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Methane Emission in a Small-Scale Rice Field under Two Different Water Management Strategies – An Insight for Landscape Level Adjustments

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ABSTRACT

The main purpose of this study was to optimize the methods for determining methane emission in a continuously flooded (CF) and an alternately wetted and dried rice system. A field experiment was conducted at Block B1, Pili Drive, Los Baños, Laguna for one cropping season to evaluate the CH_4 emission in both FP and AWD treatment plots. Fertilizer application rates were similar across treatments and were based on the recommended rate. Gas sampling was done weekly at 0, 15, and 30 – minute intervals and gas samples were analyzed using a gas chromatograph equipped with a flame-ionization detector (FID). Results showed that FP plots emitted methane at 15.07 to 459.14 mg CH_4 day^{-1} m^{-2}, which was higher than those produced in AWD plots which ranged from 1.68 to 36.26 mg CH_4 day^{-1} m^{-2} throughout the cropping period. In both treatments, a decreasing trend in methane emission was observed which was attributed to the depleting carbon source of methanotrophs where methane was utilized rather than produced at an unfavorable redox potential for methane production. Global warming potential (GWP) of 7.000 kg CO_2-eq and 1.350 kg CO_2-eq was contributed by FP and AWD treatments, respectively. Overall, CH_4 emission was reduced by 80–85% when AWD was employed without having a yield compromise. The result of this pilot study is limited to a 1.300 m^2 field area but it showed a significant comparison between the two water management strategies in rice systems. Also, the learnings in this study will be used further for landscape greenhouse gas measurements in major rice-producing areas in the Philippines and ultimately will contribute to the carbon footprint assessment of rice cultivation.

Keywords: AWD, rice production, global warming, methane, greenhouse gas, carbon footprint.

INTRODUCTION

Rice (*Oryza sativa* L.) production in the Philippines reached about 20 million tons in 2021 harvested from a land area of 4.8 million hectares. Hence, it is considered as one of the major crops in the country, and being the global primary staple, it is consumed by more than 50% of the global population. An average yield of 4.15 tons ha^{-1} was produced in 2021 and an annual improvement of about 1% has been anticipated [Awika, 2011]. Although this meets the demands for food security, there has been an environmental implication, particularly an increase in greenhouse gas (GHG) emissions, with intensive global rice production. Agriculture is the second-largest sector contributing to greenhouse gas emissions, responsible for 24% globally, following the energy sector, which accounts for 35% of emissions [IPCC, 2014]. Rice production is a significant contributor to methane (CH_4) emissions, ranking second only to enteric fermentation among agricultural operations. Methane emissions from agriculture are primarily responsible for 22% of global anthropogenic agricultural emissions, according to Smartt et al. [2016]. Methane emissions contribute to over 90% of the GWP in rice farming systems. Rice cultivation has a larger GWP compared to maize and wheat, with GWP values ranging from 2.7 to 5.7 times higher [Linquist et al., 2012].

In 2020, the CH_4 concentration reached up to 1.58 million tons in the Philippines, and 21.2 million tons in Asia, which is equivalent to a GWP of 44.2 million tons and 594 million tons of CO_2, respectively. Previous studies showed 9–11% of anthropogenic CH_4 in the atmosphere globally is generated from rice production [IPCC, 2014; Tubiello et al., 2014] while some have measured elevated concentrations of CH_4 and relatively low levels of nitrous oxide (N_2O) in the production of rice on flooded soil [Linquist et al., 2012]. However, rice fields that are drained during the mid-season until the reproductive stage showed an increase in N_2O concentrations and a decrease in CH_4 emission [Zou et al., 2007; Siopongco et al., 2013].

Alternate wetting and drying (AWD) is a water management technology that conserves water and benefits rice producers in an irrigation-limited field without having a negative impact on productivity. This regime allows alternating flooding and drying of the field throughout the crop season, rather than continuous flooding. Reflooding of the field is done when the water has subsided, leaving the soil surface dry. This allows the paddy fields to undergo dry/wet cycles instead of having it continuously flooded. With this technique, irrigation water is conserved while also mitigating GHG emissions. Overall, AWD is a beneficial and efficient approach that conserves water and reduces the greenhouse gas emissions from rice paddies. Proper AWD implementation would reduce methane emissions by 48% compared to when the field is continuously flooded [Siopongco et al., 2013]. Also, earlier studies reported that fields under AWD had shown significant CH_4 reduction with minimal to no yield losses [Yao et al., 2012; Tirol-Padre et al., 2018]. AWD method is commonly implemented in China and is gaining traction in countries such as Vietnam, Bangladesh, Myanmar, and Indonesia. In the Philippines, efforts to validate and promote AWD within national agricultural research and extension systems began in 2001 [Lampayan et al., 2015].

Although the decrease in GHG emission has been confirmed in AWD rice systems, the percent reduction may be significantly varied due to the differences in practices that could affect carbon mineralization and emission, including fertilizer management, organic material incorporation, and the duration of land preparation. These practices should be considered when the measurements are conducted on a larger scale (i.e. 1,000-hectare field). Therefore, this pilot study initially aimed to optimize the method for measuring methane emission in small-scale field experiment to gain information on adjustments that should be employed when the measurements are done on a landscape level, particularly in a major rice-producing province. Additionally, it will generate recent results that could be provided to farmers who could possibly transition from continuously flooding to alternate wetting-and-drying. For rice farmers to adapt to AWD, any change in field management practices, including water management, must not significantly affect their productivity. Finally, this study will contribute to emission inventories and carbon footprint analysis of rice cultivation which can eventually provide basis in developing sustainable management practices while reducing environmental impacts.

MATERIAL AND METHODS

Time and place of study

The field was located at B1 block (14°09’48.00” North and 121°15’01” East) along Pili Drive at the University of the Philippines Los Baños, Laguna (Figure 1). The duration of the experiment is one season from April to July 2023 (early wet season).

Edaphic condition of the study area

Los Banos, Laguna is a landlocked municipality in Laguna situated at 14°11’ North and 121°13’ East of the Philippines. The municipality lies at 22 meters above sea level comprising 54.22 square kilometers or 2.81% of the actual land area of the province of Laguna. The municipality of Los Banos is characterized by having a Lipa soil series which has a fine clayey isohyperthermic family of the Typic Eutropepts. This soil series is described as moderately deep with moderately well to well-drained soil in an undulating to rolling topography. It is also characterized by having a surface color of very dark yellowish brown, very dark brown, strong brown, dark yellowish brown and dark brown; and texture classified as clay, clay loam, silty clay, or silty clay loam

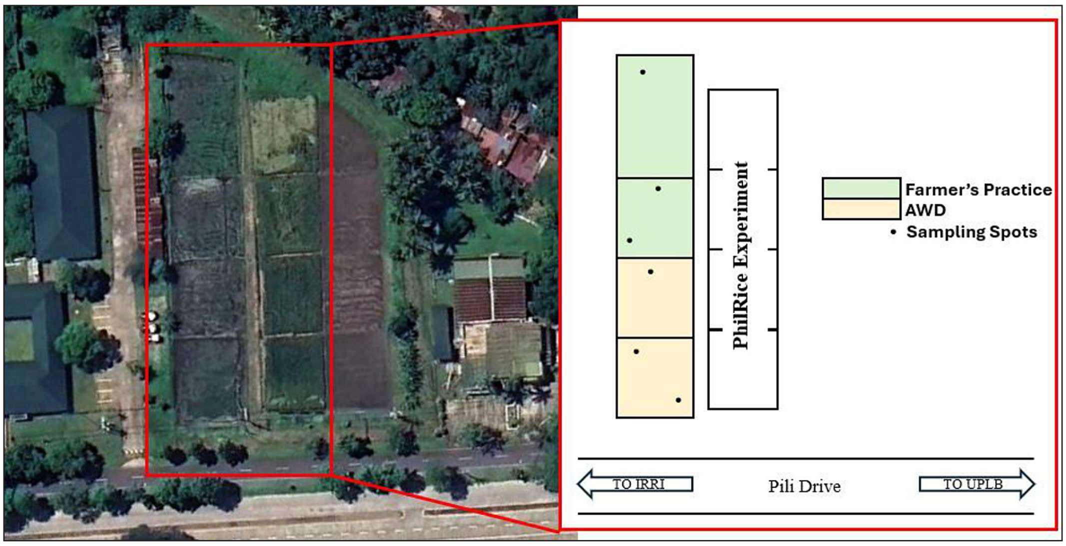

Figure 1. Study site (B1 block) and gas sampling locations

Table 1. Soil physicochemical properties of the field

Parameters	Description	Values	Methods
pH	Soil pH in water (1:1 ratio)	6.3	Potentiometric method
OM	Organic matter content, %	4.05	Walkley-Black method
Nitrogen	Total nitrogen, %	1.41	Kjeldahl method
Phosphorus	Available phosphorus, ppm	17.08	Bray II method
Potassium	Exchangeable potassium, $cmol_c$ kg^{-1}	1.17	NH_4OA_c method

[Carating et al., 2014]. Relevant physicochemical properties are shown in Table 1.

Crop establishment and treatments

NSIC Rc 222 variety of 14 – day old rice seedlings were transplanted with two to three seedlings per hill at 20 × 20 cm spacing. Molluscicide application was done before and after transplanting to minimize losses from the golden apple snail. Weed management was done by applying a post-emergence herbicide 10 days after transplanting (DAT), combined with manual weeding, as required. The total land area in all field locations was about 1300 m^2. The experimental plots were separated by bunds to minimize the risk of irrigation water entry. Water management was the only treatment in this study, which included: (1) continuous flooding (farmer's practice/FP) and (2) AWD. Continuous flooding was employed by allowing an initially three cm standing water in the field after transplanting, which was gradually increased to 5−10 cm and drained only 7−10 days before harvest. On the other hand, a safe AWD was implemented by boring a water tube made of 30 cm long PVC pipe with a diameter of 10−15 cm into the soil. The lower 15 cm of the tube, which was bored into the soil, was perforated with holes. This was done to monitor the water depth in the field. When the water level has dropped to about 15 cm below the surface of the soil, irrigation should be applied to re-flood the field to a depth of about 5 cm. From one week before to a week after flowering, the field should be kept flooded while the water level can be allowed to drop again to 15 cm below the soil surface after flowering, during grain filling and ripening. However, in the event of rain when the water level cannot be controlled and the scheduled drying in AWD cannot be implemented, floodwater was allowed to subside naturally until AWD can be implemented again. In this study, land preparation started 2-3 weeks before crop establishment where the field was kept flooded most of the time. AWD was implemented starting 9 DAT since rice seedlings cannot survive without flood water. The treatments were laid out in a randomized complete block design (RCBD) with three replications. Fertilizer application rates were similar across treatments. The recommended rate that was used for the study was 90–60–60 kg N-P_2O_5-K_2O ha^{-1}. The chemical fertilizers used for the study were urea (46–0–0) and complete fertilizer (14–14–14).

Collection of gas samples and analysis of methane

Gas sampling for methane using the closed chamber method was based on the protocol described in Romasanta et al. [2017]. This method adheres to the soil emission measurement guidelines outlined by Butterbach-Bahl et al. [2016]. Gas measurements were conducted from the land preparation stage, through growth, and up to three days following harvest.

The gas collection apparatus is composed of three major parts: 1) a chamber body made from an acrylic box (44.5 cm length, 26.6 cm width, 80.1 cm height) that can accommodate the height of mature plants, 2) a chamber top which included a 9 V battery-operated fan to ensure well-mixed air during sampling, a sampling port, a thermometer, and a vent to equilibrate the pressure, and 3) a chamber base made from a stainless-steel metal base with a length, width, and height of 44.5, 26.6, and 9.5 cm, respectively. It serves as the anchor and was inserted into the soil covering two rice hills (Figure 2). During each sampling period, measurements were taken of the water depth around the metal base and the temperature within the chamber.

Gas sampling was conducted every week starting at 0900H. There were 3 replications for FP and AWD treatments. To allow similar conditions in the replicates, the chambers were closed all at the same time. A 60-mL syringe equipped with a stopcock was used to obtain gas samples inside the chambers at 0, 15, and 30 minutes following the chamber closure. Then, the samples were promptly injected into a 30 – mL evacuated vial with a butyl rubber septum. These samples were analyzed by the gas chromatograph (GC) within 1–2 weeks (Figure 3). The gas chromatograph (SRI GC-8610C) was equipped with a flame-ionization detector (FID) for the analysis of CH_4. The temperature of the FID was 330 °C and the column temperature was set at 70 °C. Nitrogen (N_2) was used as the carrier gas. A 3 m Porapak Q (50–80 mesh) was used as the packaging material of the columns. The amount of methane in mg CH_4 was derived from the ideal gas law using the temperature and the chamber volume occupied by air measured at the time of sampling (Equation 1). An assumption of 1 atm pressure, P, is equal to a concentration, C of 1 ppm:

$$PV = n_{CH4}RT = \frac{(mass\,CH_4)RT}{MM\,CH_4} \tag{1}$$

where: $P = C$ – concentration of CH_4, ppm (GC output); V – chamber volume - volume of standing water (L), R – 0.0821 atm-L/mol-K, T – 273 + temperature inside the chamber (K), and $MM\ CH_4$ = 16 g/mol.

Linear regression of the three measurement points (0, 15, and 30 min) against the amount of methane (mg CH_4) for each time point was used to calculate the slope as the hourly flux rates of CH_4 (mg CH_4 h^{-1}) according to Minamikawa et al. [2015] (Equation 2):

$$Flux\ CH_4\ (mg\ CH_4\ m^{-2}\ h^{-1}) = \\ = \frac{\Delta mass}{\Delta t} \times \frac{60\ min}{h} \times \frac{1}{A} \tag{2}$$

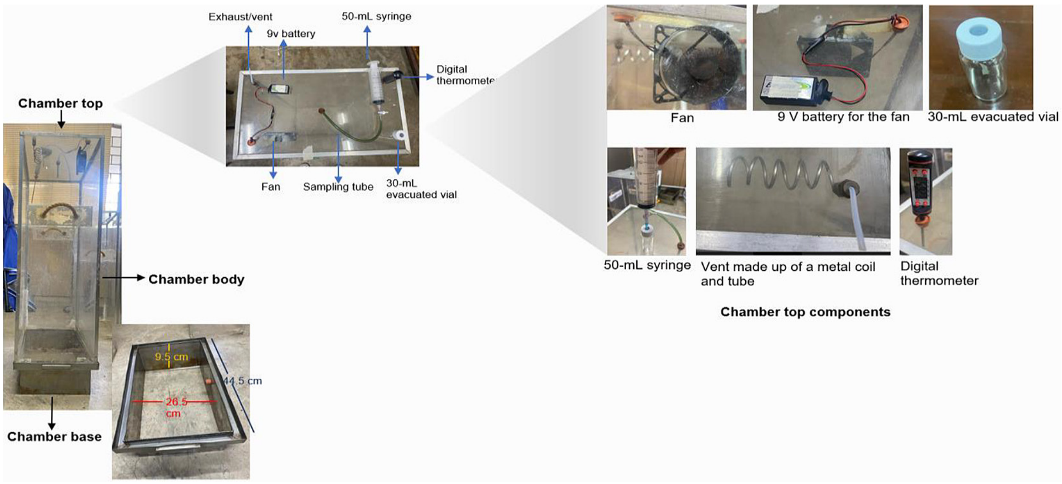

Figure 2. Gas collection apparatus

Figure 3. Gas chromatograph

where: *Δmass* – change in CH_4 amount (ppm), *Δt* – change in time (min), and *A* – area covered by the chamber (m^2).

The trapezoidal integration method (i.e., linear interpolation and numerical integration between sampling times) was employed to determine the flux of CH4 emitted for a sampling interval (i.e., the number of days between two sampling times) (Equation 3). This was accomplished by first determining the daily gas flux by multiplying the hourly gas flux by 24, resulting in a unit of mg CH_4 m^{-2} day^{-1}. Subsequently, linear interpolation was implemented to determine the emission between each pair of consecutive actual measurements. This estimation was done following an actual measurement and was continued sequentially until another actual measurement:

$$\begin{gathered} g\,CH_4\,m^{-2}\,day^{-1}\,at\,\times\,DAT\;= \\ =\,mg\,CH_4\,m^{-2}\,day^{-1}\,at\,\times -1\,DAT\,+ \\ +\left(\frac{mg\,CH_4\,m^{-2}\,day^{-1}\,at\,\times -1\,DAT+(A-B)}{(no.of\;days\;in\;between\;current\;and\;previous\;DAT+1)}\right) \end{gathered} \tag{3}$$

where: *A* – mg CH_4 m^{-2} day^{-1} at current actual DAT, and *B* – mg CH_4 m^{-2} day^{-1} at previous actual DAT

A graph of the daily methane flux (mg CH_4 m^{-2} day^{-1}) throughout the growing season was constructed. To calculate the GWP in kg CO_2-eq ha^{-1}, radiative forcing potential relative to CO_2 for a 100 – year time horizon of 28 was used for CH_4 (Equation 4):

$$\begin{gathered} GWP\;in\;kg\;CO_2-eq\;ha^{-1}-1\;= \\ =\,mgCH_4\,m^{-2}\,day^{-1}\times\frac{(28\,mg\,CO_2)}{(mg\,CH_4)}\times\frac{10{,}000\,sq}{1\,ha} \end{gathered} \tag{4}$$

Statistical analysis

Means across three replicates of methane emission and GWP were reported. A parametric test was used following homogeneity of variance and normal distribution. Water management options (FP and AWD) were compared using a two-sample t-test at α = 0.05 significance level.

RESULTS AND DISCUSSION

Methane emissions in AWD and CF treatments

To evaluate the effect of two irrigation management on CH_4 emission, a graph of methane emission for plots following FP and AWD during wet cropping season of rice is presented in Figure 4. Generally, AWD plots resulted in a lower amount of methane emission throughout the season ranging from approximately 1.68 to 36.26 mg CH_4 day^{-1} m^{-2}. While FP plots produced methane at 15.07 to 459.14 mg CH_4 day^{-1} m^{-2}. Over the entire season, the AWD practice resulted in a significant reduction in CH_4 emission compared with the FP.

The reduced condition of the paddy field is favorable for methanogen activity, thus higher emission was obtained in FP. Further, the introduction of oxygen in AWD promotes the activity of methanotrophic bacteria which relies on methane that is produced during flooded condition as its carbon source, thereby, reducing the accumulated

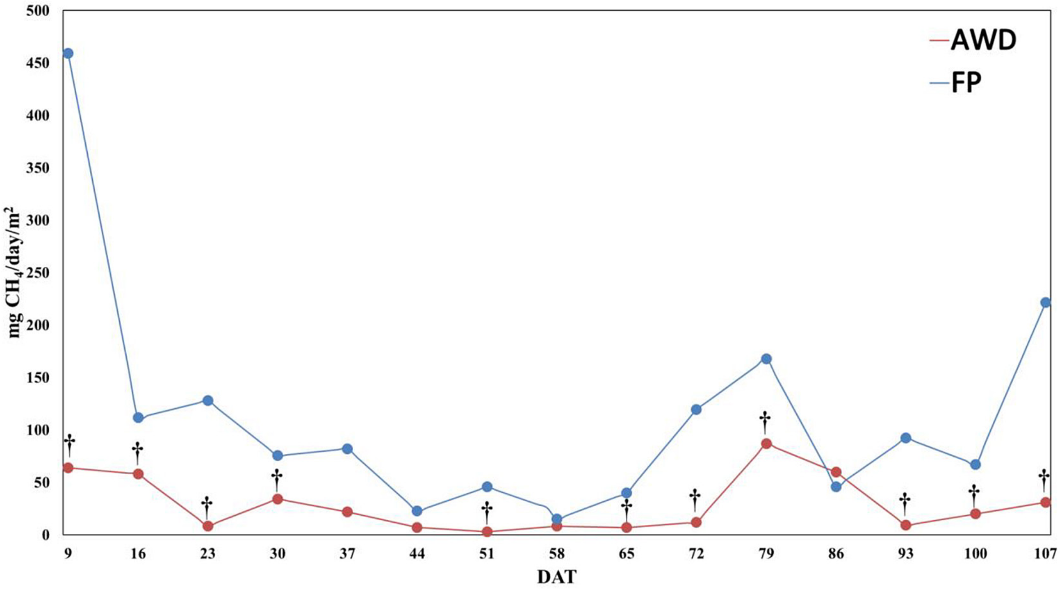

Figure 4. Daily flux of methane in FP and AWD rice systems. Dagger (†) above indicates significant difference between treatments at $p < 0.05$

methane on the soil by 60–70% [Fernandez-Baca et al., 2021]. Also, continuous reduction in methane emission was observed for both water management. Methane reduction in flooded soil until the early reproductive stage (44 DAT) can be attributed to limited microbial decomposition which releases carbon in the soil. This carbon is utilized by methanogens in order to proceed in methanogenesis. This indicates that CH_4 utilization as a carbon source by methanotrophs is greater as compared to the production of methane by methanogens. In addition, the redox potential of the soil should reach about -150 mV for a continuous reduction process that facilitates the action of methanogens [Minamikawa et al., 2006]. This will happen only when all the electron acceptors have been consumed in a continuously reducing environment, following the sequence from oxygen, to NO_3^-, to Mn^{4+}, to Fe^{3+}, to SO_4^{2-}, then lastly, CH_4. This is one of the limitations of the study, which is lacking the redox potential measurements that could explain the decreasing trend of methane production observed for both irrigation management. At the reproductive stage (58 DAT onwards), an increase in methane production was observed in both irrigation treatments. During this growth phase, root biomass increases, thus increasing the amount of organic acids released by the plants which promote the production of methane. Besides, complete fertilizer was added during this stage to which Li et al. [2022] cited to rapidly change the soil pH and ammonium level in the soil, affecting the methanotrophs' population and activity. Further, oxidation of nitrite and nitrate supplied by complete fertilizer is also a function of two major methanogen bacteria *M. oxyfera* and *M. nitroreducens.*

With the AWD plots, the fields were irrigated after 7–10 days of drainage period. However, the impact of a drainage event was still observed due to the continuously low CH_4 emission even when the soil was irrigated again. A factor for this prolonged effect is the other electron acceptors that became oxidized upon drainage of water and impeded CH_4 production in the succeeding period [Ali et al., 2013]. This phenomenon was derived using ecosystem modeling by Matthews et al. [2000] and Van Bodegom et al. [2000]. Furthermore, over the entire season, the received intermittent rainfall affects the CH_4 emissions as unstable water regimes which also influences most of the physicochemical parameters and biological processes in rice fields [Sibayan et al., 2018]. The level of CH_4 emissions during continuous flooding in the wet season of tropical rice is influenced by various stages of crop growth [Conrad, 2007]. This is mainly linked to the creation of anaerobic soil environments, the presence of easily degradable carbon from rice straw, and the rapid growth of rice plants, which enhances the transport of CH_4 through the plants [Islam et al., 2018].

Contribution to GWP

GWP serves as an index for the cumulative radiative forces between the present and a designated future time horizon through the current mass of gas emitted, expressed in kg CO_2 equivalent [Myhre et al., 2013]. The net GWP refers to overall balance between the net exchange of greenhouse gases such as CO_2, CH_4, and N_2O of a crop production system (Mosier et al., 2005). In this study, approximately 7,000 kg CO_2-eq ha^{-1} was contributed by FP treatment mainly from CH_4 emission, while only 1.350 kg CO_2-eq ha^{-1} was derived from the CH_4 emission in AWD treatment starting at land preparation up to three days after harvesting (Figure 5). Accounting only at the start of transplanting, these values were decreased down to 2.750 and 405 kg CO_2-eq ha^{-1}, for FP and AWD treatments, respectively. This shows that land preparation contributed to GWP for up to more than 60% in FP and up to more than 70% in AWD. This can be explained by the rate of microbial activity when cultural practices are done. Decomposition of organic material is faster during plowing; thus, higher rate of carbon is released during land preparation. This is because land preparation activities such as tillage and plowing disturb the soil, thereby releasing organic matter held within the aggregates. Tilling also improves soil aeration which is favorable to microbial activities. The decomposition of organic matter releases carbon which will be utilized by methanogens, thus, increasing the rate of methanogenesis during land preparation in comparison to the growing period [Magdoff and Van Es, 2021]. Besides, cultural practices also alter the physical and chemical properties of the soil [Ko and Kang, 2000]. Meanwhile, an 80% reduction in seasonal CH_4 emission was observed when AWD was employed including the emission during land preparation, while there was an emission decrease of 85% accounting only from crop establishment.

Impact of AWD on yield

Grain yield data was collected from a 5 m^2 harvest area with 5 replications from each plot. Average grain yields for FP and AWD plots were 3.998 tons ha^{-1} and 4.022 tons ha^{-1}. Similarly, other researchers recorded no significant change in yield following the adoption of water management strategies to reduce CH_4 emissions [Chidthaisong et al., 2018; Souza et al., 2021; Wu et al., 2022;]. This implies the effectiveness of AWD as a strategy to mitigate GHG emission without compromising the yield, and thus, without a negative economic impact on the farmer's productivity.

Method considerations to be applied for landscape GHG measurement

One of the most notable observations in this study is the effect of land preparation to GHG emissions. The length of time when the soil is flooded during land preparation varies among farmers. Thus, it is essential that gas samples be collected from both treatment plots at the same interval from the transplanting day (i.e. 2 weeks before transplanting).

It was also noted that AWD implementation can start only when the rice seedlings have grown enough to survive with depleting water, where in this experiment is at 9 DAT. Plots that will be under

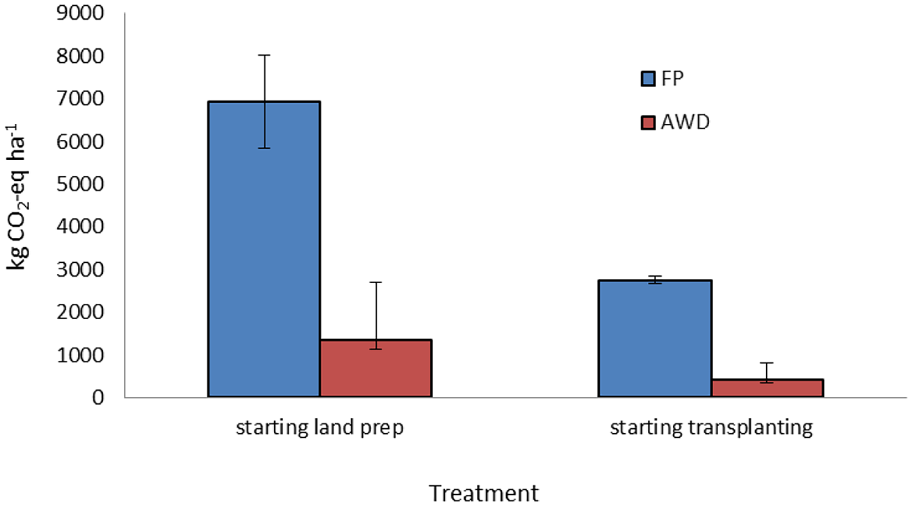

Figure 5. Seasonal GWP of FP and AWD systems

AWD are important to be selected appropriately, since drying will be difficult to achieve when the field is located down the slope. The placement of the PVC pipe in a small area is not crucial as long as it is in the middle of the field, but on a 1,000 – ha field, the number of pipes that should be placed to represent the water level of the AWD plots must be taken into account. It is essential that a pipe is located near the sample chamber.

Having a large field area would not necessarily mean more sampling spots to represent the GHG emission of the entire field, given that the field conditions are homogenous (e.g. fertilizer application rates, soil physicochemical characteristics, field management).

Logistics challenges are identified if the protocol is carried out in a large field. The need for synchronous sampling from the two water management treatments and replicates, communication in an open field area would pose a communication challenge between technicians that will collect the gas samples. Possible solutions would be the use of a handheld transceiver or the so-called walkie-talkie during sampling.

CONCLUSION

The continuous increase in population demands intensive cultivation of major crops in the Philippines, particularly rice, however, concerns about the effect of agriculture on methane and greenhouse gas emissions require control measures. Alternative practice of cultivation to mitigate GHG emission includes alternate wet and dry irrigation management.

In this research, two treatments of different irrigation management were employed. Alternate wet and dry conditions and farmer's practice or continuous flooding were assigned with two blocks each. Sample collection was replicated three times for the two treatments at time intervals of 0, 15, and 30 minutes from 9 AM to 11 AM. The collected samples were analyzed using a GC equipped with an FID.

The result showed higher methane emission in the FP field as to the plots assigned with AWD ranging from 15.07 to 459.14 mg CH_4 day^{-1} m^{-2} for FP and 1.68 to 36.26 mg CH_4 day^{-1} m^{-2} for AWD from transplanting to harvest period. The collected data also showed a decreasing trend for both irrigation management throughout the whole cropping season. Furthermore, methane is higher during land preparation as to the whole cropping period. GWP was calculated to be 7,000 kg CO_2-eq ha^{-1} for FP plots and 1,350 kg CO_2-eq ha^{-1} for AWD plots. Land preparation was also recorded to have a GWP of more than 60% in FP and 70% in AWD.

In conclusion, the method used was able to measure the methane emission in a continuously flooded (CF) and an alternately wetted and dried rice system. The field experiment conducted in a 1,300 m^2 field presented the considerations that must be taken into account when the method is conducted in a 1,000 – ha field. The study also showed the potential challenges in adapting to AWD due to the necessary additional labor requirements (e.g. PVC pipe installation and monitoring water level). With regards to measurement of methane emission, the results outlined in this paper is in consensus with previous studies where the application of AWD as irrigation management resulted in 80–85% reduction in methane emission without compromising the yield of rice plants. The findings from this study was found useful to further improve the method that is applicable for landscape level measurements so it can contribute to carbon footprint assessment of rice cultivation in the Philippines.

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