted to various levels and revealed that plant growth and grain yield would not be compromised when water was re-applied when the soil water potential depleted between 0 and -10 hPa, but depletions above this level was found to reduce yields.

In 2020, five major flooding and drying cycles were imposed, roughly until 70 days of seedling emergence (DAE) (Fig. 3a). Between 60 and 70 DAE, the plant reached the pre-booting stage. This stage also coincided with the active internode elongation stage. From this

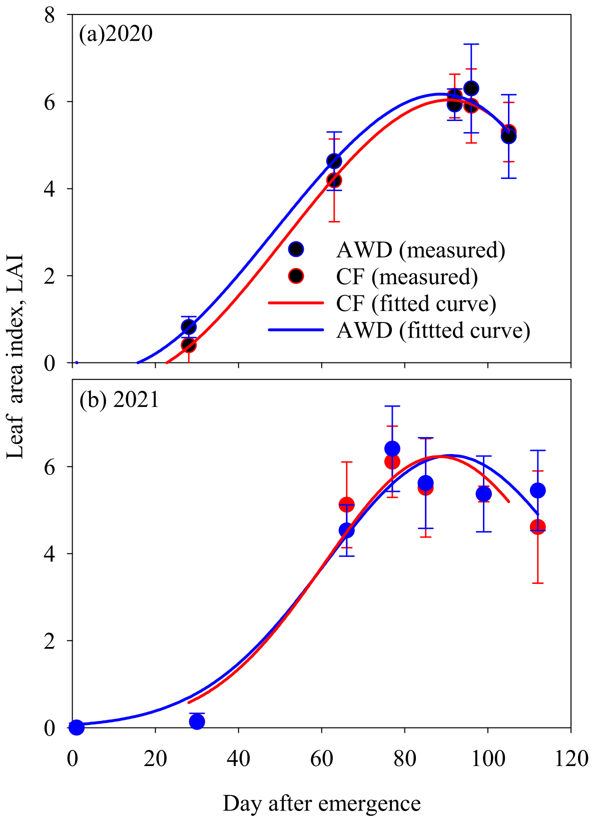

Fig. 2. Measured and fitted leaf area index (LAI) of rice grown under continuous flood (CF) and alternate wetting and drying (AWD) flood water management in 2020 and 2021 near Stoneville, Mississippi. Quadratic polynomials were fitted to spot LAI measurements to get smooth, continuous curves for comparison.

Table 2
Irrigation water applied, methane gas emitted, and grain yield harvested from rice fields managed under continuous flood (CF) and alternate wetting and drying (AWD) flood water management in 2020 and 2021 in the Lower Mississippi Delta. Crop duration is from day after emergence (DAE) to physiological maturity (R5) stage.

Flood water management	Irrigation applied, cm	Methane, kg ha^{-1}	Grain yield, T ha^{-1}	Crop duration, days
	2020			
CF	58	29	12.1	115
AWD	44	14	12.4	115
Difference (%)	−24	−52	2.2	
	2021			
CF	44	75	14.5	126
AWD	38	34	14.2	126
Difference (%)	−14	−55	−2.3	
Average difference (%)	−19	−53	0	–

stage, the farmer treated the AWD similar to CF treatment in irrigation and maintenance of ponded flood water. Normally, the full or late boot stage occurs in rice plants when the flag leaf has wholly stretched. Booting stage is where meiosis happens, and environmental stresses during this stage may reduce rice grain yield substantially [45,46]. As such, the farmers in this study did not continue AWD after this growth stage (Fig. 3a and b).

In addition to the rainfall received, additional water applied to the fields under CF management in 2020 was 58 cm, while the water applied to AWD was 44 cm (Table 2) – a reduction of 24%. In AWD, intermittent irrigation about 1–5 days after the disappearance of flooded water from the field reportedly reduces water use between 25 and 50% without lowering harvested grain yields significantly [47]. When the field is flooded like in CF, vertical movement of water beyond the root zone of the crop, known as 'deep percolation,' is a major endpoint of flooded water rather than being used to meet rice ET demands [48]. reported that a system with sufficient soil water for rice plant uptake could yield as good as a system with ponded water provided fields is not affected by weeds-related stresses. Growing rice under flooded conditions requires large quantities of water, and the primary use of the flood is as a tool for keeping the field weed-free [5,8].

In the 2021 season, until 50 DAE, three major wetting and drying events were applied (Fig. 3b). The CF treatment was supplied with 44 cm of water for keeping about the 5–10 cm of ponded flood water in the fields, while the AWD system was supplied with 38 cm –

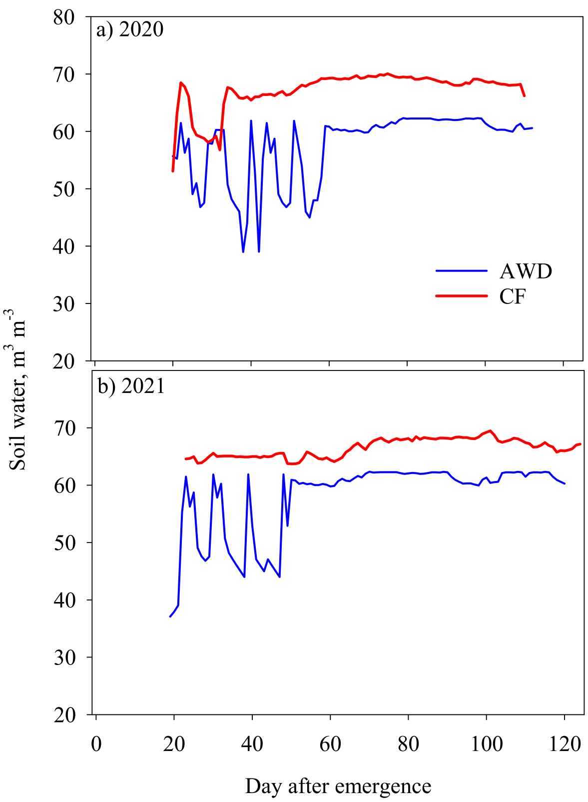

Fig. 3. Daily mean soil water at 10 cm depth measured in rice grown under continuous flood (CF) and alternate wetting and drying (AWD) flood water management in 2020 and 2021.

saving of about 14% of pumped water from the aquifer. However, the grain yield harvested in AWD was 2.3% less than in CF [49]. reported a reduction in applied flood irrigation by 15–35% without significant yield loss.

It has been argued that the water use efficiencies in lowland flooded rice cultivation systems are low because of percolation and seepage losses of the ponded water. Farmers generally adopt a method known as soil puddling to prevent high percolation rates under flooded conditions. In this system, the soil is plowed under saturated conditions and then harrowed and leveled [8,50]. However, puddling the soil before planting rice in CF systems was not reported in the LMD region, so not performed in our experiments.

4.3. Methane emissions from CF and AWD rice cropping systems

In 2020 and 2021, fields were not flooded until about 20 DAE, when rice seedlings were established. Though there were no flood water depth measurements, soil water measured at 10 cm depth reflected the flood build-up from about 20 DAE (Fig. 3a and b). In our measurements, the air turbulence-induced inward fluxes of methane gas counterbalanced its outward fluxes until about 20 DAE under both CF and AWD systems (positive and negative values; Fig. 4). During this period and after, the broad range of the magnitudes (-ve and + ve values) of fluctuations in the measured fluxes remained similar in 2020 (between −0.085 and −0.094 kg ha^{-1} under AWD and −0.15 and 0.18 kg ha^{-1} under CF) (Fig. 4a and b).

In 2021, under AWD and CF, the range of the fluxes (−ve vs.+ ve values) measured was negligibly low until about 20 DAE (Fig. 4c and d). Methane fluxes varied between −0.028 and 0.085 kg ha^{-1} under AWD and between −0.084 and 0.19 kg ha^{-1} for CF. Overall, the measured outward methane fluxes (+ve values) from the field were much stronger in 2021 than in the 2020 season. In the hypoxic soil conditions under flooded rice, methane is primarily produced by the microorganisms known as methanogens, provided sufficient substrate-carbon is available for methane-gas production [51]. However, with oxygen available in the soil, the methanotrophic bacteria get activated and stimulate the oxidation of methane gas produced [52]. When too many interacting factors other than the availability of substrate carbon and oxygen in the soil affect methane production and emission, it is not easy to point out any single or group of factors that favor enhanced methane production in 2021 over 2020.

Daily methane fluxes from CF and AWD systems differed substantially until 35 DAE in 2020 and until 68 DAE in 2021 (Fig. 5). Under CF, in 2020, daily fluxes until 35 DAE varied between 0 and 0.18 kg ha^{-1}; after that, until crop harvest, it ranged between 0.03 and 1.1 kg ha^{-1} (Fig. 5a). In the same crop season, under AWD, the daily methane fluxes ranged between 0 and 0.29 kg ha^{-1} until 35 DAE; thereafter, they were between 0 and 0.54 kg ha^{-1}. During the 2021 crop season, under CF, until about 65 DAE, daily methane fluxes ranged between 0.0 and 0.04 kg ha^{-1}; afterward, they ranged between 0.02 and 2.3 kg ha^{-1}. Under AWD, in the same year, methane fluxes were between 0.04 and 1.34 kg ha^{-1} (Fig. 5b).

In 2020, the seasonal cumulative methane emission from the CF system was 29 kg ha^{-1}, while the AWD system emitted about 52% less methane (14 kg ha^{-1}) (Table 2; Fig. 5a). Seasonal emission of methane in 2021 from the CF system was 75 kg ha^{-1}, while the AWD system emitted about 55% less (34 kg ha^{-1}) (Table 2; Fig. 5b). The reduction in methane emissions due to AWD averaged 53% across the two seasons. In three-year eddy covariance measurements comparing methane emission from a delayed flood system with an AWD

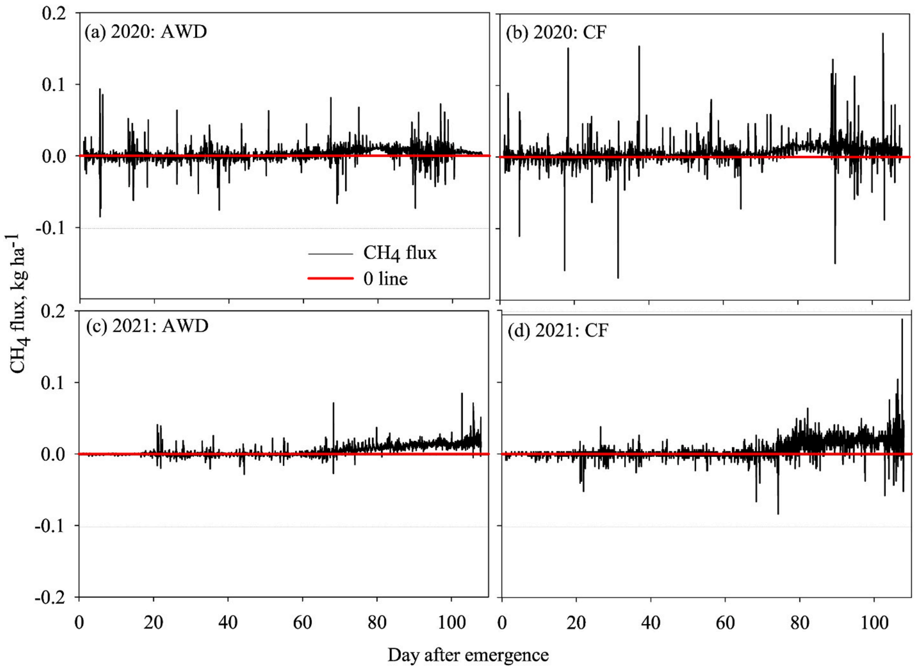

Fig. 4. Measured half-hourly methane (CH_4) flux from rice grown under continuous flood (CF) and alternate wetting and drying (AWD) flood water management in 2020 and 2021.

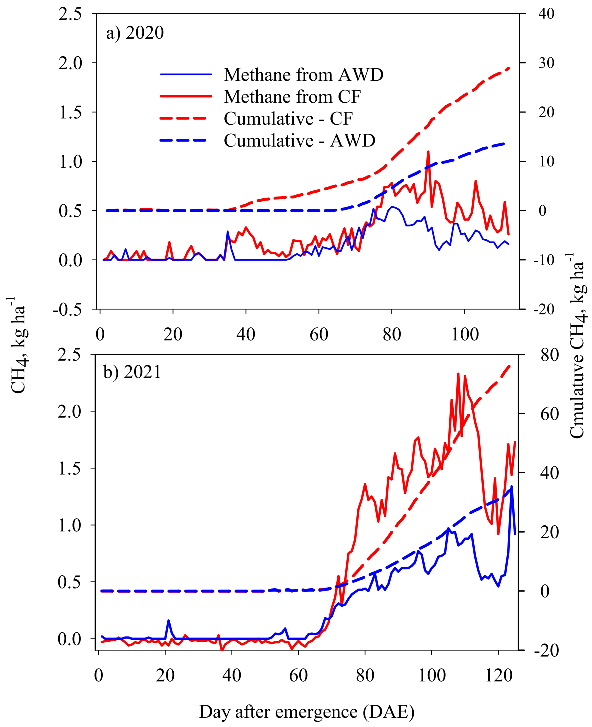

Fig. 5. Eddy covariance measured daily methane (CH_4) emitted from rice grown under continuous flood (CF) and alternate wetting and drying (AWD) flood water management in 2020 and 2021.

in Arkansas, USA [32], reported emissions between 7.1 and 31.7 kg ha^{-1} from the AWD system, which are comparable to the seasonal emission amounts between 14 and 34 kg ha^{-1}. Seasonal methane fluxes measured from a flooded rice field in Arkansas, USA, by Ref. [33] ranged between 50 and 56 kg ha^{-1}, which shows a wide range of emission values are possible depending on location-specific soil-water-crop-climate variabilities. Compared to the delayed flood system, the reduction in methane emission due to AWD reported by Ref. [32] was 65% compared to 54% reductions due to AWD over CF.

When grown under flooded soils (anaerobic conditions), rice potentially emits methane if a carbon substrate for methanogen bacteria-induced production is present [51]. It is estimated that 10% of global methane emissions were caused by rice production systems [19,31]. The AWD is an effective conservation water system invented to reduce the water footprint of rice production and is also well known to reduce methane production from rice production [8,53]. Numerous studies also reported reductions in methane emissions between 40 and 90% by switching to AWD water management systems from conventionally managed CF rice production [32,33,54,55]. Conventional measurements of greenhouse gas emissions from flooded rice have been small-plot scale measurements using static flux chambers, which have limited ability to measure variabilities of the gas concentrations in time and space. A viable alternative to this problem is the use of state-of-the-science EC-based measurements, which is continuous in time, representing footprints of the gas on large farm-scale real-life farms [32,55].

An imbalance in balancing the energy input (net solar radiation less soil heat flux) and output (primarily, latent heat and sensible heat energies) from the landscape have been reported in EC measurements [37,38,56,58,60,61]. However, how the energy balance non-closure affects EC quantified fluxes of scalars like CO_2 and methane was not well researched [57].

Following AWD [54], reported a slight reduction (about 1–13%) in rice grain yield but reduced arsenic levels in rice grains and greenhouse gas emissions. Caution should be taken when drying the field in the AWD system, as soil dry-downs beyond −20 kPa were reported to compromise yield by 23% relative to CF systems [4].

To summarize, in the past, mostly small-plot scale experiments succeeded in showing the potential of the AWD system in reducing water use and methane emissions over CF. So, our primary aim in this study was to measure and compare methane field scale, on-farm emissions and water use, continuous in time and space, from AWD and CF rice systems in the LMD, USA. On average, 53% reductions in methane emissions and 19% reduction in irrigation water we observed and represent what is achievable to a producer when AWD is applied over CF in the region.

5. Conclusion

Past studies reported reduced floodwater use and methane emissions from lowland flooded rice fields by adopting an intermittent flooding method known as alternate wetting and drying (AWD), potentially replacing continuous flooding (CF). However, uncertainties existed in the literature on the scope and extent of these benefits when practiced in varying soils and climates worldwide.

Most investigations on this issue were based on small plots and chamber-based point measurements, irrespective of the high spatial variations in observed soil properties and climate conditions. Using EC systems, we monitored methane emissions, continuous in time and space, from CF and AWD-managed large farm-scale rice fields in the humid climate of the LMD region. The study confirmed that by adopting AWD over CF floodwater management in rice cropping systems in the climate of LMD, water pumped into and methane emitted to the atmosphere from rice-farm fields can be cut down by about half. The study also confirmed that practicing AWD does not reduce harvested rice-grain yields. As this study was conducted in large-scale farmer's fields, the technology and the results derived can be used directly to advise farmers on flood water management in rice-based cropping systems in the region and elsewhere. When this study confirmed the AWD systems' potential for cutting down methane emissions, we could not monitor the system's ability to reduce emissions of other GHGs like N_2O that have more warming potential than methane or CO_2. Quantifying the possible impacts of energy balance closure in EC-monitored energy fluxes, as reported in the literature, on measured methane (a scalar) fluxes in this study might require further research.

Author contribution statement

Saseendran S. Anapalli: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Srinivasa R. Pinnamanen Contributed reagents, materials, and analysis tools or data, and performed the experiments. Krishna N. Reddy: Contributed reagents, materials, analysis tools or data. Amanda J. Ashworth analyzed and interpreted the data.

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Data availability statement

Data included in article/supp. material/referenced in article.

Additional information

Supplementary content related to this article has been published online at [URL].

Declaration of interest's statement

The authors declare no competing interests.

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