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Methane emissions from rice cultivation in West Africa and compensation options from nature reserve forests

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Supplementary material for this article is available [online](#)

Abstract

Methane (CH₄) is a major and potent greenhouse gas (GHG), and its emissions from agricultural activities, particularly rice cultivation, are a significant concern for climate change. Due to the high demand for food security, driven by rapid population growth and national initiatives to reduce dependency on rice imports, rice cultivation is intensified in West Africa. However, its contribution to atmospheric CH₄ remains largely unknown. Here, for the first time, cutting-edge eddy covariance tower measurements were conducted parallelly in a rice field (Janga) and a reserve forest (Mole National Park), both located in the Guinea savanna region of West Africa. Using CH₄ measurement data from June to October 2023 (rice cultivation period), the dynamic interplay between methane emissions from rice cultivation and its potential mitigation through forest methane uptake was assessed. Our results show that the rice field acted as a net source of CH₄ at a rate of 2037 mgCH₄m⁻², whereas the most intense flooded period (August) accounted for 70% of the total emissions. On the other hand, the forest reserve acted as a sink, with a net uptake of -560 mgCH₄m⁻², and the highest uptake observed in October. Accounting for the global warming potential (GWP) of CH₄ over a 20 year period, the forest had a wet season negative GWP of -47.04 gCO₂eq, while the rice field emitted CH₄ of 171.36 gCO₂eq. This implies that under similar conditions during the measurement campaigns, the forest per square area needs approximately a factor of ~4 to balance the positive radiative effect per square area of rice cultivated. This work emphasizes the need to integrate forests to compensate for methane released by rice cultivation in the semi-arid West African savannah region.

1. Introduction

West Africa has experienced a rapid population increase (Akintunde *et al* 2013), and it is projected to contribute to global population growth in the coming years significantly (Foley 2011, Van Bavel 2013). It will likely account for over half of the world's population growth by 2050 (Van Bavel 2013). The consequences of this population growth have exerted

considerable pressure on the environment (Weber and Sciubba 2019), leading to intensive anthropogenically land-use changes and agricultural intensification (Sy *et al* 2017, Bliedernicht *et al* 2018, Potapov *et al* 2022, Sy *et al* 2024). Consequently, rice cultivation is being intensified in West Africa, mainly driven by the high demand for food security and national initiatives to reduce dependency on rice imports in the future (Chen *et al* 2024, Yuan *et al* 2024).

Rice is one of the major cereal crops globally, consumed daily by half the world's population, leading to increasing demand (Fahad *et al* 2018, Bin Rahman and Zhang 2023). This is especially true in West Africa, where a significant upward shift in rice consumption has been observed over the last ten years (Yuan *et al* 2024). This shift has resulted in a nearly ninefold increase in rice production between 1961 and 2019 (Bin Rahman and Zhang 2023). Given the rapid population growth and the need for rice self-sufficiency, the demand for rice in Africa, particularly in sub-Saharan Africa, is expected to double by 2050 (Yuan *et al* 2024).

Among the various atmospheric methane (CH₄) sources, rice paddy fields are considered a significant contributor (Zhang *et al* 2020, Nikolaisen *et al* 2023a). Methane emissions from rice fields, including irrigated, rain-fed lowland, and flood-prone fields, account for approximately 10% to 18% of all agricultural CH₄ emissions globally (IPCC 2014, FAO 2021) and 19% to 33% of current global terrestrial CH₄ emissions (Saunio *et al* 2020). In flooded paddy fields, methane is produced by the anaerobic breakdown of organic molecules. Flooding cuts off the oxygen supply to the rhizosphere, creating an anaerobic environment. This anaerobic decomposition of soil organic matter generates methane gas, which is released into the atmosphere through diffusion, ebullition, and the aerenchyma of plant roots and stems (Rahman and Yamamoto 2020, Heredia *et al* 2022).

In the context of global agreements to keep warming below 2 °C and strive to stay within 1.5 °C above pre-industrial levels, as adopted by many countries during the Paris COP21 Agreement (IPCC 2018), stringent climate change mitigation measures can heavily impact the agriculture sector (van Loon *et al* 2019). These measures pose challenges since sustainable development goals emphasize balancing climate change mitigation with achieving food security (United Nations 2016). However, there is considerable debate that prioritizing climate mitigation over food security, especially given the current population surge, may have a more detrimental impact than climate change. For instance, if climate mitigation measures lead to decreased agricultural productivity or increased food prices, this could exacerbate food insecurity, particularly in regions with high population growth rates, such as West Africa. Forest has been proposed as a crucial solution for sequestering atmospheric CH₄, significantly influencing the global CH₄ budget (Ni and Groffman 2018, Feng *et al* 2022). While some studies suggest that the methane sink capacity of forest soils has increased in recent decades (e.g. Yu *et al* 2017), there is still considerable disagreement among studies regarding the role of forest soils in methane dynamics. For example, (O'Connell *et al* (2018) showed

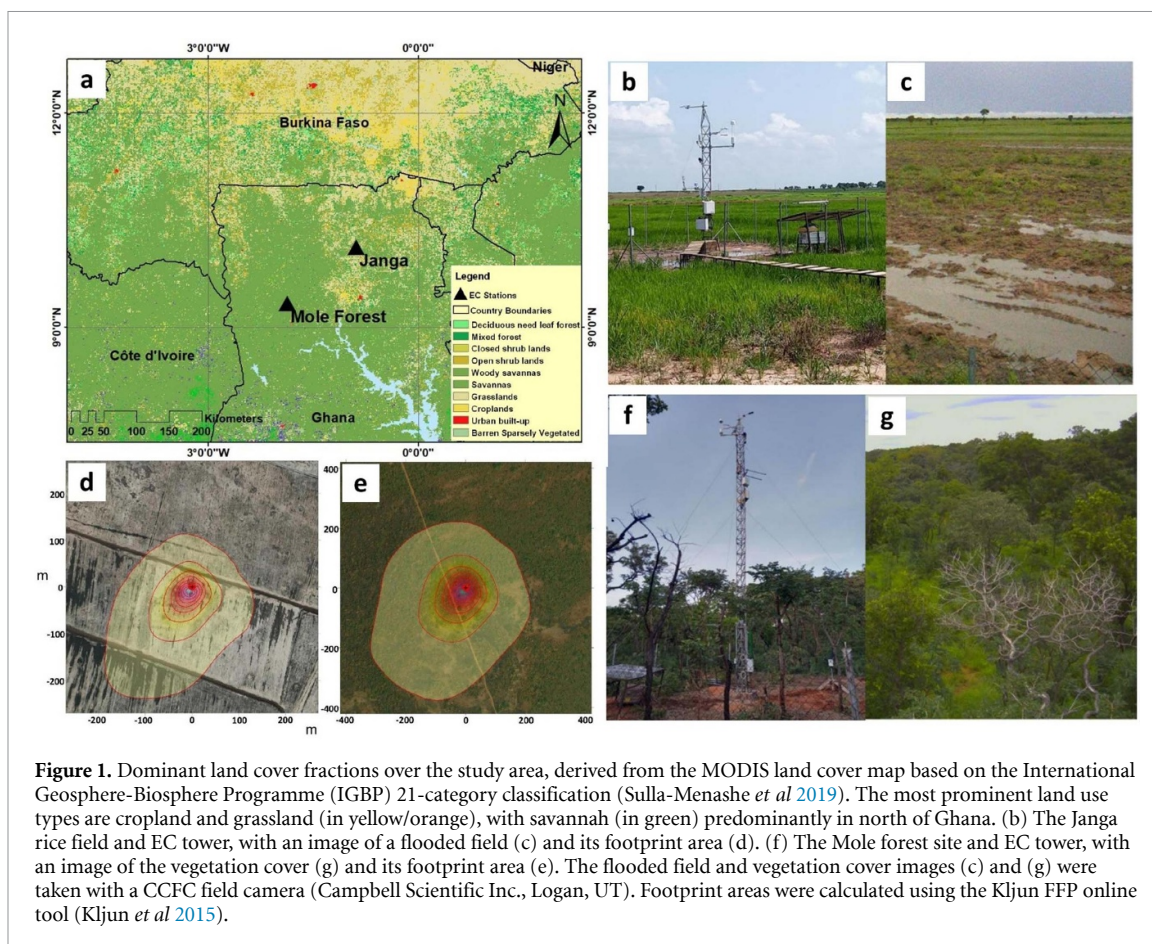
that forest soils may become larger sinks or even sources of CH₄ depending on changes in soil conditions due to drought, flooding, warming, natural disturbances, and forest management. Furthermore, Frankenberg *et al* (2005) suggested that forest soils could be significant sources of CH₄ depending on the forest ecosystem, thereby challenging the traditional view that forests consistently act as sinks for atmospheric CH₄. However, little is known about how soil CH₄ sinks or sources respond to changing environmental conditions (Feng *et al* 2022). This is especially true in the semi-arid West African savannah region, where data are scarce, and the lack of continuous CH₄ *in situ* measurements limits the available evidence (Ni and Groffman 2018, Feng *et al* 2022). Additionally, although measurements of CH₄ flux have been conducted in forests worldwide, most studies have focused on mid-latitude regions and are limited to tropical forests (Barthel *et al* 2022).

Here, for the first time, we investigate the dynamic interplay between methane emissions from rain-fed rice cultivation and their potential mitigation through forest methane uptake in the semi-arid West African savannah region. Using advanced micrometeorological measurement equipment and eddy covariance (EC) flux towers, one-year measurements of soil methane fluxes were conducted simultaneously in a paddy rice field in Janga and a protected forest reserve in Mole National Park (both located in northern Ghana) (see Methods). Notably, this study enhances our understanding of how protected forest reserves can effectively mitigate CH₄ emissions from rain-fed rice agriculture in this region. This study addresses two main scientific questions: (i) to what extent can forest in the semi-arid West African savannah region sequester methane emissions from rice cultivation? (ii) What underlying factors control methane dynamics in forest ecosystems and rice agriculture in the semi-arid West African savannah region?

2. Materials and methods

2.1. Study area and field sites

The study area (see figure 1(a)) is part of a large observatory established over the last decade, initially focused on CO₂ and H₂O measurements (Quansah *et al* 2015, Bliefernicht *et al* 2018, Berger *et al* 2019) by a German-African research initiative in the West Africa's Sudanian savanna belt. This network was extended by establishing two new EC stations: one in a rice field (hereafter 'Janga', dominated by floodplains) and another in a forest reserve (hereafter 'Mole') to include CH₄ measurements with the aim to compare CH₄ emissions/uptake in two ecosystems with contrasting land-use and land management practices in northern Ghana (see figure 1(b),c vs figure 1(f),g). The local climate at both sites is influenced by the



West African monsoon (Nicholson 2013). It is characterized by two distinct seasons: a wet season from May to October and a dry season from November to March (Nicholson 2013). Annual rainfall ranges from 900 to 1100 mm and is mainly driven by meso-scale convective systems (Nicholson 2013). These systems result in highly variable spatio-temporal rainfall patterns, which pose significant challenges to rain-fed agricultural activities. Temperatures range from 22 °C to 34 °C, with maximum temperatures of up to 40 °C occurring in March/April (Nyadzi *et al* 2021, Dakwa 2018).

Soils within the Janga rice field are predominantly Plinthic Ferralsols (groundwater laterites) and EutricNitisols (savannah ochrosols), with varying soil textures from fine sands, loam, and heavy clays (Addai 2016). The catchment is characterized by broad valleys and extensive floodplains with limited drainage (Abdul-Ganiyu *et al* 2011). Rice and maize are the major crops grown during the rainy season, mainly along the floodplains. The Mole Forest was officially designated in 1958 as a national park (Auwah 2017). The park's management is under the wildlife division of the Ghana Forestry Commission, and it is classified as a Category II National Park according to the International Union for Conservation of Nature (IUCN) classification

of protected areas (Cole Burton *et al* 2011). The dominant vegetation is open savanna woodland and other smaller plant communities, such as swamps and floodplains, with a grass layer that can grow up to 3 m tall in the rainy season (Schmitt and Adu-Nsiah 1993). According to Bowell and Ansah (1994), the forest soil characteristics consist of a combination of Ferrosol with an abundance of free iron and well-defined structural Nitisol, demonstrating effective drainage properties.

2.2. Site instrumentation

Measurement campaigns started in June 2022 with the setting up of EC towers at a rice field (figure 1(b)) in Janga (Long: -0.8838 , Lat:10.1299) and in May 2023 at a reserve forest (figure 1(f)) in the Mole National Park (Long: -1.8688 , Lat: 9.3388). CH₄ turbulent fluxes were measured at 10 Hz (12 m height) in the forest and 20 Hz (3.4 m height) in the rice field using LI-7700 laser spectroscopy gas analyzers (LI-COR Inc., Lincoln, USA) and an IRGASON, an integrated infrared gas analyzer, and sonic anemometer (Campbell Scientific Inc., Logan, UT). In addition, meteorological data such as air temperature, relative humidity, solar radiation, and precipitation were measured and stored in 30 min resolution. We also

measured soil water content (SWC) and temperature at 3, 10, and 35 cm and three ground heat flux plates placed at 8 cm to measure ground heat energy. All data variables were logged in CR6 data recording loggers with an external 16 GB storage capacity (Campbell Scientific). Field cameras were installed at each site and focused on the mean wind direction to monitor the field management and vegetation cover (e.g. figures 1(c) and (g)). In addition to our regular site visits for maintenance, the automated cleaning of the CH₄ laser sensor (LI-7700) was implemented, which routinely washed the laser mirror every three hours when the signal strength (RSSI) drops below 50%. Field computers were permanently installed at each site for data storage, pre-processing, and transmission.

2.3. Data processing

The CH₄ turbulent data were processed and quality controlled into half-hourly fluxes using the Turbulence Knight (TK3) statistical routine tool (Mauder and Foken 2006, Mauder *et al* 2008). We performed plausibility tests on the turbulent data with consistency limits and excluded physical or electronic not possible values. A signal strength (RSSI) of 10% was set as a threshold for the CH₄, similar to Staudhammer *et al* (2022), where we excluded values below this threshold. TK3 then calculated the averages, variances, and covariances of the raw data and then averaged 30 min and 5 min intervals with an automatic lag correction by maximizing covariances to account for delays of the time series caused by different sensors. A stationary test (Foken and Wichura 1996) was performed to compare the 30 min covariances with those for 5 min averaging time where data that deviates >30% is set to flag 1 and >100% to flag 2. All these steps are performed taking into consideration the EC theory. The coordinate rotation (Kaimal and Finnigan 1994) was performed considering the wind fields at each site. The data was screened for spikes, followed by detrending, and the time delay between the turbulent vertical and the scalar wind measurements of the different sensors by cross correlation analysis for each averaging interval (Mauder *et al* 2013, Vitale *et al* 2020). These were finally followed by the Webb, Pearman, and Leuning correction for density fluctuations of ambient air (Schotanus *et al* 1983, Liebethal and Foken 2003, Jentsch *et al* 2021). The CH₄ flux was calculated as:

$$F_{\text{CH}_4} = \overline{w' \rho c'} \quad (1)$$

where $\rho c'$ the instantaneous fluctuation of the CH₄ density w' is the instantaneous fluctuation between the vertical wind velocity and the overbar denotes a time average (Burba *et al* 2013). The relative random flux and noise errors were calculated on the final processed fluxes following (Mauder *et al* 2013).

We considered flagging according to Mauder and Foken (2006), where high-quality fluxes are flagged '0', intermediate-quality fluxes are flagged '1' (suitable for general analysis such as annual and seasonal budgets), and poor-quality fluxes are flagged '2' (usually discarded).

2.4. CH₄ flux drivers selection and gap-filling

We performed gap-filling to ensure a continuous time series for calculating CH₄ budgets (see figures S2 and S3). These data gaps occurred due to rain events, instrument signal quality thresholds, and filtering during data quality control, accounting for less than 30% of missing data points at both sites. Even though no single standardized approach has been developed for filling data gaps in CH₄ fluxes, we considered a machine learning approach random forest (RF) in this study (Kim *et al* 2020, Irvin *et al* 2021). Several biophysical environmental predictors were pre-selected following previous studies (e.g. Kim *et al* 2020, Irvin *et al* 2021, Lucas-Moffat *et al* 2022, Zhu *et al* 2023) on CH₄ fluxes from wetlands and forest ecosystems. To identify the most important predictors, we considered a machine learning model—RF, an ensemble decision tree built independently from bootstrapped data samples (Breiman 2001). RF has been tested and used for CH₄ flux driver selection and gap filling at several sites (Kim *et al* 2020), which have proven robust (Irvin *et al* 2021, Lucas-Moffat *et al* 2022). We used the scikit-learn library (Pedregosa *et al* 2011) to implement the RF learning regressor models and the SciPy package for statistical testing, both in Python. A supervised learning estimator was used to generate 100 decision trees randomly. We assessed the correlation between the target (CH₄) and the pre-selected predictors was performed using 70% of the quality-controlled data for training and 30% for testing. Each predictor variable was assigned a feature importance score representing their relative influence on methane flux prediction (James *et al* 2013). The predictor variables with a feature important score < 0.05 were eliminated (Maier *et al* 2022) as input predictor variables for the gap-filling process. For consistency, the gap-filled dataset was used in all analyses presented in this study.

Finally, the same process was repeated, considering the important predictors identified as input variables for the gap-filling of the CH₄ fluxes, considering 1000 randomly generated (with bootstrapped with replacement) decision trees. We calculated the R² score on the bootstrapped (original) and the predicted to ascertain how well the observed methane flux matched the predicted values from the models. The relationship between the gap-filled CH₄ fluxes and each driver was further analyzed by binning data at fixed interval increments of the independent variable corresponding to CH₄ (Emerson *et al* 2021) and averaging values within defined intervals. We applied

a simple Polynomial Regression with a quadratic fit to compare their explanatory power with a 95% confidence interval.

2.5. Global warming potential (GWP)

The impact of the concentration of CH₄ for the two sites was assessed by evaluating their radiative effects (Ali *et al* 2013). Specifically, it quantified the net CH₄ uptake of the forest ecosystem and its potential to mitigate the warming effect of CH₄ emissions from rice cultivation. This was done using CO₂ as the reference gas for calculating GWP (see Rabbi and Kovács 2024). To do this, the CH₄ flux balances from each site were converted to CO₂ equivalents, following methods described in previous studies (Ramaswamy *et al* 2001, Frolking *et al* 2004, Boucher *et al* 2009). The GWP of CH₄ was calculated as follows:

$$\text{GWP}_{\text{CH}_4}^t = \frac{\int_0^t A_{\text{CH}_4} [r_{\text{CH}_4}(t)] dt}{\int_0^t A_{\text{CO}_2} [r_{\text{CO}_2}(t)] dt} \quad (2)$$

where A is the radiative forcing per unit mass of CH₄ or CO₂, and $r(t)$ is the response function or decay in the concentration of CH₄ or CO₂ at time horizon (t), typically 20, 100 years (see Rabbi and Kovács 2024). Based on the IPCC Fifth Assessment Report (IPCC 2014), the updated values of the 20- and 100 year GWP factors for CH₄ flux in CO₂ equivalents (CO₂eq) are 84 and 27, respectively.

3. Results

3.1. Environmental variables

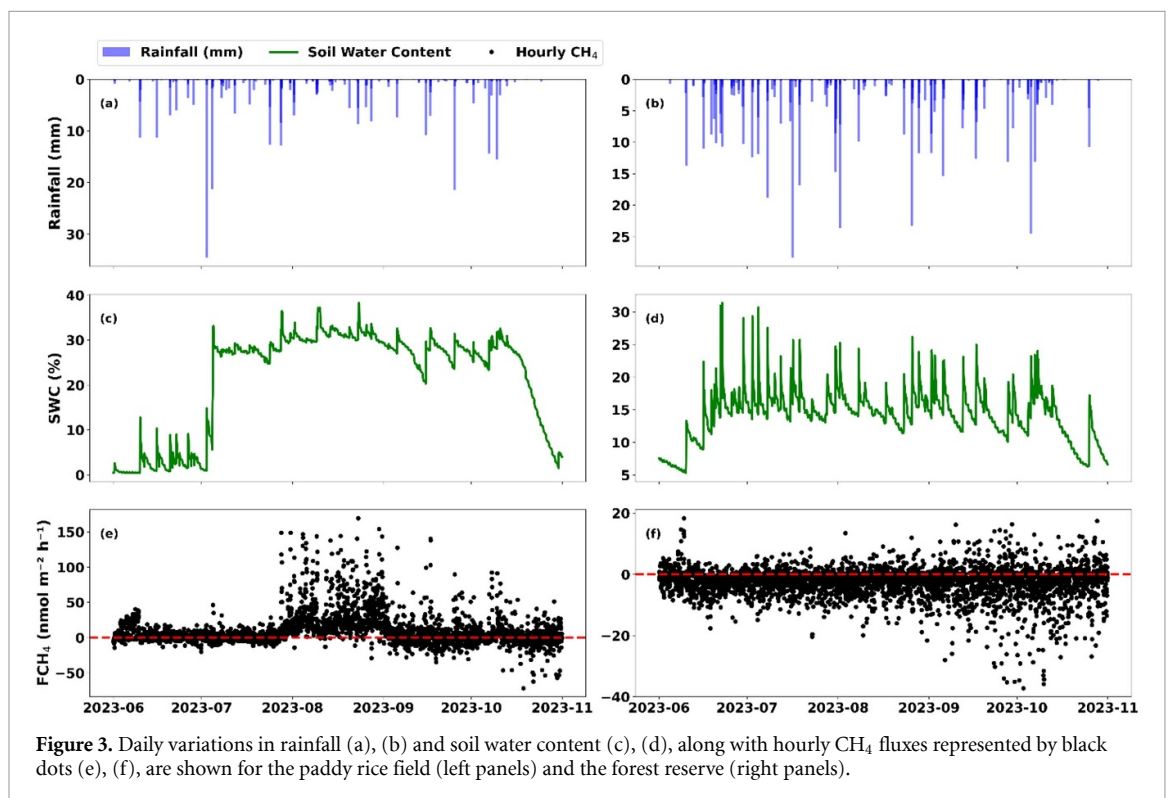
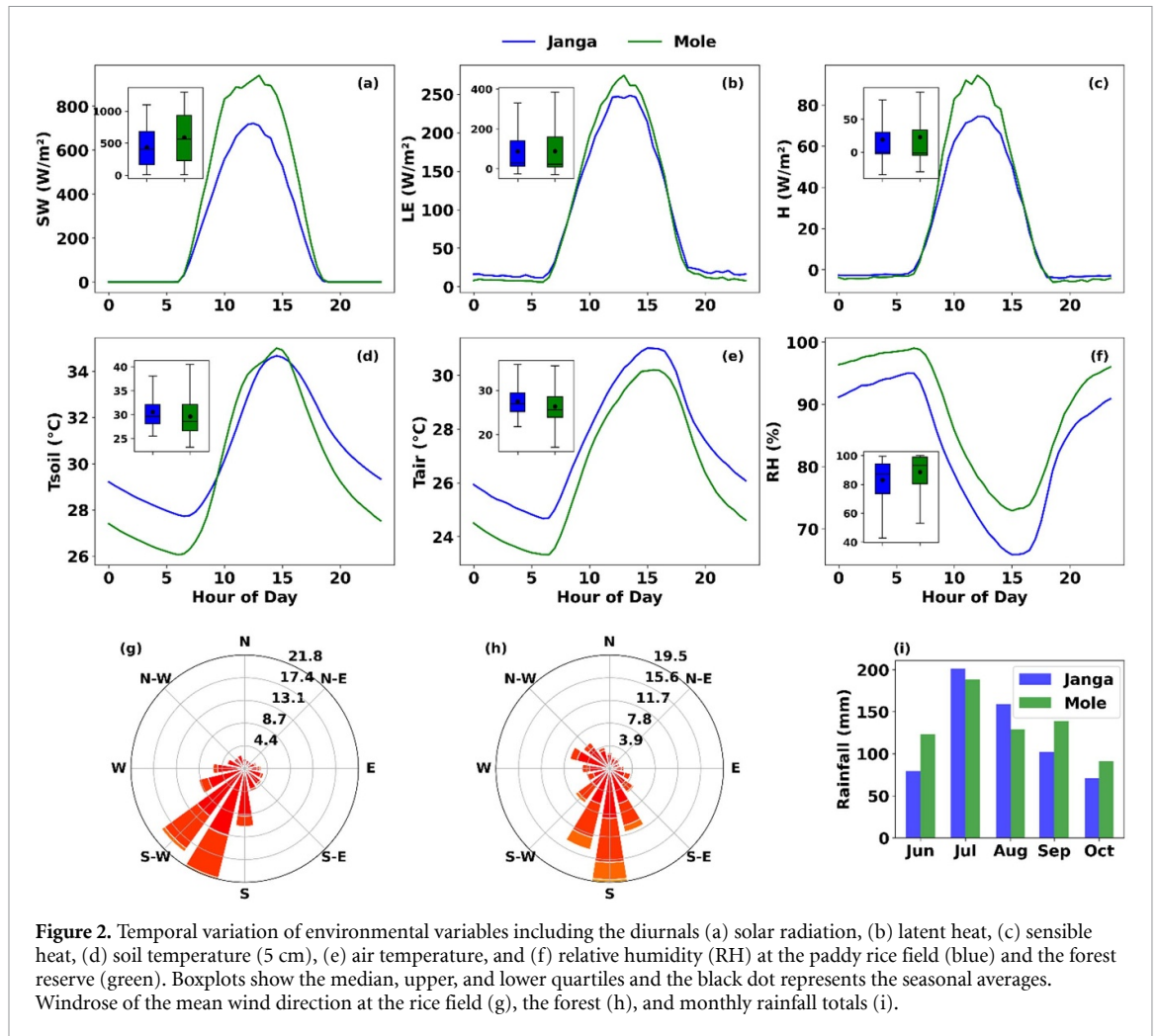
The environmental parameters at both sites during the study period (June to October) are illustrated in figure 2. On average, air temperature was slightly higher in the rice field (28.9 °C) than in the forest site (27.6 °C) (figure 2(e)). The forest site received more incoming solar radiation (SW_IN) during the daytime than the rice field (figure 2(a)). As expected, latent (LE), and sensible (H) heat fluxes peaked higher during the daytime in the forest site than in the rice field (figures 2(b) and (c)) due to the forest canopy capacity to absorb more solar energy (lower albedo) during daytime for photosynthetic activities and leading to high evapotranspiration. Furthermore, on average, the rice field (open land) wind speed was 2 times higher (2.48 m s⁻¹) than the forest site with 1.24 m s⁻¹. Winds from the southeast and southwest at the rice field were dominant and likely contributed more to the CH₄ fluxes (figure 2(g)), as seen in the footprint analysis (figure 1(d)). In contrast, winds from the forest site were distributed across the Northwest, Southeast, and Southwest directions (figure 2(h)) which resulted in the distributions of the CH₄ fluxes across all these directions as also observed in the footprint analysis (figure 1(e)). Regarding the precipitation, the

rice field and forest sites had a total rainfall of 613 and 670 mm during the rainy season respectively, where both sites recorded the highest rainfall in July (figure 2(f)). Overall, both sites exhibited comparable local climatic characteristics, with the forest site experiencing slightly cooler, wetter conditions (lower temperature and higher humidity) than the rice field.

3.2. Dynamics of CH₄ fluxes

CH₄ fluxes showed considerable variability across both sites throughout the study period (see figure 3). Additionally, obvious diurnal variations were observed at the two sites, with peak positive and negative values occurring at different times of the day (figure 4) likely driven by various underlying physical mechanisms, including meteorological and biological factors (see figure 5). Over the rice field, as expected, SWC at 5 cm vapor pressure deficit and soil temperature (T_{soil}) at 10 cm remained the predominant factors controlling CH₄ dynamics (with R^2 values up to 0.59; $p < 0.05$) (see figure 5). Significant variations were observed across different growth stages (figures 3(c) and (e)), with an average CH₄ flux of 9.70 ± 22.34 nmol m⁻² h⁻¹, ranging from -71.85 to 169.44 nmol m⁻² h⁻¹. During the start of the rainy season, the highest CH₄ flux recorded in June was 40.47 nmol m⁻² h⁻¹. Subsequently, after the field was prepared (plowed and harrowed on July 22), followed by substantial rain events, CH₄ increased sharply, resulting in substantial-high positive fluxes during August, with a peak hourly flux reaching 169.44 nmol m⁻² h⁻¹. However, notable negative CH₄ fluxes were also observed during the maturing and ripening stages (September and October), with CH₄ flux reaching -71.85 nmol m⁻² h⁻¹. The peak diurnal CH₄ fluxes for the first three months (June–August) occurred between 08:00 and 15:00 UTC (figure 4(a)). June and July had diurnal peak fluxes of 11.43 ± 11.09 nmol m⁻² h⁻¹ at 12:00 UTC and 9.65 ± 29.19 nmol m⁻² h⁻¹ at 09:00 UTC, respectively, while August showed the highest diurnal peak of the season with 58.68 ± 40.68 nmol m⁻² h⁻¹ which occurred at noon. Fluxes in September and October were notably lower during the day but peaked during nighttime at 19:00 UTC (14.66 ± 32.39 nmol m⁻² h⁻¹) and 20:00 UTC (6.38 ± 8.98 nmol m⁻² h⁻¹), respectively.

In contrast, at the forest site, the dominant factors influencing CH₄ dynamics were vapor pressure deficit, latent heat flux, ecosystem respiration, and soil temperature (figure 5(b)). These factors showed statistically significant relationships (with R^2 up to 0.65; $p < 0.05$). Furthermore, the forest site demonstrated a gradual variation in CH₄ fluxes (figure 3(f)), with



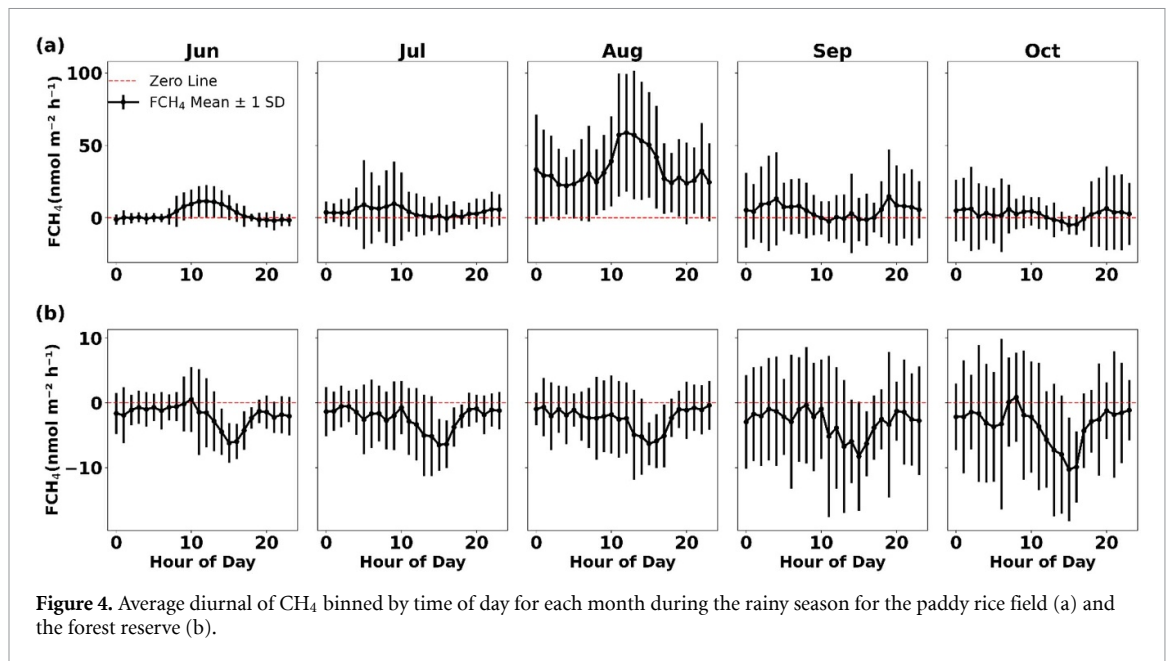


Figure 4. Average diurnal of CH₄ binned by time of day for each month during the rainy season for the paddy rice field (a) and the forest reserve (b).

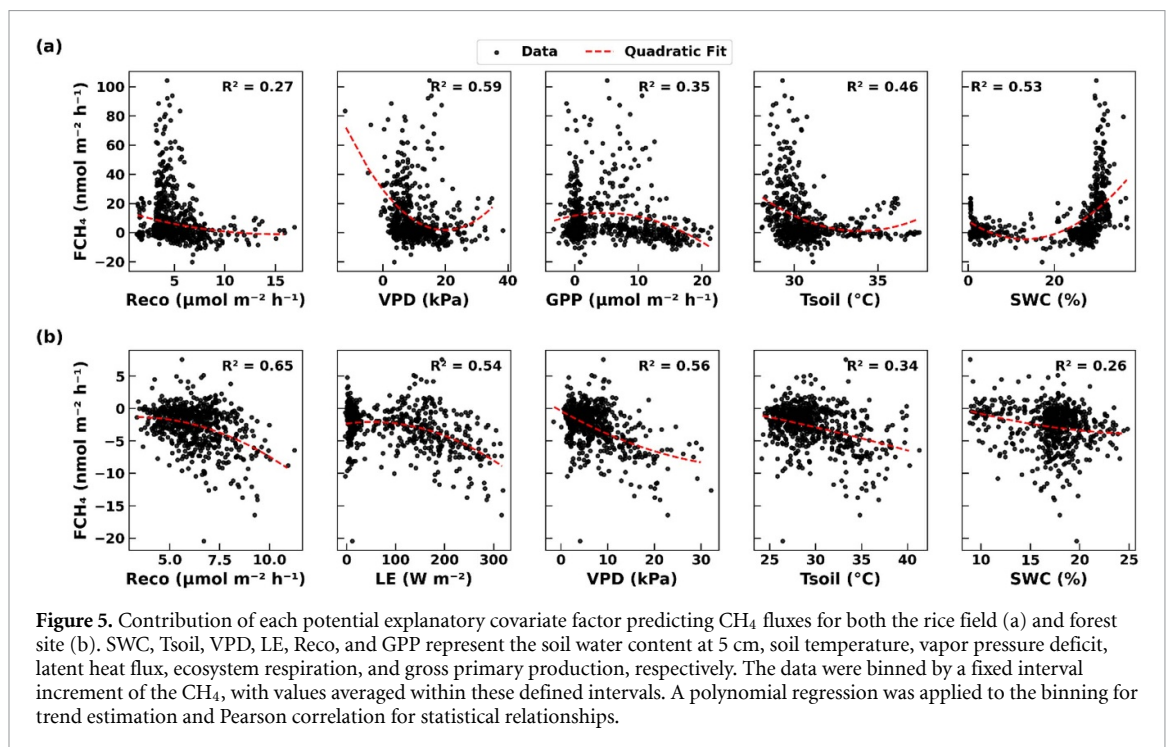


Figure 5. Contribution of each potential explanatory covariate predicting CH₄ fluxes for both the rice field (a) and forest site (b). SWC, Tsoil, VPD, LE, Reco, and GPP represent the soil water content at 5 cm, soil temperature, vapor pressure deficit, latent heat flux, ecosystem respiration, and gross primary production, respectively. The data were binned by a fixed interval increment of the CH₄, with values averaged within these defined intervals. A polynomial regression was applied to the binning for trend estimation and Pearson correlation for statistical relationships.

an average of -2.64 ± 5.10 nmol m⁻² h⁻¹, ranging from -37.26 to 18.34 nmol m⁻² h⁻¹. During the early part of the rainy season (June), CH₄ fluxes varied from -17.67 to 18.34 nmol m⁻² h⁻¹, and afterward, negative fluxes were frequently observed in September (-35.29 to 16.34 nmol m⁻² h⁻¹) and October (-37.26 to 17.45 nmol m⁻² h⁻¹). There were more consistent negative CH₄ fluxes throughout the diurnal cycles (figure 4(b)), with all peaks observed at around 15:00 UTC. The highest diurnal negative flux of -10.30 ± 7.99 nmol m⁻² h⁻¹, was recorded in October, while August had a diurnal peak of -8.26 ± 8.45 nmol m⁻² h⁻¹. Consistent upward

increases in CH₄ fluxes in the early morning (between 06:00 and 10:00 UTC) were observed due to the nighttime storage of CH₄ fluxes.

3.3. Daily and seasonal CH₄ balance

The seasonal CH₄ balance is presented in figure 6, where negative CH₄ values denote the ecosystem's uptake (sink), and positive indicates emission (source) into the environment. The rice field (figure 6(a)) exhibited more frequent daily CH₄ emissions than uptake, with daily cumulative values ranging from -12.36 to 86.78 mgCH₄ m⁻² d⁻¹. During the initial stage

of the cultivation, emissions were low, with total net emissions in June and July at 117.06 and 178.04 mgCH₄ m⁻² month⁻¹, respectively. The highest CH₄ emission was recorded in August, reaching a total of 1440.97 mgCH₄ m⁻² month⁻¹. Consequently, emissions dropped to a net cumulative of 206.75 mg CH₄ m⁻² month⁻¹ in September and to 94.26 mgCH₄ m⁻² month⁻¹ in October. However, despite this decline, the rice field acted as a net CH₄ source throughout the cultivation period, with a total cumulative emission value reaching 2037.09 mgCH₄ m⁻². Notably, August, characterized by extended periods of flooding, accounted for 70% of these emissions. In contrast, the forest area (figure 6(b)) demonstrated more frequent daily CH₄ uptake than emissions, with daily cumulative values ranging from -13.12 to 1.83 mgCH₄ m⁻² d⁻¹. In other words, the forest was consistently a CH₄ sink during the study period, showing minimal variation in the monthly uptakes. During the early part of the season, cumulative CH₄ uptake was -81.99 mgCH₄ m⁻² month⁻¹ in June. Uptake gradually increased throughout the season, peaking in October at -145.17 mgCH₄ m⁻² month⁻¹, resulting in a total net seasonal uptake of -560.23 mgCH₄ m⁻².

In terms of GWP, table 1 shows that CH₄ emissions from the rice field, totaling 2.04 g CH₄ m⁻² result in a positive radiative forcing equivalent to 171.11 g CO₂-eq over a 20 year GWP period. In contrast, the forest had a net CH₄ uptake of -0.56 g CH₄ m⁻², corresponding to a negative radiative forcing of -47.04 g CO₂-eq over the same period. To offset the positive radiative effect of CH₄ emissions from an equivalent area of rice fields would require about four times the area of forest per m².

4. Discussion

This study represents the first investigation of CH₄ dynamics between two distinct ecosystems (a rice field and a forest reserve), with contrasting land use and management practices and their seasonal CH₄ balance in the semi-arid savanna region of West Africa. Although numerous studies have examined CH₄ emissions from wetland and forest ecosystems globally using various approaches, including remote sensing, modeling, EC, and chamber measurements (e.g. Peltola *et al* 2019, Wang *et al* 2021, Saderne *et al* 2023, Ouyang *et al* 2023), the majority of these studies have focused on mid-latitude regions and/or have been limited to tropical forests (Barthel *et al* 2022). Additionally, studies focusing on African ecosystems are relatively scarce and have predominantly relied on static chamber methods (e.g. Otter and Scholes 2000,

Gasore 2007, Wanyama *et al* 2019, Castaldi *et al* 2020, Laris *et al* 2021).

Our study shows significant variations in CH₄ emissions during the rice growing season, mainly due to variations in hydrological conditions. Specifically, increased CH₄ emissions were observed on days following precipitation events, increasing SWC and leading to prolonged field flooding (figure 3(c)), consistent with previous studies (e.g. Alberto *et al* 2014). The intense flooding, and early stages of rice plant growth, created anaerobic conditions conducive to CH₄ production through methanogenesis, resulting in significant emissions in August (figure 6). During the maturation and ripening stages, the development of intercellular aerenchyma in rice plants likely facilitated oxygen transport between the atmosphere and the anaerobic zone (Lou *et al* 2008, Meijide *et al* 2011, Swain *et al* 2018). Furthermore, reduced field inundation contributed to a sharp decrease in CH₄ emissions in September and October, consistent with the observations of Wang *et al* (2017). Furthermore, the reported CH₄ fluxes from this study, ranging from -4.15 to 9.78 mgCH₄ m⁻² h⁻¹ (-12.36 to 86.78 mgCH₄ m⁻² d⁻¹), were comparable to values observed in previous studies based on paddy rice fields (Alberto *et al* 2014, Haque *et al* 2016, Martínez-Eixarch *et al* 2021), as well daily emissions rates (0.24 to 0.38 kgCH₄-C ha⁻¹ d⁻¹ or 32 to 50.1 gCH₄ m⁻² d⁻¹) in Ghana by Nikolaisen *et al* (2023b). The total amount of CH₄ emitted from June to October (2.01 gCH₄ m⁻²), was close to reported seasonal fluxes of 3.26 gCH₄ m⁻² (Alberto *et al* 2014), 2.1 to 2.9 gCH₄ m⁻², (Hatala *et al* 2012) and 5.01 gCH₄ m⁻² (Reba *et al* 2020). However, our study cumulated flux value was far lower than values of 27.9 gC m⁻² or 37.2 gCH₄ m⁻² (Meijide *et al* 2011) and 36.05 gCH₄ m⁻² (Maboni *et al* 2021) for continuous flooded rice fields. The relatively lower cumulative flux observed in our study could be attributed to the intermittent rainfall events which created multiple drying cycles. This may have inhibited continuous CH₄ production while enhancing CH₄ oxidation by methanotrophs. Notably, periods of continuous flooding, particularly in July and August, accounted for more than 75% of the cumulative emissions.

In the case of the forest reserve, CH₄ uptake increased slightly from June to July. However, CH₄ emissions remained at the same rate in August due to high SWC, which suppressed soil temperature and limited oxygen exchange. These conditions inhibited methanotrophic activity while promoting methanogenesis, consistent with findings from previous studies Wang *et al* (2021); Zhu *et al* (2021). As SWC decreased to an average of ~15% in September and further to ~12% in October (figure S1(a)) due to reduced rainfall and slightly elevated soil temperatures (figure S1(b)),

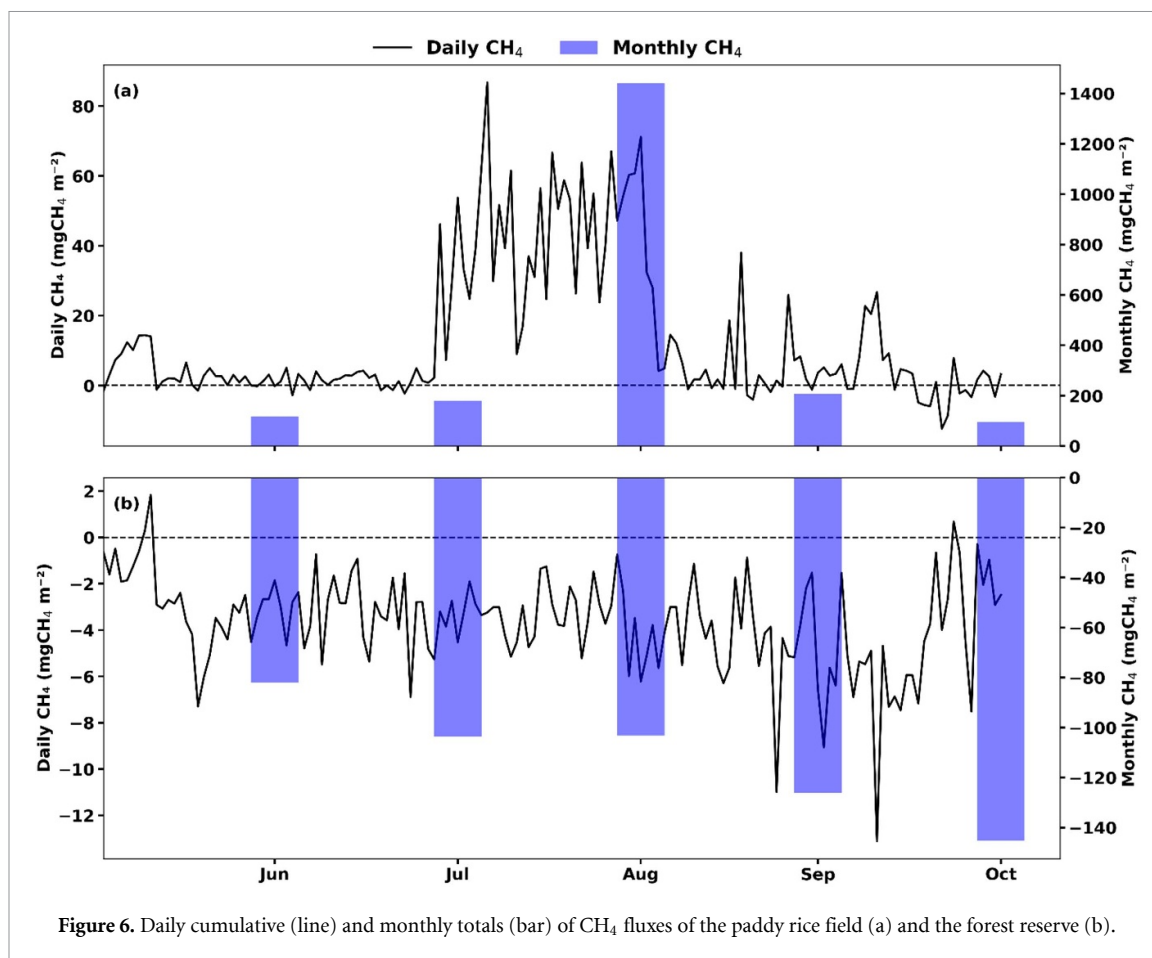


Figure 6. Daily cumulative (line) and monthly totals (bar) of CH₄ fluxes of the paddy rice field (a) and the forest reserve (b).

Table 1. Net radiative forcing of CH₄ expressed as CO₂ equivalent (gCO₂eq) using 20 and 100 year global warming potential (GWP) factors.

Month		June	July	August	September	October	Wet season (Total)
Rice field	CH ₄ (gCH ₄ m ⁻²)	0.12	0.18	1.44	0.21	0.09	2.04
	GWP_20 (gCO ₂ eq)	9.83	14.95	120.96	17.31	7.89	171.11
	GWP_100 (gCO ₂ eq)	3.27	4.98	40.32	5.79	2.63	57.04
Forest reserved	CH ₄ (gCH ₄ m ⁻²)	-0.08	-0.10	-0.10	-0.13	-0.14	-0.56
	GWP_20 (gCO ₂ eq)	-6.88	-8.74	-8.65	-10.58	-12.18	-47.04
	GWP_100 (gCO ₂ eq)	-2.30	-2.91	-2.88	-3.53	-4.06	-15.68

conditions became favorable for methanotrophic activity, thereby increasing CH₄ uptake. This result was expected, as methanotrophs are more sensitive to soil desiccation than methanogens (Meronigal and Guenther 2008), and elevated temperatures are known to accelerate their activity (Yvon-Durocher *et al* 2014, Knox *et al* 2021). In particular, vapor pressure deficit and latent heat flux, which regulate soil moisture and evaporation, respectively, emerged as key factors influencing CH₄ dynamics in the forest site (figure 5(b)). Our finding is also consistent with previous studies showing that upland forests function as CH₄ sinks (e.g. Zhao *et al* 2019, Castaldi *et al* 2020). The seasonal average CH₄ uptake value (-3.66 ± 2.09 mg CH₄ m⁻² d⁻¹) observed in our study aligns with the range reported in other forest ecosystems. For example, Castaldi

et al (2020) found that CH₄ uptake values ranged from -1.29 to -0.44 mg CH₄ m⁻² d⁻¹, while Barthel *et al* (2022) reported similar findings in the Congo Basin using static chambers. Additionally, Wang *et al* (2021) observed CH₄ uptake ranging from -2 to -6 mg CH₄ m⁻² d⁻¹ in a subtropical forest during the rainy season (June to October). Differences in daily CH₄ dynamics across these studies can likely be attributed to variations in plant composition, soil characteristics, and microbial communities among forest ecosystems. Nevertheless, these findings reinforce our conclusion that the Mole forest (Guinea savanna) acts as a CH₄ sink during the rainy season, emphasizing the importance of environmental factors in regulating CH₄ fluxes.

Our findings also reveal a significantly strong positive CH₄ radiative forcing from the rice field at

Janga, highlighting the need for special and resilient mitigation options, especially considering its impact on global warming over a 20 year horizon. In other words, rainfed rice cultivation in paddy fields may be a strong net positive radiative forcing in the next decades, considering the self-sufficiency rice production policy in the African continent than perhaps previously recognized (Arouna *et al* 2021, Luo *et al* 2023). Although the Mole forest exhibited a relatively weak negative radiative forcing per unit area ($-47.04 \text{ g CO}_2\text{-eq m}^{-2}$) compared to the positive radiative forcing of the rice field ($171.11 \text{ g CO}_2\text{-eq m}^{-2}$), its extensive land area of about 4840 km^2 (Schmitt and Adu-Nsiah 1993), with a significant proportion of which consists of upland soils favorable for methane uptake, could represent a substantial CH_4 sink. This sink can potentially offset the radiative forcing produced by several hectares of rice cultivation under paddy conditions. These findings highlight the critical role of protected upland forests as climate-smart, nature-based solutions for mitigating CH_4 emissions. Moreover, this is in line with international policies that promote forest conservation as an effective strategy for carbon sequestration and greenhouse gas mitigation (van der Gaast *et al* 2018).

5. Conclusion

At the regional level, our results have important implications for climate change mitigation strategies and policy development. They highlight the importance of recognizing the capacity of forest areas as CH_4 sinks to offset its emissions from rice cultivation and their impact on regional and global climate change. Our study showed that the rice field was a continuous source of CH_4 throughout the cultivation period, with SWC and vapor pressure deficit identified as the main driver of these high emissions. Conversely, the forest area acted as a net CH_4 sink, with key influencing factors including ecosystem respiration, vapor pressure deficit, latent heat, and soil temperature. These results provide important insights into the dynamics, environmental controls, and seasonal balance of CH_4 emissions and uptake in contrasting ecosystems with different land use and land management practices. In other words, this study emphasized the critical need for exploring mitigation strategies to combat climate change, particularly through the measurement of CH_4 due to its high radiative forcing potential in the atmosphere.

Our continuous EC measurements of CH_4 fluxes, which integrate emissions from soil and atmosphere within a footprint area, provided a more comprehensive and representative dataset than conventional static chamber methods. It is worth noting that our results are based on observations from a single rainy season. However, long-term measurements, including other key greenhouse gases such as N_2O , are essential to

capture the two contrasted ecosystems' full variability, dynamics, and overall carbon balance. Although our study focuses on rainfed rice cultivation, which accounts for about 70% of the total rice area harvested in sub-Saharan Africa—of which about 40% is classified as lowland rainfed without water control (Dossou-Yovo *et al* 2022, Saito *et al* 2023)—future research should include irrigated rice fields to assess their contribution to methane emissions relative to rainfed systems. In addition, further studies are needed to assess the impact of anthropogenic activities, such as fire events at the forest site, which could diminish its CH_4 uptake capacity. These findings demonstrated that forests could hold significant potential as climate-smart solutions for balancing ecosystem CH_4 emissions, particularly from rice cultivation, when protected from activities that compromise their CH_4 sink capacity. This highlights the dual benefits of integrating forest conservation with rice cultivation expansion as a viable land-based climate change mitigation strategy.

Data availability statement

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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Conflict of interest

The authors declare no competing financial interests.

Contributions

Samuel Guug performed the analyses and drafted the first manuscript. Samuel Guug, Frank Neidl, Rainer Steinbrecher, Souleymane Sy, Alex Frempong, Ines Spangenberg, Patrick Davies, and Michael Ayamba set up the EC stations and performed calibrations and maintenance. Souleymane Sy, Emmanuel Quansah

and Harald Kunstmann supervised the research. All authors contributed their expertise in developing the manuscript.

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