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Evaluating greenhouse gas mitigation through alternate wetting and drying irrigation in Colombian rice production

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ABSTRACT

Rice demand in Latin America is increasing rapidly, but few studies have identified management practices to reduce water demand and soil greenhouse gas (GHG) emissions for irrigated rice systems in this region. Therefore, we tested the hypothesis that alternate wetting and drying (AWD) irrigation could maintain crop yields while mitigating global warming potential (GWP) compared to a conventional system with recommended irrigation and nutrient management practices for tropical rice in Colombia. Over four consecutive growing seasons, we monitored CH_4 and N_2O emissions, grain yield, and water consumption for two AWD treatments ($AWD_{5\ cm}$ and $AWD_{10\ cm}$ - where water drained to depths of 5 and 10 cm below the soil surface, respectively) and a control, in which the field was drained multiple times during fertilizer applications and then continuously flooded until harvest. The control had the highest water use across all rice seasons, with values ranging from 9260 to 16559 $m^3\ ha^{-1}\ harvest^{-1}$. Implementation of AWD reduced cumulative water use by 19–56%, especially in dry seasons. Both AWD treatments significantly reduced cumulative CH_4 emissions by 72–100%, which is consistent with previous research. A new finding is that AWD also decreased N_2O emissions by 12–70%, which was attributed to management of soil moisture during fertilizer application events. In total, AWD reduced GWP by 25–73% compared to the control, with minimal impacts on crop productivity. Rice yields ranged from 5.2 to 8.2 Mg ha^{-1}, with no significant difference among treatments in three of four seasons. This study shows that AWD saves irrigation water while greatly reducing GWP with little agronomic penalty, suggesting this technology could be a promising strategy for GHG mitigation in tropical rice in Colombia. Because there are important barriers to AWD adoption, future work should explore challenges at the farm-level as well as changes in policy, irrigation infrastructure, and institutional arrangements to understand the potential for broader implementation.

1. Introduction

Rice is the third most important cereal crop in the world after wheat and maize, with a global production level of 515 million tons in 2022 (OECD/FAO, 2020). Rice is a staple supply of calories for half of humanity, with more than 3 billion people depending on this crop as their main source of energy and livelihood. However, much of rice cultivation takes place under flooded conditions, with around 79 million irrigated hectares worldwide, leading to serious sustainability challenges (Wassmann et al., 2019). It is estimated that agriculture consumes about 70% of the world's freshwater supplies (Campbell et al., 2017), of which approximately 30–40% is used for rice cultivation (Bouman et al., 2007; FAOSTAT, 2020; Surendran et al., 2021). Due to CH_4 production in flooded soils, rice accounts for nearly half of GHG emissions from global croplands (Carlson et al., 2017). Most rice is produced in Asia, but population growth and changing diets in Latin America and the

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Caribbean (LAC) are rapidly increasing the demand for rice. Recent work suggests the LAC region has great potential for future agricultural expansion (Méndez, 2020), however this could lead to a corresponding increase in freshwater consumption and elevated GHG emissions. Colombia is the third largest rice producing country in LAC after Brazil and Peru, with a total production of 2.5 million tons per year (ENAM, 2021; World Agricultural Production, 2022). Competition for water use among different sectors in this region, combined with growing threats of climate change (increasing variability in rainfall and hotter, drier periods) currently makes it difficult for farmers to have enough water in the right place at the right time. To address these challenges, rice management practices that reduce water use and CH_4 emissions without negatively impacting crop productivity are needed.

Rice cultivation is an important source of anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions (IPCC, 2014). Carbon cycling in flooded rice soils is controlled by anaerobic decomposition (methanogenesis) and CH_4 exchange between the soil and atmosphere, primarily via plant transport (Bhattacharyya et al., 2019). The two biochemical processes responsible for the production of N_2O are nitrification and denitrification, which are regulated by environmental and biological factors such as temperature, water level, oxygen concentration, pH, and carbon and nitrogen substrate availability (Tian et al., 2020). When considering the relative impact of each gas on GWP ($CH_4 + N_2O = GWP$), the vast majority of GWP is CH_4 emissions caused by continuous flooding (Linquist et al., 2012). Therefore, GHG mitigation efforts are often focused on water management such as non-continuous flooding or alternate wetting and drying (AWD) irrigation to introduce atmospheric O_2 into soil (Liao et al., 2021). Soil drainage not only promotes aerobic conditions which quickly inhibits methanogenesis and stimulates oxidation of CH_4 (methanotrophy), but also increases sulphate and ferric iron concentrations which delays subsequent CH_4 production when soils are re-flooded (Ratering and Conrad, 1998). However, N_2O emissions may increase at AWD due to periodic drying cycles during the growing season that increase the redox potential of the soil. This increased redox potential can promote nitrification, resulting in N_2O emissions under subsequent aerobic conditions. In addition, when the soil is re-flooded, denitrification processes may prevail, potentially further contributing to N_2O emissions (Balaine et al., 2019; Oertel et al., 2016).

From an irrigation perspective, AWD is a widely researched water-saving technology for rice cultivation (Carrijo et al., 2017; Lampayan et al., 2015). However, whether N_2O increases due to drainage events more than the decrease in CH_4 emissions will determine if AWD supports a net reduction in GWP. Lagomarsino et al. (2016) found that AWD reduced water use by 70% and CH_4 emission by 97%, but increased N_2O emissions fivefold in soils with a clay texture. Abid et al. (2019) reported that N_2O emissions were higher under AWD than under permanent flooding, while Islam et al. (2018) showed that AWD reduced seasonal CH_4 emissions but increased N_2O emissions by 23%. Colombia is one of the first countries in LAC where AWD was tested in 2015 and 2016, with CH_4 emissions decreasing by 69% but N_2O emissions being higher than flooded rice (Chirinda et al., 2017). In general, previous work has found that AWD reduces GWP despite higher N_2O emissions (Jiang et al., 2019), but an important consideration is that most studies compare AWD with a continuously flooded control, emphasizing the benefits of CH_4 relative to N_2O mitigation. In contrast, little work has evaluated the performance of AWD in the context of non-continuous flooding, which is an increasingly common agronomic practice. For example, recommended water and nutrient management practices for rice production in Colombia include multiple drainage events early in the season during the timing of N fertilizer application (Fedearroz, 2017). These wet-dry cycles could trigger higher N_2O emissions, while also decreasing the overall magnitude and importance of CH_4 emissions compared to a continuously flooded system. Thus, considering AWD is increasingly promoted in different contexts, an important knowledge gap is how additional wet-dry cycles under AWD influence net GHG mitigation compared to a non-continuously flooded system as the representative management practice for a region.

Changes in crop productivity under AWD can be variable, especially when implemented in different soil-climate combinations with different severities of soil drying (Carrijo et al., 2017). Rice is sensitive to drought stress, which significantly affects grain yield (Ahmad et al., 2021). While some studies show no impact on yield (Carrijo et al., 2018; Leon et al., 2021; Setyanto et al., 2018), other studies show an increase or decrease in productivity (Carrijo et al., 2017; Djaman et al., 2018; Yang et al., 2017). Mild-drought stress can reduce rice yield by 31%–64%, while severe stress reduced it by 65%–85% compared to normal conditions (Kumar et al., 2008). Considering this, the frequency and depth of field drainage events are important factors to investigate when adapting AWD practices to a region, especially in soils with a high percentage of sand as they are likely to dry out more quickly. While the general recommendation for AWD in Asia is to irrigate once water levels reach 15 cm depth below the soil surface (Lampayan et al., 2015), most research has occurred in lowland fields with higher clay content. Given that average yield reductions can be >20% due to water stress under AWD (Carrijo et al., 2017), research is needed to identify appropriate drainage depths in soils with high sand content to achieve GHG mitigation without negatively impacting grain yield.

In the present study, we investigated CH_4 and N_2O emissions, grain yield, and water use under two levels of AWD (5 and 10 cm drainage depth) compared with recommended management practices for tropical rice in Colombia. The control included direct seeded rice with straw removal, and flood irrigation except for drainage events to facilitate multiple fertilizer application events during the first two months of crop development. We hypothesized that implementing AWD could reduce not only water consumption and CH_4 emissions, but also N_2O emissions without affecting crop yield compared to the control by allowing soil to dry slightly more during fertilizer application events. In a two-year field experiment covering four rice growing seasons, the specific objectives were to: i) quantify seasonal CH_4 and N_2O emissions, ii) determine water use and grain yield, and iii) evaluate GWP for each treatment.

2. Methodology

2.1. Site information and experimental design

From 2018–2020, a two-year experiment was conducted at the Experimental Center "Lagunas" of the Colombian Rice Federation (Fedearroz, Spanish acronym) (3° 55' 59" North, 75° 1′ 1" West) in the city of Saldaña (Tolima, Colombia). In Saldaña, the direct income of the agricultural sector depends 100% on rice farming, which comprises 60% irrigated rice and 35% dry rice. This activity generates 7.8–8.4% of the gross value added at the national level (Dane, 2023). At an altitude of 305 m, the climate is characterized by pronounced dry seasons and bimodal rainfall (Feb - Jun) and (Sep - Dec). The average annual rainfall is 1099 mm, and the average annual temperature is 29 °C. Corresponding to the two rainy seasons, there are usually two rice sowing seasons per year, from April to June in the first semester and from October to December in the second semester (Fedearroz, 2021). Soils at the trial site are classified as shallow to moderately deep, well to moderately well drained, low in organic carbon, slightly acidic, and moderately fertile. The soil texture was a sandy loam (59% sand, 29% silt, and 12% cay) with the following selected properties: 1.58 g cm^{-3} bulk density, 0.85% total organic C, and pH of 6.50 for the 0–10 cm depth.

The field trial was designed as a randomized complete block (RCBD) design with four replicates per treatment. Each plot covered an area of 170 m^2 (Fig. S1). Experiments were conducted during four consecutive rice growing seasons (seasons I and II in 2019 and 2020). Details of crop management including sowing, fertilizer application, irrigation, and harvest dates for each season are shown in Table 1. All plots were planted with the rice cultivar Fedearroz 67, a widely used commercial

Table 1
Crop management events during the 4 growing seasons of rice from 2018 to 2020. Treatments included the control, AWD$_{5\ cm}$ (moderate drying to 5 cm depth), and AWD$_{10\ cm}$ (more intensive drying to 10 cm depth). Fertilizer sources included a combination of urea (U) – 46% N, ammonium sulfate (AS) – 21% N and 24% S, and MicroEssentials (ME) – 12% N, 40% P_2O_5, 10%S, 1% Zn.

Agronomic practices	Growing season I		Growing season II		Growing season III		Growing season IV	
Sowing date (dd/mm/yy)	18/12/18		29/05/19		03/12/2019		11/05/2020	
Germination date (dd/mm/yy)	26/12/18		07/06/19		12/12/2019		22/05/2020	
Fertilizer N rate (kg N ha^{-1})	170		176		152		175	
# Fertilizer splits	4		5		4		5	
Fertilizer application dates (dd/mm/yy)	05/01/19 (0 days) 16/01/19 (11 days) 28/01/19 (23 days) 13/02/19 (39 days)		20/06/19 (0 days) 08/07/19 (18 days) 22/07/19 (32 days) 05/08/19 (46 days) 20/08/19 (61 days)		08/01/20 (0 days) 20/01/20 (12 days) 04/02/20 (27 days) 18/02/20 (41 days)		2/06/20 (0 days) 16/06/20 (14 days) 1/07/20 (29 days) 21/07/20 (49 days) 4/08/20 (63 days)	
Fraction of N dose (kg N ha^{-1})	05/01/19→23 (U+ME) 16/01/19→45 (U+AS) 28/01/19→45 (U+AS) 13/02/19→56 (U+AS)		20/06/19→41 (U+ME) 08/07/19→34 (U+AS) 22/07/19→45 (U+AS) 05/08/19→34 (U+AS) 20/08/19→23 (U+AS)		08/01/20→35 (U+ME) 20/01/20→34 (U+AS) 04/02/20→50 (U+AS) 18/02/20→34 (U+AS)		2/06/20→35 (U+ME) 16/06/20→34 (U+AS) 1/07/20→50 (U+AS) 21/07/20→34 (U+AS) 4/08/20→23 (U+AS)	
Irrigation dates (dd/mm/yy)	**AWD$_{5\ cm}$** 04/02/19 04/03/19	**AWD$_{10\ cm}$** 05/02/19 05/03/19	**AWD$_{5\ cm}$** 28/06/19 04/07/19 15/07/19 30/07/19 12/08/19 27/08/19 05/09/19 11/09/19 17/09/19 23/09/19	**AWD$_{10\ cm}$** 29/06/19 05/07/19 01/08/19 14/08/19 29/08/19 06/09/19 18/09/19 24/09/19	**AWD$_{5\ cm}$** 15/01/20 27/01/20 12/02/20 04/03/20	**AWD$_{10\ cm}$** 17/01/20 11/02/20 03/03/20	**AWD$_{5\ cm}$** 11/06/20 26/06/20 11/07/20 03/08/20	**AWD$_{10\ cm}$** 30/06/20 13/07/20 01/08/20
Harvest date (dd/mm/yy)	08/04/19		17/10/2019		04/04/2020		09/09/2020	

variety characterized by rapid initial growth and high tillering ability (Ospina et al., 2022). Dry rice was sown directly with a drill at 120 kg ha^{-1}. Fertilizer application was divided into 4–5 dates depending on the climatic conditions during the production cycle (Table 1). Weather conditions for each season are reported in the results.

Three water management treatments were implemented: two AWD treatments and a control (C). In the control group, the soils remained continuously flooded, except during the fertilizer application dates when the plots were briefly drained, as described below. After the fertilization period, typically within the first 40–60 days of crop development, depending on the growing season, the rice fields were consistently flooded to a depth of about 5 cm until harvest. During this period, two AWD levels were employed: AWD5cm, considered moderate AWD, involved lowering the water level to 5 cm below the soil surface before irrigation, and AWD10cm, considered more intensive AWD, lowered the water level to 10 cm below the soil surface before irrigation. To regulate the water level below the soil surface for both treatments, we utilized a piezometer constructed with a 30 cm long PVC pipe with a 15 cm diameter, buried 15 cm below the soil surface, and equipped with side perforations to allow for free water movement in each treatment. These levels were selected to prevent plant stress, as the soil was expected to drain quickly due to a high sand content and low soil organic matter.

Water management was similar in both the control and AWD treatments during the first two months of the season, where plots were drained to facilitate fertilizer application (Fedearroz, 2017). However, AWD soils were allowed to dry to a greater extent during each fertilizer application event, targeting soil moisture near field capacity instead of remaining close to saturation. In each growing season, the two AWD treatments differed slightly in irrigation dates, with water levels typically dropping to 10 cm below the soil surface in AWD$_{10\ cm}$ a few days after AWD$_{5\ cm}$. In addition, the number of irrigation events varied between growing seasons due to differences in rainfall, crop demand, and the extent of soil drying (Table 1). In 2019, AWD treatments were irrigated twice in the first growing season, and 9–10 times in the second growing season. In 2020, AWD treatments were irrigated 3–4 times in both growing seasons. In order to maintain the desired water levels for the AWD$_5$ and AWD$_{10}$ treatments, a systematic approach was employed. Piezometers were strategically installed in the soil at specific locations within the experimental plots. These piezometers serve as monitoring devices to measure the water depth continuously.

2.2. *Greenhouse gas emissions*

Gas sampling was performed using the static closed chambers technique described by Chirinda et al. (2017), with precautions taken in chamber design, on-site gas sampling, and gas analysis to improve data accuracy. Polyethylene chambers (114 L in volume and 80 cm in height) were used in conjunction with custom-made chambers bases (40 cm in height and 38 cm in diameter) that were sunk 5 cm into the soil immediately after planting and were required to remain in equilibrium for at least three days before sampling. A total of 12 static chambers were installed in each of the plots (170 m^2) in the center of the growing area during the sampling season to avoid disturbance and edge effects. During each gas sampling event, the chambers were closed for 45 minutes, and four gas samples were collected at regular intervals (0, 15, 30, and 45 min). A system of vents was installed in the static chambers to avoid pressure differences between the interior and exterior of the chamber during gas sampling. A battery-powered fan was installed to ensure homogeneity of the sample in the chamber before gas sampling. Gas samples of 15 mL were collected with a propylene syringe and filled with positive pressure into a pre-evacuated 5-mL glass Exetainer® vial (Labco Ltd., Buckinghamshire, UK). Wooden walkways were placed in the rice field prior to flooding periods to prevent soil disturbance during sampling.

The measurement periods were the following: In the first growing season, measurements were taken from January 5 to April 5, 2019; for the second growing season, from June 20 to September 24, 2019; in the third growing season, from January 8 to March 20, 2020; and in the fourth growing season from June 2 to August 7, 2020. During each growing season, gas sampling focused on fertilization events, with measurements taken one day before fertilization and three consecutive days after fertilization, and when irrigation was based on water levels that fell 5 or 10 cm below the soil surface. After the fertilization period which lasted the first 40–60 days of each season, measurements were taken approximately weekly until harvest weather permitting. All samples were collected between 8:00 and 11:00 a.m., when soil temperature was expected to be equal to the average daily values (Arenas Calle 2016). The total number of sampling events for the first, second, third, and fourth growing seasons was 20, 37, 23, and 27, respectively.

Concentrations of CH_4 and N_2O were determined by gas chromatography (GC) using a Shimadzu GC −2014 with a ^{63}Ni electron capture detector (ECD) for N_2O and a flame ionization detector (FID) for CH_4. The detection range was 0.1 ppm for N_2O and 0.061 ppm for CH_4. Gas samples were analyzed within four weeks of collection. Gas concentrations were converted to fluxes based on the duration of chamber closure (45 minutes) combined with the ideal gas law equation and measured temperature and volume of the chamber. Cumulative fluxes for the growing season were calculated by linear interpolation between sampling dates. The total length of GHG monitoring was 59, 96, 56, and 66 days for the first, second, third, and fourth growing seasons, respectively. We calculated N_2O emissions in units of N and CH_4 emissions in units of C. To calculate total GWP we first multiplied CH_4-C and N_2O-N emissions by 16/12 and 44/28, respectively, to convert to units of CH_4 and N_2O and then multiplied by the 100-year GWP values of 273 for N_2O and 27.2 for CH_4 to convert each gas to CO_2 equivalents (IPCC, 2021). Total GWP is reported as the sum of N_2O and CH_4 in units of kg CO_2 eq. ha^{-1}.

2.3. Rice grain yield, aboveground biomass, water use, and soil moisture

During each growing season, aboveground biomass was sampled at two main phenological phases (flowering and harvest). Samples were collected by randomly placing 0.25 m^2 quadrants within treatment plots and cutting all aboveground biomass (including stems, leaves, and panicles). Biomass samples were dried in a convection drying oven (Colres industrial) at 70 °C for 24 hours until constant weight (Yepes et al., 2011). Rice grains were harvested at physiological maturity from a 20 m^2 area within each plot. The grains were dried in an oven at 70 °C for 72 hours. Grain yield is reported at 14% grain moisture content.

Water use was measured for each irrigation event using a Parshall flume. The Parshall flume is an open channel in which water flows horizontally, so the water flow rate (Q in m^3 $harvest^{-1}$) can be determined by the water level in the Parshall flume (H in cm), assuming shallow and horizontal water movement (Takeda et al., 2019). The water level was measured using a level gage attached to the sidewall of the Parshall Channel. Seasonal irrigation volumes were calculated by summing the values obtained over the growing season. The number of irrigation events during each season is shown in Table 1. Soil matric potential (kPa) was measured using electrical resistance sensors from WATERMARK (Irrometer Company Inc., California USA). This provided an indication of soil moisture during field drainage periods for fertilization and irrigation events.

2.4. Statistical analysis

To investigate treatments effects, the following statistical tests were conducted using R statistical software (RStudio Team, 2020) with the significance level set at $p < 0.05$. Analysis of variance (ANOVA) was performed for cumulative fluxes of CH_4 and N_2O emissions, GWP, water use, and grain yield using a randomized complete block design model. When results violated the assumptions of homogeneity of variance and normality of the ANOVA test, they were transformed accordingly using log10 or power functions. Due to significant interactions between treatment and season, results were analyzed separately for each season.

3. Results

3.1. Weather conditions

Air temperature and precipitation data for each season are shown in Fig. 1. Average daily temperatures during this period ranged from 24 to 34°C for season one (Jan. – Apr. 2019), 27–34°C for season two (Jun. – Sep. 2019), 26–36°C for season three (Jan. – Mar. 2020), and 23–30°C for season four (May. – Aug. 2020). Seasons one, two, and four recorded 39, 30, and 31 precipitation days, respectively, while season three had only 15 precipitation days. In growing seasons one and two, cumulative precipitation was 650 and 111 mm, respectively, while in seasons three and four it was 83 and 209 mm, respectively. The precipitation distribution was uniform in growing periods one and four. While precipitation was concentrated in the early stages of plant development in growing period two, it was concentrated in the phenological growth stages of tillering and flowering in the third season.

3.2. Rice grain yield, biomass, and water consumption

Rice grain yields were highest in the second and fourth growing seasons, ranging from 7.25 to 8.15 Mg ha^{-1} (Table 2). In three of four growing seasons (I, III, and IV seasons), there were no significant differences in yield among treatments ($P > 0.05$). Only the yield of $AWD_{5\ cm}$ was significantly reduced by 11% in the second season compared with the control. In other seasons, the control treatment had a slightly higher numerical yield compared to AWD treatments, but this did not translate to statistical differences. In the third and fourth seasons, aboveground biomass differed at the flowering stage in both seasons but only at the harvest stage in the third season. At the two growth stages evaluated, aboveground biomass was higher for the second season of 2019 than in the other seasons for all treatments (Table 3), which resulted in a greater grain yield.

The control had the highest water consumption in all seasons compared to the treatments with AWD, ranging from 9260 to 16559 m^3 ha^{-1} $harvest^{-1}$ (Fig. 2). Among the four growing seasons, water use for the control was lowest in the first season, which was due to high rainfall and lower irrigation demand. In this season, water use was lower by 33% for $AWD_{5\ cm}$ and 50% for $AWD_{10\ cm}$ treatments compared to the control. In the second season, water use was lower by a similar amount for both AWD treatments (34% for $AWD_{5\ cm}$ and 35% for $AWD_{10\ cm}$). In the third season, irrigation use was 33% lower for $AWD_{5\ cm}$ and 19% lower for $AWD_{10\ cm}$ compared to the control. The climatic conditions of the third season indicate that it was a drier semester. The water level in the treatment at $AWD_{10\ cm}$ was dropped to 10 cm below the soil surface, and this indicates that it has fewer irrigation events, but more water had to be added compared to the other semesters to reach the sheet of water. In the fourth season, AWD decreased water use more than any other season, resulting in a 50% reduction for $AWD_{5\ cm}$ and 56% reduction for $AWD_{10\ cm}$. Water consumption was generally reduced more by $AWD_{10\ cm}$ than $AWD_{5\ cm}$ across seasons.

3.3. Daily GHG fluxes and soil moisture

The daily fluxes of CH_4 and N_2O emissions were different for each rice growing season evaluated (Figs. 3–6). Daily CH_4 fluxes between treatments showed high variability, with emissions ranging between −5.79 and 6.22 mg CH_4 - C m^{-2} d^{-1} for the first season; −1.56 to 104.69 mg CH_4 - C m^{-2} d^{-1} for the second season; −2.08 to 154.70 mg CH_4 - C m^{-2} d^{-1} for the third season, and −0.82 to 27.28 mg CH_4 - C m^{-2} d^{-1} for the fourth season. In the control, an increase in CH_4 emission was generally observed in the second half of the growing season near to the finish of the flowering stage when the fertilizing was finished, and the water level was constant (flooded). In the first season, daily CH_4 emissions were relatively low at < 6.22 mg CH_4 - C m^{-2} d^{-1} compared with the other seasons (Fig. 3a). In the second season, the increase in daily

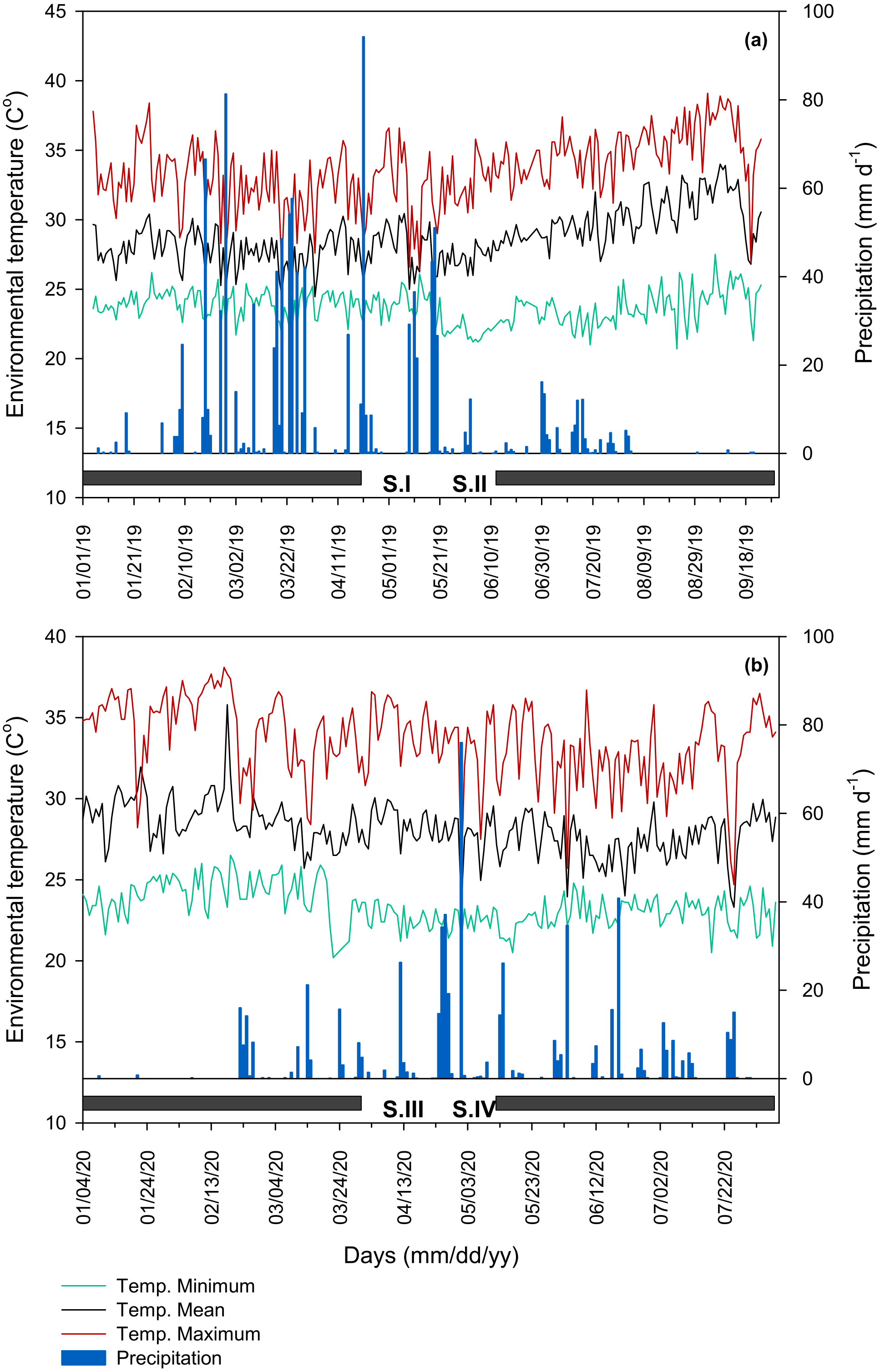

Fig. 1. Minimum, mean, and maximum air temperatures and daily precipitation over four rice growing seasons between 2019 and 2020. Horizontal gray bars represent growing seasons (S.I – S.IV). (a) Season I (January – April 2019) and season II (June – September 2019) and (b) season III (January – March 2020), and season IV (May – august, 2020).

CH_4 emissions began after about 62 days in all treatments (Fig. 4a). The increase in daily CH_4 emissions in season two is likely due to a higher number of irrigation events after the flowering stage owing to dry conditions that increased water demand. The highest emissions occurred toward the end of the growing season on days 77–96 in the control treatment (101.95 ± 15.17, 104.59 ± 2.79, 56.20 ± 16.9, and 94.43 ± 7.61 mg CH_4 - C m^{-2} d^{-1} on days 77, 89, 95, and 96, respectively). The variation in CH_4 emissions between the AWD treatments and the control was lower in the third season except for one sampling date (Fig. 5a). Among treatments there were no notable changes until day 13, yet high CH_4 emissions (154.70 ± 1.95 mg CH_4 - C m^{-2} d^{-1}) were observed for the control 14 days after germination, while for AWD treatments the

Table 2
Effect of irrigation treatments on rice grain yield (Mg ha^{-1}) in four growing seasons. Within each column, values followed by the same letter are not significantly different at $p < 0.05$.

Seasons	2019		2020	
	I	II	III	IV
Treatments	**Rice grain yield (Mg ha^{-1})**			
Control	6.23 ± 0.42a	8.15 ± 0.27 a	6.90 ± 0.63 a	7.61 ± 0.16 a
AWD$_{5\ cm}$	5.93 ± 0.20a	7.25 ± 0.36 b	5.82 ± 0.77 a	7.51 ± 0.47 a
AWD$_{10\ cm}$	5.16 ± 0.38a	7.48 ± 0.13 ab	6.25 ± 0.23 a	7.43 ± 0.49 a

changes in CH_4 emissions were minor. In the fourth growing season, an increase in daily CH_4 emissions was observed 49 days after seeding following the third fertilization event in the control treatment (Fig. 6a), with soil matric potential mostly at saturation levels. Weather and soil matric potential did not correlate directly with CH_4 emissions, except for the third season, where precipitation was positively correlated with CH4 emissions and soil matric potential was negatively correlated with CH4 emissions ($P < 0.05$). This season was drier than the other seasons evaluated (83 mm).

The pattern of N_2O emissions recorded was not consistent, with peak fluxes sometimes occurring earlier and sometimes later each growing season (Figs. 3b-6b). Importantly, N_2O emissions following chemical fertilizer application events during vegetative rice growth tended to be higher under the control than AWD treatments, although there was often variation between treatments in different seasons. In the first season (Fig. 3b), the highest N_2O peaks occurred after the first fertilization in the control and AWD$_{5\ cm}$ treatments where soil matric potential was 12 and 27 kPa (Fig. 3c), respectively, and after the last fertilization dose (41 days) in the control treatment (0 kPa). In contrast, the high peaks of N_2O in season II occurred 2–4 days after the last fertilizer application for the AWD$_{10\ cm}$ treatment (61 after seeding) (Fig. 4b). In season III, emissions reached their highest levels 15 days after fertilization and 55 days after the AWD$_{10\ cm}$ treatment, but AWD$_{5\ cm}$ and the control also showed elevated emissions during the second half of the season (Fig. 5b). The highest N_2O emission peaks during season IV were 2 days after the second fertilizer application for the control and AWD$_{5\ cm}$ treatments (Fig. 6b). No correlations were observed between weather and soil matric potential and N_2O emissions in any season.

Soil matric potential increased sharply during field drainage events in the AWD treatments, albeit with a different magnitude among seasons (Figs. 3c-6c). The values of sandy loam soil matric potential typically varied across treatments, ranging from near saturation (0–10 kPa) to field capacity (10–36 kPa), or even drier under AWD management between irrigation events (> 36 kPa usual margin for irrigation). While season one had high rainfall and only a few drainage events with moderate soil drying, season two had the lowest precipitation, which resulted in frequent and more severe soil drying events and the highest number of irrigations (Figs. 3c and 4c). Seasonal patterns of soil matric potential were more similar in seasons three and four, especially between irrigations in AWD (Figs. 5c and 6c). Despite flood irrigation being practiced in the control except during fertilizer applications, it was not always possible to keep the soil saturated due to the high sand content and hydraulic conductivity, especially in years with lower rainfall. The difficulty of retaining water in fields in dry years is typical of conventional farming practices in the study region, meaning these results are relevant to local production systems. As soil in the AWD treatments was allowed to dry further than the control, matric potential in AWD treatments either reached around field capacity during fertilizer applications (season one), or lower soil moisture in years with less precipitation (seasons two-four). The fluctuation in soil matric potential explains the large changes in soil N_2O emissions and reduction in CH_4 emissions during the fertilization period across the four growing seasons.

3.4. Cumulative GHG emissions and GWP

The AWD treatments significantly reduced CH_4 emissions compared to the control in every growing season (Table 4). For the control, CH_4 emissions were lowest in season I, highest in season II, and similar in seasons III and IV. The CH_4 mitigation achieved by AWD$_{5\ cm}$ and AWD$_{10\ cm}$ was 91 and >100%, respectively, in season I, 74% and 88% in season II, 81% and 90% in season III, and 72% and 100% season IV. Cumulative N_2O emissions significantly differed by treatment in three of the four growing seasons studied, except in the fourth season. Comparing AWD treatments to the control, cumulative N_2O emissions were reduced by 12–70% across seasons. However, in the second season, the AWD$_{5\ cm}$ treatment showed a 91% increase in N_2O emissions. Cumulative N_2O emissions were highest in the second season (reaching

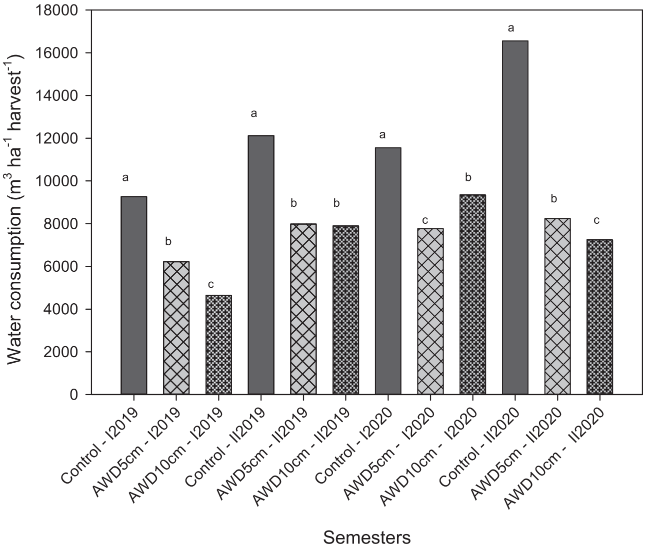

Fig. 2. Water consumption for the control and two AWD treatments across four rice cropping seasons. Season I (January – April 2019); season II (June – September 2019); season III (January – March 2020), and season IV (May – august, 2020).

Table 3
Rice aboveground biomass at flowering and harvest growth stages in four rice production seasons. Within each column and sampling date, values followed by the same letter are not significantly different at $p < 0.05$.

Seasons	2019		2020		2019		2020	
	I	II	III	IV	I	II	III	IV
	Aboveground biomass (Mg ha^{-1})							
Treatments	**Flowering stage**				**Maturity stage**			
Date (mm/dd/yy)	**3/8/2019**	**9/13/2019**	**3/7/2020**	**8/15/2020**	**4/8/2019**	**10/17/2019**	**4/4/2020**	**9/9/2020**
Control	6.50 ± 0.59 a	10.68 ± 0.84 a	7.05 ± 0.25 a	7.25 ± 0.20 a	14.77 ± 1.16 a	17.35 ± 1.26 a	9.59 ± 0.25 a	12.00 ± 3.61 a
AWD$_{5\ cm}$	6.18 ± 0.13 a	9.92 ± 2.08 a	4.63 ± 0.29 b	5.96 ± 0.30 a	15.84 ± 0.73 a	17.76 ± 0.24 a	8.57 ± 0.11 ab	10.18 ± 2.47 a
AWD$_{10\ cm}$	6.12 ± 0.42 a	8.76 ± 1.28 a	4.47 ± 0.13 b	5.70 ± 1.20 b	14.61 ± 1.17 a	15.79 ± 4.56 a	7.63 ± 0.70 b	9.93 ± 0.55 a

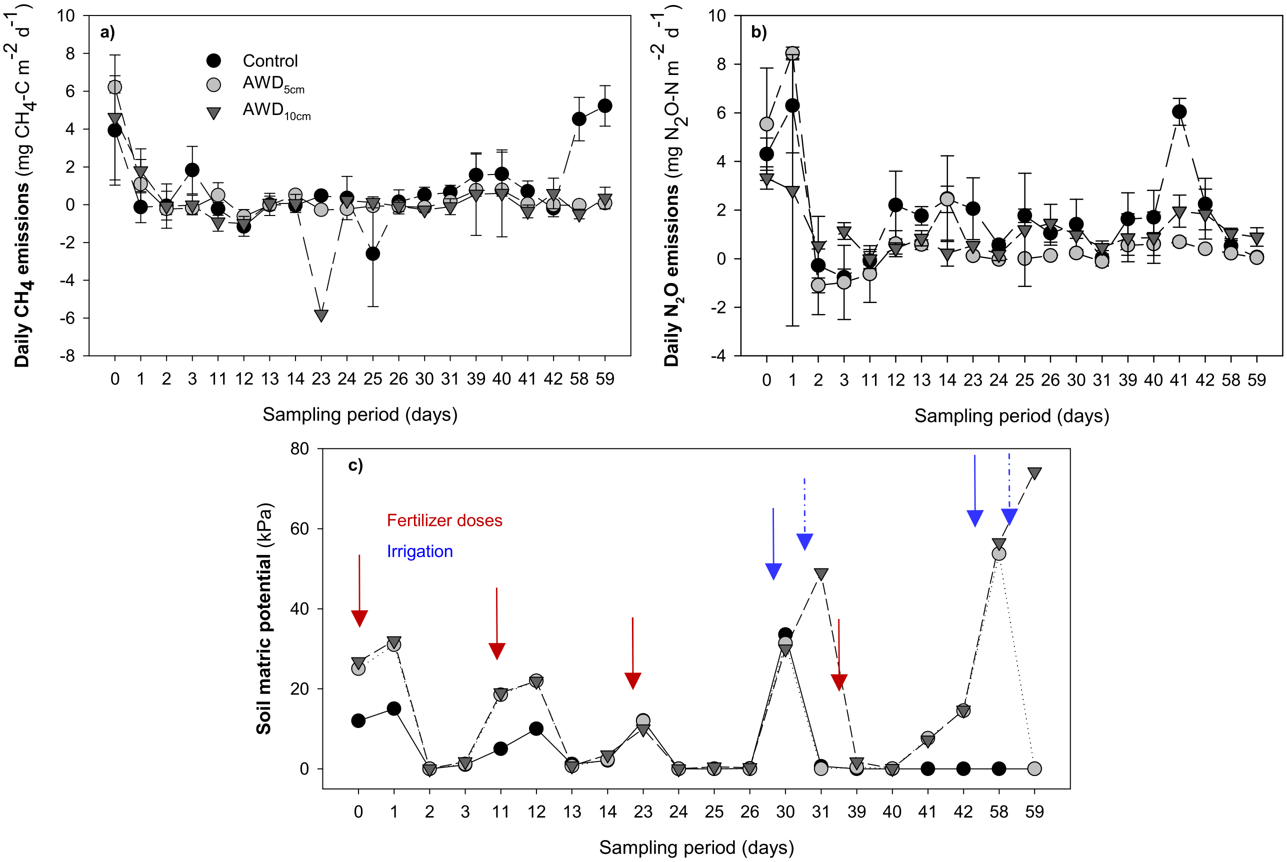

Fig. 3. Daily CH_4 emissions (a), N_2O emissions (b), and soil matric potential (c) during rice cropping season I (2019). Red arrows show fertilizer split dates, blue solid arrows show irrigation events for $AWD_{5\ cm}$, and blue dash-dot arrows show irrigation events for $AWD_{10\ cm}$. Error bars indicate ± 1 SE (n=3).

over 3 kg N_2O ha^{-1}), and similar in range for the other seasons (0.48–1.63 kg N_2O ha^{-1}).

On a 100-year time horizon, GWP was significantly higher in the control than both AWD treatments in each of the four seasons evaluated (Table 4). The highest GWP was found in season II, which presented minor precipitation events, due to both elevated CH_4 and N_2O emissions compared to other seasons. Across seasons the GWP of AWD was 25–73% less than that of control, owing to a 72–100% reduction in cumulative CH_4 emissions and a 12–70% decrease in cumulative N_2O emissions in both wet and dry seasons. The average contribution of N_2O to GWP across the three treatments was 58–100%, while for CH_4 emissions it ranged from 0% to 42%. In general, the relative contribution of N_2O to GWP increased with increasing soil drying (control < $AWD_{5\ cm}$ < $AWD_{10\ cm}$), whereas it decreased for CH_4 emissions. There was no apparent tradeoff between CH_4 and N_2O mitigation in AWD treatments. In fact, there was a synergy with treatments that achieved the highest reduction in CH_4 emissions also showing the highest reduction in N_2O emissions.

4. Discussion

4.1. Yields and water use

In this experiment, AWD significantly reduced water use without negatively affecting yield in three of four growing seasons. This is consistent with a large number of studies showing that AWD can decrease water inputs by around 25–70% without causing a reduction in yield (Ishfaq et al., 2020). The lack of an agronomic penalty could be due to the fact that water management was relatively similar in the AWD and control during vegetative growth (Carrijo et al., 2017). During the fertilization period early in the season (ending approximately 40–60 days after sowing, depending on season), fertilizer was applied in 4–5 doses. Each time soil drainage occurred in the AWD treatments, soil matric potential decreased to somewhere between field capacity or greater, while matric potential in the control was between saturation and field capacity (sometimes with a small amount of standing floodwater). Due to the relatively shallow drainage depth (5 or 10 cm) where the soil matric potential reached the margin of irrigation, water stress may not have occurred during these events. This could explain the similar biomass observed between treatments at flowering during most growing seasons. Moreover, later in the season during rice reproductive growth, the period of soil drying between irrigation events in AWD treatments was relatively short before irrigation was triggered. This was due to the combination of high temperatures and high evaporative demand by the plants, as well as rapid drainage in the sandy loam soil, which typically resulted in only 1–3 days of soil drying time in AWD treatments. A recent global analysis found that the number of unflooded days in a rice growing season was among the strongest factors influencing rice yield under AWD compared to other soil and climate variables (Bo et al., 2022). Therefore, the relatively short periods of drainage likely allowed soil water availability to be maintained below 5 or 10 cm depth, providing roots sufficient access to water, and helping avoid drought stress that would normally result in yield loss (Carrijo et al., 2018).

Previous studies suggest that AWD applied only during the early growing season (45–65 days) or when the water table does not fall >15 cm below the soil surface when practiced throughout the season does not reduce yield (Carrijo et al., 2017; Zhou et al., 2017). Other studies show there is often no yield reduction when AWD irrigation is applied compared to continuous flooded rice systems (Oo et al., 2018a; Setyanto et al., 2018), while others have documented a small yield loss (Liao et al., 2021). Although soil matric potential increased to over 100

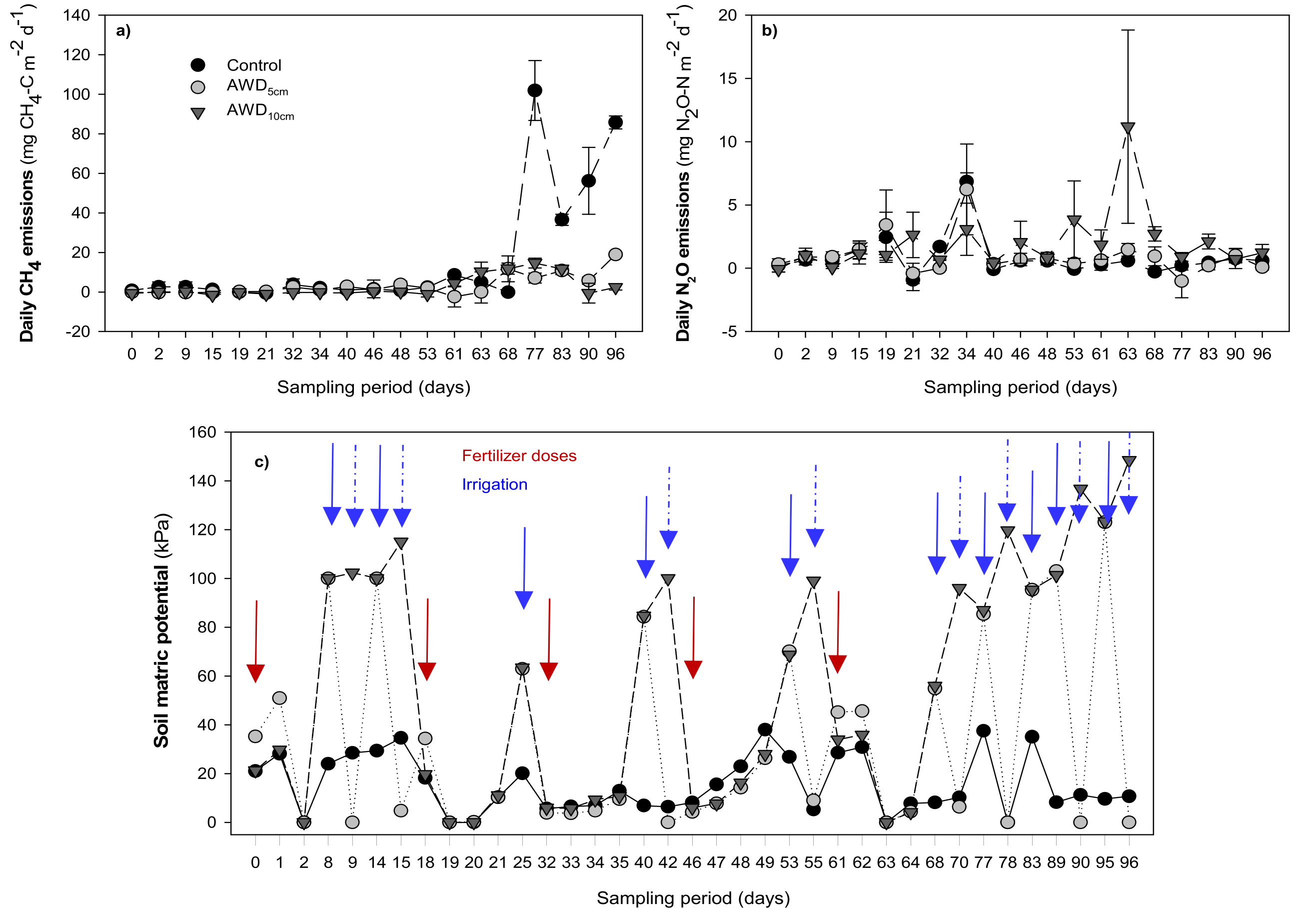

Fig. 4. Daily CH_4 emissions (a), N_2O emissions (b), and soil matric potential (c) during rice cropping season II (2019). Red arrows show fertilizer split dates, blue solid arrows show irrigation events for $AWD_{5\ cm}$, and blue dash-dot arrows show irrigation events for $AWD_{10\ cm}$. Error bars indicate ± 1 SE (n=3).

kPa at points in our study, this did not impact yield, similar to findings from Kukal et al. (2005). These results suggest it may not be necessary to continuously irrigate or saturate the soil throughout the vegetative growth season of rice because rice growing under continuous flooding conditions can adapt to intermittent flood irrigation (Jiang et al., 2019). In some cases, increasing air exchange into the soil with AWD can provide sufficient oxygen to the root system to facilitate the mineralization of soil organic matter, thereby increasing soil fertility and enhancing rice production (Oo et al., 2018b).

Our results may differ from studies reporting a yield decline with AWD for several reasons. Much work in Asia is based on promoting drainage 15 cm below the soil surface or more (Lampayan et al., 2015), which may take longer in clay soils and increase the risk of crop water stress. On the other hand, soil properties such as pH and organic carbon also affect rice yield under AWD management. In particular, while some research suggests that the most substantial yield losses occur in soils with a pH greater than 7 or a carbon content less than 1% (Carrijo et al., 2017), it is worth highlighting that our experimental site record pH values of 6.5 and carbon content of 0.85%, respectively. By presenting slightly acidic pH conditions, it prevents the formation of impermeable soil layers that can potentially obstruct root development in AWD treatments (Carrijo et al., 2017; Huang et al., 2017; Ishfaq et al., 2020).

The control had the highest water use across seasons that included both irrigation and precipitation. Since rice production requires more water than most other crops (Mekonnen and Hoekstra, 2011), identifying practices that can reduce both water use and GHG without affecting yields is an attractive option for sustainable intensification. Despite the relatively shallow drainage depths of 5 or 10 cm evaluated for the sandy loam soil in this study, corresponding to relatively short periods of non-flooded conditions, water savings were still significant (19–56% across seasons). In general, evaluation of AWD in tropical, subtropical, and temperate regions has shown great potential for non-continuous irrigation to reduce water use (Bo et al., 2022). In our study this was particularly noteworthy in seasons with lower precipitation and higher irrigation demands (e.g. AWD decreased water use by around 35% in the second season and more than 50% in the fourth season). The ability to save irrigation water is becoming increasingly important in Colombia due to water scarcity and climate change. These findings are supported by the literature which indicates that the application of AWD under different climatic and soil conditions decreases water use by 20–44% (Hasan et al., 2016; Liang et al., 2016), with grain yield remaining the same or even increasing compared to continuous flooding (Djaman et al., 2018; Xu et al., 2020). To ensure Colombia's food security and access to freshwater, our results suggest rice production can be optimized through AWD management to maintain rice yields while increasing water productivity.

4.2. Daily and cumulative GHG emissions

This study is unique because AWD was tested in a non-continuously flooded system which is typical for tropical rice in Colombia and increasingly elsewhere due to water shortages, providing new insights on the CH_4 and N_2O mitigation potential under these conditions. While the daily pattern of CH_4 fluxes differed among the four rice seasons studied (Figs. 3a-6a), cumulative CH_4 emissions for the control were low compared to continuously flooded systems reported elsewhere (Jiang et al., 2019; Linquist et al., 2012; Wu et al., 2022). Daily CH_4 emissions remained low in the control until later in the season, which can be

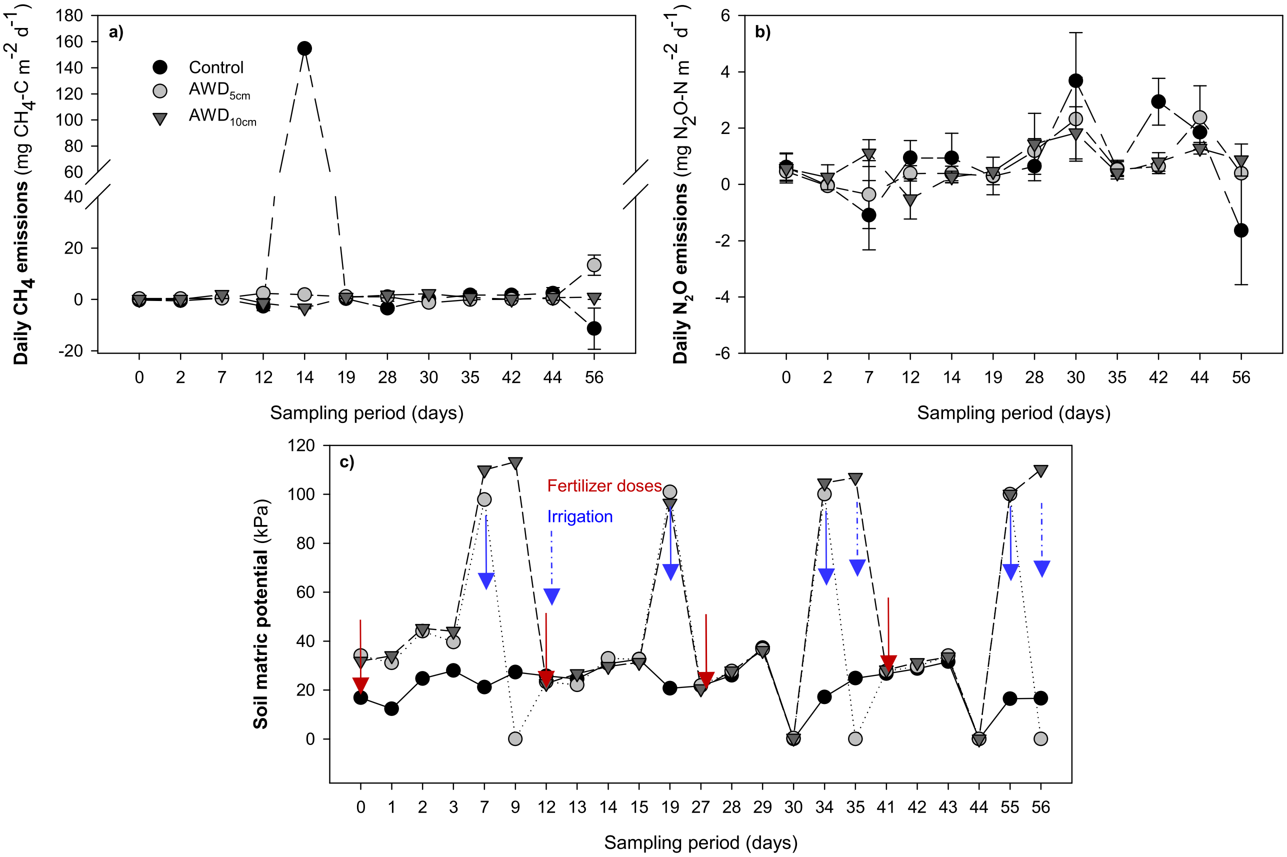

Fig. 5. Daily CH_4 emissions (a), N_2O emissions (b), and soil matric potential (c) during rice cropping season III (2020). Red arrows show fertilizer split dates, blue solid arrows show irrigation events for $AWD_{5\ cm}$, and blue dash-dot arrows show irrigation events for $AWD_{10\ cm}$. Error bars indicate ± 1 SE (n=3).

attributed to drainage events implemented during the first 40–60 days of crop development to facilitate 4–5 fertilizer applications. Drainage increases soil aeration, reducing methanogenic activity and decreasing the survival rate of methane-producing archaea (Ratering and Conrad, 1998; Sahrawat, 2006). Even when control plots were continuously flooded during reproductive growth, emissions were still below 160 mg CH_4 - C m^{-2} d^{-1} in all seasons studied. Short drainage events early in crop development have been shown to inhibit CH_4 emissions throughout much of the growing season for several reasons. Oxygen availability in soil stimulates methanotrophic activity (oxidation of CH_4), while also increasing sulphate and ferric iron concentrations which continue to inhibit CH_4 production even when soil redox potential drops to low levels following re-flooding (Malyan et al., 2016; Nazaries et al., 2013; Ratering and Conrad, 1998; Sahrawat, 2006; Souza et al., 2021). In addition, rice plants may develop fewer aerenchyma due to less anoxic conditions during early crop development, decreasing CH_4 transport to the atmosphere despite high CH_4 production in soil later in the season (Le Mer and Roger, 2001; Islam et al., 2018). Ammonium sulfate was also used as an N fertilizer source and straw from the previous season was removed from the field, decreasing carbon substrate for methanogenesis, and causing soil redox to drop more slowly (Gao et al., 2002; Sander et al., 2014).

Despite low CH_4 emissions in the control, the two AWD treatments further reduced CH_4 emissions by 72–100% across seasons (Table 4). Although the conditions for implementing the AWD technology were generally different from those in our study, the mitigation potential is well-documented with many other experiments showing that soil drainage significantly reduces CH_4 emissions (Bo et al., 2022; Carrijo et al., 2017; Islam et al., 2020; Jiang et al., 2019; Oo et al., 2018a; Setyanto et al., 2018; Zhang et al., 2011). In our study, the additional introduction of dry periods beyond the first two months of the growing season to 5 and 10 cm drainage depth under both AWD treatments appeared sufficient to increase oxygen penetration into the soil, causing soil organic carbon to be oxidized to CO_2 instead of CH_4, effectively suppressing CH_4 emissions compared to the control. Tariq et al. (2017) and Islam et al. (2018) reported that early and mid-season drainage reduced cumulative CH_4 emissions by 88–91% compared to continuous flooding. Chirinda et al. (2017) found similar results in a study conducted in the same study area under traditional AWD management (15 cm below ground level) compared to continuous flooding. Sometimes it can be challenging to maintain aerated soil conditions in AWD due to high rainfall volumes during wet seasons in tropical climates. Despite frequent rainfall occurring in the two wettest seasons of this study (I and IV), the high hydraulic conductivity of the sandy loam soil supported rapid drainage and sufficient soil drying between irrigations (Figs. 3c-6c), maintaining the effectiveness of AWD for CH_4 mitigation in both seasons. Since rice farmers in Colombia are used to draining fields during fertilizer applications as conventional practice, they may be able to extend the AWD management practice throughout the growing season.

For all seasons, N_2O emissions showed high variability after N fertilization events and during transient dry periods (Figs. 3b-6b). An important finding is that despite multiple drainage events occurring in all treatments during the first two months prior to fertilizer applications, N_2O emissions remained relatively low during these wet-dry cycles in all treatments (less than 20 mg N_2O - N m^{-2} d^{-1}). In contrast to other studies, the control had slightly higher cumulative N_2O emissions than the AWD treatments across three growing seasons, except in season two when $AWD_{10\ cm}$ produced significantly higher emissions (Table 4). This is because most research has evaluated AWD compared to continuous flooding, thus N_2O emissions in the control are extremely low due to anaerobic conditions in submerged soils causing complete

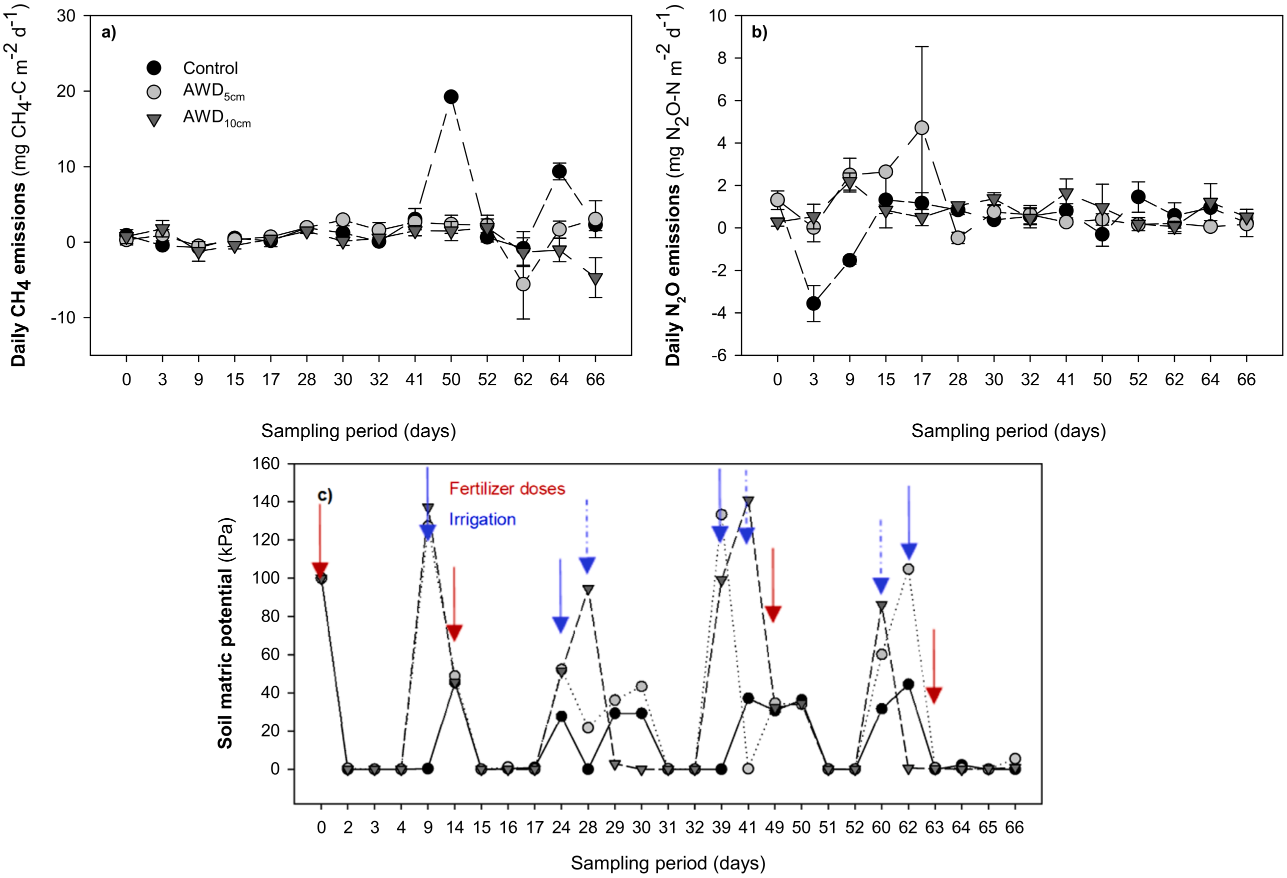

Fig. 6. Daily CH_4 emissions (a), N_2O emissions (b), and soil matric potential (c) during rice cropping season IV (2020). Red arrows show fertilizer split dates, blue solid arrows show irrigation events for $AWD_{5\ cm}$, and blue dash-dot arrows show irrigation events for $AWD_{10\ cm}$. Error bars indicate ± 1 SE (n=3).

Table 4

Cumulative CH_4 - C and N_2O – N emissions from three irrigation treatments and total GWP (kg CO_2 eq. ha^{-1}). Within each column, values followed by the same letter are not significantly different at 0.05 level.

Seasons	**2019**						**2020**					
	I			**II**			**III**			**IV**		
Treatments	**CH_4 - C (kg ha^{-1})**	**N_2O - N (kg ha^{-1})**	**GWP**	**CH_4 - C (kg ha^{-1})**	**N_2O - N (kg ha^{-1})**	**GWP**	**CH_4 - C (kg ha^{-1})**	**N_2O - N (kg ha^{-1})**	**GWP**	**CH_4 - C (kg ha^{-1})**	**N_2O - N (kg ha^{-1})**	**GWP**
Control	0.64 ± 0.09 a	1.01 ± 0.03 a	458.15 a	25.25 ± 9.39 a	1.04 ± 0.24 b	1361.71 a	4.49 ± 0.77 a	0.58 ± 0.01 a	410.82 a	3.35 ± 0.86 a	1.04 ± 0.41 a	565.92 a
$AWD_{5\ cm}$	0.06 ± 0.02 b	0.39 ± 0.12 b	169.62 b	6.51 ± 0.47 b	0.64 ± 0.04 b	511.81 a	0.86 ± 0.70 b	0.36 ± 0.07 b	185.25 b	0.95 ± 0.02 b	0.91 ± 0.08 a	425.01 ab
$AWD_{10\ cm}$	- 0.20 ± 0.04 c	0.31 ± 0.10 b	123.67 b	3.05 ± 0.47 b	1.99 ± 0.34 a	963.19 a	0.46 ± 0.32 b	0.35 ± 0.03 b	166.66 b	-0.32 ± 0.36 b	0.46 ± 0.06 a	187.66 b

denitrification, and any drainage tends to increase N_2O losses. For example, in a meta-analysis Jiang et al. (2019) found that CH_4 emissions were reduced by 53% but N_2O emissions increased by 105%. Another meta-analysis by Wu et al. (2022) found that drainage decreased CH_4 emissions by 58% but increased N_2O emissions by 150%. However, in the present study the control and AWD treatments both experienced non-continuous flooding during fertilizer applications in the first two months of the season, with soil moisture remaining close to saturated in the control but drying to field capacity or lower levels in the AWD treatments. As denitrification processes tend to increase as soil approach saturated conditions (Wang et al., 2021), it is likely that the enhanced soil drying in AWD during fertilizer applications helped limit N_2O losses compared to the control. These results highlight that management of soil moisture during drainage events can avoid a tradeoff in N_2O emissions for AWD management compared to a non-continuously flooded control.

Despite relatively high N inputs and multiple drainage events, cumulative N_2O emissions were relatively low across seasons, generally ranging from 0.5 to 1.6 kg N_2O ha^{-1} (Table 4). According to several studies (Kritee et al., 2018; Lagomarsino et al., 2016; LaHue et al., 2016), N_2O emissions may be low under AWD management if the amount of mineral N in soil at the time of field drainage to support fertilizer application is low. Thus, applying fertilizer to moist soils between field capacity and optimal moisture depending on soil texture (Chapuis-lardy et al., 2007) helps ensure that the applied N fertilizer is absorbed by roots and therefore little mineral N remains in the soil, limiting nitrification and denitrification processes that trigger N_2O emissions. In addition, the type of N fertilizer, in conjunction with soil moisture at the time of application, can affect N_2O emissions. Urea and ammonium sulfate were used in this study which provides plant-available NH_4^+-N, limiting nitrification and subsequent denitrification transformations in submerged soils while also preventing NO_3- N leaching (Rahman and Forrestal, 2021). Fertilization with ammonium sulfate has been shown to mitigate methane emissions by increasing methane oxidation and stimulating sulfate-reducing bacterial populations. This suggests that competition for mineral nitrogen between rice roots and microbes in the rhizosphere plays a critical role in modulating microbial activity (Ali et al., 2012; Bodelier et al., 2000a, b; Rath et al., 2002; Sahrawat, 2006).

4.3. GWP and relevance of AWD in this region

According to several AWD studies, it is possible to reduce CH_4 emissions, but this typically results in higher N_2O emissions which represents a tradeoff (Kraus et al., 2022; Lagomarsino et al., 2016; Wang et al., 2021; Wu et al., 2022). When water and N inputs are not properly managed during field drainage events, elevated N_2O emissions can partially or fully offset the reductions in GWP. Our study provides new insights into how this tradeoff can be resolved while reducing both CH_4 and N_2O emissions through changes in water management during the timing of N fertilization, leading to consistent reductions in GWP. Due to lower CH_4 emissions from the non-continuously flooded control, N_2O emissions represented a greater proportion of total GWP (Table 4), which is uncommon in flooded rice systems. This places increased importance on avoiding higher N_2O emissions during wet-dry irrigation cycles. As mentioned earlier, draining to field capacity during fertilizer applications may have helped AWD maintain lower N_2O emissions compared to the control which remained close to saturated soil conditions. This suggests that effective GWP mitigation can be achieved by focusing on the combined management of N fertilizer and soil moisture during irrigation events, promoting nutrient availability early in the season during rapid vegetative growth while reducing both N_2O and CH_4 emissions in a non-continuously flooded system.

The effects of AWD on GWP are variable in the literature, as N_2O emissions are not always higher. Prangbang et al. (2020) reported that AWD could reduce annual CH_4 emissions by 32%, while yield and N_2O emissions remained the same. Meanwhile, Lahue et al. (2016) observed no increase in N_2O emissions under AWD, while Cuevas and Ardila. (2018) found that maintaining soil moisture near field capacity can help reduce both CH_4 and N_2O emissions. Yagi et al. (2020) showed that multiple drainage events generally increased N_2O emissions but the combined impacts on GWP were 29% lower. Similarly, Bo et al. (2022) found that non-continuous flooding increased N_2O emissions by 92%, but the substantial reduction in CH_4 emissions (54%) still reduced total GWP by 47% in a recent global analysis. Our work helps address an important knowledge gap because it is not only one of the first studies for tropical rice in Latin America, but as noted by Bo et al. (2022), many rice systems are switching to some sort of intermittent irrigation and the effectiveness of AWD in this context remains uncertain. Given the promising results for AWD compared to non-continuously flooded rice observed here, agronomic practices focused on managing soil moisture during field drainage events should be evaluated elsewhere in future research, ideally with other strategies to further reduce GHG emissions. For example, AWD can be combined with efficient rice varieties that have high crop N requirements, further reducing the risk of N_2O production and keeping N_2O emissions low. This is an opportunity that should be explored in future research under different climate and soil conditions in Colombia.

AWD is a technology that, if properly applied, has the potential to benefit both rice farmers and the environment by reducing overall production costs (depending on water pricing) while maintaining rice yields and reducing GHG emissions. However, there are important barriers to adoption that have been explored in other works (Enriquez et al., 2021; Pearson et al., 2018). For example, farmers need the ability to have level fields and reliable access to irrigation water to quickly irrigate field, when necessary, but this is not always possible in a smallholder context (Islam et al., 2018). When evaluating the feasibility of this type of water management in Colombia, it is important to keep in mind that current irrigation fees are based on rice area cultivated as there is not yet a policy that charges for actual water use, which does not provide an economic incentive for farmers to reduce the number of irrigations. In the absence of incentives for farmers to reduce GHG emissions, implementing this type of management could face challenges. Therefore, changes in agricultural policy, irrigation infrastructure, and institutional arrangements are likely needed to facilitate AWD adoption more broadly (Enriquez et al., 2021). In the short-term, considering that implementing field drainage events while controlling soil moisture during the early season fertilization period is a common practice for farmers in Colombia, it could make it easier for farmers to implement this version of AWD throughout the growing season to achieve environmental benefits. Such an approach would allow for the reduction of GHG emissions and water use without compromising farmer yields and profitability.

5. Conclusions

We quantified water use, grain yield, and GHG emissions in response to two AWD irrigation treatments compared to the conventional management regime of tropical rice in Colombia. We found that both CH_4 and N_2O emissions significantly decreased under AWD management with little difference in rice yields in three of four seasons. Our findings are consistent with our hypothesis: that AWD treatments with drainage depths of 5 or 10 cm can help reduce CH_4 and N_2O emissions in the Colombian context without reducing yields by maintaining soil water content at levels that do not induce crop water stress compared to the control. An important aspect of this study is that AWD was compared against a non-continuously flooded control, which is becoming a more common management practice due to water scarcity. The significant reduction in water use and CH_4 emissions is aligned with the large body of evidence on AWD irrigation. However, the simultaneous reduction in N_2O emissions is an important contribution because many AWD studies report an increase in N_2O emissions. We attribute the reduction in N_2O emission to optimal water management at the time of fertilization events early in the season to achieve a soil moisture near field capacity for AWD treatments, whereas this differs from conventional rice management where the soil is maintained at near saturation conditions. Thus, fine tuning water management during drainage events may be the key to lowering GHG emissions without reducing productivity in non-continuously flooded systems where N_2O emissions represent an important contribution to GWP. Future work should explore whether the control treatment could produce similar results if soil water content continued to be maintained near field capacity after fertilization to avoid water stress. Our results suggest implementation of AWD can be a low GHG emission, climate-resilient practice for Colombian rice farmers because it ensures yields and food security and improves water use efficiency during dry and wet seasons.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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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.2023.108787.

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