Potential of Rice (Oryza Sativa L.) Cultivars to Mitigate Methane Emissions from Irrigated Systems in Latin America and the Caribbean

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Abstract

Irrigated rice, represents a methane (CH_4) emissions source. In rice fields, the dominance of plant-mediated transportation of CH_4 from submerged soils to the atmosphere raises the possibility of varietal differences in CH_4 emissions. Previous findings remain inconclusive and no study has explored varietal differences in CH_4 emissions of rice in Latin America. A field experiment was conducted in Colombia to investigate the potential of a breeding line, a commercial variety, and two rice hybrids to mitigate CH_4 emissions from irrigated rice. Data on CH_4 emissions, phenotypic, physiological, root traits, and grain yield were collected. Results showed CH_4 emissions, grain yield, root length and root surface area differences followed the order Hybrid 2 > Hybrid 1 > breeding line > Commercial variety. Whereas CH_4 emissions per unit area for the two rice hybrids were within the of range 29–62% higher than the commercial variety and breeding line, CH_4 emission per unit grain yield were similar across the rice genotypes. Our data suggests that differences in root development and grain yields explain genetic influence on CH_4 emissions. We conclude that by exploiting differences in productivity and root characteristics among rice cultivars the transition towards low emission rice production systems can be accelerated.

Introduction

Rice (*Oryza sativa* L.) is a primary source of nutrients for over 50% of the world's inhabitants (GRiSP, 2013). In Latin America and the Caribbean (LAC), where per capita rice consumption is about 30 kg per year, most countries have rice deficits and require imports to cover their rice shortfalls (Durand-Morat and Bairagi, 2021; Maclean et al., 2002). However, the region is endowed with enormous terrestrial and water resources that can potentially support the expansion of the rice-growing area, particularly in Brazil, Colombia, and Venezuela (Espinosa, 2002). Currently, the area under irrigated rice represents between 73–74% of the overall rice cultivation area in the region (FLAR, 2021).

To produce rice in an environmentally benign manner, deliberate efforts are needed to reduce its contribution to total anthropogenic methane (CH_4) emissions without compromising yields (Islam et al., 2018). In irrigated rice systems, CH_4 is produced by methanogenic bacteria, which dominate under anaerobic conditions that are prevalent in water-covered rice fields (Sass and Fisher, 1997). Subsequently, three pathways are responsible for CH_4 transmission from the soil to the atmosphere: molecular diffusion, ebullition, and plant-mediated transport (Khosa et al., 2010). Previous studies have reported that > 90% of methane emitted from rice fields is lost through plant-mediated transport (Holzapfel-Pschorn et al., 1986; Butterbach-Bahl et al., 1997; Wassmann and Aulakh, 2000). Yet, despite the importance of plants in transmitting CH_4 from the soil to the atmosphere, research on varietal differences in CH_4 emissions is limited.

The focus of previous mitigation actions has targeted cultural practices such as fertilizer, crop residues, and irrigation management (Wassmann et al., 1993; Yagi et al., 1997; Wassmann et al., 2000), even though changing these aspects is challenging in the absence of supportive policies and economic incentives. Chirinda et al. (2018) suggested that taking advantage of varietal differences in CH_4 emission is probably a more cost-effective approach for mitigating CH_4 emission in LAC as the accompanying adjustment would not significantly alter farmer practices.

Various previous studies (e.g., Gogoi et al., 2008; Qin et al., 2015; Wang et al., 2017) suggest genotypic variations in CH_4 emissions. In a study conducted in China comparing one rice variety to a rice hybrid, Zhang et al. (2019) reported that root morphology and physiological traits were negatively and significantly correlated with total CH_4 emissions. Also, the rice hybrid used in the Chinese study had lower CH_4 emissions and higher yields than the rice variety. This study hypothesized that rice hybrids would emit less CH_4 emissions per unit yield due to having higher harvesting indexes than rice varieties. The possibility of rice genotypes that emit less CH_4 without compromising yield represents an attractive approach for mitigating climate change while achieving food security goals (Balakrishnan et al., 2018). Therefore, monitoring CH_4 emissions from different commercial varieties and hybrids is necessary to identify genotypes that reduce CH_4 emissions without compromising grain yield. In addition, there is a need to understand the factors driving CH_4 emission reductions to inform the focus of future breeding efforts.

Materials And Methods

Experimental site and set-up

The experiment was conducted at the experimental rice field at the International Center of Tropical Agriculture (CIAT), Cali, Colombia, from June to October 2019. The field was laid out in a randomized complete block design with four treatments in four replicates. The treatments were four rice cultivars comprising a commercial variety in Colombia, a CIAT experimental breeding line previously selected by its augmented root length, and two hybrids (Hybrid 1 and Hybrid 2) selected for their record of superior yield performance in field trials conducted at CIAT, as compared to check-inbred-varieties. Rice seedlings that were twenty-one days old were transplanted in the field plots on 17th June 2019. Soil properties at the experimental field are presented in Table 1. The overall soil fertility is rated highly for rice production. Recommended irrigation rice management practices were conducted during the experimental period. All the plant materials used in this study come from a working germplasm collection conventionally bred by the International Center for Tropical Agriculture (CIAT) in Colombia. CIAT granted permission for the use of all the plant materials in this study. Seed sources used in this study are part of the working germplasm collection from the Rice Program at CIAT.

Table 1
Soil properties at the study site.

Soil property	Unit	Value
pH	-	7.42
Nitrogen	g kg^{-1}	1.03
Available phosphorus	mg kg^{-1}	49.39
Cation exchange capacity	cmol kg^{-1}	37.1
Soil organic matter	g kg^{-1}	42.6
Calcium	cmol kg^{-1}	18.3
Magnesium	cmol kg^{-1}	9.5
Potassium	cmol kg^{-1}	0.7
Sodium	cmol kg^{-1}	0.6
Iron	mg kg^{-1}	14.0
Manganese	mg kg^{-1}	105.7
Copper	mg kg^{-1}	3.1
Zinc	mg kg^{-1}	21.9
Boron	mg kg^{-1}	0.5
Sulphur	mg kg^{-1}	44.5
Oxidized carbon	g kg^{-1}	18.75

Land preparation and plot description

The experimental site was ploughed, harrowed, and pulverized before transplanting mechanically. Then the fields were irrigated and puddled. Sixteen different plots (5 m × 4 m) were then demarcated and used to host the different plant genotypes randomly. The gross plot size was 5 m × 4 m (20 m^2), while the harvested net plot was 4 m × 3 m (12 m^2).

Fertiliser management

The experimental plots were fertilized with nitrogen in the form of urea at 180 kg N ha^{-1} and 200 kg N ha^{-1} for the varieties and hybrids, respectively. The nitrogen were applied in three split applications of

10%, 70% and 20% at 2, 10 and 55 days after transplanting, respectively. Similar rates of phosphorus (65 kg ha^{-1}) and potassium (90 kg ha^{-1}) were applied in soils under the different varieties and hybrids.

Plant measurements and analysis

At least four times during the growing season, five aboveground plant samples were collected from each treatment plot (outside the harvest net plot). The plant samples were subsequently dried for 72 h at 60^{o}C. At harvest maturity dry weight of plants collected from different net plots (4 m × 3 m) were partitioned between the leaves, stems, roots and panicles. Also, grain moisture content was determined at harvest maturity using agroTronix MT-PRO moisture metre. Following harvest, sub-samples of the harvested grain were used to characterize chalkiness using the method described by CIAT (1989). Root length, volume and surface area were determined using the method described by Ogawa et al. (2014). Briefly, at maturity, roots of five plants were harvested using a core sampler prior to washing and scanning using the EPSON scanner and analyzed using WinRhizo.

Greenhouse gas sampling

Gas measurements were conducted from the 10th of July to the 25th of September 2019. During the measurement campaign, gas sampling was initially aligned to fertilization, with measurements conducted one day before and three consecutive days after fertilization. After the fertilization period, measurements were conducted weekly until harvest. All samples were taken in the morning (8:00 to 11:00 a.m.). The method used for gas sampling was the static-closed chamber technique. Specifically, plastic buckets (114 L in volume and 80 cm height) were combined with custom-made chamber bases (40 cm height) that included a canal, making it possible to have a water seal during chamber deployment. Vents were installed on each static chamber. A fan was also installed inside the chamber to mix air; therefore, each sample (20 mL), collected using a syringe and stored in a pre-evacuated vial, was representative of the air inside the chamber.

The methane concentration in the collected vials was analyzed by gas chromatography (Shimadzu GC-2014). Methane fluxes were calculated using a gas concentration rate and sampling time (45 min) and the ideal gas equation. The cumulative fluxes for the monitoring period were calculated using linear interpolation and expressed in emissions per unit area (absolute emissions). CH_4 emission intensities were calculated as a ratio of the cumulative emissions and the grain yield and expressed in mg CH_4 per kg of grain dry matter yield.

Statistical Analyses

The data were tested for normality. Since data on crop parameters were normally distributed, we analyzed it using the proc mixed procedure of SAS. The models used tested the responses of the different crop parameters to the genotype. The replicates were included as random effects. In connection with these models, pairwise comparisons were made using Differences of Least Square means. The methane data were non-normally distributed, and none of the transformation analyses obtained variance homogeneity and normal distribution. Therefore, we used a non-parametric method (the Wilcoxon Signed Rank test), which does not require an assumption of normality, to test the paired difference in methane emissions between the genotypes. While the adopted methods do not offer the breadth of statistical insights similar to parametric methods, the non-parametric methods are valuable when flux data are non-normal (Corre et al., 1996).

Results

Aboveground biomass accumulation

Figure 1 showed similar aboveground biomass accumulation in the hybrids, breeding line, and commercial variety at the active tillering and maximum tillering growth stages. However, at 50% flowering and physiological maturity, the two hybrids had significantly higher aboveground biomass than the breeding line and commercial variety.

Root properties

At physiological maturity, the root system was significantly longer in Hybrid 2 than other genotypes (Table 2). The root volume and surface area followed the same trend as root length, but values obtained in the breeding line (which was bred to develop longer roots) were similar to those in Hybrid 2 (which had the highest root volume) and higher than those obtained for Hybrid 1 and the commercial variety.

Table 2
Root parameters measured during the rice-growing season.

Genotype	Root length at physiological maturity (cm)	Root volume at physiological maturity (cm^3)	Root surface area at physiological maturity (cm^2)
Commercial variety	2763[a]	6.4[a]	465[a]
Breeding line	3567[a]	8.4[ab]	607[ab]
Hybrid 1	2908[a]	8.1[a]	540[a]
Hybrid 2	3826[b]	11.0[b]	725[b]

Grain yield

Rice grain yields obtained were similar for the hybrids but significantly higher than those obtained for the breeding line and commercial variety (Table 3). The relative increase of hybrids' yield over the commercial variety was 26.4% and 26.7% for Hybrid 1 and Hybrid 2, respectively. When compared to the breeding line, Hybrid 1 and Hybrid 2 had 46.0% and 46.3% higher grain yield, respectively.

Table 3
Cumulative greenhouse gas emissions, grain yield and grain quality parameters.

Genotype	Cumulative methane (mg CH_4 m^{-2})	Emission intentisty (mg CH_4 kg^{-1} dry matter)	Grain yield (kg ha^{-1})	Grains per panicle	1000 grain weight (g)	Harvest index (%)
Commercial variety	4338[a]	0.73[a]	6333[a]	284[a]	25.9[a]	45.3
Breeding line	4482[a]	0.75[a]	5801[a]	376[b]	26.2[ab]	48.3
Hybrid 1	5761[b]	0.65[a]	8607[b]	303[ab]	24.2[b]	43.0
Hybrid 2	7068[c]	1.19[a]	8647[b]	397[c]	23.9[b]	52.0

Methane emissions

Daily methane fluxes followed a similar trend in different genotypes (Fig. 2). However, the magnitude of cumulative methane emissions followed the order Hybrid 2 > Hybrid 1 > breeding line > Commercial variety (Table 3). Hybrid 2 emitted 18.5% higher than Hybrid 1, which emitted 22.2% higher than the breeding line, and the breeding lines' methane emissions were 3.2% higher than those of the commercial variety. Despite differences in the magnitude of absolute CH_4 emissions (i.e., emissions per unit area), being significantly higher in the hybrids than the breeding line and commercial variety, CH_4 emission intensities (i.e., emissions per unit yield) were similar across genotypes.

Discussion

Based on the dominance of rice-mediated pathway of CH_4 transmission from the submerged soil to the atmosphere (Jia and Cai, 2003), there is evidence that genetic variations of rice and their effects on plant parameters influence CH_4 emissions from irrigated rice systems (Su et al., 2015; Qin et al., 2015; Baruah et al., 2010). The present study also demonstrated a significant difference between rice genotypes for methane emissions, with commercial variety and the breeding line emitting significantly less methane than the Hybrid genotypes.

Previous studies have reported that the difference between rice genotypes on methane emissions is mainly related to rice phenotypic and physiological parameters, i.e. the number of plant tillers, plant above and belowground biomass (Sinha 1995; Setyanto et al., 2004; Khosa et al., 2010). Other mechanisms that may influence observed genotypic variations in CH_4 emissions include differences in (1) root exudates, which represent methanogenic substrate (Kerdchoechuen, 2005); (2) the development of aerenchyma (Aulakh et al. 2000); and (3) the size of methane-oxidizing sites in the rhizosphere (Win et al., 2012; Gutierrez et al., 2014).

The roots of different rice genotypes may have other influences on the soil methanotrophic community composition (Lüke et al., 2011). Furthermore, some cultivars appear to allocate more of the products of photosynthesis to root exudation than others (Gutierrez et al., 2013; Su et al., 2015). Previous studies have reported that root exudates constitute an organic substrate for microbial organisms that could be utilized for methane production and oxidation by methanogens and methanotrophs, respectively (Win et al., 2012). Root exudates include simple sugars, which act as an electron donor under a flooded field, resulting in anaerobic conditions conducive to CH_4 production (Wassman and Aulakh, 2000 and Le Mer and Roger, 2001).

To compare rice grain yield and methane emissions in irrigated rice systems, researchers have used yield-scaled emissions to indicate the global warming impact of rice production (Moiser et al., 2006; Pittelkow et al., 2013; Bayer et al., 2014). As suggested by Grassini and Cassman (2012), the yield-scaled metric is increasingly used to provide a measure of agronomic efficiency that begins to address both climate change and future food supply concerns. The present study aimed to identify rice genotypes with a high yield potential but lower methane emissions from among four rice genotypes. The results indicate that Hybrid 1 had high yield potential and moderate CH_4 emissions resulting in low yield-scaled emissions. A higher rate of the partitioning of photosynthates to the developing panicles and grain accompanied by a higher rate of photosynthesis at the grain filling stage might be the reason for the higher grain yield in varieties with low methane emissions (Das and Baruah, 2008; Baruah et al., 2010). The partitioning of photosynthates to the panicles and grain will result in fewer carbohydrates being disposable for root exudates, an essential substrate for methanogens responsible for CH_4 production (Su et al., 2015).

content

Previously a global range of seasonal CH_4 emissions was reported to be between 2.7 to 1059 kg ha^{-1} (Minami, 1995; Yan et al., 2009). The magnitude of CH_4 emissions observed in this study ranged between 43.4–70.7 kg CH_4 ha^{-1}, well within the global range. Within the LAC region, using the commercial variety El Paso 144, a study conducted in Uruguay reported cumulative emissions ranging between 172.0 to 207.0 kg CH_4 ha^{-1} (Irisarri et al., 2012). Another study conducted in Uruguay, using the same commercial variety El Paso 144, also reported higher cumulative emissions ranging from 208.0 to 249.0 kg CH_4 ha^{-1} (Tarlera et al., 2016). In Colombia, a study conducted using the commercial variety FEDEARROZ-60 reported lower cumulative emissions of 7.5 and 19.5 kg CH_4 ha^{-1} in 2015 and 2016, respectively (Chirinda et al., 2017). In Brazil, CH_4 cumulative emissions observed for variety IRGA, 424 were 303.0-424.0 kg CH_4 ha^{-1} (Zschornack et al., 2016) which was higher than those reported in the present study. The varietal differences may have contributed to the wide variation in the LAC region's methane emissions. The ideal rice cultivars for reducing methane emissions would probably need a high harvesting index, fewer ineffective tillers, panicles, and nodes (Wang et al., 1997). Additionally, the selection or breeding of rice genotypes that do not have well-developed aerenchyma systems may also mitigate CH_4 emissions (Wassmann et al., 1993; Kludze et al., 1993). Focusing on rice cultivars for mitigating CH_4 emissions is a more manageable approach, as it does not require farmers to change agronomic practices significantly (Balakrishnan et al., 2018).

Perspectives

While there is a need for further studies that explore CH_4 emissions from more rice varieties and hybrids, our findings suggest a breeding solution for mitigating CH_4 emissions from irrigated rice systems. Climate change mitigation-relevant breeding may need to focus on root systems – the interface between the plant (through which CH_4 is transported to the atmosphere) and the soil (where the methane is formed). Specifically, our findings propose that breeding for shorter roots, lower root volume, and surface area without compromising yields may be beneficial in reducing rice-based methane emissions. On the other hand, to further incentivize the adoption of high-yielding and low CH_4 emitting rice, such rice should be considered a clean development technology that could qualify for carbon credits. A low-yielding rice variety may result in low absolute emissions (per unit area). However, farmers will require more land to produce sufficient rice to reduce rice deficits in the region. Promoting hybrids could be a more promising approach for simultaneously achieving food security and emission goals.

Declarations

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Authors contributions

N.C., E.G. and M.A. conceived the study. P.S., N.C., E.G., and M.A. experimented and collected the data. N.C. and P.S. analyzed the data. P.S., N.C., and M.A. wrote the manuscript. All authors reviewed the manuscript.

Competing interests

The authors declare that they have no competing interests.

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Figures

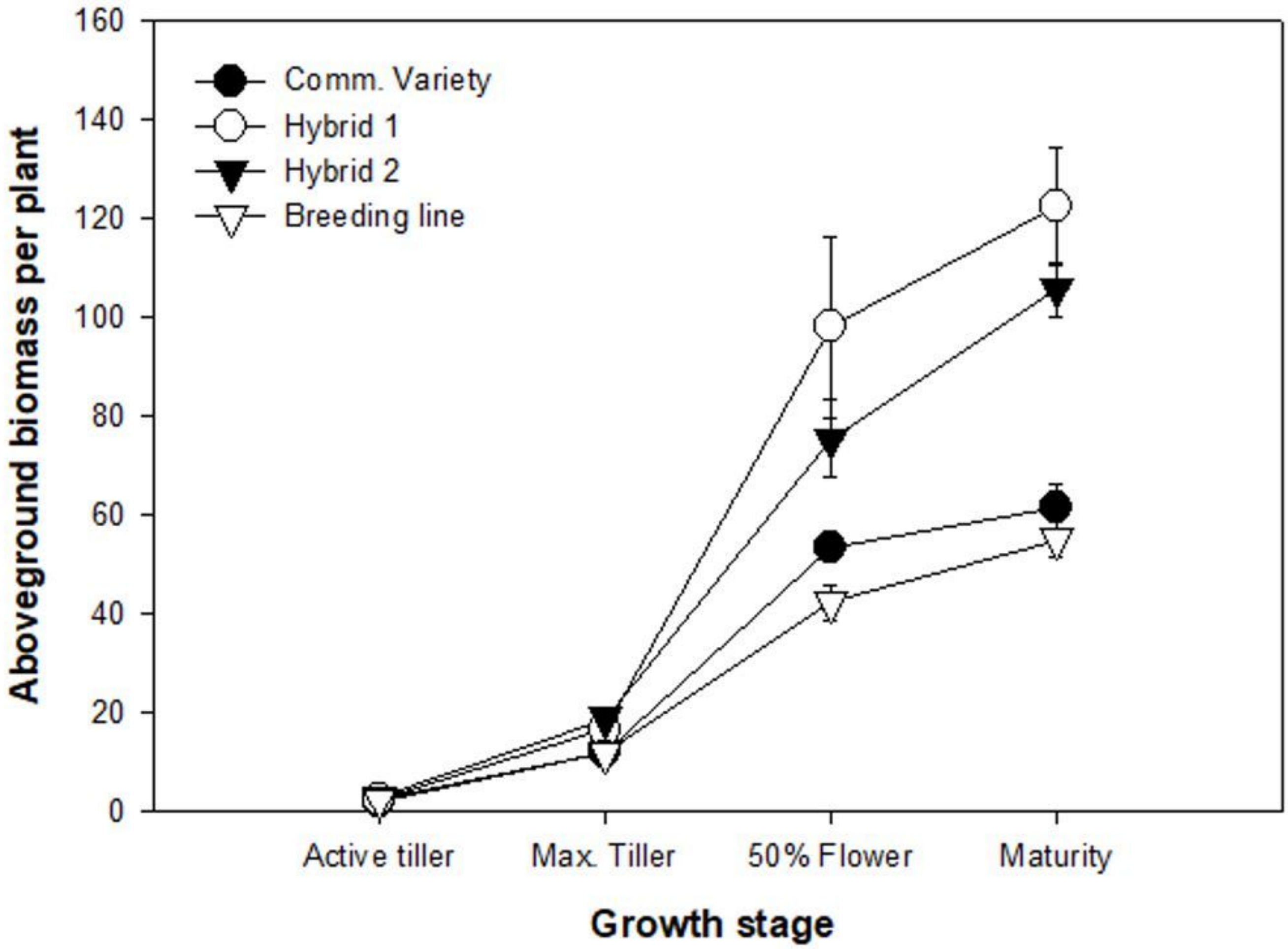

Figure 1

Aboveground biomass accumulation by the four rice cultivars at four growth stages (active tillering, maximum tillering, 50% flowering and maturity).

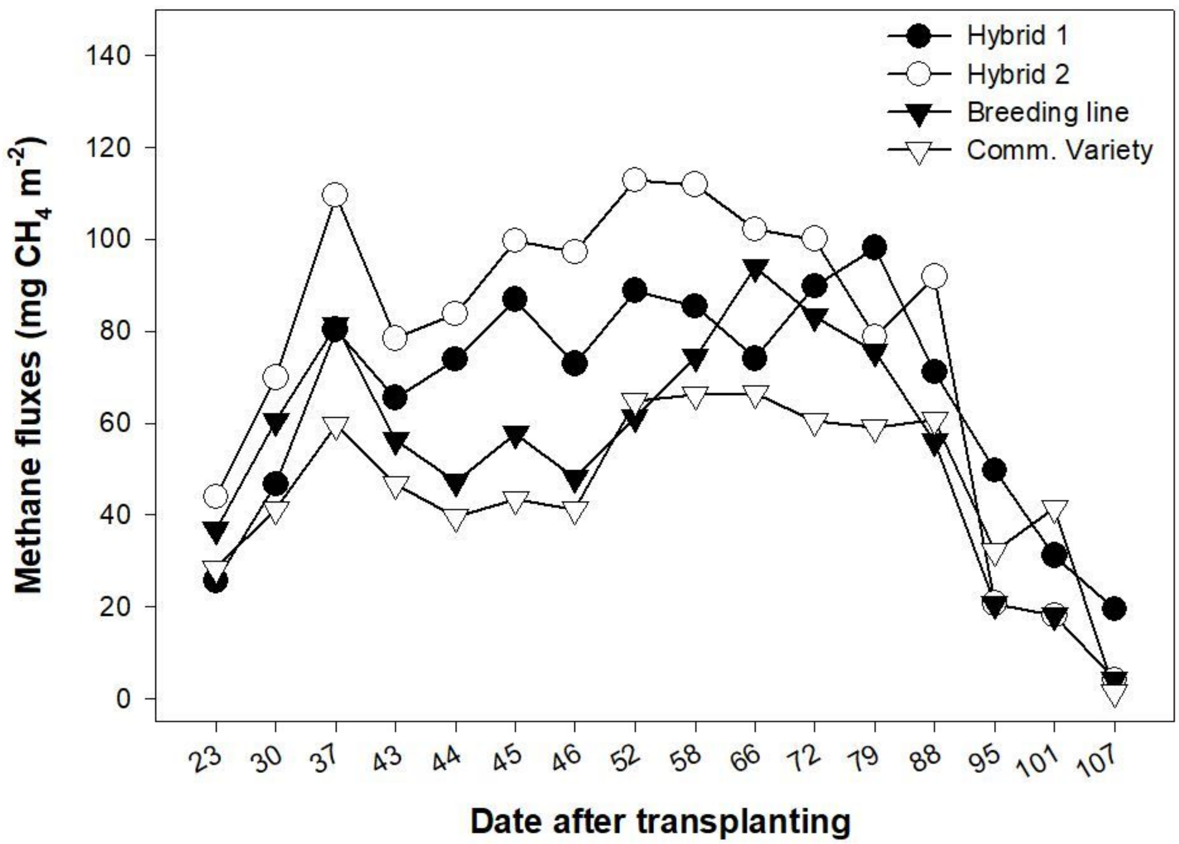

Figure 2

Methane emission dynamics of four rice cultivars as affected by days after transplanting.

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