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Gross Ecosystem Productivity Dominates the Control of Ecosystem Methane Flux in Rice Paddies

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Abstract: Although rice paddy fields are one of the world's largest anthropogenic sources of methane CH_4, the budget of ecosystem CH_4 and its' controls in rice paddies remain unclear. Here, we analyze seasonal dynamics of direct ecosystem-scale measurements of CH_4 flux in a rice-wheat rotation agroecosystem over 3 consecutive years. Results showed that the averaged CO_2 uptakes and CH_4 emissions in rice seasons were 2.2 and 20.9 folds of the wheat seasons, respectively. In sum, the wheat-rice rotation agroecosystem acted as a large net C sink (averaged 460.79 g C m^{-2}) and a GHG (averaged 174.38 g CO_2eq m^{-2}) source except for a GHG sink in one year (2016) with a very high rice seeding density. While the linear correlation between daily CH_4 fluxes and gross ecosystem productivity (GEP) was not significant for the whole rice season, daily CH_4 fluxes were significantly correlated to daily GEP both before (R^2: 0.52–0.83) and after the mid-season drainage (R^2: 0.71–0.79). Furthermore, the *F* partial test showed that GEP was much greater than that of any other variable including soil temperature for the rice season in each year. Meanwhile, the parameters of the best-fit functions between daily CH_4 fluxes and GEP shifted between rice growth stages. This study highlights that GEP is a good predictor of daily CH_4 fluxes in rice paddies.

Keywords: CH_4 flux; eddy covariance; budget; gross ecosystem productivity; rice paddy

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1. Introduction

Rice paddies provide the dominant staple food crop for over 5 billion people worldwide while acting as a major source of atmospheric methane (CH_4) which is the second most important greenhouse gas following carbon dioxide (CO_2) [1,2]. Thereby, constraint and mitigation of CH_4 emissions from irrigated rice fields emerges as a major scientific and policy issue. Previous studies on global estimation of CH_4 emissions from rice paddies showed that the budget of CH_4 flux remain great uncertainties [2,3], which indicated more efforts are needed to understand the responses of CH_4 flux to biological and environmental factors.

Previous CH_4 flux from rice paddies have predominantly been measured using the manual closed chamber technique [4,5]. Chamber-based measurements can introduce some potential biases due to direct interaction with the near-surface environment and are also limited to estimate annual budgets due to the discrete sampling in time [6,7]. In recent years, the eddy covariance (EC) technique advantaged in measuring CH_4 flux since it provides continuous ecosystem-scale CH_4 flux without interfering with the processes of gas exchange between the surface and the atmosphere [6,8]. Several studies using EC methods have advantaged our understanding of the dynamics and process of CH_4 flux from rice paddies [9–11]. However, to date few studies have used this method to measure CH_4 flux from rice paddies in China [9,10].

Methane-producing microbes (methanogens) produce CH_4 in soils as the end product of the anaerobic decomposition of organic matter, which would be mineralized to carbon dioxide under aerobic conditions before being released to the atmosphere. Thus, soil water content and soil temperature, which regulate the reduced soil conditions and enzyme-mediated processes, have been widely considered as the most important environmental controlling factors of CH_4 flux. However, rice plants growing in water-saturated soils are also closely associated with the production and transport of CH_4. Recently, several studies revealed that gross ecosystem productivity (GEP) is the dominant cause of the diel pattern of half-hourly CH_4 flux in rice paddies [9,10,12,13], and that GEP represents one of the most important factors regulating seasonal variations in daily CH_4 flux [9,14–16]. However, in some sites, GEP are not that important as temperature for CH_4 flux [10,11].

China has 19% of the global rice field area and provides 30% of the production, in which winter wheat-paddy rice cropping rotation are very common practiced. Over 80% of these rice paddies apply water-saving techniques, such as mid-season drainage and alternate wetting and drying, which has largely decreased the amount of CH_4 emissions [17–20]. In addition to changes in the redox environment, soil water status can influence stomatal conductance and photosynthesis of rice plants [21–23]. While Dai et al. (2019) using EC technique in a rice paddy in China has reported a correlation between GEP and CH_4 flux. How rice plants control CH_4 flux in rice paddies applying water-saving techniques remains unclear. In this study, we measured CH_4 flux using the eddy covariance technique over 3 consecutive rice growing cycles in a rice paddy where water-saving techniques are applied, to: (1) identify factors affecting CH_4 flux during rice season; (2) estimate annual carbon budget and greenhouse gas (GHG) budget for the rice-wheat rotation agroecosystem. We hypothesized that rice plant productivity would exert a strong control on CH_4 flux in the rice season.

2. Methods

2.1. Study Site and Crop Management

The studied rice-wheat rotation agroecosystem is located at the Yuejin Farm on the Chongming Island, Shanghai, China (31°48′37.54′′ N, 121°15′0.43′′ E, Figure 1a). The farm covers a flat and homogenous area of 18.95 km^2. The climate here is characterized as northern subtropical monsoon climate. The mean air temperature and annual precipitation were 17.1 ± 0.6 °C and 1156.1 ± 190.6 mm (1991 to 2012), respectively. The soil texture is characterized as silt loam. The soil organic carbon and total nitrogen in the topsoil (0–8 cm) are 20 g C kg^{-1} and 1.6 g N kg^{-1}, respectively.

2.2. Crop Establishment

An annual winter wheat-paddy rice cropping rotation was practiced in the field (Figure 1b). Winter wheat was sowed in October or December and rice was direct-seeded in June (Table 1). Seeds of the wheat and rice cultivar were Ningmai 13 and Wuyunjing 31, respectively. Chopped rice and wheat straw at 5–10 cm length is mixed into the soil layer when farmers plow in the cropping systems. The cropping regime and water management at the wheat-paddy field are representative of common practices in southeast China. The cropping regimes are detailed in Li et al. (2019) [16]. Irrigation was only started at a few days before the rice season and ended at about two weeks before the ends of the rice season. During the rice season, alternate wetting and drying regime (AWD) was deployed. The mid-season drainage (MSD) was also applied from late July to early August in each year [16]. In short, a typical water regime of AWD-MSD-AWD-moisture irrigation was practiced in the rice season.

The paddy rice sequentially experienced 3 growth stages related to rice plant phenology, including: vegetative (DOY 164–208, 159–206, 158–202 in 2016, 2017, and 2018, respectively), reproductive (DOY 209–271, 207–269, 203–271 in 2016, 2017, and 2018, respectively), and ripening stage (DOY 272–315, 270–296, 272–318 in 2016, 2017, and 2018, respectively). Mid-season drainage represents a strong artificial disturbance, and thus the MSD period (DOY 204–222, 200–216, 199–214 in 2016, 2017, and 2018, respectively) was separated from the late vegetative and early reproductive stage in our study. Accordingly, neither the vegetative stage nor the reproductive stage includes the MSD practice in the following analyses.

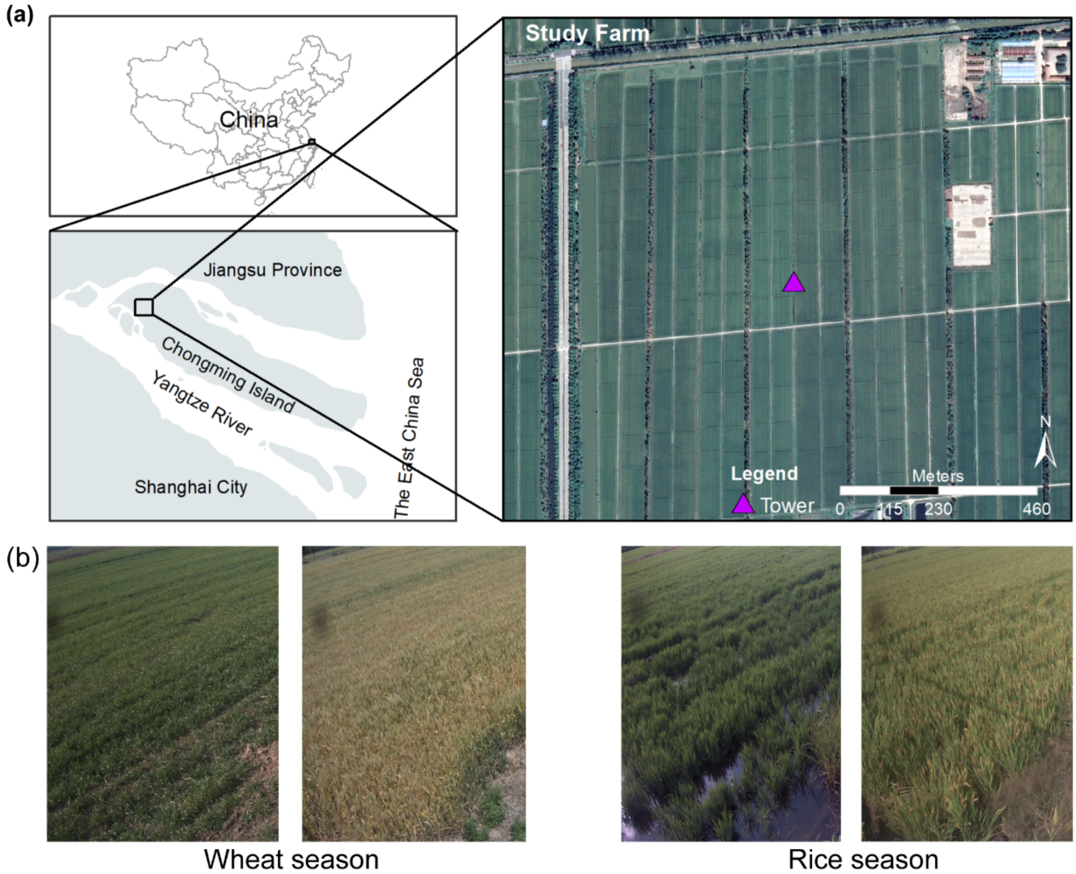

Figure 1. Location and the satellite image from Google Earth taken on 1st October 2018 of the study area (**a**), and the photos of wheat season and rice season, respectively (**b**).

Table 1. Planting and harvest date in the rice-wheat rotation agroecosystem.

Year	2015–2016		2016–2017		2017–2018	
Season	**Wheat**	**Rice**	**Wheat**	**Rice**	**Wheat**	**Rice**
Plant date	28 October	11 June	18 December	7 June	26 October	6 June
Harvest date	30 May	11 November	26 May	24 October	28 May	15 November

2.3. *Eddy Covariance Measurements and Data Processing*

The eddy covariance (EC) technique was used to continuously collect net CH_4 fluxes and net CO_2 fluxes between the wheat-rice rotation field and the atmosphere from 2016 to 2018. The EC measurement station was in the middle of the farmland (Figure 1). The EC system included an open-path CH_4 gas analyzer (LI-7700, LI−COR), an open-path CO_2/H_2O gas analyzer (EC150, Campbell Scientific), and a sonic anemometer (CSAT3, Campbell Scientific). The turbulence data was sampled with a frequency of 10 Hz.

Fluxes were calculated using the 30 min covariance of gas scalar concentrations of interest and vertical wind velocity after applying a series of standard correction. The

EddyPro 7.0.4 software (LI−COR) was used as outlined in Li et al. (2018, 2019) [16,24]. Briefly, these included a despiking procedure including detecting and eliminating individual out-of-range values [25], time lag detection applying covariance maximization with default, double coordinate rotations [26], compensation of Webb-Pearman-Leuning density fluctuations [27]. The random uncertainty for half-hourly fluxes were estimated [28].

The subsequent QA/QC processing for half-hourly fluxes were performed as detailed in Li et al. (2018, 2019) [16,24]. The data were removed when rainfall events occurred, relative signal strength indicator (RSSI) < 20%, and friction velocity < 0.13 m s^{-1} [29]. The the steady state test and the well-developed turbulence test were used to generate flux quality flags [30]. After QA/QC, data coverage during the rice growing seasons 2016–2018 were 49–56% for CH_4 flux and 52–64% for CO_2 flux. Daily averaged fluxes were only calculated when more than 12 data points were available for both daytime and nighttime.

To estimate seasonal budgets, gaps of CO_2 and CH_4 fluxes were filled using both the marginal distribution sampling method and a random forest algorithm [29,31]. GEP were estimated based on the gap-filling of the marginal distribution sampling method of CO_2 fluxes time series [29]. The uncertainty introduced by the gap-filling procedure were estimated [29,31]. The uncertainty of seasonal budgets was obtained according to Aurela et al. (2002) [32]. The net GHG budget was calculated assuming that 1 g CH_4 is equivalent to 28 g CO_2 with respect to the greenhouse effect over a time horizon of 100 years.

Basic hydrological and micrometeorological data were collected in conjunction with the EC data, including air temperature (3.3 m above ground, HMP155 A, Campbell Scientific), soil temperature (5 cm underground, 109, Campbell Scientific), and volumetric water content (VWC) (5 cm underground, CS616, Campbell Scientific), and water table depth (Pro 30, YSI).

2.4. Statistics

To investigate the seasonal variation in CH_4 flux, a semi-empirical multiplicative model was employed. Based on previous studies, several potential driving factors of the CH_4 flux were included in the model:

$$F_{CH4} = a \times b^{Tg} \times c^{GEP} \times d^{VWC} \times e^{u*} \times f^{P} \quad (1)$$

where F_{CH4} is the daily CH_4 flux, Tg, GEP, VWC, u*, P are the normalized soil temperature, gross ecosystem photosynthesis, volumetric water content, friction velocity, ambient pressure, respectively, and a, b, c, d, e and f are the model parameters. In 2018, water conductivity (g) and water table depth (h) were also tested as model parameters.

To identify the importance of each driving factor in synchronous controls of CH_4 flux, a partial F test was performed to determine whether including the independent variables in the model could significantly increase the model's ability to explain the variation of the dependent variable. A partial F value larger than the threshold F value ($F\alpha$, $\alpha = 0.05$) indicates that the excluded variable can significantly increase the explanation of the dependent variable at the significance level of 5% if it is included in the model. A larger F value suggests that the excluded variable can explain more of the variation of the dependent variable than other independent variables.

3. Results and Discussion

3.1. Seasonal Variations in CH_4 Fluxes and Predictors

Large seasonal variations in daily mean CH_4 fluxes were observed each year in the rice-wheat rotation agroecosystem (Figure 2). Daily CH_4 fluxes during 2016–2018 averaged at 10.57 and 408.07 mg CH_4 m^{-2} d^{-1} in the wheat and rice season, respectively. Daily CH_4 fluxes kept a relatively low range between −52.06 and 199.00 mg CH_4 m^{-2} d^{-1} in the wheat growing season and a range between 0.57 and 1488.70 mg CH_4 m^{-2} d^{-1} in the rice growing season. CH_4 fluxes sharply increased when the field was first flooded for the rice season in June. CH_4 fluxes reach peaks in late July and then gradually decreased to low emissions at the end of the rice season between late October and early November.

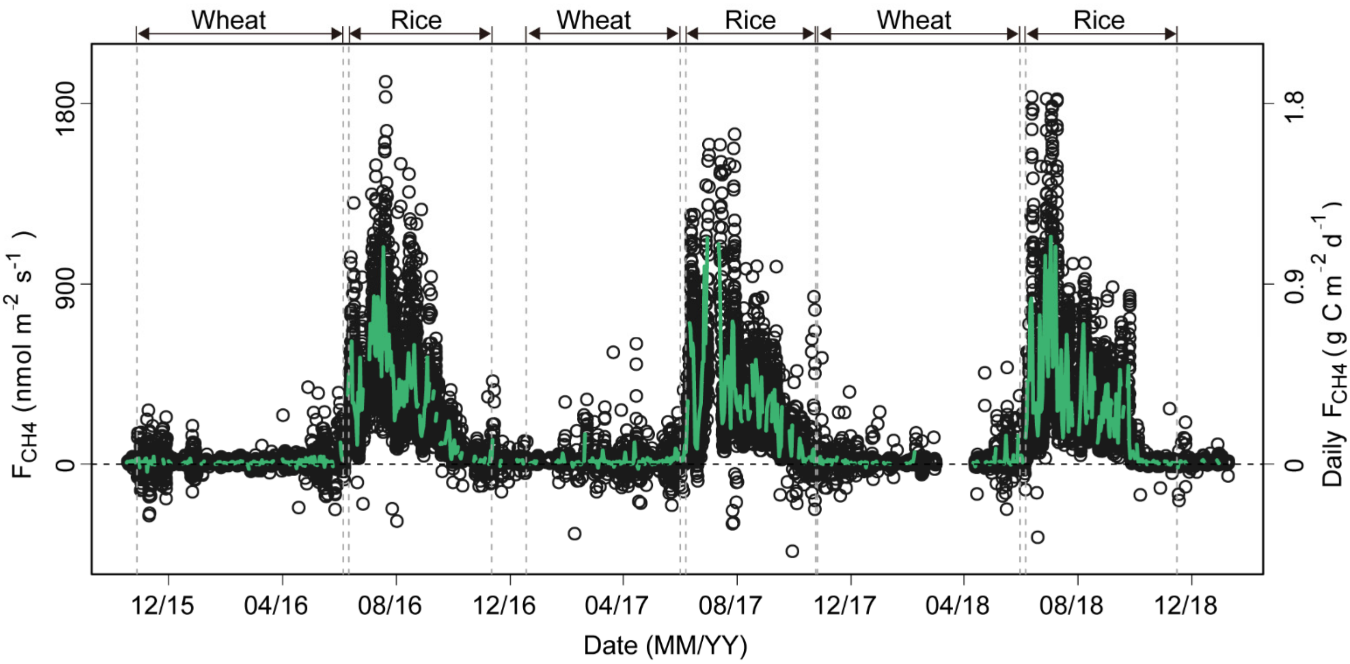

Figure 2. Time series of daily (green lines) and half-hourly (black circles) CH_4 fluxes during the rice growing season in 2016–2018.

For the rice season, daily CH_4 fluxes varied among rice growth stages (Figure 2). In the vegetative stage, daily CH_4 fluxes, as well as GEP and soil temperature, exhibited an increasing trend until the mid-season drainage (Figures 2 and 3). Daily CH_4 fluxes reached peaks of 1.45–1.47g CH_4 m^{-2} d^{-1} at the end of the vegetative stage in middle July of each year. Daily CH_4 fluxes sharply dropped by 81–88% during the mid-season drainage despite GEP and soil temperature continuing to increase (Figures 2 and 3). After the drainage, daily CH_4 flux increased to an average emission of 0.47, 0.42, and 0.44 g m^{-2} d^{-1} in August in 2016, 2017, and 2018, respectively. At the ripening stage, CH_4 flux was much lower compared to other stages (Figure 2). In total, cumulative CH_4 emissions at the vegetative, mid-season drainage, reproductive and, ripening stage were 46–48%, 13–18%, 31–38%, and 1–4%, respectively.

As discussed in Li et al. (2019) [16], CH_4 fluxes in the rice paddy represents a strong CH_4 source for atmosphere CH_4 during the rice growing season. The seasonal pattern (Figure 3) of CH_4 fluxes which was observed to peak before the mid-season drainage with a secondary peak after the mid-season drainage was consistent with previous studies under similar cropping regimes in southeast China [19,33].

During the rice growing season, the linear correlation between daily CH_4 fluxes and GEP were not significant. However, daily CH_4 fluxes were significantly correlated to GEP both before (Figure 4, R^2: 0.52–0.83) and after the mid-season drainage (Figure 4, R^2: 0.71–0.79) in each year. Furthermore, the partial *F* test showed that GEP during all periods were identified as significant variables in each year. Soil temperature during periods except for before the mid-season drainage in 2016 and after the mid-season drainage in 2018 were significant variables. The *F* value of GEP was much greater than that of any other variable including soil temperature in each year (Table 2), which demonstrated that GEP was much more important than any other variable included in the model although when other variables were added, a larger proportion of the variance in CH_4 fluxes could be explained at the seasonal timescale (Table 3, R^2: 0.80–0.98).

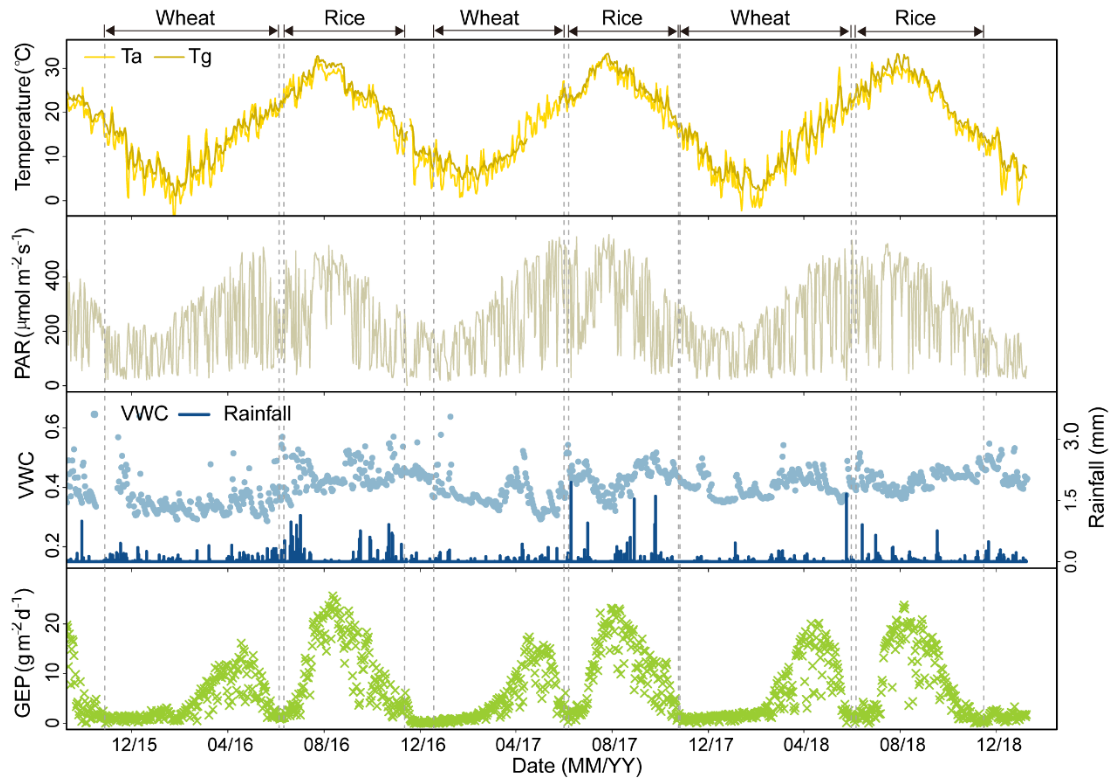

Figure 3. Time series of daily averaged air temperature (yellow lines), 5cm soil temperature (dark yellow lines), photosynthetically active radiation (PAR), volumetric water content (VWC, navy blue lines), rainfall (blue columns), and gross ecosystem productivity (GEP, green forks).

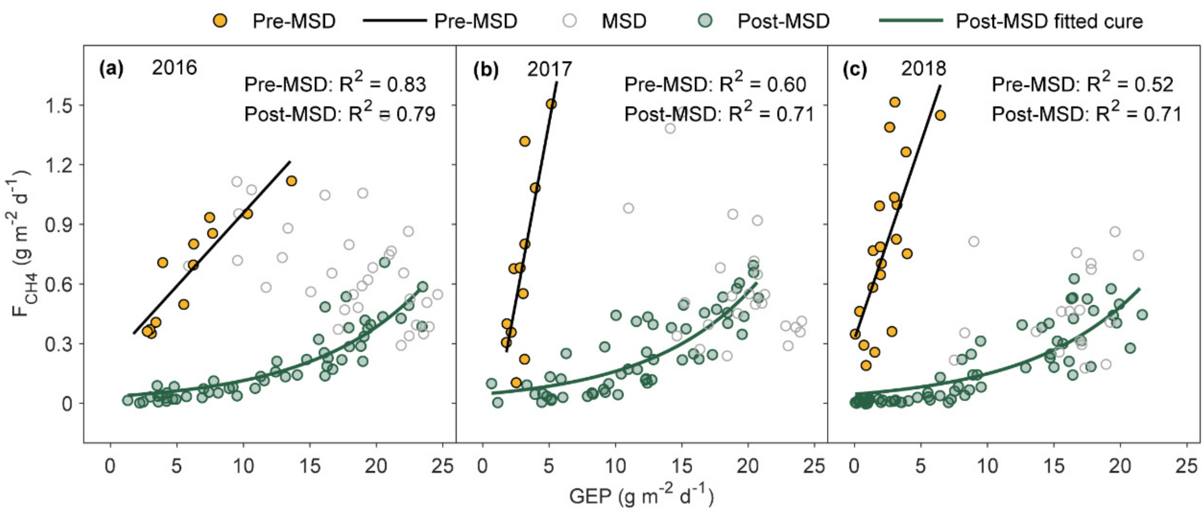

Figure 4. Linear and exponential regression models of daily CH_4 fluxes against GEP for the periods before (yellow points) and after (green points) the mid-season drainage, respectively. The grey circles (**a**–**c**) represent CH_4 fluxes during mid-season drainage each year.

While the linear correlation between daily CH_4 fluxes and GEP were not significant for the whole rice season, the regression (Figure 4) and *F* partial test (Table 2) both before (Figure 4, R^2: 0.52–0.83) and after the mid-season drainage demonstrated that daily GEP was the most important predictor of daily CH_4 fluxes as we hypothesized. This separate analysis for each rice growing stage may be a helpful way to identify the factors of CH_4 fluxes in rice paddies. The close relationship between daily CH_4 fluxes and GEP as well as plant biomass was also reported in a few previous studies [9,15,34,35]. Meanwhile, the functional relationship between daily CH_4 fluxes and GEP shifted (Figure 4) between growth stages. The linear response of CH_4 fluxes to GEP indicated a direct limitation of substrate supply for methanogenesis in the early cultivation stage while the exponential response might indicate multiple processes associated with GEP controls on CH_4 fluxes in the later stage related to carbon supply and transport processes. The slope of CH_4 flux to GEP becomes smaller after the MSD maybe due to a limited environmental condition for CH_4 production during the AWD period. Overall, the evidence of GEP dominating CH_4 fluxes highlights the importance of rice plant productivity in controlling CH_4 emissions.

Table 2. The results of Partial F test for daily CH_4 fluxes and other variables before and after the mid-season drainage. Signifiant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

Year	Period	GEP	Tg	Pa	u*	VWC	WTD	Cond
2016	Before MSD	**66.87** ***	3.91	3.55	8.99 *	0.11		
2017		**18.36** **	24.64 **	0.01	0.54	0.15		
2018		**22.94** ***	8.47 *	9.15	0.60		2.56	4.10
2016	After MSD	**171.29** ***	18.14 ***	5.22 *	4.64 *	2.15		
2017		**157.40** ***	15.88 **	2.54	0.43	5.94 *		
2018		**86.74** ***	1.61	2.07	2.35		0.18	0.05

Table 3. Statistical tests (Coefficient of Determination (R^2) and Akaike Information Criterion (AIC)) for the biophysical drivers in the models of daily CH_4 fluxes in 2016–2018, including stepwise multivariate linear and hierarchical Neural Network Models. Daily CH_4 fluxes were log transformed before being fit with linear models. The results were only presented when the addition of the variable improved the R^2 of the model and was justified by a reduction in the AIC of the model. F_{CH4} is the daily CH_4 flux, Tg, Tw, GEP, VWC, u*, Pa, and spcond are abbreviated soil temperature, water temperature, gross ecosystem photosynthesis, volumetric water content, friction velocity, ambient pressure, and conductivity, respectively.

	Before Mid-Season Drainage			After Mid-Season Drainage		
Year	**Variable**	**R^2**	**AIC**	**Variable**	**R^2**	**AIC**
2016	GEP	0.83	−49.76	GEP	0.79	−25.96
	GEP + Tg	0.87	−50.81	GEP + Tg	0.84	−32.07
	GEP + Tg + u*	0.92	−54.95	GEP + Tg + Pa	0.88	−36.96
	GEP + Tg + u* + Pa	0.98	−68.16	GEP + Tg+ Pa + u*	0.89	−38.74
				GEP + Tg+ Pa + VPD	0.89	−38.75
2017	GEP	0.60	−27.51	GEP	0.71	−42.84
	GEP + Tg	0.91	−43	GEP + Tg	0.73	−44.97
				GEP + Tg + VWC	0.85	−65.39
2018	GEP	0.52	−44.95	GEP	0.71	9.39
	GEP + Tg	0.63	−47.05	GEP + Tw	0.76	−3.18
	GEP + Tg + spcond	0.68	−47.18	GEP + Tw + spcond	0.77	−5.44
	GEP + Tg + spcond + WTD	0.73	−47.7	GEP + Tw + spcond + WTD	0.78	−4.53
	GEP + Tg + spcond + WTD + Pa	0.91	−55.82	GEP + Tw + spcond + WTD + Pa	0.80	−10.45

Water management contributed to the changing magnitude of daily CH_4 fluxes in the rice season. For example, daily CH_4 fluxes sharply increased when the first flooded before the rice season and decreased during the operation of mid-season drainage in each year. Meanwhile, no significant positive correlation between CH_4 fluxes and VWC (even after accounting for possible time lags) was found at each growth stage (Figure 5a–e). CH_4 fluxes was significantly correlated to water table depth only during the ripening stage when water table depth was very low (<0) (Figure 5j). However, daily CH_4 fluxes was significantly correlated with water table depth when analyzing the entire rice growing season even though no significant correlation was observed for the vegetative, mid-season drainage, and reproductive stages (Figure 5f).

Although the results highlight the importance of plants control on CH_4 fluxes in rice paddies, the effect of environmental factors remains important. Higher soil temperature can enhance methanogenesis, molecular diffusion, and transport within plants [36–38]. Although the relative importance was less than GEP, soil temperature was significantly correlated with CH_4 fluxes during some growth stages (Table 2). Anaerobic soil conditions, which depend on soil water content in rice fields, are a prerequisite for CH_4 production by methanogens in rice paddies. This dependence on anaerobic conditions could explain why CH_4 fluxes decreased during the middle season drainage in each year. The significance between daily CH_4 fluxes and water table depth (<0) also indicated the importance of soil water conditions which decides anaerobic conditions of the paddy fields on CH_4 flux.

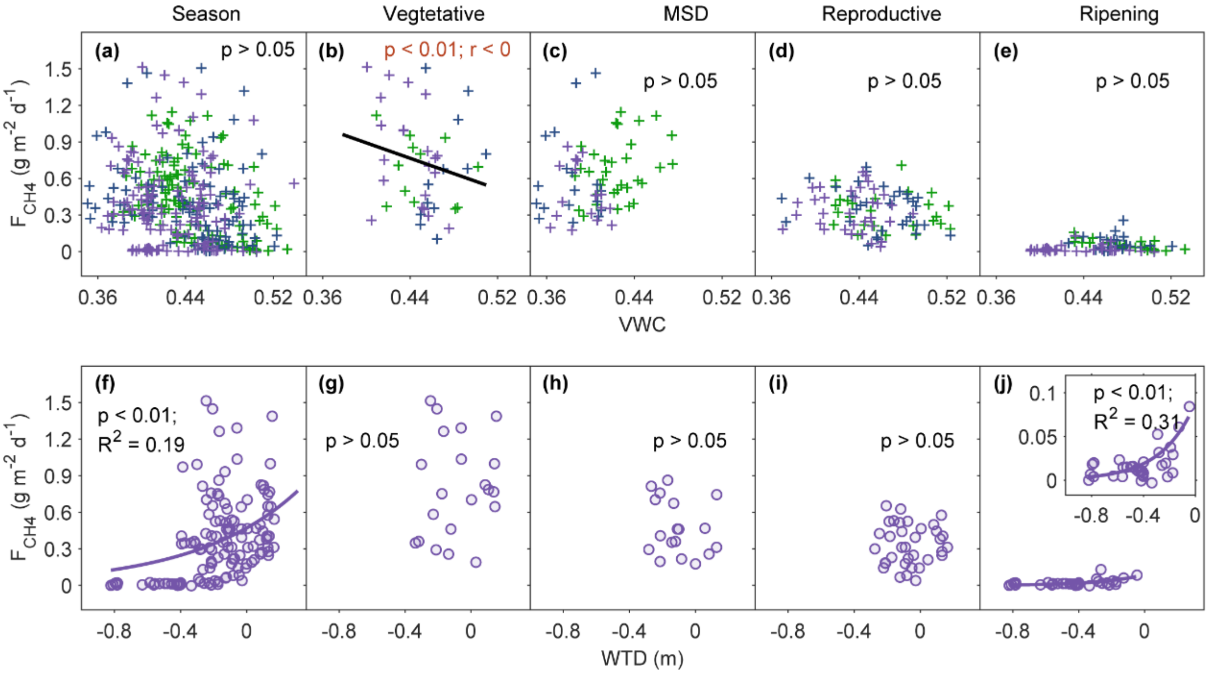

Figure 5. The relationship between daily CH_4 fluxes and volumetric water content (VWC, (**a**–**e**)) in 2016 (green), 2017 (blue) and 2018 (purple), water table depth (WTD, (**f**–**j**)) in 2018 (purple) over the whole rice season (**a**,**f**), during the vegetative stage (**b**,**g**), during the mid-season drainage periods (**c**,**h**), during the reproductive stage (**d**,**i**), during the ripening stage (**e**,**j**). Daily CH_4 fluxes and VWC showed a significant negative correlation only during the vegetative stage (**b**). Daily CH_4 fluxes and WTD showed a significant positive correlation for the whole season (**f**) and during the ripening stage when WTD was very low (**j**).

3.2. Annual C and GHG Budgets

For the wheat season, cumulative CO_2 uptake were estimated at 683.61 ± 43.26, 579.87 ± 50.68, 617.98 ± 4.91 g CO_2 m^{-1} in 2016, 2017, and 2018, respectively (Table 4). Wheat cumulative CH_4 emissions were 3.45 ± 0.40, 2.55 ± 0.13, 4.27 ± 0.21, g CH_4 m^{-1} in 2016, 2017, and 2018, respectively. In total, wheat season acted as both net C and GHG sink (averaged 168.97 g C m^{-2} and 1648.39 g CO_2eq m^{-2}, respectively).

For the rice season, cumulative CO_2 uptake was estimated at −2048.34 ± 193.50, −1299.69 ± 107.91, −839.56 ± 91.62 g CO_2 m^{-1} in 2016, 2017, and 2018, respectively (Table 4). Rice cumulative CH_4 emissions were 59.42 ± 5.11, 57.68 ± 4.90, 56.88 ± 6.29, g CH_4 m^{-1} in 2016, 2017, and 2018, respectively. In total, although rice season acted as a net C sink (averaged 337.20 g C m^{-2}), it existed a GHG source (averaged 227.98 g CO_2eq m^{-2} for 3 years) due to great CH_4 emissions except for the season with very high seeding density in 2016 [16].

Both the wheat and rice season acted as large atmospheric sinks for CO_2 and sources for CH_4. The averaged CO_2 uptakes and CH_4 emissions in rice seasons were 2.2 and 20.9 folds of the wheat seasons, respectively (Table 4). In sum, the rice-wheat rotation agroecosystem acted as net C sink (averaged 460.79 g C m^{-2}) and GHG source (averaged 174.38 g CO_2eq m^{-2} in 2017–2018) except for 2016. Although the magnitude of CO_2 and CH_4 budget in our study were higher than results reported from other regions [7,12,39–41], they are comparable with EC measurements in the near province of Jiangsu in China [9,10]. The harvest carbon was not accounted for in this study, while rice season might be a C source when harvested carbon was added [42]. The N_2O emissions was not included in the calculation of GHG budget in this study, while N_2O emission especially in the wheat season is a very strong source for atmosphere N_2O.

Table 4. Annual sums of net CO_2 fluxes, GEP, CH_4 fluxes, total ecosystem carbon (C) and greenhouse gas (GHG) budgets in wheat and rice season were estimated. The total C and GHG budget for one year were also calculated.

Season		NEE	GEP	CH_4		C Budget	GHG Budget
		g C m^{-2}	g C m^{-2}	g C m^{-2}	g CO_2eq m^{-2}	g C m^{-2}	g CO_2eq m^{-2}
2016	wheat	−186.44	972.03	2.03	75.91	−184.41	−607.71
	rice	−558.64	1786.52	44.56	1663.74	−514.08	−384.60
	year	−689.13	2743.44	48.86	1824.00	−640.27	−702.81
2017	wheat	−158.15	857.22	1.98	74.03	−156.17	−505.84
	rice	−354.46	1573.59	43.26	1615.06	−311.20	315.37
	year	−407.31	2535.42	46.23	1726.03	−361.08	232.54
2018	wheat	−168.54	1195.16	2.22	83.13	−166.32	−534.84
	rice	−228.97	1474.50	42.66	1592.73	−186.31	753.17
	year	−425.98	2675.04	44.95	1678.14	−381.03	116.21

More than half of the global rice crop experience drought and high temperatures, which are predicted to become more frequent under climate change, resulting that water-saving techniques have been widely employed in rice cropping regimes [17–20]. In some models [18], CH_4 fluxes are often predicted as a function of soil temperature and/or other environmental variables while the importance of rice plant controls on CH_4 fluxes is rarely accounted for. We found daily GEP is a good predictor (R^2: 0.52–0.83) of daily CH_4 fluxes if accounting for growth stage specific responses in water-saving paddy fields. Thus, more studies are needed to further optimize the prediction of CH_4 fluxes in rice paddies under climate change. The strong connection between GEP and CH_4 flux found in this study indicates a possible trade-off in using irrigated ecosystems for carbon capture and sequestration [43,44]. Meanwhile, increasing human population demands for food further increases in rice production. Thus, a balance between increase of photosynthetically fixed carbon for rice grain yield and mitigation of methane emissions is required for irrigated rice fields. In addition to water limiting techniques, practices to control excessive carbon input such as a better-informed management of planting density [16] and to decrease the plant-mediated transport of CH_4 similar to a modified rice plant with low stomatal density has a great potential to limit increases in CH_4 emissions.

4. Conclusions

In this paper, we analyzed 3 consecutive years of eddy covariance measurements of CH_4 fluxes from a rice-wheat rotation agroecosystem located in Southeast China. The wheat-rice rotation agroecosystem acted as a large net C sink (averaged 460.79 g C m^{-2}) and a GHG (averaged 174.38 g CO_2eq m^{-2}) source except for a GHG sink in one year with a very high rice seeding density. The averaged CO_2 uptakes and CH_4 emissions in rice seasons were 2.2 and 20.9 folds of the wheat seasons, respectively. Although daily CH_4 flux and GEP existed not significantly correlated for the whole season, GEP dominates the control of CH_4 flux when the rice season was divided into the periods before and after the mid-season drainage. The reason is that the functional relationship between daily CH_4 flux and GEP shifted between growth stages. The separate analysis for each rice growing stage can be a helpful way to identify the factors of CH_4 flux in rice paddies. We highlight daily GEP was a good predictor of daily CH_4 flux in rice paddies.

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